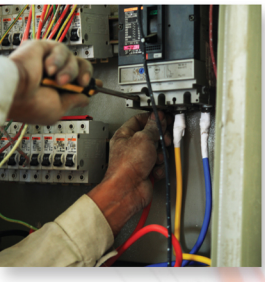
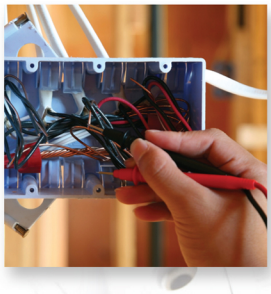
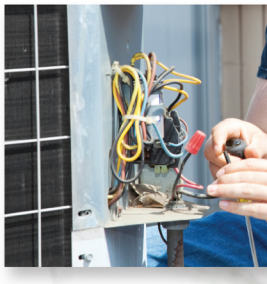
5th Edition

Electrical Studies for Trades







Stephen L. Herman

5th Edition

Electrical Studies for Trades

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

This is an electronic version of the print textbook. Due to electronic rights restrictions, some third party content may be suppressed. Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. The publisher reserves the right to remove content from this title at any time if subsequent rights restrictions require it. For valuable information on pricing, previous editions, changes to current editions, and alternate formats, please visit www.cengage.com/highered to search by ISBN#, author, title, or keyword for materials in your areas of interest.

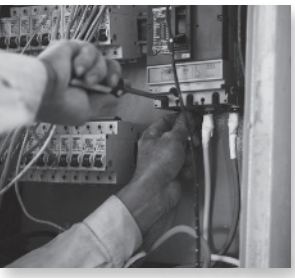
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

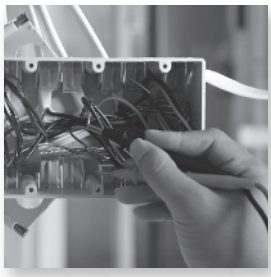
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5th Edition

Electrical Studies for Trades

Stephen L. Herman







DELMAR
CENGAGE Learning

Australia • Brazil • Japan • Korea • Mexico • Singapore • Spain • United Kingdom • United States

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

DELMAR
CENGAGE Learning®

Electrical Studies in Trades, 5E
Stephen L. Herman

Vice President, Careers & Computing: Dave Garza

Director of Learning Solutions: Sandy Clark

Acquisitions Editor: Stacy Masucci

Director, Development-Career and Computing: Marah Bellegarde

Managing Editor: Larry Main

Senior Product Manager: John Fisher

Editorial Assistant: Kaitlin Murphy

Brand Manager: Kristin McNary

Market Development Manager: Erin Brennan

Senior Production Director: Wendy Troeger

Production Manager: Mark Bernard

Senior Content Project Manager: Glenn Castle

Senior Art Director: David Arsenault

Technology Project Manager: Sheila Kosztowny

Cover image(s): Air Condition Service © iStockphoto/Janice Richard; Electric Works © iStockphoto/Danish Khan; Air Conditioning Repair © iStockphoto/Lisa F. Young; Electrical Switch Testing © iStockphoto/Yenwen Lu; Men Building Cabinet © iStockphoto/Steven Frame; Electrical Equipment On House Plans © iStockphoto/Catherine Yeulet

© 2014, 2010 Delmar, Cengage Learning

ALL RIGHTS RESERVED. No part of this work covered by the copyright herein may be reproduced, transmitted, stored or used in any form or by any means graphic, electronic, or mechanical, including but not limited to photocopying, recording, scanning, digitizing, taping, Web distribution, information networks, or information storage and retrieval systems, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without the prior written permission of the publisher.

For product information and technology assistance, contact us at
Cengage Learning Customer & Sales Support, 1-800-354-9706

For permission to use material from this text or product, submit all requests online at **www.cengage.com/permissions.**
Further permissions questions can be e-mailed to
permissionrequest@cengage.com

Library of Congress Control Number: 2012952120

ISBN-13: 978-1-133-27823-8

ISBN-10: 1-133-27823-X

Delmar
5 Maxwell Drive
Clifton Park, NY 12065-2919
USA

Cengage Learning is a leading provider of customized learning solutions with office locations around the globe, including Singapore, the United Kingdom, Australia, Mexico, Brazil, and Japan. Locate your local office at:
international.cengage.com/region

Cengage Learning products are represented in Canada by Nelson Education, Ltd.

To learn more about Delmar, visit **www.cengage.com/delmar**

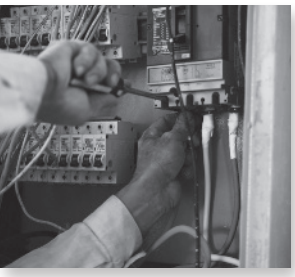
Purchase any of our products at your local college store or at our preferred online store **www.cengagebrain.com**

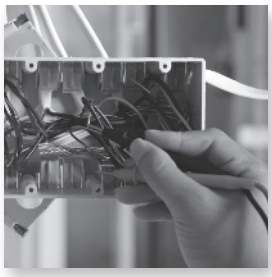
Notice to the Reader
Publisher does not warrant or guarantee any of the products described herein or perform any independent analysis in connection with any of the product information contained herein. Publisher does not assume, and expressly disclaims, any obligation to obtain and include information other than that provided to it by the manufacturer. The reader is expressly warned to consider and adopt all safety precautions that might be indicated by the activities described herein and to avoid all potential hazards. By following the instructions contained herein, the reader willingly assumes all risks in connection with such instructions. The publisher makes no representations or warranties of any kind, including but not limited to, the warranties of fitness for particular purpose or merchantability, nor are any such representations implied with respect to the material set forth herein, and the publisher takes no responsibility with respect to such material. The publisher shall not be liable for any special, consequential, or exemplary damages resulting, in whole or part, from the readers' use of, or reliance upon, this material.

Printed in the United States of America
1 2 3 4 5 6 7 16 15 14 13

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Contents







vii Preface

1 UNIT 1 Atomic Structure

21 UNIT 2 Electrical Quantities, Ohm's Law, and Resistors

62 UNIT 3 Electrical Sources and Static Charges

84 UNIT 4 Magnetism

115 UNIT 5 Series Circuits

140 UNIT 6 Parallel Circuits

164 UNIT 7 Combination Circuits

191 UNIT 8 Measuring Instruments

240 UNIT 9 Alternating Current

255 UNIT 10 Alternating Current Loads

270 UNIT 11 Capacitive Loads

300 UNIT 12 Three-Phase Circuits

319 UNIT 13 Transformers

348 UNIT 14 Three-Phase Transformers

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

367 UNIT 15 Electrical Services

399 UNIT 16 General Wiring Practices Part 1—Receptacle and Switch Connections

433 UNIT 17 General Wiring Practices Part 2—Protection Circuits, Dimmers, and Chimes

455 UNIT 18 Three-Phase Motors

493 UNIT 19 Single-Phase Motors

523 UNIT 20 Schematics and Wiring Diagrams

545 UNIT 21 Motor Installation

577 APPENDIX A American Wire Gauge Table

578 APPENDIX B Identification of Mica and Tubular Capacitors

582 APPENDIX C Alternating Current Formulas

595 APPENDIX D Greek Alphabet

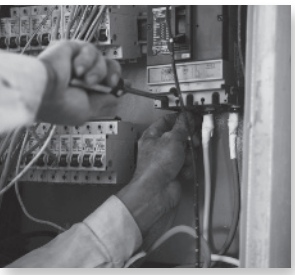
596 APPENDIX E Answers to Practice Problems

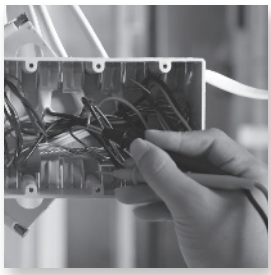
605 Glossary

611 Index

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Preface







There are many technical fields that require a working knowledge of electricity, such as air conditioning and refrigeration, automotive repair, electrical apprenticing, carpentry, building maintenance, construction work, and appliance repair. *Electrical Studies for Trades, 5th Edition* is written for technicians who are not electricians but who must have a practical working knowledge of electricity in their chosen field. The 5th edition of *Electrical Studies for Trades* is the most comprehensive revision of the text since it was first published in 1997.

This text assumes the students have no knowledge of electricity. *Electrical Studies for Trades, 5th Edition* begins with atomic structure and basic electricity. The text progresses through Ohm's Law calculations and series, parallel, and combination circuits. These concepts are presented in an easy-to-follow, step-by-step procedure. The math level is kept to basic algebra and trigonometry. It is not the intent of this text to present electricity from a purely mathematical standpoint, but rather to explain it in an easy-to-read, straightforward manner using examples and illustration.

Electrical Studies for Trades, 5th Edition includes concepts of inductance and capacitance in alternating current circuits. Both single-phase and three-phase power systems are covered. Some of the electrical machines discussed in the text are transformers, three-phase motors, and single-phase motors. Common measuring instruments such as voltmeters, ammeters, and ohmmeters are covered. The text also includes information on oscilloscopes because there are many circuits that require the use of an oscilloscope in troubleshooting.

Electrical Studies for Trades, 5th Edition provides information on basic wiring practices such as connection of electrical outlets and switch connections. Detailed explanations for the connection of single-pole, three-way, and four-way switches are presented in an easy-to-follow step-by-step

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

procedure. The text includes information on ground fault interrupters, arc-fault interrupters, light dimmers, and chime circuits. The final unit includes information on motor control schematics and wiring diagrams.

NEW FOR THE FIFTH EDITION

1. A completely new unit on three-phase transformers
2. Additional information on phase rotation
3. Updated graphics
4. The chapters concerning the installation of switches have been updated to the 2011 NEC

SUPPLEMENTS

An online Instructor Companion website contains an Instructor Guide with answers to end of chapter review questions, test banks, and chapter presentations done in PowerPoint.

ACCESSING AN INSTRUCTOR COMPANION WEBSITE SITE FROM SSO FRONT DOOR

1. Go to http://login.cengage.com and login using the Instructor email address and password.
2. Enter author, title, or ISBN in the "Add a Title to Your Bookshelf" search box, click on Search button.
3. Click Add to My Bookshelf to add Instructor Resources.
4. At the Product page, click on the Instructor Companion site link.

NEW USERS

If you're new to Cengage.com and do not have a password, contact your sales representative.

ACKNOWLEDGMENTS

The author and Cengage Delmar Learning would like to acknowledge and thank the reviewers for the many suggestions and comments given during the development of this fifth edition. Thanks go to:

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Daniel A. Blount
Holmes Community College
Ridgeland, MS

Ron Meyer
Central Community College
Hastings, NE

Marvin Moak
Hinds Community College
Raymond, MS

Larry Snyder
Red Rocks Community College
Lakewood, CO

Randy Ludington
Guilford Technical Community College
Jamestown, NC

Wes Evans
Truckee Meadows Community College
Reno, NV

Patrick Ottesen
Milwaukee Area Technical College
Oak Creek, WI

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 1

Atomic Structure

OBJECTIVES: After studying this unit, you should be able to:

- List the three major parts of an atom.
- State the law of charges.
- Discuss the law of centrifugal force.
- Discuss the differences between conductors, insulators, and semiconductors.

Electricity is the driving force that provides most of the power for the industrialized world. It is used to light homes, cook meals, heat and cool buildings, drive motors, and supply the ignition for most automobiles. The technician who understands electricity can seek employment in almost any part of the world.

Electrical sources are divided into two basic types, **direct current** (DC) and **alternating current** (AC). Direct current is **unidirectional,** which means that it flows in only one direction. The first part of this text will be devoted mainly to the study of direct current. Alternating current is **bidirectional,** which means that it reverses its direction of flow at regular intervals. The latter part of this text is devoted mainly to the study of alternating current.

direct current
current that does not reverse its direction of flow.

alternating current
current that reverses its direction of flow periodically. Reversals generally occur at regular intervals.

unidirectional
current that flows in one direction only.

bidirectional
current that flows in more than one direction.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EARLY ELECTRICAL HISTORY

Although the practical use of electricity has become common within the last hundred years, it has been known as a force for much longer. The Greeks discovered electricity about 2,500 years ago. They noticed that when amber was rubbed with other materials, it became charged with an unknown force. This force had the power to attract other objects, such as dried leaves, feathers, bits of cloth, or other lightweight materials. The Greeks called amber *elektron.* The word *electric* was derived from this word because like amber, it had the ability to attract other objects. This mysterious force remained a curious phenomenon until other people began to conduct experiments about 2,000 years later. In the early 1600s, William Gilbert discovered that materials other than amber could be charged to attract other objects. He called materials that could be charged *electriks* and materials that could not be charged *nonelektriks.*

About 300 years ago, a few men began to study the behavior of various charged objects. In 1733, a Frenchman named Charles DuFay found that a piece of charged glass would repel some charged objects and attract others. These men soon learned that the force of **repulsion** was just as important as the force of **attraction.** From these experiments, two lists were developed, FIGURE 1-1. Any material in list A would attract any of the materials in list B. All materials in list A would repel each other, and all the materials in

repulsion
the force that repels one object from another.

attraction
the force that attracts one object to another.

LIST A	LIST B
Glass (rubbed on silk)	Hard rubber (rubbed on wool)
Glass (rubbed on wool or cotton)	Block of sulfur (rubbed on wool or fur)
Mica (rubbed on cloth)	Most kinds of rubber (rubbed on cloth)
Asbestos (rubbed on cloth or paper)	Sealing wax (rubbed on silk, wool, or fur)
Stick of sealing wax (rubbed on wool)	Glass or mica (rubbed on dry wool)
	Amber (rubbed on cloth)

© Cengage Learning 2014

FIGURE 1-1 List of charged materials.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

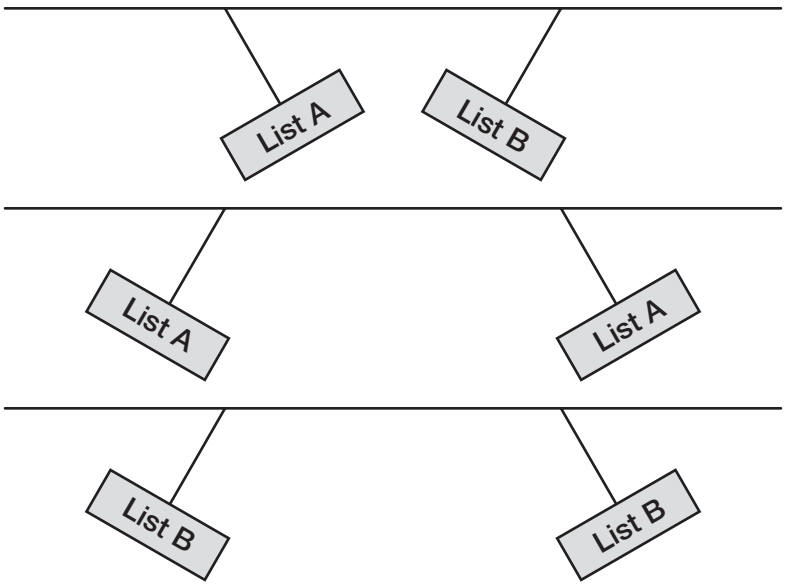


FIGURE 1-2 Unlike charges attract and like charges repel.

list B would repel each other, FIGURE 1-2. Various names were suggested for the materials in lists A and B. Any opposite-sounding names such as east and west, north and south, male and female could have been chosen. Benjamin Franklin named the materials in list A **positive** and the materials in list B **negative.** These names are still used today. The first item in each list was used as a standard for determining if a charged object was positive or negative. Any object repelled by a piece of glass rubbed on silk had a positive charge, and any item repelled by a hard rubber rod rubbed on wool had a negative charge.

ATOMS

To understand electricity, it is necessary to start with the study of atoms. The **atom** is the basic building block of the universe. All **matter** is made from a combination of atoms. Matter is any substance that has mass and occupies space. Matter can exist in any of three states: solid, liquid, or gas. Water, for example, can exist as a solid in the form of ice, as a liquid, or as a gas in the form of steam, FIGURE 1-3. An atom is the smallest part of an **element.** A chart listing both natural and artificial elements is shown in FIGURE 1-4. The three principal parts of an atom are the **electron, neutron,** and **proton.** The smallest atom is hydrogen which contains one proton and one electron. The smallest atom that contains both electrons and protons in the nucleus is helium which contains two protons and two neutrons.

positive/negative
one polarity of a voltage, current, or charge.

atom
smallest part of an element that contains all the properties of that element.

matter
a physical substance.

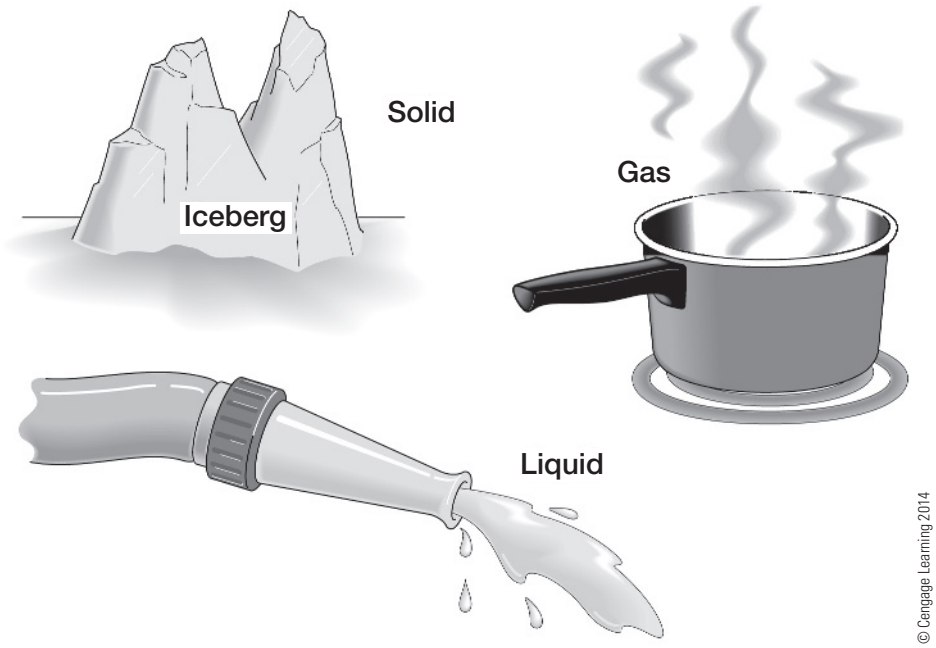
element
(1) One of the basic building blocks of nature. An atom is the smallest part of an element. (2) One part of a group of devices.

electron
one of the three major parts of an atom. The electron carries a negative charge.

neutron
one of the principal parts of an atom. The neutron has no charge and is part of the nucleus.

proton
one of the three major parts of an atom. The proton has a positive charge.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 1-3 Water can exist in three states depending on temperature and pressure.

nucleus
the center of an atom composed of protons and neutrons.

atomic number
the number of protons contained in the nucleus of an atom.

Notice that the proton has a positive charge, the electron has a negative charge, and the neutron has no charge. The neutron and proton combine to form the **nucleus** of the atom. Because the neutron has no charge, the nucleus will have a net positive charge. The number of protons in the nucleus determines the element of an atom. Oxygen, for example, contains eight protons in its nucleus, and gold contains seventy-nine. The **atomic number** of an element is the same as the number of protons in the nucleus. The lines of force produced by the positive charge of the proton extend outward in all directions, FIGURE 1-6. The nucleus may or may not contain as many neutrons as protons. For example, an atom of helium contains two protons and two neutrons in its nucleus. An atom of copper contains twenty-nine protons and thirty-five neutrons, FIGURE 1-7.

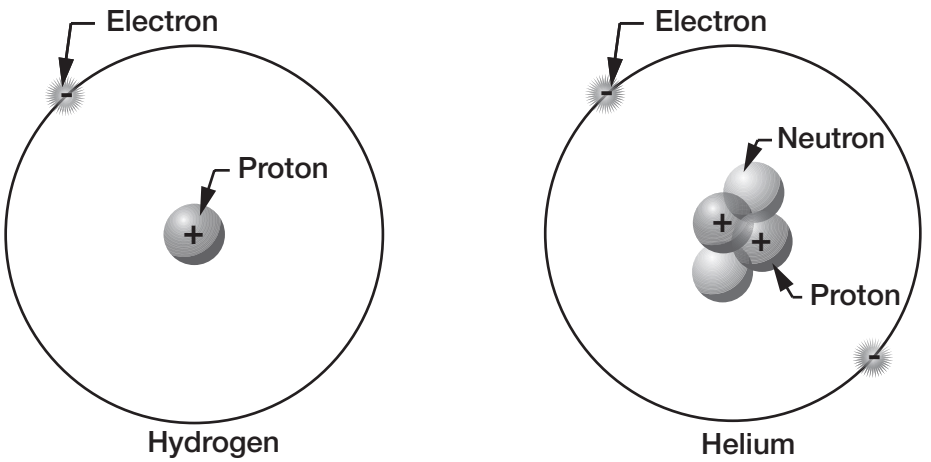
The electron orbits around the outside of the nucleus. The latest scientific measurements suggest protons and neutrons weigh about 1838 times more than the electron, and that the electron is approximately 1/1000 the size of a proton, FIGURE 1-5. Many scientists believe that it is almost impossible to accurately measure the size of these particles and the actual size is of no real importance. It is the characteristics of the particles that is

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

ATOMIC NUMBER	NAME	VALENCE ELECTRONS	SYMBOL
1	Hydrogen	1	H
2	Helium	2	He
3	Lithium	1	Li
4	Beryllum	2	Be
5	Boron	3	B
6	Carbon	4	C
7	Nitrogen	5	N
8	Oxygen	6	O
9	Fluorine	7	F
10	Neon	8	Ne
11	Sodium	1	Na
12	Magnesium	2	Ma
13	Aluminum	3	Al
14	Silicon	4	Si
15	Phosphorus	5	P
16	Sulfur	6	S
17	Chlorine	7	Cl
18	Argon	8	A
19	Potassium	1	K
20	Calcium	2	Ca
21	Scandium	2	Sc
22	Titanium	2	Ti
23	Vanadium	2	V
24	Chromium	1	Cr
25	Manganese	2	Mn
26	Iron	2	Fe
27	Cobalt	2	Co
28	Nickel	2	Ni
29	Copper	1	Cu
30	Zinc	2	Zn
31	Gallium	3	Ga
32	Germanium	4	Ge
33	Arsenic	5	As
34	Selenium	6	Se
35	Bromine	7	Br
36	Krypton	8	Kr
37	Rubidium	1	Rb
38	Strontium	2	Sr
39	Yttrium	2	Y
40	Zirconium	2	Zr
41	Niobium	1	Nb
42	Molybdenum	1	Mo
43	Technetium	2	Tc
44	Ruthenium	1	Ru
45	Rhodium	1	Rh
46	Palladium	–	Pd
47	Silver	1	Ag
48	Cadmium	2	Cd
49	Indium	3	In
50	Tin	4	Sn
51	Antimony	5	Sb
52	Tellurium	6	Te
53	Iodine	7	I
54	Xenon	8	Xe
55	Cesium	1	Cs
56	Barium	2	Ba
57	Lanthanum	2	La
58	Cerium	2	Ce
59	Praseodymium	2	Pr
60	Neodymium	2	Nd
61	Promethium	2	Pm
62	Samarium	2	Sm
63	Europium	2	Eu
64	Gadolinium	2	Gd
65	Terbium	2	Tb
66	Dysprosium	2	Dy
67	Holmium	2	Ho
68	Erbium	2	Er
69	Thulium	2	Tm
70	Ytterbium	2	Yb
71	Lutetium	2	Lu
72	Hafnium	2	Hf
73	Tantalum	2	Ta
74	Tungsten	2	W
75	Rhenium	2	Re
76	Osmium	2	Os
77	Iridium	2	Ir
78	Platinum	1	Pt
79	Gold	1	Au
80	Mercury	2	Hg
81	Thallium	3	Tl
82	Lead	4	Pb
83	Bismuth	5	Bl
84	Polonium	6	Po
85	Astatine	7	At
86	Radon	8	Rd
87	Francium	1	Fr
88	Radium	2	Ra
89	Actinium	2	Ac
90	Thorium	2	Th
91	Protactinium	2	Pa
92	Uranium	2	U
	Artifical Elements		
93	Neptunium	2	Np
94	Plutonium	2	Pu
95	Americium	2	Am
96	Curium	2	Cm
97	Berkelium	2	Bk
98	Californium	2	Cf
99	Einsteinium	2	E
100	Fermium	2	Fm
101	Mendelevium	2	Mv
102	Nobelium	2	No
103	Lawrencium	2	Lw

© Cengage Learning 2014

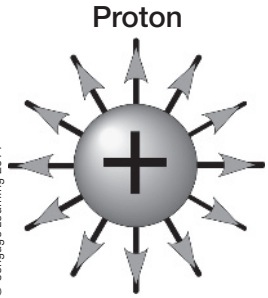
FIGURE 1-4 Table of elements.



© Cengage Learning 2014

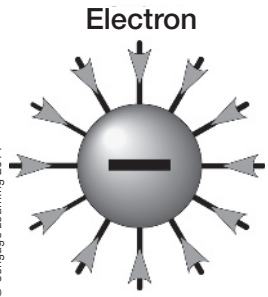
FIGURE 1-5 The smallest atom that contains both protons and neutrons in the nucleus is helium.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



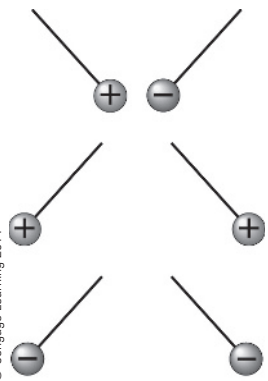
© Cengage Learning 2014

FIGURE 1-6 The lines of force extend outward.



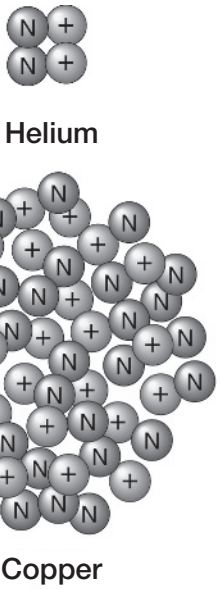
© Cengage Learning 2014

FIGURE 1-8 The lines of force move toward the electron.



© Cengage Learning 2014

FIGURE 1-9 Unlike charges attract and like charges repel.



The nucleus of a helium atom contains 2 protons and 2 neutrons.

The nucleus of a copper atom contains 29 protons and 35 neutrons.

© Cengage Learning 2014

FIGURE 1-7 The nucleus may or may not contain the same number of protons and neutrons.

of importance. Because the electron exhibits a negative charge, the lines of force come from all directions, FIGURE 1-8.

THE LAW OF CHARGES

One of the basic laws concerning atoms is the law of charges, which states that **opposite charges attract and like charges repel.** FIGURE 1-9 illustrates this principle. In Figure 1-9, charged balls are suspended from strings. Notice that the two balls that contain opposite charges are attracted to each other. The two positively charged balls and the two negatively charged balls are repelled from each other. The reason for this is that a basic law of physics states that lines of force can never cross each other. The outward-going lines of force of a positively charged object combine with the inward-going lines of force of a negatively charged object, FIGURE 1-10. This produces an attraction between the two objects. If two objects with like charges come in proximity with each other, the lines of force repel, FIGURE 1-11. Since the nucleus has a net positive charge and the electron has a negative charge, the electron is attracted to the nucleus.

Because the nucleus of an atom is formed from the combination of protons and neutrons, one might ask why the protons of the nucleus do not repel each other since they all have the same charge. Two theories attempt to explain this. The first theory, which is no longer supported, asserted that

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

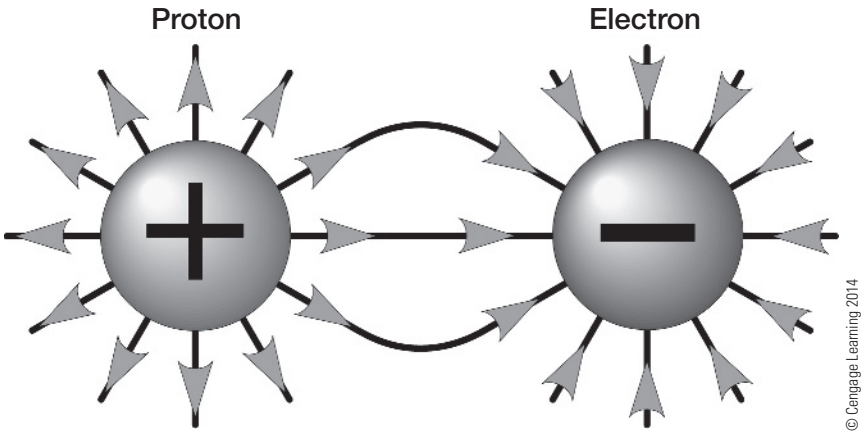


FIGURE 1-10 Unlike charges attract each other.

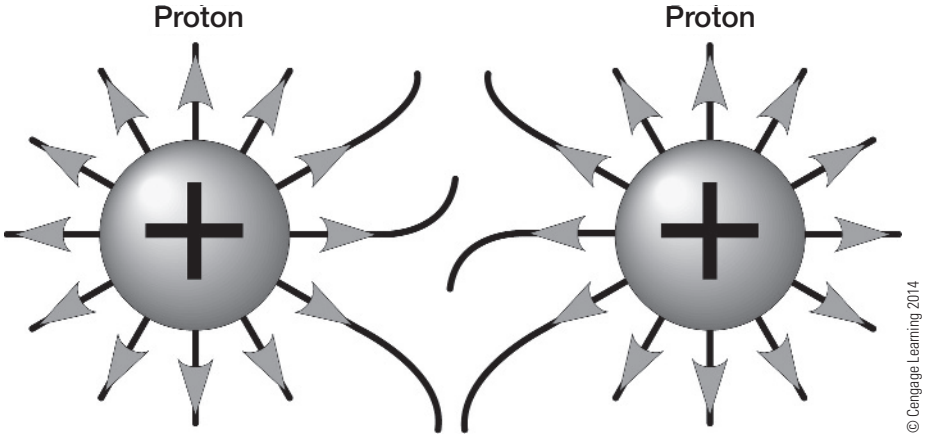


FIGURE 1-11 Like charges repel each other.

the force of gravity held the nucleus together. Neutrons, like protons, are extremely massive particles. It was first theorized that the gravitational attraction caused by their mass overcame the repelling force of the positive charges. By the mid-1930s, however, it was known that the force of gravity could not hold the nucleus together. According to Coulomb's Law, the electromagnetic force in helium is about 1.1×10^{36} times greater than Newton's Law of gravitational force. In 1947 the Japanese physicist, Hideki Yukawa, introduced the second theory by identifying a subatomic particle that acts as a mediator to hold the nucleus together. The particle is a quark known as a *gluon.* The force of the gluon is about 10^2 times stronger than the electromagnetic force.

KEY POINT

Opposite charges attract and like charges repel.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

STRUCTURE OF THE ATOM

In 1808, a scientist named John Dalton proposed that all matter was composed of atoms. Although the assumptions that Dalton used to prove his theory were later found to be factually incorrect, the idea that all matter is composed of atoms was adopted by most of the scientific world. Then in 1897, J.J. Thompson discovered the electron. Thompson determined that electrons have a negative charge and that they have very little mass compared to the atom. He proposed that atoms have a large positively charged massive body with negatively charged electrons scattered throughout it. Thompson also proposed that the negative charge of the electrons exactly balanced the positive charge of the large mass, causing the atom to have a net charge of zero. Thompson's model of the atom proposed that electrons existed in a random manner within the atom, much like firing BBs from a BB gun into a slab of cheese. This was referred to as the plum pudding model of the atom.

In 1913, a Danish scientist named Niels Bohr presented the most accepted theory concerning the structure of an atom. In the Bohr model, electrons exist in specific or "allowed" orbits around the nucleus in much the same that planets orbit the sun, FIGURE 1-12. The orbit in which the electron exists is determined by the electron's mass, times its speed, times the radius of the orbit. These factors must equal the positive force of the nucleus. In theory there can be an infinite number of allowed orbits.

When an electron receives enough energy from some other source it "quantum jumps" into a higher allowed orbit. Electrons, however, tend to return to a lower allowed orbit. When this occurs, the electron emits the excess energy as a single photon of electromagnetic energy.

ELECTRON ORBITS

Atoms have a set number of electrons that can be contained in one orbit, or shell, called an **electron orbit,** FIGURE 1-13. The number of electrons that can be contained in any one shell is found by the formula ($2N^2$). The letter *N* represents the number of the orbit, or shell. For example, the first orbit can hold no more than two electrons.

$$2 \times (1)^2 \textbf{ or}$$

$$2 \times 1 = 2$$

The second orbit can hold no more than eight electrons.

$$2 \times (2)^2 \textbf{ or}$$

$$2 \times 4 = 8$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

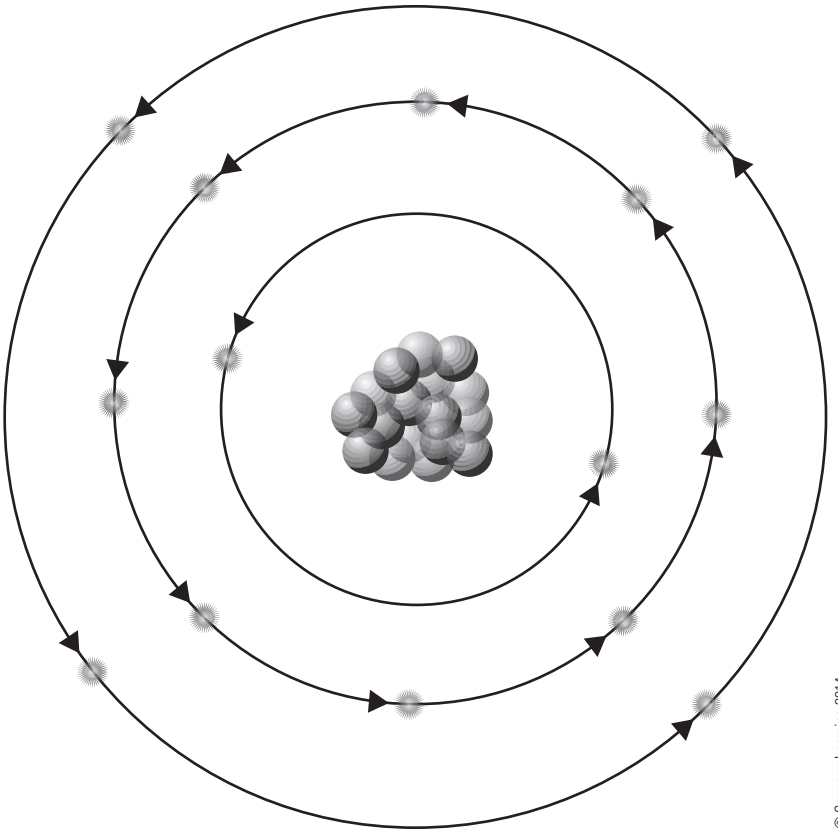

© Cengage Learning 2014

FIGURE 1-12 Electrons exist in allowed orbits around the nucleus.

The third orbit can contain no more than eighteen electrons.

$$2 \times (3)^2 \textbf{ or}$$

$$2 \times 9 = 18$$

The fourth and fifth orbits can hold no more than thirty-two electrons. Thirty-two is the maximum number of electrons that can be contained in any orbit.

$$2 \times (4)^2 \textbf{ or}$$

$$2 \times 16 = 32$$

Although atoms are often drawn flat, as illustrated in Figure 1-13, the electrons orbit around the nucleus in a circular fashion, as shown in FIGURE 1-14. The electrons travel at such a high rate of speed that they form

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

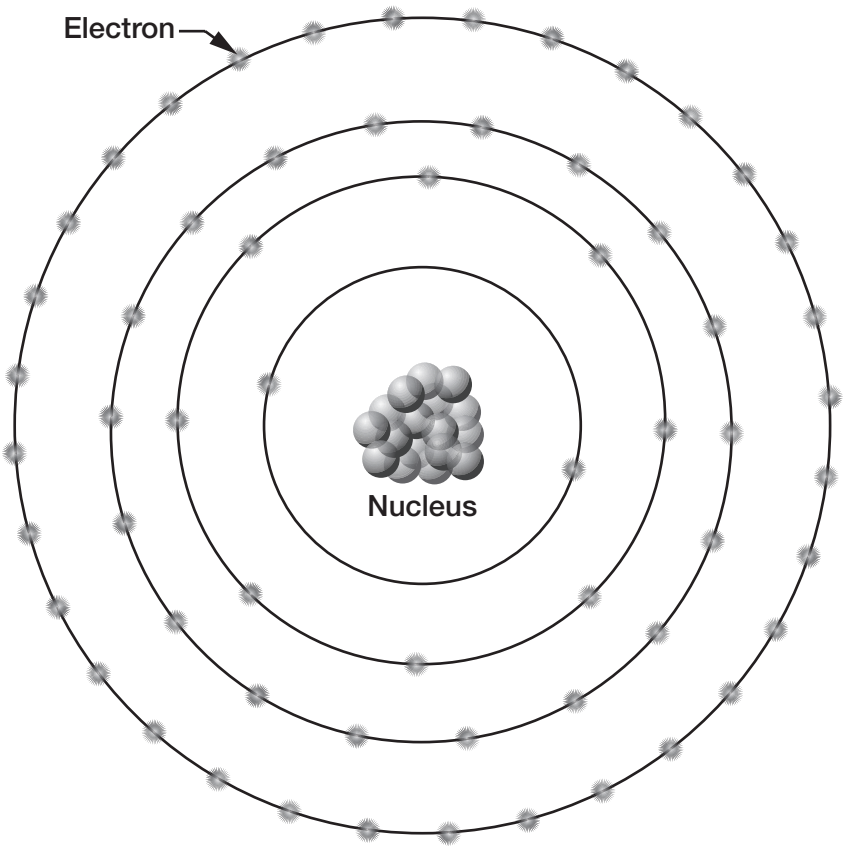


FIGURE 1-13 Electron orbits.

a shell around the nucleus. This is similar to a golf ball that is surrounded by a tennis ball that is surrounded by a basketball. For this reason, electron orbits are often referred to as *shells.*

VALENCE ELECTRONS

valence electrons electrons located in the outer orbit of an atom.

conductor device or material that permits current to flow through it easily.

The outer shell of an atom is known as the *valence* shell. Electrons located in the outer shell of an atom are known as **valence electrons,** FIGURE 1-15. The valence shell of an atom cannot hold more than eight electrons. It is the valence electrons that are of primary concern in the study of electricity, because it is these electrons that explain much of electrical theory. A **conductor,** for instance, is made from a material that contains one or two valence electrons. Conductors are materials that permit electrons to flow through them easily. When an atom has only one or two valence electrons, the electrons are loosely

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

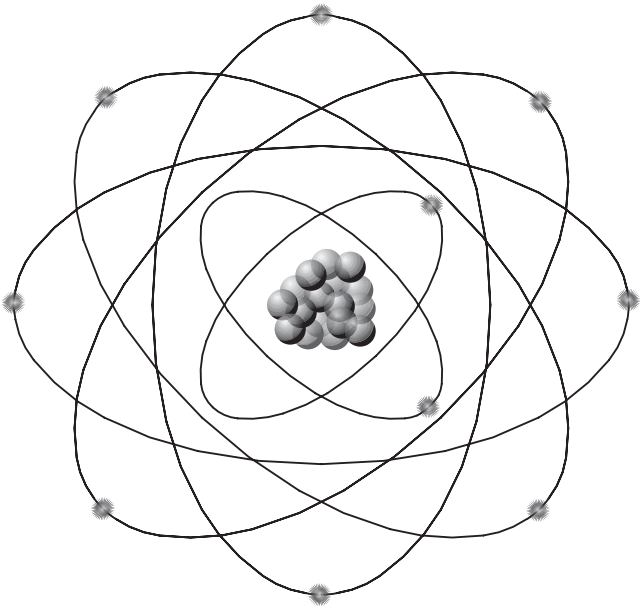
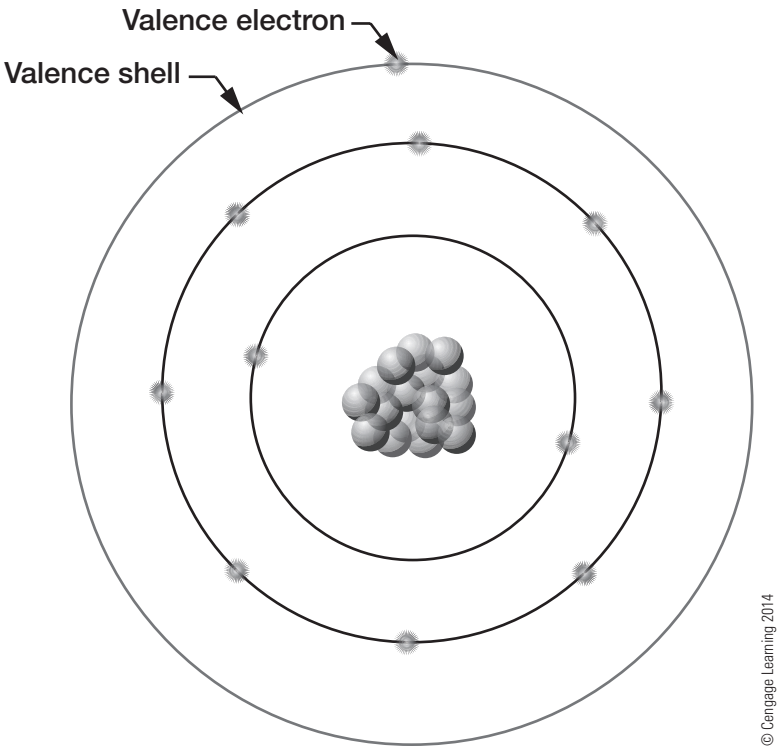

© Cengage Learning 2014

FIGURE 1-14 Electrons orbit the nucleus in a circular fashion.



© Cengage Learning 2014

FIGURE 1-15 The electrons located in the outer orbit of an atom are valence electrons.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

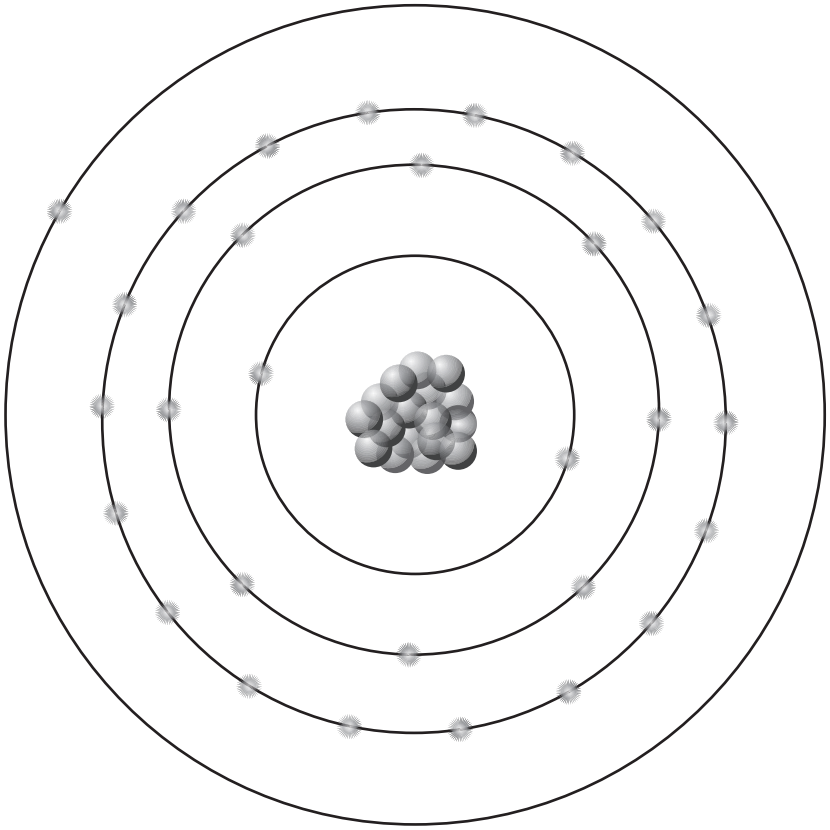

© Cengage Learning 2014

FIGURE 1-16 A copper atom contains twenty-nine electrons and has one valence electron.

held by the atom and are easily given up for current flow. Silver, copper, gold, and platinum all contain one valence electron and are excellent conductors of electricity. Silver is the best natural conductor of electricity, followed by copper, gold, and aluminum. Aluminum, which contains three valence electrons, is a better conductor of electricity than platinum, which contains only one valence electron. An atom of copper is shown in FIGURE 1-16. Although it is known that atoms that contain few valence electrons are the best conductors, it is not known why some of these materials are better conductors than others.

ELECTRON FLOW

Electrical current is the flow of electrons. There are several theories concerning how electrons are made to flow through a conductor. One theory is generally referred to as the *bump theory*. It states that current flow is produced when an electron from one atom knocks electrons of another atom out of orbit. FIGURE 1-17 illustrates this action. When an atom contains only one

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

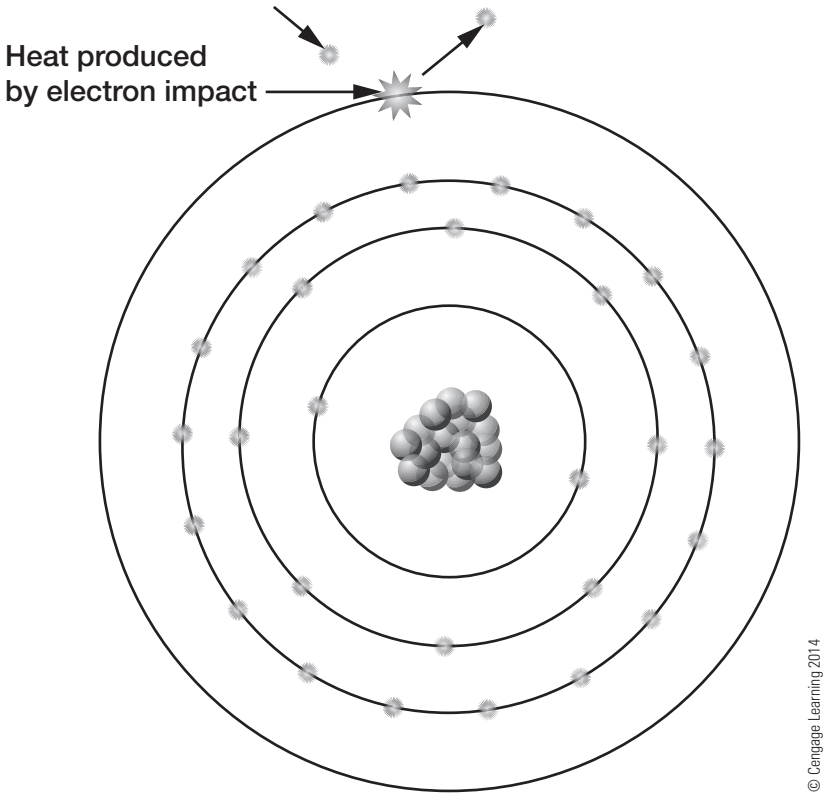
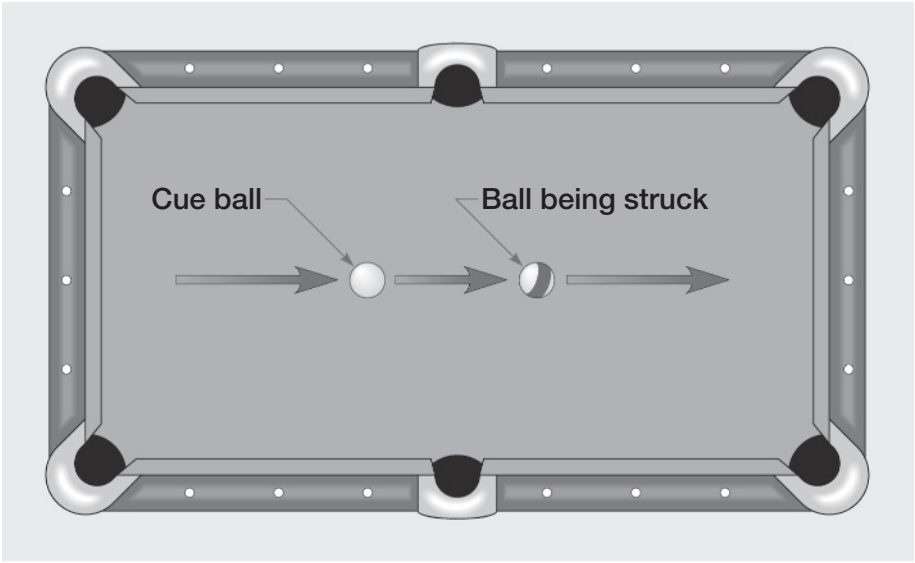


FIGURE 1-17 An electron of one atom knocks an electron of another atom out of orbit.

valence electron, it is easily given up when struck by another electron. The striking electron gives its energy to the electron being struck. The striking electron settles into orbit around the atom, and the electron that was struck moves off to strike another electron. This same action can often be seen in the game of pool. If the moving cue ball strikes a stationary ball exactly right, the energy of the cue ball is given to the stationary ball. The stationary ball then moves off with most of the energy of the cue ball, and the cue ball stops moving, FIGURE 1-18. The stationary ball did not move off with *all* of the energy of the cue ball; it moved off with most of the energy of the cue ball. Some of the energy of the cue ball was lost to heat when it struck the stationary ball. This is true when one electron strikes another. This is the reason why a wire heats when current flows through it. If too much current flows through a wire, it will overheat and become damaged and possibly become a fire hazard.

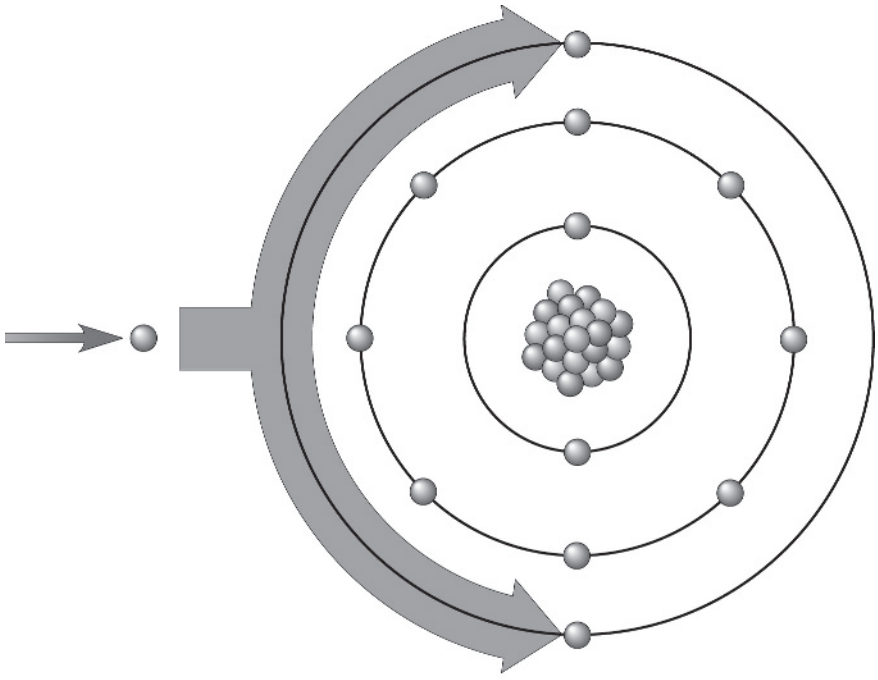
If an atom that contains two valence electrons is struck by a moving electron, the energy of the striking electron is divided between the two valence electrons, FIGURE 1-19. If the valence electrons are knocked out of orbit, they

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 1-18 The energy of the cue ball is given to the ball being struck.



© Cengage Learning 2014

FIGURE 1-19 The energy of the striking electron is divided.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

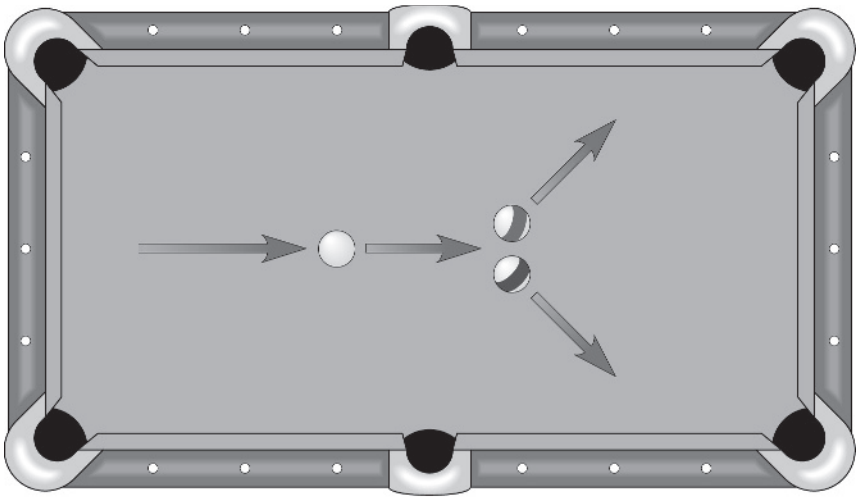

© Cengage Learning 2014

FIGURE 1-20 The energy of the cue ball is divided between the two other balls.

will contain only half the energy of the striking electron. This action can also be seen in the game of pool, FIGURE 1-20. If a moving cue ball strikes two stationary balls at the same time, the energy of the cue ball is divided between the two stationary balls. Both stationary balls will move, but with only half the energy of the cue ball.

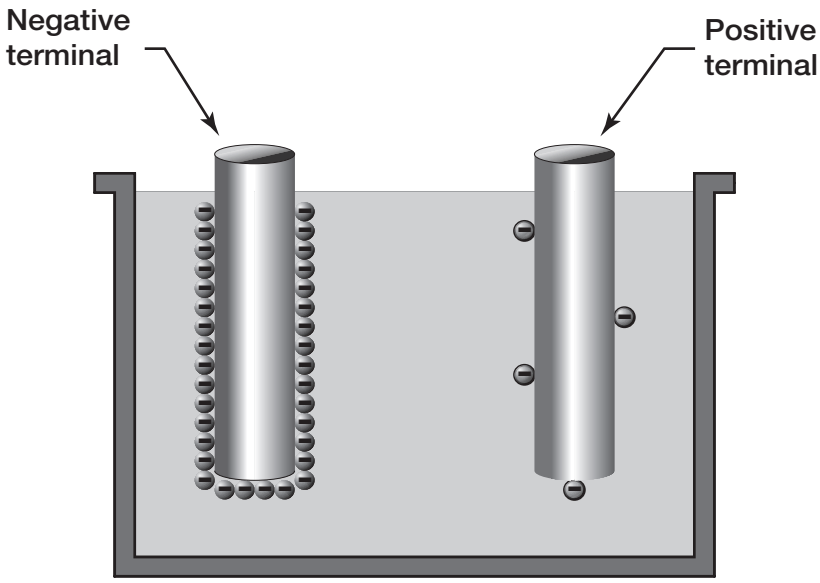
Other theories deal with the fact that all electric power sources produce a **positive** and **negative** terminal. The negative terminal is created by causing an excess of electrons to form at that terminal and the positive terminal is created by removing a large number of electrons from that terminal, FIGURE 1-21. Different methods can be employed to produce the excess of electrons at one terminal and deficiency of electrons at the other, but when a circuit is completed between the two terminals, negative electrons are **repelled** away from the negative terminal and **attracted** to the positive, FIGURE 1-22. The greater the difference in the number of electrons between the negative and positive terminals, the greater the force of repulsion and attraction.

INSULATORS

Materials that are made from atoms that contain seven or eight valence electrons are known as **insulators.** Insulators are materials that resist the flow of electricity. When the valence shell of an atom is full, or almost full, of electrons, the electrons are tightly held and not easily given up. Some good examples of insulator materials are rubber, plastic, glass, and wood. FIGURE 1-23 illustrates what happens when a moving electron strikes an

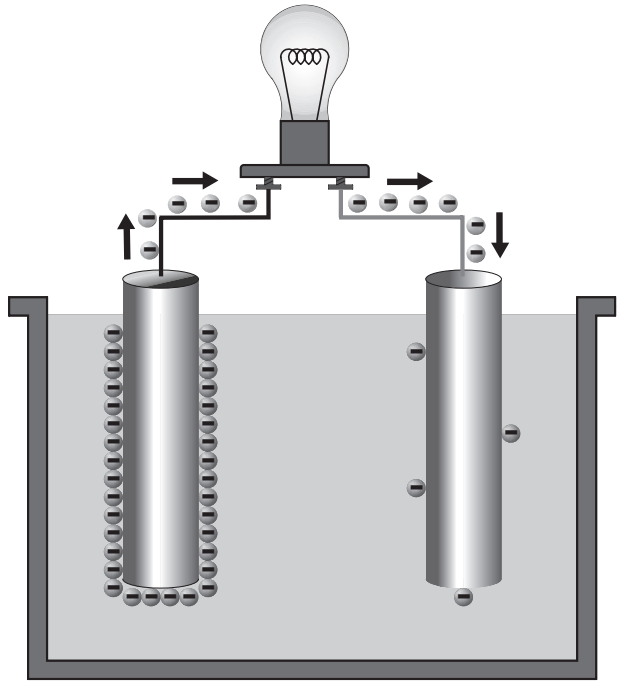
insulators
materials used to electrically isolate two conductive surfaces.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 1-21 All electrical power sources produce a positive and negative terminal.



© Cengage Learning 2014

FIGURE 1-22 Completing a circuit between the positive and negative terminals causes electrons to be repelled from the negative terminal and attracted to the positive terminal.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

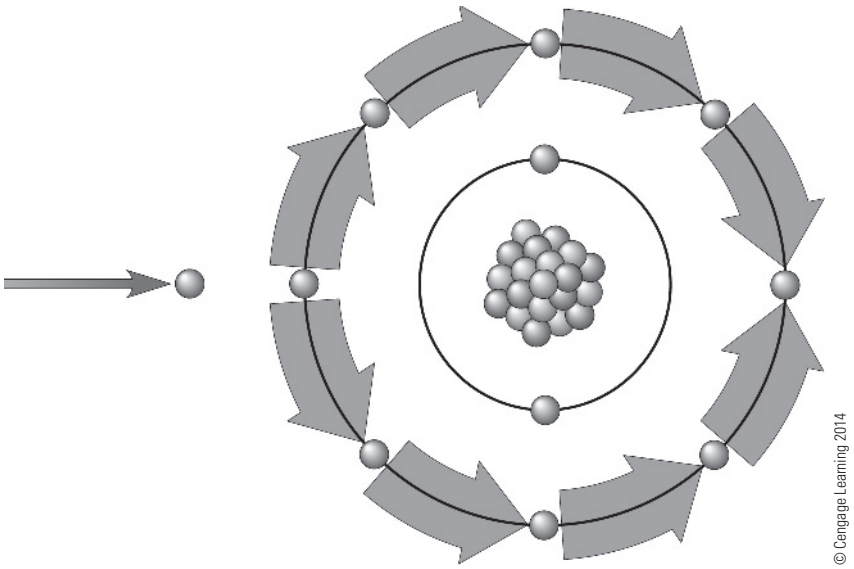


FIGURE 1-23 The energy of the striking electron is divided among the eight electrons.

atom that contains eight valence electrons. The energy of the moving electron is divided so many times that it has little effect on the atom. An atom that has seven or eight valence electrons is extremely stable and does not easily give up an electron.

SEMICONDUCTORS

Semiconductors are materials that are neither good conductors nor good insulators. They contain four valence electrons, FIGURE 1-24. Semiconductors are also characterized by the fact that as they are heated, their resistance decreases. This is the opposite of a conductor, which *increases* its resistance with an increase of temperature. Semiconductors have become extremely important in the electrical industry since the invention of the transistor in 1947. All solid-state devices, such as diodes, transistors, and integrated circuits, are made from combinations of semiconductor materials. The two most common materials used in the production of electronic components are silicon and germanium. Of the two, silicon is used more often because of its ability to withstand heat.

Semiconductors material that contains four valence electrons and is used in the production of solid-state devices.

Metal oxides are also popular for the production of semiconductor devices. Metal oxide semiconductor (MOS) devices are used where low power drain is essential. These devices are used in electronic watches, computer memories, calculators, and hundreds of other low-current devices.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

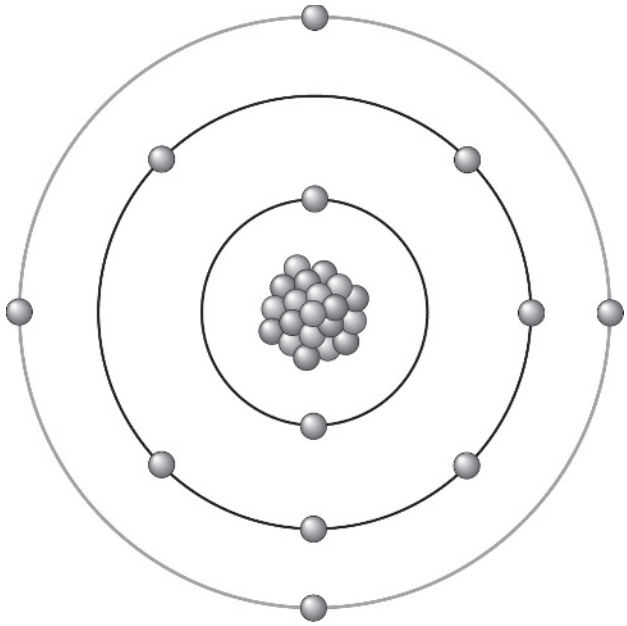

© Cengage Learning 2014

FIGURE 1-24 Semiconductors contain four valence electrons.

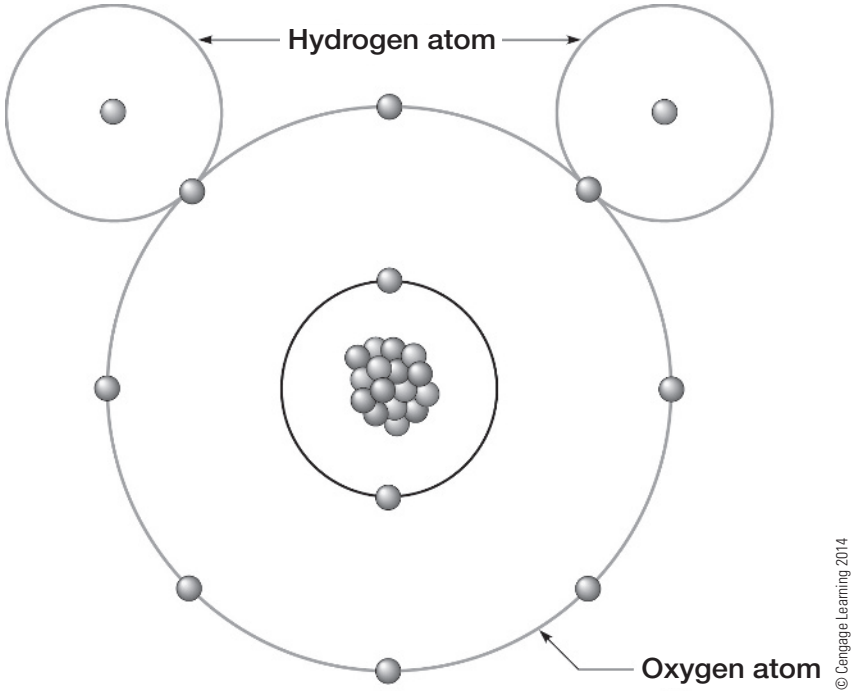


FIGURE 1-25 Water molecule.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

MOLECULES

molecules
the smallest part of a compound.

Although all matter is made from atoms, atoms should not be confused with **molecules,** which are the smallest part of a compound. Water, for example, is a compound, not an element. The smallest particle of water that can exist is a molecule, which is made of two atoms of hydrogen and one atom of oxygen, H_2O, FIGURE 1-25. If the molecule of water is broken apart, it becomes two hydrogen atoms and one oxygen atom, but it is no longer water.

Summary

1. The atom is the smallest part of an element.
2. The three basic parts of an atom are the proton, electron, and neutron.
3. Protons have a positive charge, electrons have a negative charge, and neutrons have no charge.
4. Valence electrons are the electrons located in the outer orbit of an atom.
5. Conductors are materials that provide an easy path for electron flow.
6. Conductors are made from materials that contain one, two, or three valence electrons.
7. Insulators are materials that do not provide an easy path for the flow of electrons.
8. Insulators are generally made from materials that contain seven or eight valence electrons.
9. Semiconductors contain four valence electrons.
10. Semiconductors are used in the construction of all solid-state devices, such as diodes, transistors, and integrated circuits.
11. Molecules are the smallest part of a compound.

Review Questions

1. What are the three subatomic parts of an atom and what charge does each carry?
2. How many times smaller is an electron than a proton?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

3. How many times greater is the weight of a proton than an electron?
4. State the law of charges.
5. What force keeps the electron from falling into the nucleus of the atom?
6. How many valence electrons are generally contained in materials that are used for conductors?
7. How many valence electrons are generally contained in materials that are used for insulators?
8. What is electricity?
9. What is a gluon?
10. It is theorized that electrons, protons, and neutrons are actually formed from a combination of smaller particles. What are these particles called?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 2

Electrical Quantities, Ohm's Law, and Resistors

OBJECTIVES: After studying this unit, you should be able to:

- Define a coulomb.
- State the definition of *amp.*
- State the definition of *volt.*
- State the definition of *ohm.*
- State the definition of *watt.*
- Compute different electrical values using Ohm's Law formulas.
- Discuss different types of electric circuits.
- Select the proper Ohm's Law formula from a chart.
- List the major types of fixed resistors.
- Determine the resistance of a resistor using the color code.
- Determine if a resistor is operating within its power rating.
- Connect a variable resistor used as a potentiometer.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Electricity has a standard set of values. Before technicians can work with electricity, they must have a knowledge of these values and how to use them. Since the values of electrical measurement have been standardized, they are understood by everyone who uses them. For instance, carpenters use a standard system for measuring length, such as the inch, foot, meter, or centimeter. Imagine what a house would look like that was constructed by two carpenters that used different lengths of measure for an inch or foot. The same holds true for people who work with electricity. The standards of measure must be the same for everyone. Meters should be calibrated to indicate the same quantity of current flow, or voltage, or resistance. A volt, amp, or ohm is the same for everyone who uses it, regardless of where in the world they live and work.

coulomb
quantity of electrons equal to 6.25×10^{18}.

KEY POINT
Coulomb's Law of electrostatic charges states that the force of electrostatic attraction or repulsion is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.

THE COULOMB

The first electrical quantity to be discussed is the **coulomb.** A coulomb is a quantity measurement of electrons. One coulomb contains 6.25×10^{18} or 6,250,000,000,000,000,000 electrons. To better understand the number of electrons contained in a coulomb, think of comparing one second to two hundred billion years. Since the coulomb is a quantity measurement, it is similar to a quart, gallon, or liter. It takes a certain amount of liquid to equal a liter, just as it takes a certain amount of electrons to equal a coulomb.

The coulomb is named for a scientist named Coulomb who lived in the 1700s. Coulomb experimented with electrostatic charges and developed a law dealing with the attraction and repulsion of these forces. This law, known as **Coulomb's Law of electrostatic charges, states that the force of electrostatic attraction or repulsion is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.** The number of electrons contained in the coulomb was actually determined by the average charge of an electron.

THE AMP

amp
unit of measure for the rate of current flow.

The next electrical measurement to be discussed is the **amp** or *ampere*. The ampere is named for a scientist named Andre Ampere who lived in the late 1700s and early 1800s. Ampere is most famous for his work dealing with electromagnetism, which will be discussed in a later chapter in this text. *The amp is defined as one coulomb per second.* Notice that the definition of an amp involves a quantity measurement, the coulomb, combined with a time

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

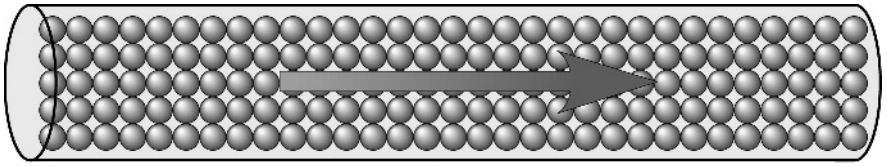


FIGURE 2-1 One ampere equals one coulomb per second.

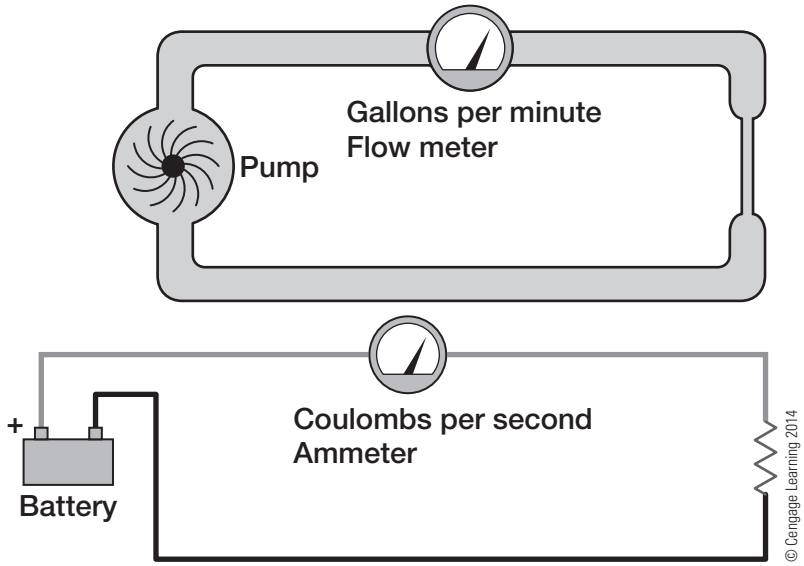


FIGURE 2-2 Current in an electrical circuit can be compared to flow rate in a water system.

measurement, the second. One amp of current flows through a wire when one coulomb flows past a point in one second, FIGURE 2-1. The ampere is a measurement of the actual amount of electricity that is flowing through a circuit. In a water system, it would be comparable to gallons per minute or gallons per second, FIGURE 2-2. The letter I, which stands for intensity of current, or the letter A, which stands for amp, is predominately used to represent current flow in algebraic formulas. This text will use the letter I to represent current.

THE ELECTRON THEORY

There are actually two theories concerning current flow. One theory is known as the **electron theory,** and states that since electrons are negative particles, current flows from the most negative point in the circuit to the most positive. The electron theory is the most widely accepted as being correct and is used throughout this text.

electron theory
the theory states that current flows from the most negative potential to the most positive potential.

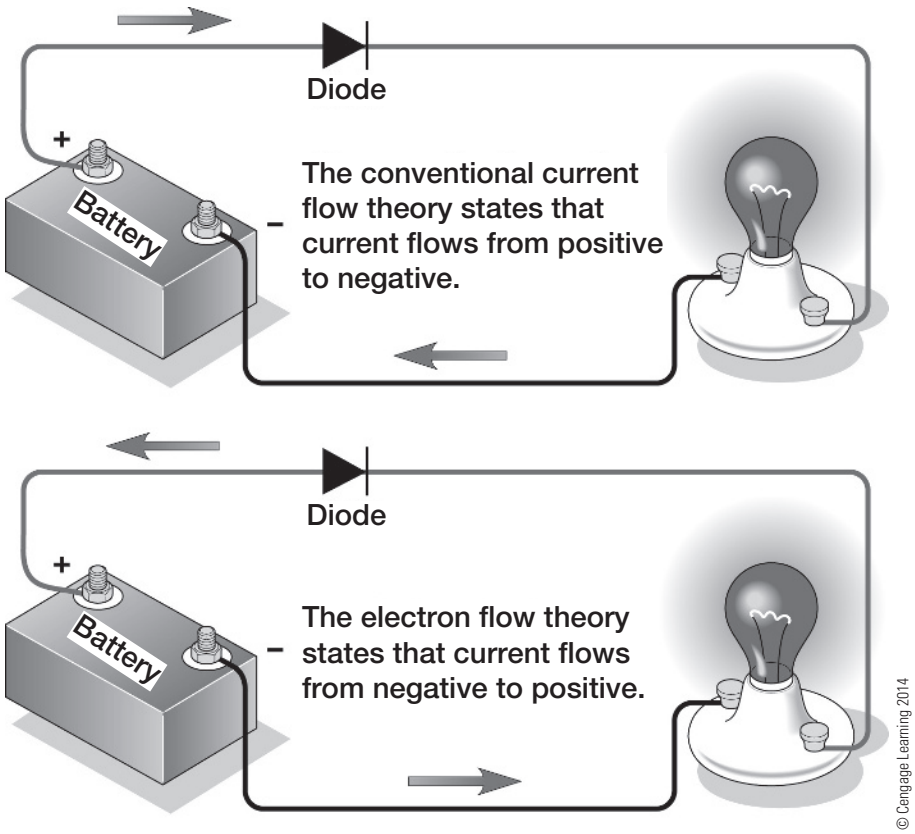
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

THE CONVENTIONAL CURRENT THEORY

conventional current flow theory
considers current to flow from the most positive source to the most negative source.

The second theory is known as the **conventional current flow theory.** This theory is older than the electron theory, and it states that current flows from the most positive point to the most negative. Although it has been established that the electron theory is probably correct, the conventional current theory is still used to a large extent. There are several reasons for this. Most electronic circuits use the negative terminal as ground or common. When this is done, the positive terminal is considered to be above ground, or hot. It is easier for most people to think of something flowing down rather than up, or from a point above ground to ground. An automobile electrical system is a good example of this type of circuit. Most people consider the positive battery terminal to be the hot terminal.

Many of the people who work in the electronics field prefer the conventional current flow theory because all the arrows on the semiconductor symbols point in the direction of conventional current flow. If the electron



© Cengage Learning 2014

FIGURE 2-3 Conventional current flow theory and electron flow theory.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

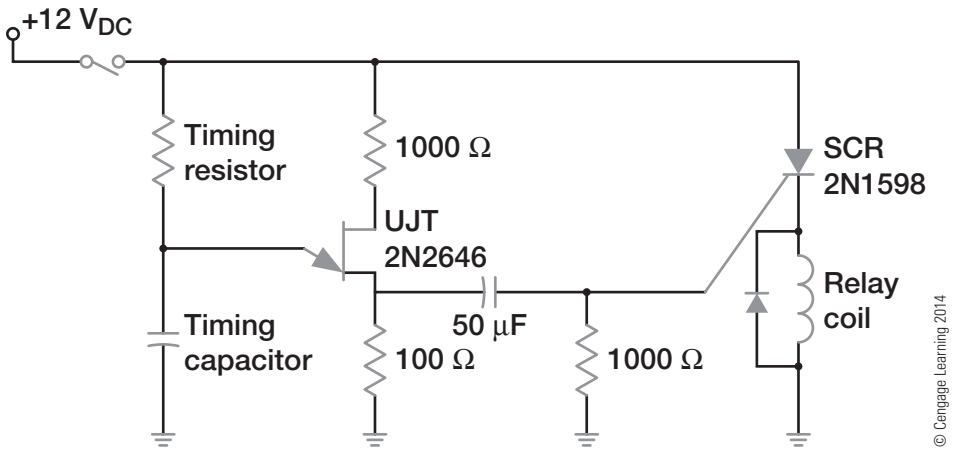


FIGURE 2-4 On-delay timer.

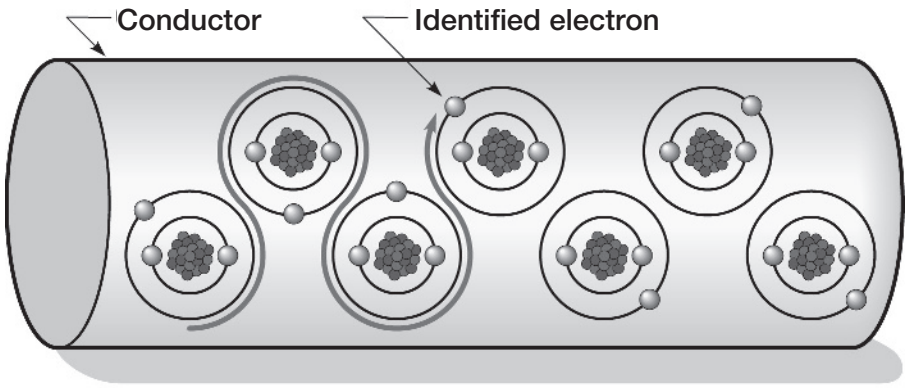
flow theory is used, it must be assumed that current flows against the arrow, FIGURE 2-3. Another reason why many people prefer using the conventional current flow theory is that most electronic schematics are drawn in a manner assuming current to flow from the more positive to the more negative source, FIGURE 2-4. In this schematic, the positive voltage point is shown at the top, and negative (ground) is shown at the bottom. When tracing the flow of current through a circuit, most people find it easier to understand something flowing from top to bottom rather than bottom to top.

SPEED OF CURRENT

Before it is possible to determine the speed of current flow through a wire, we must first establish exactly what is being determined. As stated previously, current is a flow of electrons through a conductive substance. Assume for a moment that it is possible to remove a single electron from a wire and identify it by painting it red. If it were possible to observe the progress of the identified electron as it moved from atom to atom, you would see that a single electron moves rather slowly, FIGURE 2-5. It is estimated that a single electron moves at a rate of about three inches per hour at one ampere of current flow.

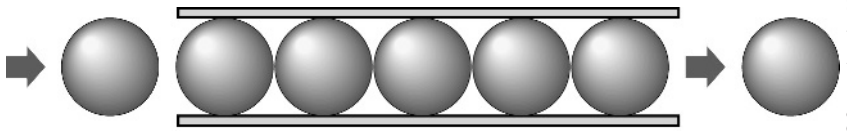
The *impulse* of electricity, however, is extremely fast. Assume for a moment that a pipe has been filled with ping-pong balls, FIGURE 2-6. If another ball is forced into one end of the pipe, the ball at the other end of the pipe is forced out. Each time a ball enters one end of the pipe, another ball is forced out the other end. This same principle is true for electrons in a wire. There are billions of electrons that exist in a wire. If an electron enters one end of a wire, another electron is forced out the other end of the wire.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-5 Electrons moving from atom to atom.



© Cengage Learning 2014

FIGURE 2-6 When a ball is pushed into one end, another ball is forced out the other end.

For many years it was assumed that the speed of the electrical impulse had a theoretical limit of 186,000 miles per second, or 300,000,000 meters per second, which is the speed of light. In recent years, however, it has been shown that the impulse of electricity can actually travel faster than light. Assume that a wire is long enough to be wound around the earth ten times. If a power source and switch were to be connected at one end of the wire, and a light at the other end, FIGURE 2-7, you would see that the light would turn on immediately when the switch was closed. It would take light approximately 1.3 seconds to travel around the earth ten times.

BASIC ELECTRIC CIRCUITS

complete path
a current path that exists from the most negative potential to the most positive potential.

A **complete path** must exist before current can flow through a circuit, FIGURE 2-8. A complete circuit is often referred to as a *closed* circuit, because the power source, conductors, and load form a closed loop. In FIGURE 2-8 a lamp is used as the load. Although the load offers resistance to the circuit and limits the amount of current that can flow, do not confuse *load* with *resistance*. A load can be anything that permits current to flow. The greater the amount of current flow, the greater the load. Since current flow is inversely proportional to resistance, more current will flow when circuit resistance is decreased, not increased. If the switch is opened, there is no longer a closed

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

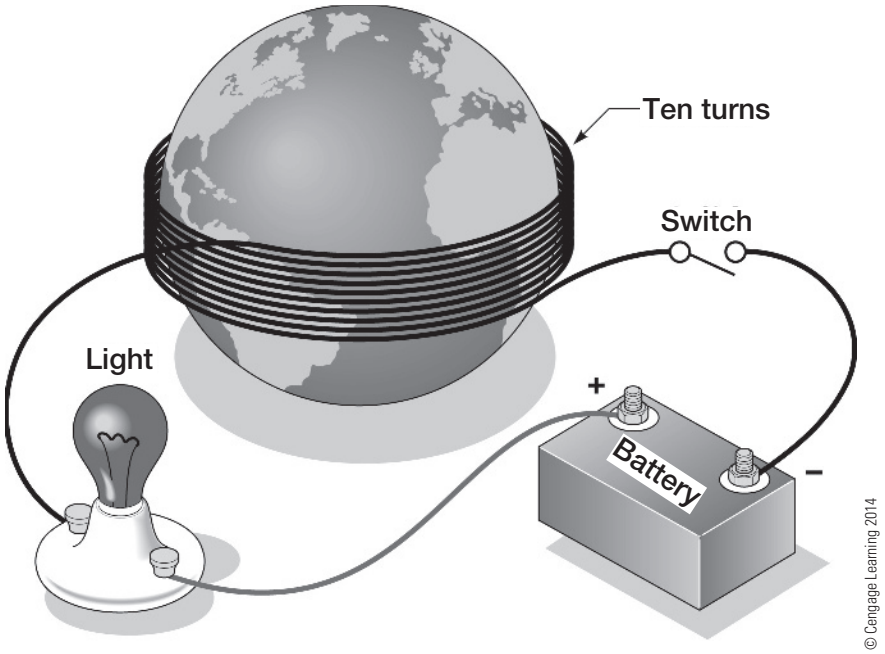


FIGURE 2-7 The impulse of electricity can travel faster than light.

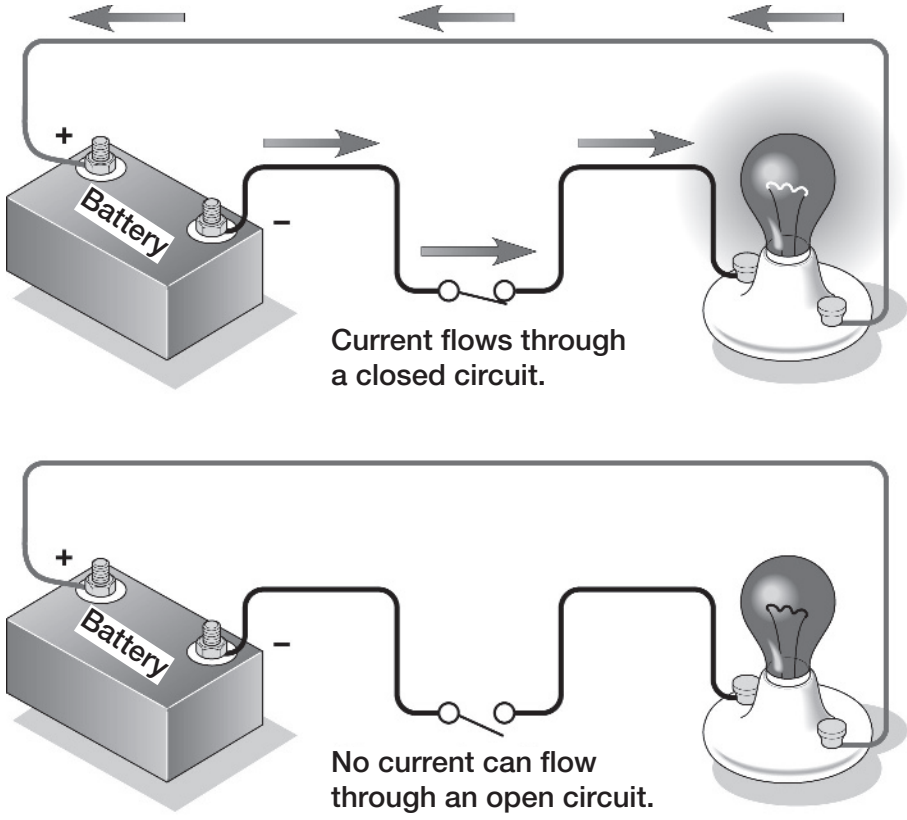
loop and no current can flow. This is often referred to as an *incomplete* or *open* circuit. When the switch is opened, an infinite amount of resistance is added to the circuit and no current can flow.

Another type of circuit is the short circuit. The definition of a short circuit is a circuit that has very little or no resistance to limit the flow of current. A short circuit generally occurs when the conductors leading from and back to the power source become connected, FIGURE 2-9. In this example, a separate current path has been established to bypass the load. Since the load is the device that limits the flow of current, when it is bypassed, an excessive amount of current can flow. Short circuits generally cause a fuse to blow or a circuit breaker to open. If the circuit has not been protected by a fuse or circuit breaker, a short circuit can damage equipment, melt wires, and start fires.

Another type of circuit that is often confused with a short circuit is a grounded circuit. Grounded circuits can cause an excessive amount of current flow just as a short circuit can. Grounded circuits occur when a path, other than that intended, is established to ground. Many circuits contain an extra conductor called the **grounding conductor.** A typical 120-V appliance circuit is shown in FIGURE 2-10. In this circuit, the *ungrounded* or *hot* conductor is connected to the fuse or circuit breaker. The hot conductor

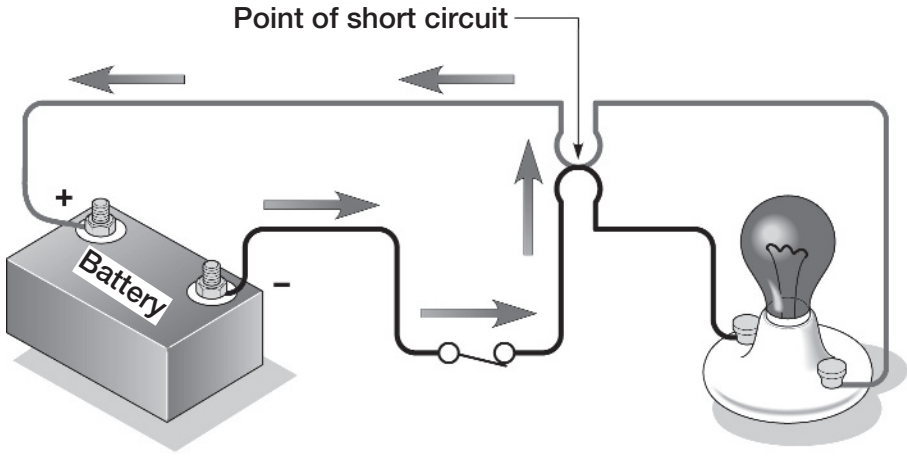
grounding conductor the conductor used to ground a piece of equipment.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-8 Current flows only through a closed circuit.



© Cengage Learning 2014

FIGURE 2-9 A short circuit bypasses the load and permits too much current to flow.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

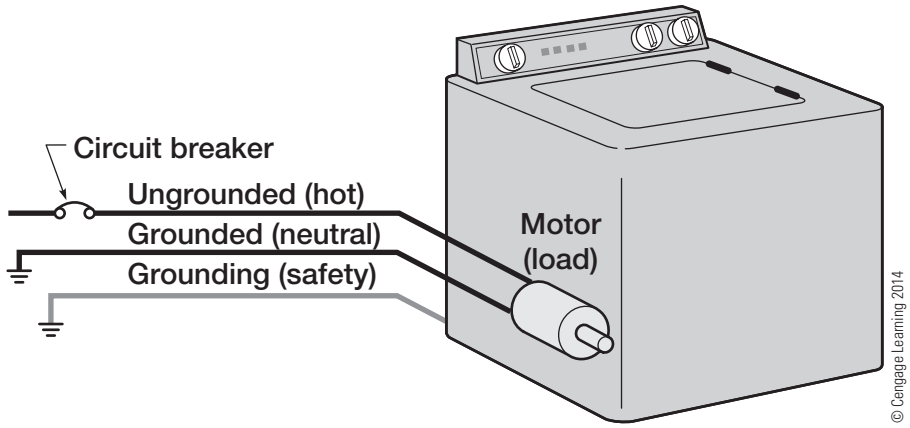


FIGURE 2-10 120 V appliance circuit.

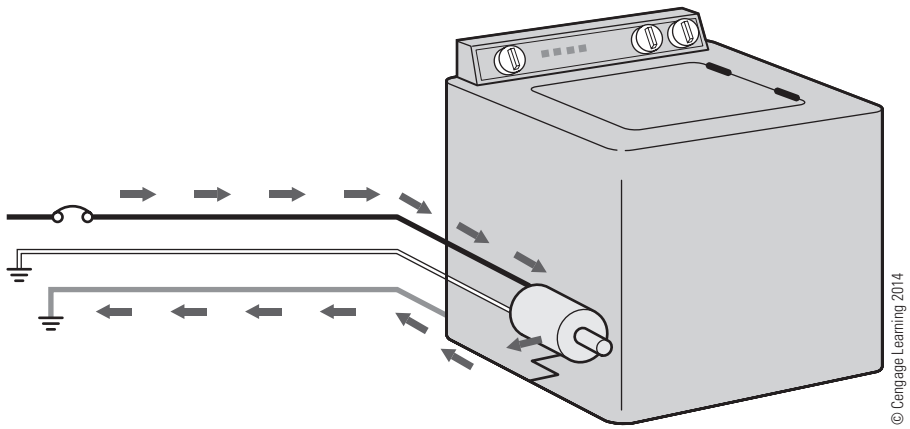


FIGURE 2-11 The grounding conductor provides a low-resistance path to ground.

supplies power to the load. The grounded conductor, or **neutral conductor,** provides the return path and completes the circuit back to the power source. The grounding conductor is generally connected to the case of the appliance to provide a low-resistance path to ground. Although both the neutral and grounding conductors are grounded at the power source, the grounding conductor is not considered to be a circuit conductor. The reason for this is that the only time current will flow through the grounding conductor is when a circuit fault develops. In normal operation, current flows through the hot and neutral conductors only.

The grounding conductor is used to help prevent a shock hazard in the event that the ungrounded, or hot, conductor comes in contact with the case or frame of the appliance, FIGURE 2-11. This condition could occur in several

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

ways. In this example it will be assumed that the motor winding becomes damaged and makes connection to the frame of the motor. Since the frame of the motor is connected to the frame of the appliance, the grounding conductor will provide a circuit path to ground. If enough current flows, the circuit breaker will open. Imagine this condition occurring without the grounding conductor being connected to the frame of the appliance. The frame of the appliance would become hot and anyone touching the case and a grounded point, such as a water line, would complete the circuit to ground. The person would receive an electrical shock and perhaps an injury as well. For this reason, **the grounding prong of a plug should never be cut off or bypassed**.

KEY POINT

The grounding prong of a plug should never be cut off or bypassed.

THE VOLT

electromotive force
voltage; electrical pressure.

volt
the unit of measure for potential.

Voltage is actually defined as **electromotive force** or EMF. It is the force that pushes the electrons through a wire and is often referred to as *electrical* pressure. A **volt** is the amount of potential necessary to cause one coulomb to produce one joule of work. One thing to remember is that voltage cannot flow. To say that voltage flows through a circuit is like saying that pressure flows through a pipe. Pressure can push water through a pipe, and it is correct to say that water flows through a pipe, but it is not correct to say that pressure flows through a pipe. The same is true for voltage. Voltage pushes current through a wire, but voltage cannot flow through a wire. In a water system, the voltage could be compared to the pressure of the system, FIGURE 2-12.

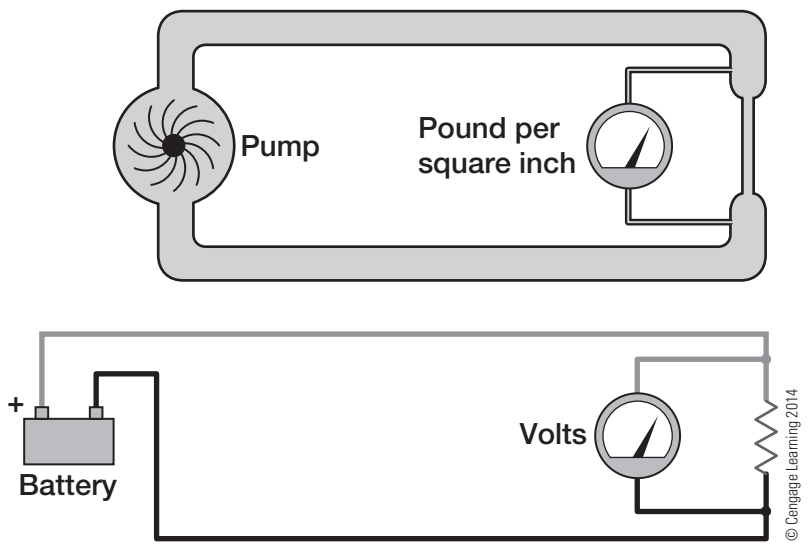


FIGURE 2-12 Voltage in an electrical circuit can be compared to pressure in a water system.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Voltage is often thought of as the potential to do something. For this reason it is frequently referred to as *potential,* especially in older publications and service manuals. Voltage must be present before current can flow, just as pressure must be present before water can flow. A voltage, or potential, of 120 V is present at a common wall outlet, but there is no flow until some device is connected and a complete circuit exists. The same is true in a water system. Pressure is present, but water cannot flow until the valve is opened and a path is provided to a region of lower pressure. The letter E, which stands for EMF, or the letter V, which stands for volt, is generally used to represent voltage in an algebraic formula. This text uses the letter E to represent voltage in algebraic formulas.

THE OHM

An **ohm** is the measurement of **resistance** to the flow of current. The ohm is named for a German scientist named Georg S. Ohm. The symbol used to represent an ohm, or resistance, is the Greek letter omega (Ω). The letter R, which stands for resistance, is used to represent ohms in algebraic formulas. The voltage of the circuit must overcome the resistance before it can cause electrons to flow through it. Without resistance, every electrical circuit would be a short circuit. All electrical loads, such as heating elements, lamps, motors, transformers, and so on, are measured in ohms. In a water system, a reducer can be used to control the flow of water. In an electrical circuit, a resistor can be used to control the flow of electrons. FIGURE 2-13 illustrates this concept.

ohm
unit of measure for electrical resistance.

resistance
opposition to current flow in an AC or DC circuit.

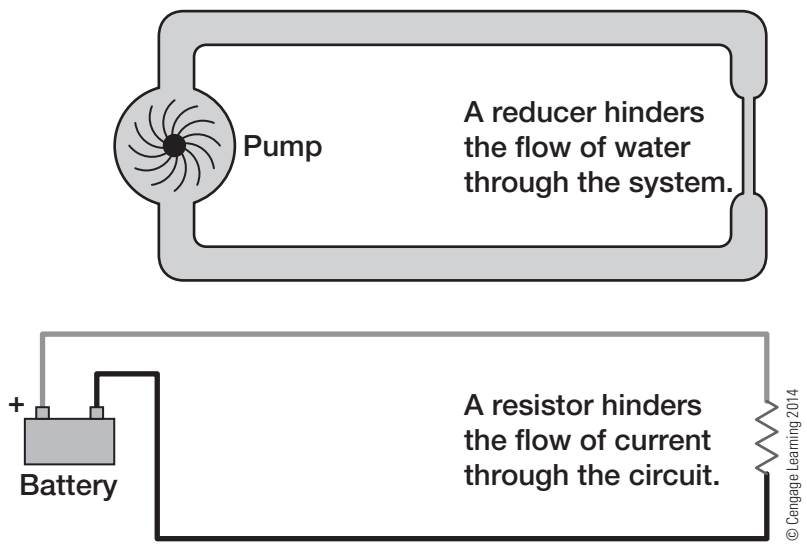


FIGURE 2-13 A resistor in an electrical circuit can be compared to a reducer in a water system.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

To understand the effect of resistance on an electric circuit, consider a person running along a beach. As long as the runner stays on the hard, compact sand, he can run easily along the beach. This is like current flowing through a good conductive material, such as a copper wire. Now imagine the runner wades out into the water until it is knee deep. He will no longer be able to run along the beach as easily because of the resistance of the water. Now assume that the runner wades out into the water until it is waist deep. His ability to run along the beach will be hindered to a greater extent because of the increased resistance of the water against his body. The same is true for resistance in an electric circuit. The higher the resistance, the greater the hindrance to current flow.

KEY POINT
Whenever current flows through a resistance, heat is produced.

Another fact that an electrician should be aware of is that **whenever current flows through a resistance, heat is produced**, FIGURE 2-14. This is the reason why wire becomes warm when current flows through it. The filament of an incandescent lamp becomes extremely hot, and the elements of an electric range become hot, because of the resistance of the element.

A term that has a similar meaning as resistance is **impedance.** Impedance is most often used in calculations of alternating current rather than direct current. Impedance will be discussed to a greater extent later in this text.

impedance
total opposition to current flow in an electrical circuit.

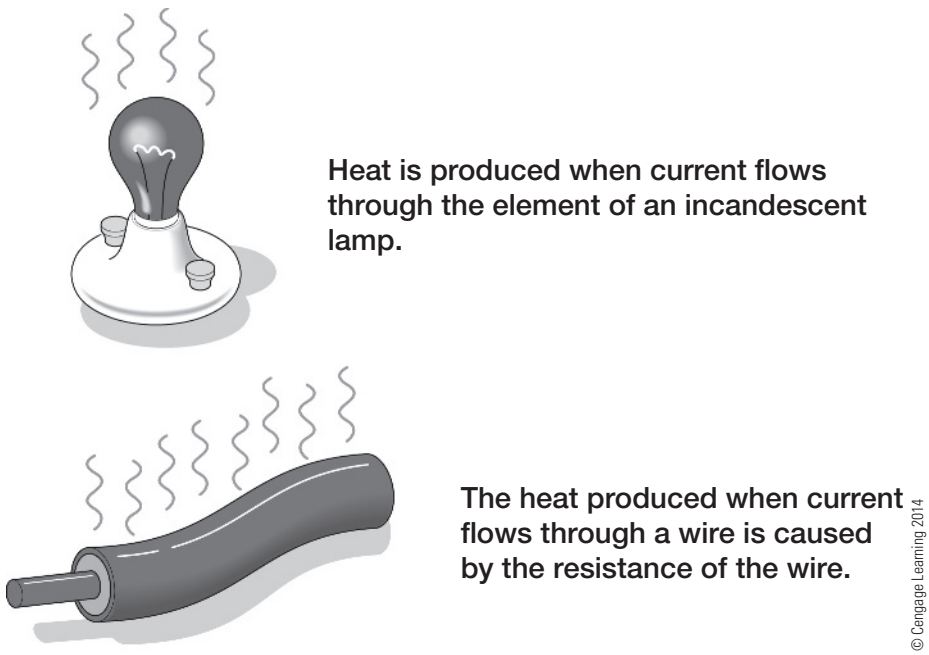


FIGURE 2-14 Heat is produced when current flows through resistance.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

THE WATT

Wattage is a measure of the amount of power that is being used in the circuit. The **watt** is named in honor of an English scientist named James Watt. In algebraic formulas, it is generally represented by the letter P, for power, or W, for watts.

watt
measure of the amount of electrical energy converted into some other form.

power
the amount of electrical energy converted into some other form.

A very important concept that should be understood concerning **power** in an electrical circuit is that before true power, or watts, can exist, there must be some type of energy change or conversion. Electricity is a form of pure energy, and in accord with physical laws, energy cannot be created or destroyed, but its form can be changed. A watt is a measure of this change. When current flows through a resistive element, electrical energy is converted into heat energy. The electric power supplied to a motor is converted into mechanical energy, FIGURE 2-15.

Watts in an electric circuit can be computed using several formulas. Probably the most common formula is: watts equals volts times amps, FIGURE 2-16.

$$P = E \times I$$

Assume that a circuit has a voltage of 120 V and a current draw of 3 A. If the current is flowing through a resistive load, 360 W of electrical energy is being converted into heat (120 V $\times$ 3 A = 360 W). Power can also be computed by dividing the square of the voltage by the resistance.

$$P = \frac{E^2}{R}$$

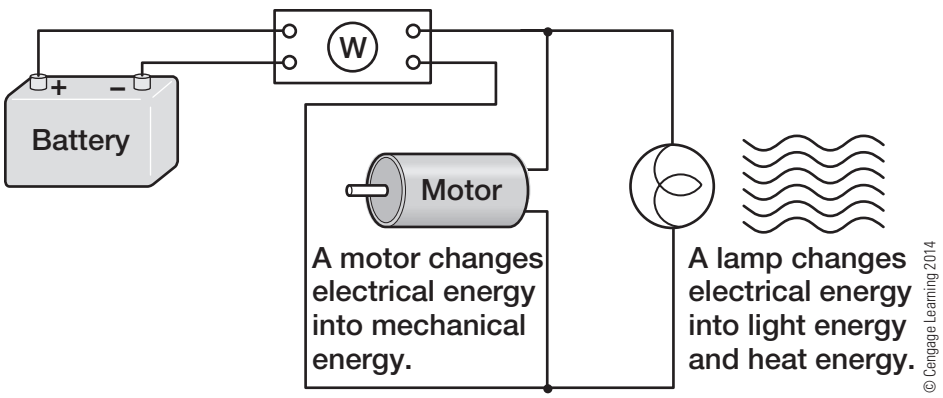


FIGURE 2-15 Watts are produced when electrical energy is converted into some other form.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

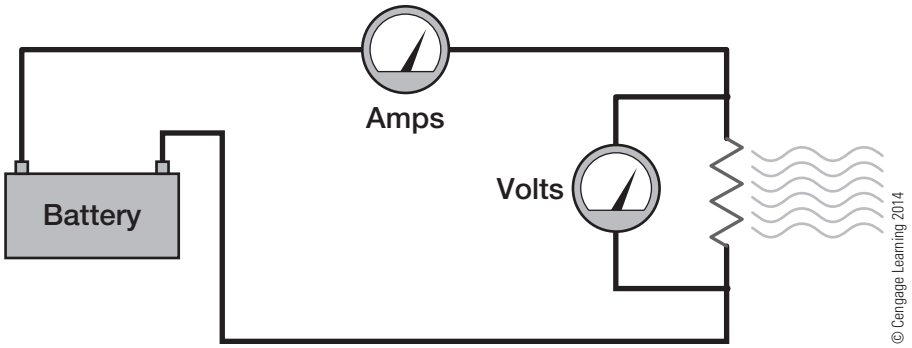


FIGURE 2-16 Amps times volts equals watts.

Example: A 24-Ω resistor is connected to a 6-V battery. How much power is converted into heat?

$$P = \frac{6 \times 6}{24}$$

$$P = 1.5 \text{ W}$$

A third formula used to compute the power dissipation of an electric circuit is the current squared multiplied by the resistance.

$$P = I^2 \times R$$

Example: A 15-Ω resistor has a current of 2.5 A flowing through it. How much power is being dissipated into heat by the resistor?

$$P = 2.5 \times 2.5 \times 15$$

$$P = 93.75 \text{ W}$$

OTHER MEASURES OF POWER

The watt is not the only unit of power measure. Many years ago, James Watt decided that to sell his steam engines, he would have to rate their power in terms that the average person could understand. He decided to compare his steam engines with the horses he hoped to replace with his engines. After experimentation, Watt found that the average horse, working at a steady rate, could do 550 ft-lb of work per second. A foot-pound is the amount of force required to raise a one pound weight one foot. This rate of doing work is the definition of a **horsepower** (hp).

horsepower
measure of power for electrical and mechanical devices.

$$1 \text{ hp} = 550 \text{ ft-lb}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Horsepower can also be expressed as 33,000 ft-lb per minute (550 ft-lb × 60 = 33,000).

$$1 \text{ hp} = 33{,}000 \text{ ft-lb/min}$$

It was later computed that the amount of electrical energy needed to produce one horsepower was 746 W.

$$1 \text{ hp} = 746 \text{ W}$$

Another measure of energy frequently used in the English system of measure is the **BTU (British Thermal Unit).** A BTU is defined as the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. In the metric system, the *calorie* is used to measure heat instead of the BTU. A calorie is the amount of heat needed to raise the temperature of one gram of water one degree Celsius.

BTU (British Thermal unit)
English measure of thermal energy.

The **joule** is the metric equivalent of the watt. A joule is defined as one newton per meter. A newton is a force of 100,000 dyn, or about 3½ oz, and a meter is about 39 in. The joule can also be expressed as the amount of work done by one coulomb flowing through a potential of one volt. The joule can also be expressed as the amount of work done by one watt for one second.

joule
basic unit of electrical energy. A joule is the amount of power used when 1 amp flows through 1 ohm for 1 second. A joule is equal to 1 watt/second.

$$1 \text{ joule} = 1 \text{ watt/s}$$

The chart in FIGURE 2-17 gives some common conversions for different quantities. These quantities can be used to calculate different values.

1 Horsepower	= 746 Watts
1 Horsepower	= 550 Ft-lb/s
1 Watt	= 0.00134 Horsepower
1 Watt	= 3.412 BTU/hr
1 Watt/s	= 1 Joule
1 BTU/s	= 1.055 Watts
1 Cal/s	= 4.19 Watts
1 Ft-lb/s	= 1.36 Watts
1 BTU	= 1050 Joules
1 Joule	= 0.2389 Cal
1 Cal	= 4.186 Joules

© Cengage Learning 2014

FIGURE 2-17 Common power units.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 1: An elevator must lift a load of 4,000 pounds to a height of 50 feet in 20 seconds. How much horsepower is required to operate the elevator?

Solution:
Find the amount of work that must be performed, and then convert that to horsepower.

$$4000 \text{ lb} \times 50 \text{ ft} = 200{,}000 \text{ ft-lb}$$

$$\frac{200{,}000 \text{ ft-lb}}{20 \text{ s}} = 10{,}000 \text{ ft-lb/s}$$

$$\frac{10{,}000 \text{ ft-lb/s}}{550 \text{ ft-lb/s}} = 18.18 \text{ hp}$$

EXAMPLE 2: A water heater contains 40 gallons of water. Water weighs 8.34 pounds per gallon. The present temperature of the water is 68°F. The water must be raised to a temperature of 160°F in 1 hour. How much power will be required to raise the water to the desired temperature?

Solution:
First determine the weight of the water in the tank, because a BTU is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.

$$40 \text{ gal} \times 8.34 \text{ lb/gal} = 333.6 \text{ lb}$$

The second step is to determine how many degrees of temperature the water must be raised. This will be the difference between the present temperature and the desired temperature.

$$160°\text{F} - 68°\text{F} = 92°\text{F}$$

The amount of heat required in BTUs will be the product of the pounds of water and the desired increase in temperature.

$$333.6 \text{ lb} \times 92° = 30{,}691.2 \text{ BTU}$$

$$1 \text{ W} = 3.412 \text{ BTU/hr}$$

Therefore

$$\frac{30{,}691 \text{ BTU}}{3.412 \text{ BTU/hr}} = 8995.1 \text{ W/hr}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

OHM'S LAW

Ohm's Law is named for Dr. Ohm, who discovered that all electrical quantities are proportional to each other and can, therefore, be expressed as mathematical formulas. In its simplest form, Ohm's Law states that **it takes one volt to push one amp through one ohm.** Ohm's Law is actually a statement of proportion. Ohm discovered that if the resistance of a circuit remained constant and the voltage increased, there was a corresponding proportional increase of current. If the resistance remained constant and the voltage decreased, there would be a proportional decrease of current. He also found that if the voltage remained constant and the resistance increased, there would be a decrease of current. If the voltage remained constant and the resistance decreased, there would be an increase of current. This led Ohm to the conclusion that **in a DC circuit, the current is directly proportional to the voltage and inversely proportional to the resistance.**

Ohm's Law
law to measure electrical resistance.

KEY POINT
It takes one volt to push one amp through one ohm.

KEY POINT
In a DC circuit, the current is directly proportional to the voltage and inversely proportional to the resistance.

Since Ohm's Law is a statement of proportion, it can be expressed as an algebraic formula when standard values such as the volt, ampere, and ohm are used. The three basic Ohm's Law formulas are shown.

$$E = I \times R$$

$$I = \frac{E}{R}$$

$$R = \frac{E}{I}$$

E = EMF, or voltage

I = intensity of current, or amperage

R = resistance

The first formula states that the voltage can be found if the current and resistance are known. Voltage is equal to amps multiplied by ohms. For example, assume a circuit has a resistance of 50 Ω and a current flow through it of 2 A. The voltage connected to this circuit is 100 V.

$$E = I \times R$$

$$E = 2 \times 50$$

$$E = 100 \text{ V}$$

The second formula states that the current can be found if the voltage and resistance are known. In the example shown, 120 V is connected to a resistance of 30 Ω. The amount of current flow will be 4 A.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$I = \frac{E}{R}$$

$$I = \frac{120}{30}$$

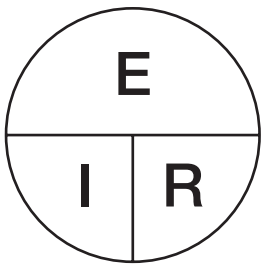
$$I = 4$$

The third formula states that if the voltage and current are known, the resistance can be found. Assume a circuit has a voltage of 240 V and a current flow of 10 A. The resistance in the circuit is 24 Ω.

$$R = \frac{E}{I}$$

$$R = \frac{240}{10}$$

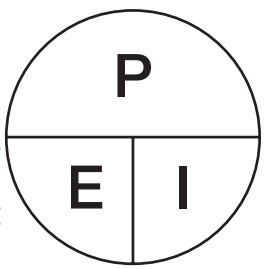
$$R = 24\ \Omega$$



© Cengage Learning 2014

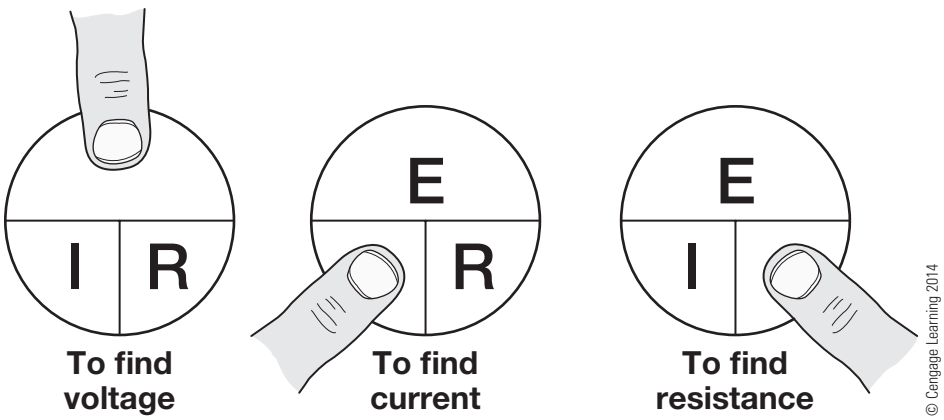
FIGURE 2-18 Chart for finding values of voltage, current, and resistance.

FIGURE 2-18 shows a simple chart that can be a great help when trying to remember an Ohm's Law formula. To use the chart, cover the quantity that is to be found. For example, if the voltage, E, is to be found, cover the E on the chart. The chart now shows the remaining letters I and R, FIGURE 2-19, thus $E = I \times R$. If the current is to be found, cover the I on the chart. The chart now shows $I = E \times R$. If the resistance is to be found, cover the R on the chart. The chart now shows $R = E \times I$. A similar chart for determining formulas for power (watts), voltage, and current is shown in FIGURE 2-20. This chart is used in the same manner as the chart shown in FIGURE 2-18.



© Cengage Learning 2014

FIGURE 2-20 Chart for finding values of power, voltage, and current.



© Cengage Learning 2014

FIGURE 2-19 Using the Ohm's Law chart.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

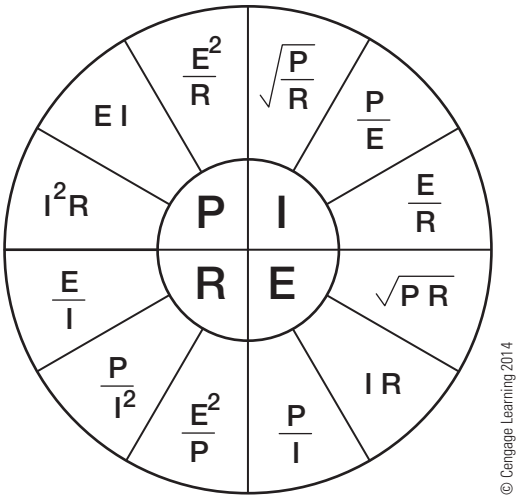


FIGURE 2-21 Formula chart for finding values of voltage, current, resistance, and power.

A larger chart, which shows the formulas needed to find watts, voltage, amperage, and resistance, is shown in FIGURE 2-21. The letter P (power) is used to represent the value of watts. Notice that this chart is divided into four sections, and each section contains three different formulas. To use this chart, find the section that contains the quantity to be found, and then choose the proper formula from the given quantities.

EXAMPLE 3: An electric iron is connected to 120 V and has a current draw of 8 A. How much power is used by the iron?

Solution:
The quantity to be found is watts, or power. The known quantities are voltage and amperage. The proper formula to use is shown in FIGURE 2-22.

$$P = EI$$

$$P = 120 \times 8$$

$$P = 960 \text{ W}$$

EXAMPLE 4: An electric hair dryer has a power rating of 1,000 W. How much current will it draw when connected to 120 V?

Solution:
The quantity to be found is amperage or current. The known quantities are power and voltage. To solve this problem, choose the formula shown in FIGURE 2-23.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

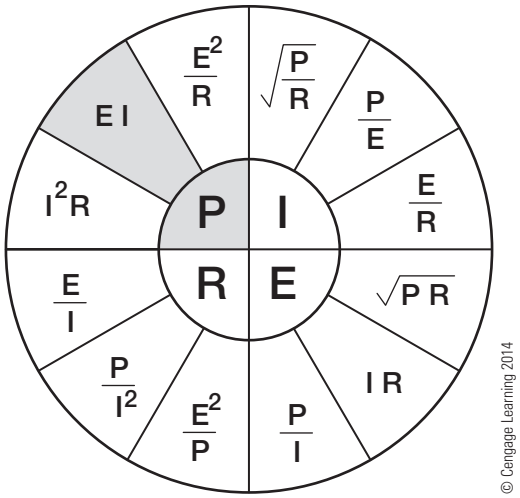


FIGURE 2-22 Finding power when voltage and current are known.

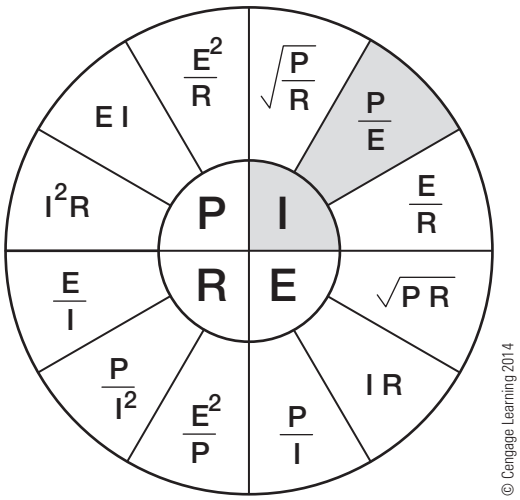


FIGURE 2-23 Finding current when power and voltage are known.

$$I = \frac{P}{E}$$

$$I = \frac{1000}{120}$$

$$I = 8.33 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

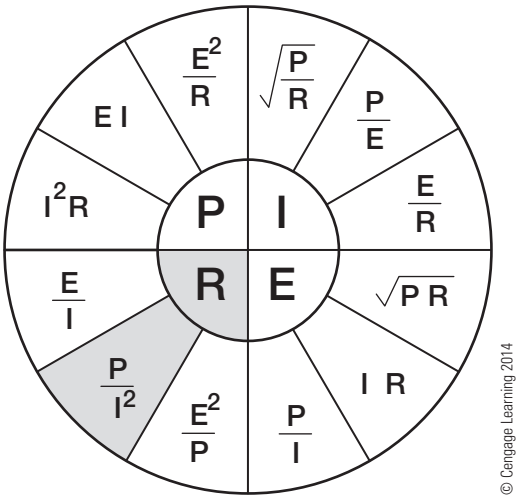


FIGURE 2-24 Finding resistance when power and current are known.

EXAMPLE 5: An electric hotplate has a power rating of 1,440 W and a current draw of 12 A. What is the resistance of the hotplate?

Solution:

The quantity to be found is resistance, and the known quantities are power and current. Use the formula shown in FIGURE 2-24.

$$R = \frac{P}{I^2}$$

$$R = \frac{1440}{12 \times 12}$$

$$R = \frac{1440}{144}$$

$$R = 10\ \Omega$$

METRIC UNITS

Metric units of measure are used in the electrical field just as they are in most scientific fields. A special type of metric notation known as *engineering notation* is used in electrical measurements. Engineering notation is the same as any other metric measure, except that engineering notation is

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Kilo	1000
Hecto	100
Deka	10
Base unit	1
Deci	1/10 or 0.1
Centi	1/100 or 0.01
Milli	1/1000 or 0.001

© Cengage Learning 2014

FIGURE 2-25 Standard units of metric measure.

in steps of 1,000 instead of ten. The chart in FIGURE 2-25 shows standard metric units. The first step above the base unit is deka, which means 10; the second unit is hecto, which means 100; and the third unit is kilo, which means 1,000. The first unit below the base unit is deci, which means 1/10; the second unit is centi, which means 1/100; and the third unit is milli, which means 1/1000.

The chart in FIGURE 2-26 shows engineering units. The first unit above the base unit is kilo, or 1,000; the second unit is mega, or 1,000,000; and the third unit is giga, or 1,000,000,000. Notice that each unit is 1,000 times greater than the previous unit. The chart also shows that the first unit below the base unit is milli, or 1/1000; the second unit is micro, represented by the Greek letter mu (μ), or 1/1,000,000; and the third unit is nano, or 1/1,000,000,000.

Metric units are used in almost all scientific measurements for ease of notation. It is much easier to write a value such as 10 MΩ than it is to write 10,000,000 Ω, or to write 0.5 ns than to write .000,000,000,5 second. Once the metric system has been learned, measurements such as 47 kilohms (kΩ) or 50 milliamps (mA) become commonplace to the technician.

ENGINEERING UNIT	SYMBOL	MULTIPLY BY	
Tera	T	1,000,000,000,000	$\times 10^{12}$
Giga	G	1,000,000,000	$\times 10^{9}$
Mega	M	1,000,000	$\times 10^{6}$
Kilo	k	1,000	$\times 10^{3}$
Base unit		1	
Milli	m	0.001	$\times 10^{-3}$
Micro	μ	0.000,001	$\times 10^{-6}$
Nano	n	0.000,000,001	$\times 10^{-9}$
Pico	p	0.000,000,000,001	$\times 10^{-12}$

© Cengage Learning 2014

FIGURE 2-26 Standard units of engineering notation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTORS

Resistors are one of the most common components found in electrical circuits. The unit of measure for resistance (R) is the *ohm,* which was named for a German scientist named Georg S. Ohm. The symbol used to represent resistance is the Greek letter omega (Ω). Resistors come in various sizes, types, and ratings to accommodate the needs of almost any circuit applications.

USES OF RESISTORS

Resistors are commonly used to perform two functions in a circuit. One is to limit the flow of current through the circuit. In FIGURE 2-27 a 30-Ω resistor is connected to a 15-V battery. The current in this circuit is limited to a value of 0.5 A.

$$I = \frac{E}{R}$$

$$I = \frac{15}{30}$$

$$I = 0.5 \text{ A}$$

If this resistor were not present, the circuit current would be limited only by the resistance of the conductor, which would be very low, and a large amount of current would flow. Assume for example that the wire has a resistance of

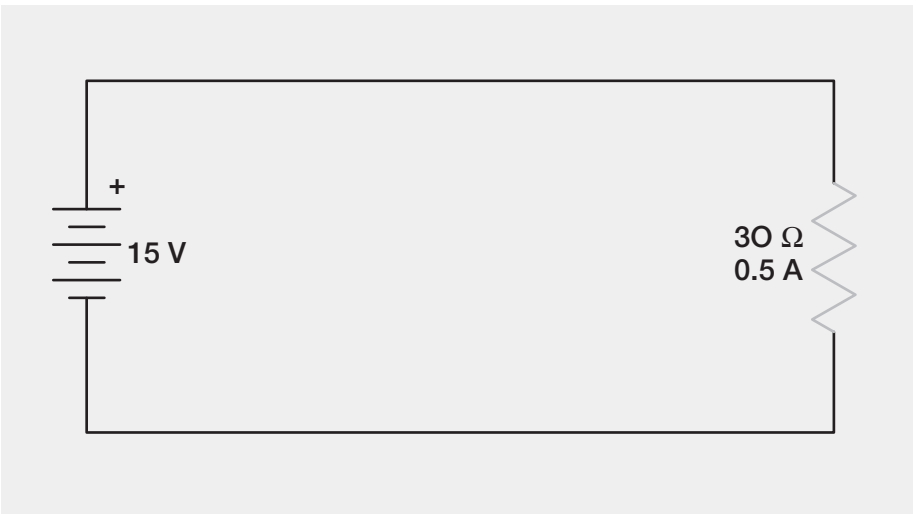


FIGURE 2-27 Resistor used to limit the flow of current.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

0.0001 Ω. When the wire is connected across the 15-V power source, a current of 150,000 A would try to flow through the circuit (15/0.0001 = 150,000). This is commonly known as a **short circuit.**

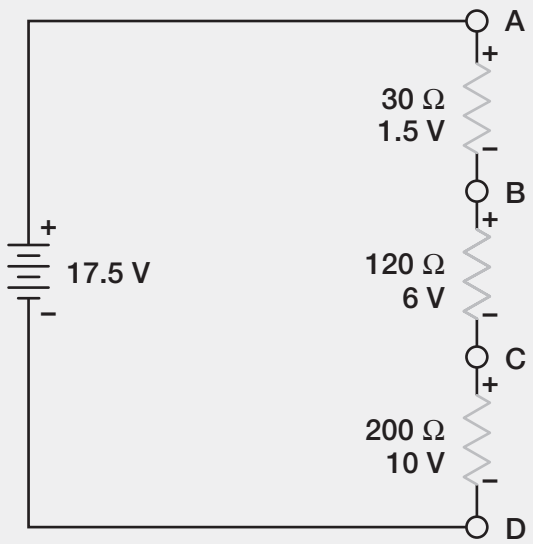
short circuit
electrical circuit that contains no resistance to limit the flow of current.

The second principal function of resistors is to produce a **voltage divider.** The three resistors shown in FIGURE 2-28 are connected in series with a 17.5-V battery. If the leads of a volunteer were connected between different points in the circuit, it would indicate the following voltages:

voltage divider
a circuit that provides different voltage drops across electrical components.

A to B, 1.5 V
A to C, 7.5 V
A to D, 17.5 V
B to C, 6 V
B to D, 16 V
C to D, 10 V

By connecting resistors of the proper value, almost any voltage desired can be obtained. Voltage dividers were used to a large extent in vacuum tube circuits many years ago. Voltage divider circuits are still used today



© Cengage Learning 2014

FIGURE 2-28 Resistors used as a voltage divider.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

in applications involving field effect transistors (FETs) and in multirange voltmeter circuits.

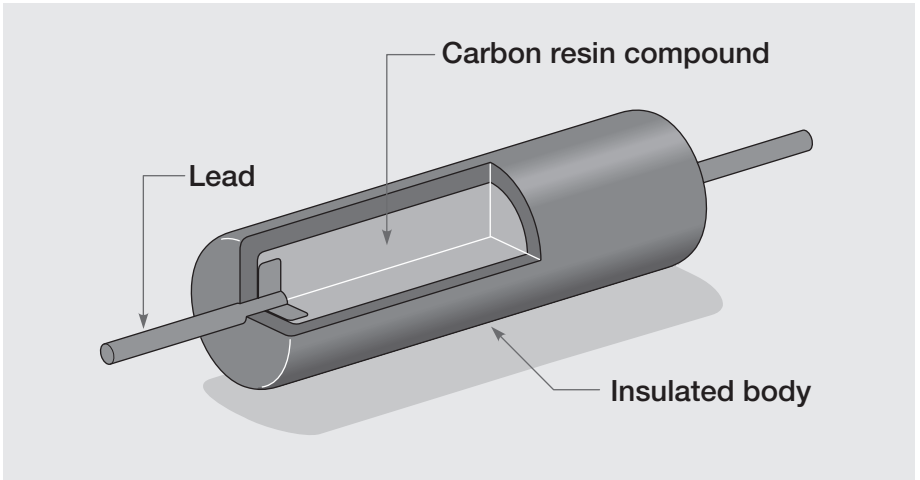
FIXED RESISTORS

Fixed resistors have only one ohmic value, which cannot be changed or adjusted. There are several different types of fixed resistors. One of the most common types of fixed resistors is the **composition carbon resistor.** Carbon resistors are made from a compound of carbon graphite and a resin bonding material. The proportions of carbon and resin material determine the value of resistance. This compound is enclosed in a case of conductive material with connecting leads, FIGURE 2-29.

fixed resistors
resistors with one ohmic value that cannot be changed.

composition carbon resistor
resistors made with a carbon compound as the resistive material.

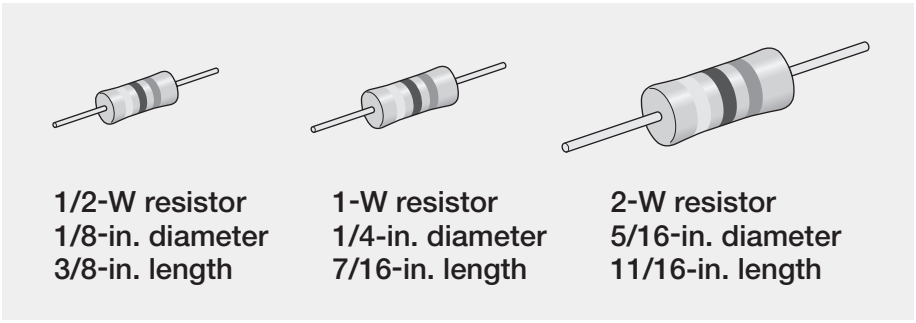
Carbon resistors are very popular for most applications because they are inexpensive and readily available. They are made in standard values that range from about 1 Ω to about 22 MΩ (M represents mega), and they can be obtained in power ratings of 1/8, 1/4, 1/2, 1, and 2 W. The power rating of the resistor is indicated by its size. A 1/2-W resistor is approximately 3/8 in. in length and 1/8 in. in diameter. A 2-W resistor has a length of approximately 11/16 in. and a diameter of approximately 5/16 in., FIGURE 2-30. The 2-W resistor is larger than the 1/2-W or 1-W because it must have a larger surface area to be able to dissipate more heat. Although carbon resistors have a lot of desirable characteristics, they have one characteristic that is not desirable. Carbon resistors will change their value with age or if they are overheated. Carbon resistors generally increase instead of decrease in value.



© Cengage Learning 2014

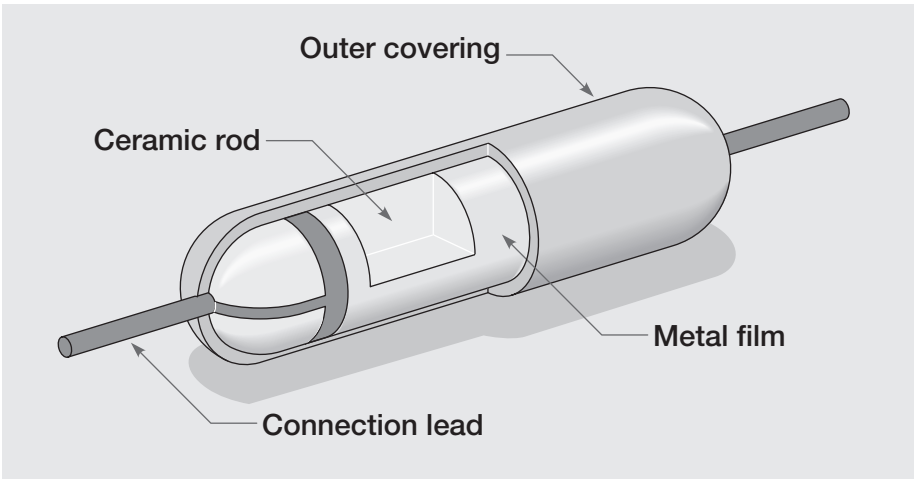
FIGURE 2-29 Composition carbon resistor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-30 Power rating is indicated by size.



© Cengage Learning 2014

FIGURE 2-31 Metal film resistor.

Metal Film Resistors

metal film resistors
resistors that employ a thin metal coating as the resistive element.

Another type of fixed resistor is the metal film resistor. **Metal film resistors** are constructed by applying a film of metal to a ceramic rod in a vacuum, FIGURE 2-31. The resistance is determined by the type of metal used to form the film and the thickness of the film. Typical thicknesses for the film are from 0.00001 to 0.00000001 in. Leads are then attached to the film coating, and the entire assembly is covered with a coating. These resistors are superior to carbon resistors in several respects. Metal film resistors do not change their value with age, and their tolerance is generally better than carbon resistors.

tolerance
the upper and lower resistive limits.

Tolerance indicates the plus and minus limits of a resistor's ohmic value. Carbon resistors commonly have a tolerance range of 20%, 10%, or 5%. Metal

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

film resistors generally range in tolerance from 2% to 0.1%. The disadvantage of the metal film resistor is that it costs more.

Carbon Film Resistors

Another type of fixed resistor that is constructed in a similar manner is the **carbon film resistor.** This resistor is made by coating a ceramic rod with a film of carbon instead of metal. Carbon film resistors are less expensive to manufacture than metal film resistors and can have a higher tolerance rating than composition carbon resistors.

carbon film resistor resistors that employ a film of carbon as the resistive element.

Metal Glaze Resistors

The **metal glaze resistor** is also a fixed resistor, similar to the metal film resistor. This resistor is made by combining metal with glass. The compound is then applied to a ceramic base as a thick film. The resistance is determined by the amount of metal used in the compound. Tolerance ratings of 2% and 1% are common.

metal glaze resistor resistors that combine carbon and glass as the resistive element.

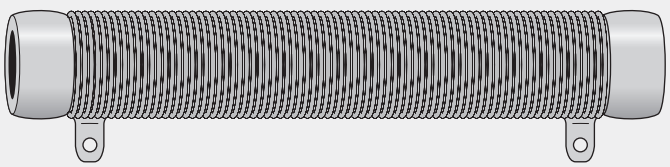
Wire Wound Resistors

Wire wound resistors are fixed resistors that are made by winding a piece of resistive wire around a ceramic core, FIGURE 2-32. The resistance of a wire wound resistor is determined by three factors:

wire wound resistors resistor that use resistive wire as the resistive element.

1. the type of material used to make the resistive wire,
2. the diameter of the wire, and
3. the length of the wire.

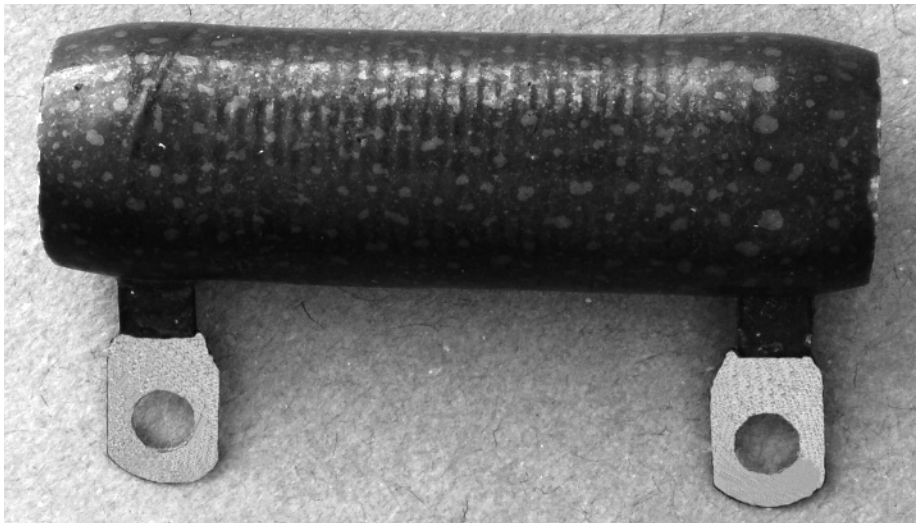
Wire wound resistors can be found in various case styles and sizes. These resistors are generally used when a high power rating is needed. Wire wound resistors can operate at higher temperatures than any other type of resistor. A wire wound resistor that has a hollow center is shown in FIGURE 2-33. This type of resistor should be mounted vertically and not horizontally. The center



© Cengage Learning 2014

FIGURE 2-32 Wire wound resistor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-33 Wire wound resistor with hollow core.

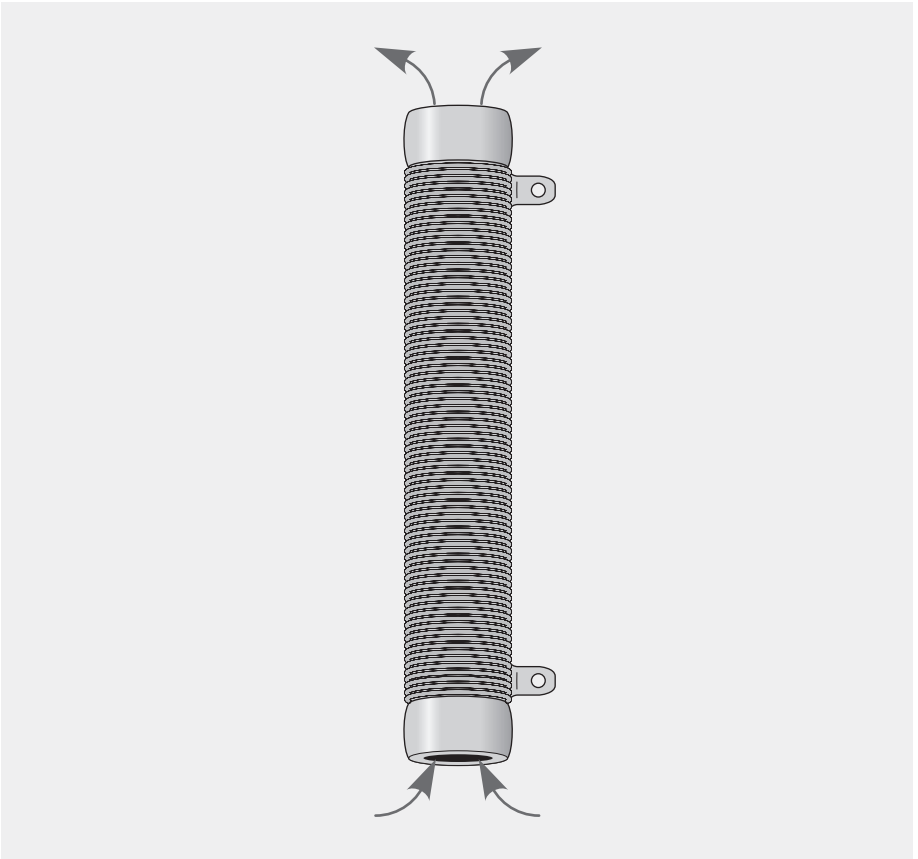
of the resistor is hollow for a very good reason. When the resistor is mounted vertically, the heat from the resistor produces a chimney effect and causes air to circulate through the center, FIGURE 2-34. This increase of air flow dissipates heat at a faster rate to help keep the resistor from overheating. The disadvantages of wire wound resistors are that they are expensive and generally require a large amount of space for mounting. They can also exhibit an amount of inductance in circuits that operate at high frequencies. This added inductance can cause problems to the rest of the circuit. Inductance will be covered in later units.

THE COLOR CODE

The values of a resistor can often be determined by the color code. Many resistors have bands of color that are used to determine the resistance value, tolerance, and, in some cases, reliability. Resistors typically contain from three to five bands of color. Resistors with three bands of color have a tolerance of $\pm$ 20%. Resistors that have tolerance rating from 10% to 2% have four bands of color. Resistors with a tolerance rating of 1% and some military resistors use five bands of color.

The color bands represent numbers. Each color represents a different numerical value, FIGURE 2-35. The chart shown in FIGURE 2-35 lists the color and number value assigned to each color. The resistor shown in FIGURE 2-36 illustrates how to determine the resistance value and the tolerance of a four-band resistor. The first two bands represent number values, the second band is the multiplier, and the fourth band is the tolerance.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-34 Air flow helps cool the resistor.

For example, assume a resistor has color bands of brown, green, red, and silver (FIGURE 2-36). The first two bands represent the numbers 1 and 5 (brown is 1 and green is 5). The third band is red, which has a number value of 2. The number 15 should be multiplied by 10^2, or 100. The value of the resistor is 1,500 Ω. Another method, which is simpler to understand, is to add the number of zeroes indicated by the multiplier band to the combined first two numbers. The multiplier band in this example is red, which has a numeric value of 2. Add two zeroes to the first two numbers. The number 15 becomes 1,500.

The fourth band is the tolerance band. The tolerance band in this example is silver, which means ±10%. This resistor should be 1,500 Ω ± 10%. To determine the value limits of this resistor, find 10% of 1,500.

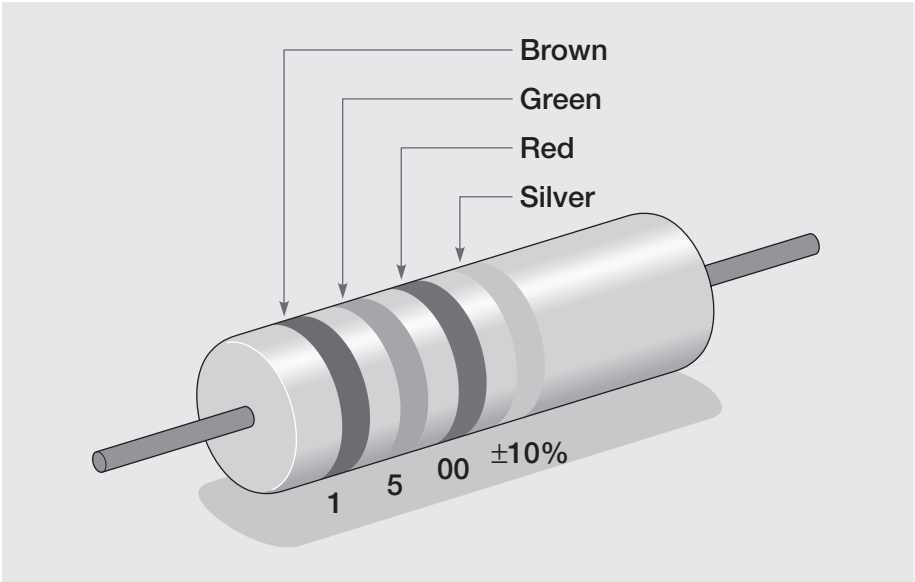
$$1500 \times 0.10 = 150$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

COLOR	VALUE	TOLERANCE
Black	0	No color band ± 20%
Brown	1	Silver ± 10%
Red	2	Gold ± 5%
Orange	3	Red ± 2%
Yellow	4	Brown ± 1%
Green	5	
Blue	6	
Violet	7	
Gray	8	
White	9	

© Cengage Learning 2014

FIGURE 2-35 Color code chart.



© Cengage Learning 2014

FIGURE 2-36 Determining resistor values using the color code.

The value can range from 1,500 + 10%, or 1,500 + 150 = 1,650 Ω to 1,500 − 10% or 1,500 − 150 = 1,350 Ω.

Resistors that have a tolerance of ±1%, as well as some military resistors, contain five bands of color.

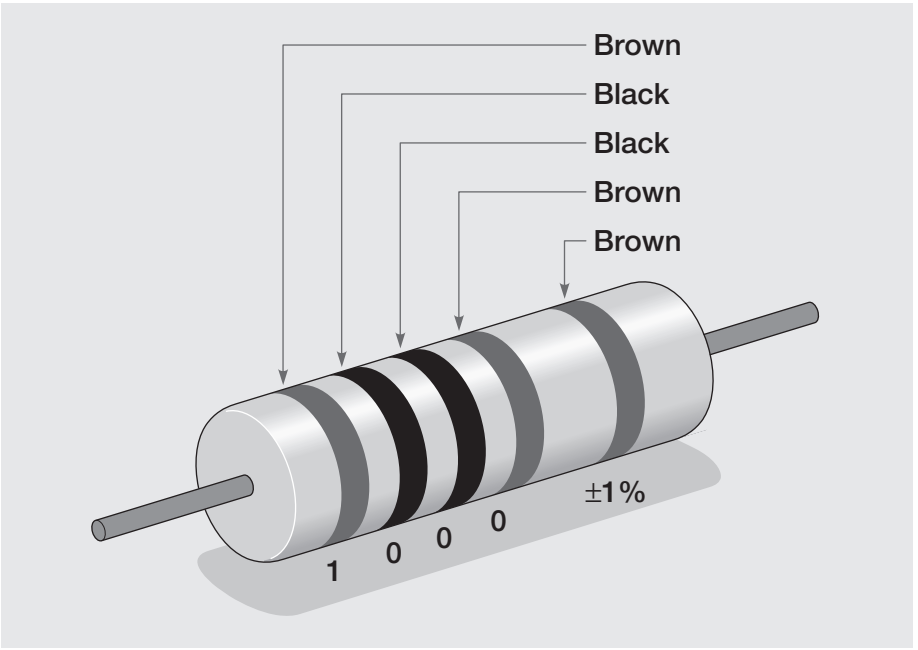
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 6: The resistor shown in FIGURE 2-37 contains the following bands of color:

first band = brown
second band = black
third band = black
fourth band = brown
fifth band = brown

Solution:

The brown fifth band indicates that this resistor has a tolerance of ±1%. To determine the value of a 1% resistor, the first three bands are numbers, and the fourth band is the multiplier. In this example, the first band is brown, which has a number value of 1. The next two bands are black, which represent a number value of 0. The fourth band is brown, which means add one 0 to the first three numbers. The value of this resistor is 1000 Ω ± 1%.



© Cengage Learning 2014

FIGURE 2-37 Determining the value of a ±1% resistor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 7: A five-band resistor has the following color bands:

first band = red
second band = orange
third band = violet
fourth band = red
fifth band = brown

Solution:
The first three bands represent number values. Red is 2, orange is 3, and violet is 7. The fourth band is the multiplier; in this case, red represents 2. Add two zeroes to the number 237. The value of the resistor is 23,700 Ω. The fifth band is brown, which indicates a tolerance of ±1%.

Military resistors also often have five bands of color. These resistors are read in the same manner as a resistor with four bands of color. The fifth band can represent different things. A fifth band of orange or yellow is used to indicate reliability. Resistors with a fifth band of orange have a reliability good enough to be used in missile systems, and a resistor with a fifth band of yellow can be used in space-flight equipment. A military resistor with a fifth band of white indicates that the resistor has solderable leads.

Resistors with tolerance ratings ranging from 0.5% to 0.1% will generally have their values printed directly on the resistor.

Gold and Silver as Multipliers

The colors gold and silver are generally found in the fourth band of a resistor, but they can be used in the multiplier band also. When the color gold is used as the multiplier band it means to divide the combined first two numbers by 10. If silver is used as the multiplier band it means to divide the combined first two numbers by 100. For example, assume a resistor has color bands of orange, white, gold, gold. The value of this resistor is 3.9 Ω with a tolerance of ±5% (orange = 3; white = 9; gold means to divide 39 by 10 = 3.9; and gold in the fourth band means ±5% tolerance).

STANDARD RESISTANCE VALUES OF FIXED RESISTORS

Fixed resistors are generally produced in standard values. The higher the tolerance value, the fewer resistance values available. Standard resistance values are listed in the chart shown in FIGURE 2-38. In the column under 10% only twelve values of resistors are listed. These standard values, however, can be multiplied by factors of ten. Notice that one

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

STANDARD RESISTANCE VALUES (Ω)

0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%
10.0	10.0	17.2	–	29.4	29.4	50.5	–	86.6	86.6
10.1	–	17.4	17.4	29.8	–	51.1	51.1	87.6	–
10.2	10.2	17.6	–	30.1	30.1	51.7	–	88.7	88.7
10.4	–	17.8	17.8	30.5	–	52.3	52.3	89.8	–
10.5	10.5	18.0	–	30.9	30.9	53.0	–	90.9	90.9
10.6	–	18.2	18.2	31.2	–	53.6	53.6	92.0	–
10.7	10.7	18.4	–	31.6	31.6	54.2	–	93.1	93.1
10.9	–	18.7	18.7	32.0	–	54.9	54.9	94.2	–
11.0	11.0	18.9	–	32.4	32.4	55.6	–	95.3	95.3
11.1	–	19.1	19.1	32.8	–	56.2	56.2	96.5	–
11.3	11.3	19.3	–	33.2	33.2	56.9	–	97.6	97.6
11.4	–	19.6	19.6	33.6	–	57.6	57.6	98.8	–
11.5	11.5	19.8	–	34.0	34.0	58.3	–		
11.7	–	20.0	20.0	34.4	–	59.0	59.0		
11.8	11.8	20.3	–	34.8	34.8	59.7	–		
12.0	–	20.5	20.5	35.2	–	60.4	60.4		
12.1	12.1	20.8	–	35.7	35.7	61.2	–		
12.3	–	21.0	21.0	36.1	–	61.9	61.9		
12.4	12.4	21.3	–	36.5	36.5	62.6	–		
12.6	–	21.5	21.5	37.0	–	63.4	63.4		
12.7	12.7	21.8	–	37.4	37.4	64.2	–	2%,5%	10%
12.9	–	22.1	22.1	37.9	–	64.9	64.9	10	10
13.0	13.0	22.3	–	38.3	38.3	65.7	–	11	–
13.2	–	22.6	22.6	38.8	–	66.5	66.5	12	12
13.3	13.3	22.9	–	39.2	39.2	67.3	–	13	–
13.5	–	23.2	23.2	39.7	–	68.1	68.1	15	15
13.7	13.7	23.4	–	40.2	40.2	69.0	–	16	–
13.8	–	23.7	23.7	40.7	–	69.8	69.8	18	18
14.0	14.0	24.0	–	41.2	41.2	70.6	–	20	–
14.2	–	24.3	24.3	41.7	–	71.5	71.5	22	22
14.3	14.3	24.6	–	42.2	42.2	72.3	–	24	–
14.5	–	24.9	24.9	42.7	–	73.2	73.2	27	27
14.7	14.7	25.2	–	43.2	43.2	74.1	–	30	–
14.9	–	25.5	25.5	43.7	–	75.0	75.0	33	33
15.0	15.0	25.8	–	44.2	44.2	75.9	–	36	–
15.2	–	26.1	26.1	44.8	–	76.8	76.8	39	39
15.4	15.4	26.4	–	45.3	45.3	77.7	–	43	–
15.6	–	26.7	26.7	45.9	–	78.7	78.7	47	47
15.8	15.8	27.1	–	46.4	46.4	79.6	–	51	–
16.0	–	27.4	27.4	47.0	–	80.6	80.6	56	56
16.2	16.2	27.7	–	47.5	47.5	81.6	–	62	–
16.4	–	28.0	28.0	48.1	–	82.5	82.5	68	68
16.5	16.5	28.4	–	48.7	48.7	83.5	–	75	–
16.7	–	28.7	28.7	49.3	–	84.5	84.5	82	82
16.9	16.9	29.1	–	49.9	49.9	85.6	–	91	–

© Cengage Learning 2014

FIGURE 2-38 Standard resistance values.

of the standard values listed is 33 Ω. There are also standard values in 10% resistors of 0.33, 3.3, 330, 3300, 33,000, 330,000, and 3,300,000 ohms. The 2% and 5% column shows twenty-four resistor values, and the 1% column lists ninety-six values. All of the values listed in the chart can be multiplied by factors of ten to obtain other resistance values.

POWER RATINGS

Resistors also have a power rating in watts that should not be exceeded or the resistor will be damaged. The amount of heat that must be dissipated by

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

(given off to the surrounding air) the resistor can be determined by the use of the following formulas.

$$P = I^2R$$

$$P = \frac{E^2}{R}$$

$$P = EI$$

EXAMPLE 8: The resistor shown in FIGURE 2-39 has a value of 100 Ω and a power rating of 1/2 W. If the resistor is connected to a 10-V power supply, will it be damaged?

Solution:
Using the formula $P = \frac{E^2}{R}$ determine the amount of heat that will be dissipated by the resistor.

$$P = \frac{E^2}{R}$$

$$P = \frac{10 \times 10}{100}$$

$$P = \frac{100}{100}$$

$$P = 1 \text{ W}$$

Since the resistor has a power rating of 1/2 W, and the amount of heat that will be dissipated is 1 W, the resistor will be damaged.

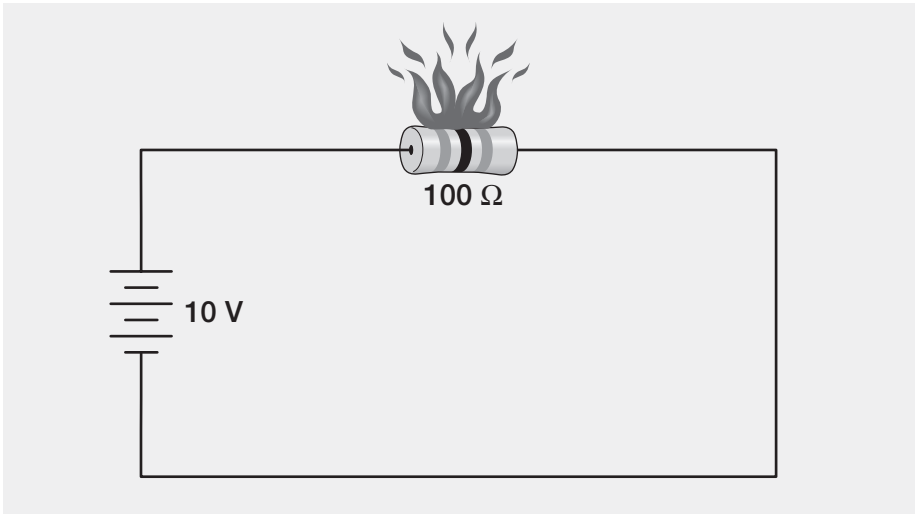
VARIABLE RESISTORS

variable resistor
resistor whose resistance value can be varied between its minimum and maximum values.

A **variable resistor** is a resistor whose values can be changed or varied over a range. Variable resistors can be obtained in different case styles and power ratings. FIGURE 2-40 illustrates how a variable resistor is constructed. In this example, a resistive wire is wound in a circular pattern, and a sliding tap makes contact with the wire. The value of a resistance can be adjusted between one end of the resistive wire and the sliding tap. If the resistive wire has a total value of 100 Ω, the resistor can be set between the values of 0 and 100 Ω.

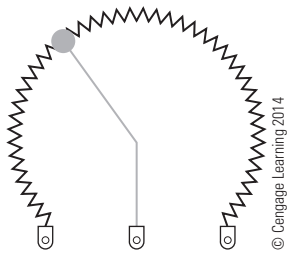
A variable resistor with three terminals is shown in FIGURE 2-41. This type of resistor has a wiper arm inside the case that makes contact with the resistive element. The full resistance value is between the two outside terminals, and the wiper arm is connected to the center terminal. The resistance

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



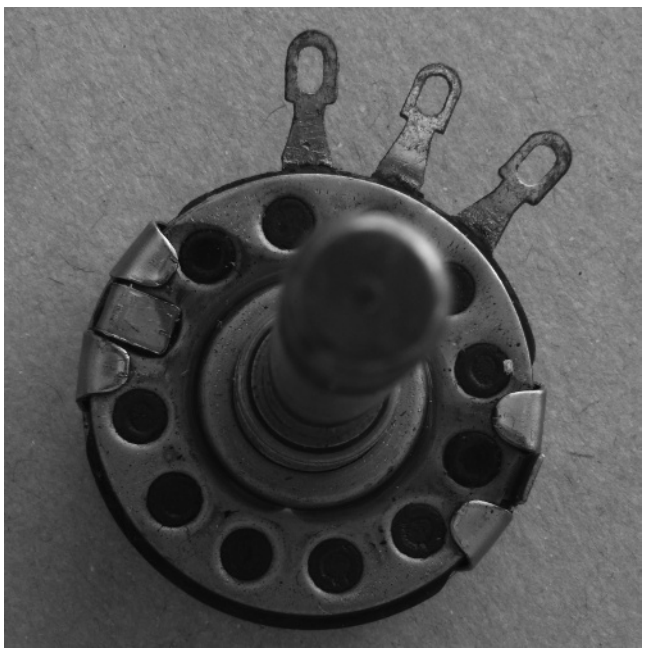
© Cengage Learning 2014

FIGURE 2-39 Exceeding the power rating causes damage to the resistor.



© Cengage Learning 2014

FIGURE 2-40 Variable resistor.

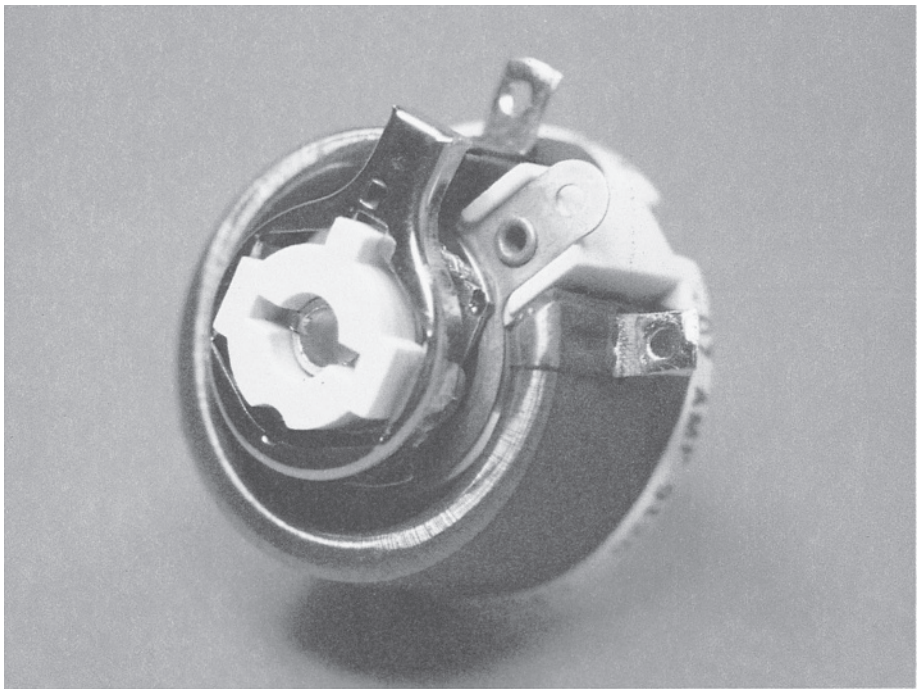


© Cengage Learning 2014

FIGURE 2-41 Variable resistor with three terminals.

between the center terminal and either of the two outside terminals can be adjusted by turning the shaft and changing the position of the wiper arm. Wire wound variable resistors of this type can be obtained also, FIGURE 2-42. The advantage of the wire wound type is a higher power rating.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-42 Wire wound variable resistor.

The resistor shown in FIGURE 2-41 can be adjusted from its minimum to maximum value by turning the control approximately three-quarters of a turn. In some types of electrical equipment this range of adjustment may be too coarse to allow for sensitive adjustments. When this becomes a problem, a multiturn resistor (FIGURE 2-43) can be used. **Multiturn variable resistors** operate by moving the wiper arm with a screw of some number of turns. They generally range from three turns to ten turns. If a ten-turn variable resistor is used, it will require ten turns of the control knob to move the wiper from one end of the resistor to the other end instead of three-quarters of a turn.

multiturn variable resistors
resisters that operate by moving the wiper arm with a screw of some number of turns.

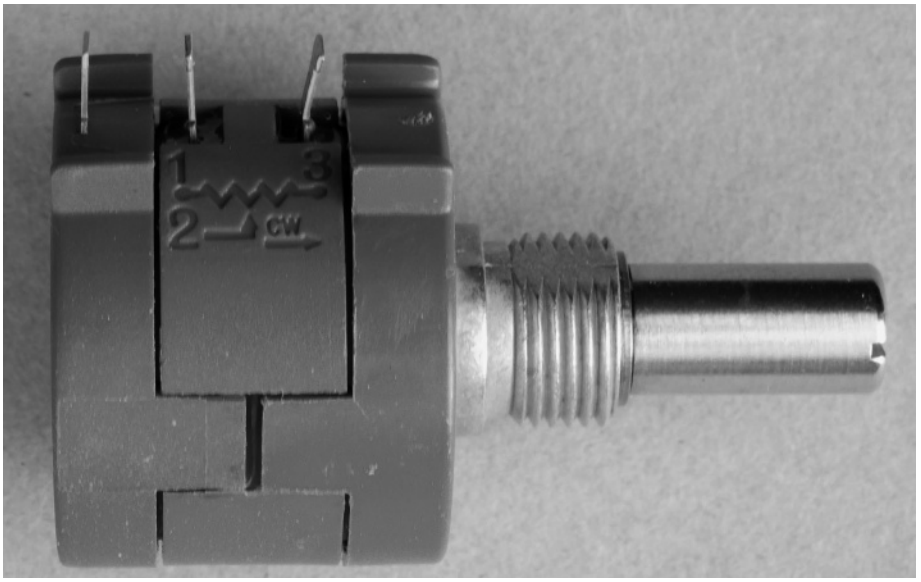
Variable Resistor Terminology

Variable resistors are known by several common names. The most popular name is **pot,** which is shortened from the word *potentiometer*. Another common name is **rheostat.** A rheostat is actually a variable resistor that has two terminals. They are used to adjust the current in a circuit to a certain value. A potentiometer is a variable resistor that has three terminals. Potentiometers can be used as rheostats by only using two of their three terminals. A **potentiometer** describes how a variable resistor is used rather than some specific type of resistor. The word *potentiometer* comes from the word *potential,* or

pot/rheostat
variable resistor.

potentiometer
variable resistor with a sliding contact that is used as a voltage divider.

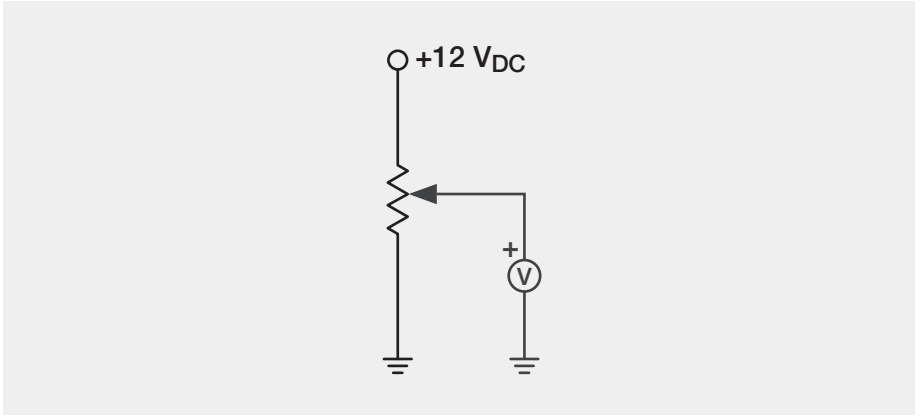
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-43 Multiturn variable resistor.

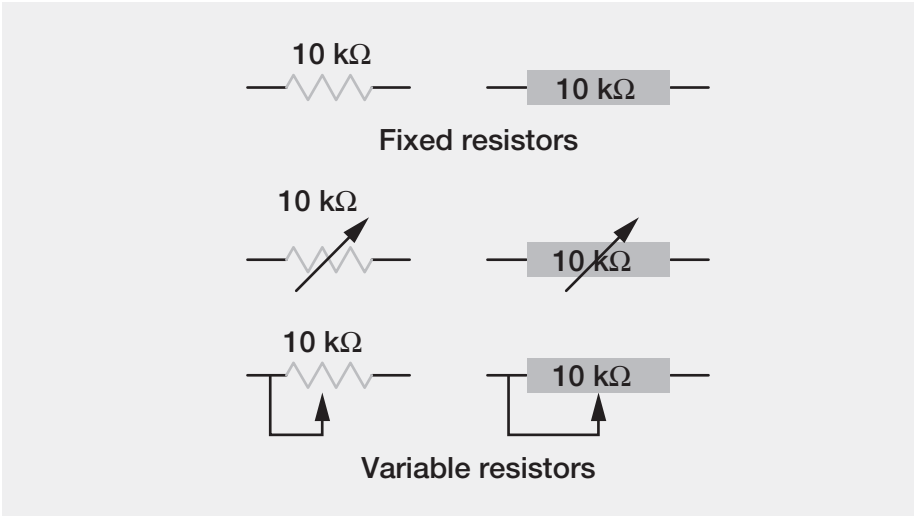
voltage. A potentiometer is a variable resistor used to provide a variable voltage, as shown in FIGURE 2-44. In this example, one end of a variable resistor is connected to +12 V, and the other end is connected to ground. The middle terminal, or wiper, is connected to the positive terminal of a volunteer and the negative lead is connected to ground. If the wiper is moved to the upper end of the resistor, the volunteer will indicate a potential of 12 V. If the wiper is moved to the bottom, the volunteer will indicate a value of 0 V. The wiper can be adjusted to provide any value of voltage between 12 and 0 V.



© Cengage Learning 2014

FIGURE 2-44 Variable resistor used as a potentiometer.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 2-45 Schematic symbols used to represent resistors.

SCHEMATIC SYMBOLS

Electrical schematics use symbols to represent the use of a resistor. Unfortunately, the symbol used to represent a resistor is not standard. FIGURE 2-45 illustrates several schematic symbols used to represent both fixed and variable resistors.

Summary

1. A coulomb is a quantity measurement of electrons.
2. The definition of an amp (A) is one coulomb per second.
3. The letters I, which stands for intensity of current flow, or A, which stands for amps, are often used in Ohm's Law formulas.
4. Voltage is referred to as electrical pressure, potential difference, or electromotive force. The letters E and V are used to represent voltage in Ohm's Law formulas.
5. An ohm (Ω) is a measurement of resistance (R) in an electrical circuit. The letter R is used to represent Ohm's Law formulas.
6. The watt (W) is a measurement of power in an electrical circuit. It is represented by the letters W or P (power) in Ohm's Law formulas.
7. Electrical measurements generally use engineering notation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

8. Engineering notation differs from the standard metric system in that it uses steps of 1,000 instead of steps of 10.
9. Before current can flow, there must be a complete circuit.
10. A short circuit has little or no resistance.
11. Resistors are used in two main applications: as voltage dividers and to limit the flow of current in a circuit.
12. The value of a fixed resistor cannot be changed.
13. There are several types of fixed resistors, such as composition carbon, metal film, and wire wound.
14. Carbon resistors change their value with age or if overheated.
15. Metal film resistors never change their value, but they are more costly than carbon resistors.
16. The advantage of wire wound resistors is their high power ratings.
17. Resistors often have bands of color to indicate their resistance value and tolerance.
18. Resistors are produced in standard values. The number of values between 0 Ω and 100 Ω is determined by the tolerance.
19. Variable resistors can change their value within the limit of their full value.
20. A potentiometer is a variable resistor used as a voltage divider.

Review Questions

1. What is a coulomb?
2. What is an amp?
3. Define voltage.
4. Define ohm.
5. Define watt.
6. An electric heating element has a resistance of 16 Ω and is connected to a voltage of 120 V. How much current will flow in this circuit?
7. How many watts of heat are being produced by the heating element in question 6?
8. A 240-V circuit has a current flow of 20 A. How much resistance is connected to the circuit?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

9. An electric motor has an apparent resistance of 15 Ω. If 8 A of current are flowing through the motor, what is the connected voltage?
10. A 240-V air conditioning compressor has an apparent resistance of 8 Ω. How much current will flow in the circuit?
11. How much power is being used by the compressor in question 8?
12. A 5-kW electric heating unit is connected to a 240-V line. What is the current flow in the circuit?
13. If the voltage in question 12 is reduced to 120 V, how much current would be needed to reduce the same amount of power?
14. Is it less expensive to operate the electric heating unit in question 12 on 240 V or 120 V?
15. Name three types of fixed resistors.
16. What is the advantage of a metal film resistor over a carbon resistor?
17. What is the advantage of a wire wound resistor?
18. How should tubular wire wound resistors be mounted and why?
19. A half-watt 2,000-Ω resistor has a current flow of .01 amps through it. Is this resistor operating within its power rating?
20. A one-watt 350-Ω resistor is connected to 24 V. Is this resistor operating within its power rating?
21. A resistor has color bands of orange, blue, yellow, and gold. What is the resistance and tolerance of this resistor?
22. A 10,000-Ω resistor has a tolerance of 5%. What are the minimum and maximum ratings of this resistor?
23. Is 51,000 Ω a standard value for a 5% resistor?
24. What is a potentiometer?

Practice Problems

OHM'S LAW

1. A 1,500-W heating element has a resistance of 38.4 Ω. How much current is flowing through the heating element?
2. How much voltage is applied to the heating element in question 1?
3. A 100-W lamp is connected to a 120-V circuit. How much current will flow through the lamp?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

4. A 15-W soldering iron is connected to a 120-V circuit. What is the resistance of the iron?
5. Four 300-W heating elements are connected to a 277-V line. How much current will flow in the circuit?
6. A 1.5-KΩ resistor has a current of 8 mA flowing through it. How much voltage is applied to the resistor?
7. Change 0.00045 A into milliamps (mA).
8. Change 0.00045 A into microamps (μA).
9. An alternator produces 850 megawatts (MW) at a voltage of 13,800 V. What is the current output of the alternator?
10. Change 2,542 V into kilovolts (kV).

Practice Problems

RESISTORS

1st Band	2nd Band	3rd Band	4th Band	Value	%Tol
Red	Yellow	Brown	Silver		
				6800 Ω	5
Orange	Orange	Orange	Gold		
				12 Ω	2
Brown	Green	Silver	Silver		
				1.8 MΩ	10
Brown	Black	Yellow	None		
				10 kΩ	5
Violet	Green	Black	Red		
				4.7 kΩ	20
Gray	Red	Green	Red		
				5.6 kΩ	2

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 3

Electrical Sources and Static Charges

OBJECTIVES: After studying this unit you should be able to:

- Discuss static electricity.
- Give examples of static charges.
- List different methods of producing electricity.
- Discuss the operation of batteries.
- Discuss piezoelectric devices.
- Discuss solar cells.
- Discuss the operation of thermocouples.
- List methods of lightning protection.

alternators
machines for producing alternating current.

electromagnetic
magnetism produced by electricity.

Various methods can be employed to produce electricity such as magnetic, chemical, pressure, solar, and heat. Most of the world's electric power is produced by **alternators.** Alternators operate on the principle of **electromagnetic** induction. Two of the basic principles concerning electricity are that any time current flows through a conductor a magnetic field is produced around the conductor, and any time a conductor is moved through a magnetic field a voltage is induced in the conductor. These concepts will be discussed more fully in Unit 4.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

BATTERIES

Probably the second most prominent method of producing electricity is **voltaic cells.** Voltaic cells use chemical action to produce a potential between two electrodes. Voltaic cells can be divided into two basic types, **primary** and **secondary.** They can be constructed from virtually any two unlike metals and an **electrolyte** of acid, alkaline, or salt solution. The first practical battery was produced by Alessandro Volta in 1800. Volta used zinc and silver discs separated by cardboard soaked in brine (salt water), FIGURE 3-1. Volta called his battery a voltaic pile because it was a series of cells connected together. Each cell produces a certain amount of voltage depending on the materials used in the construction of the cell. A battery is actually a group of cells connected together, although the word battery is often used in everyday language to refer to a single cell. The symbols for a cell and a battery are shown in FIGURE 3-2.

voltaic cells
device that converts chemical energy into electrical energy.

primary
voltaic cell that cannot be recharged.

secondary
voltaic cell that can be recharged.

electrolyte
chemical compound capable of conducting electric current by being broken down into ions. Electrolytes can be acids or alkalines.

PRIMARY CELLS

Primary cells cannot be recharged. They operate by using up their materials in the production of electricity. The construction of a basic carbon-zinc cell is shown in FIGURE 3-3. The chemical action employed to produce electric current causes the zinc can to dissolve over a period of time. If the cell is not removed from the device it operates, the electrolyte will eventually leak and damage the device. Primary cells should always be removed from a device when they are discharged. There are different types of

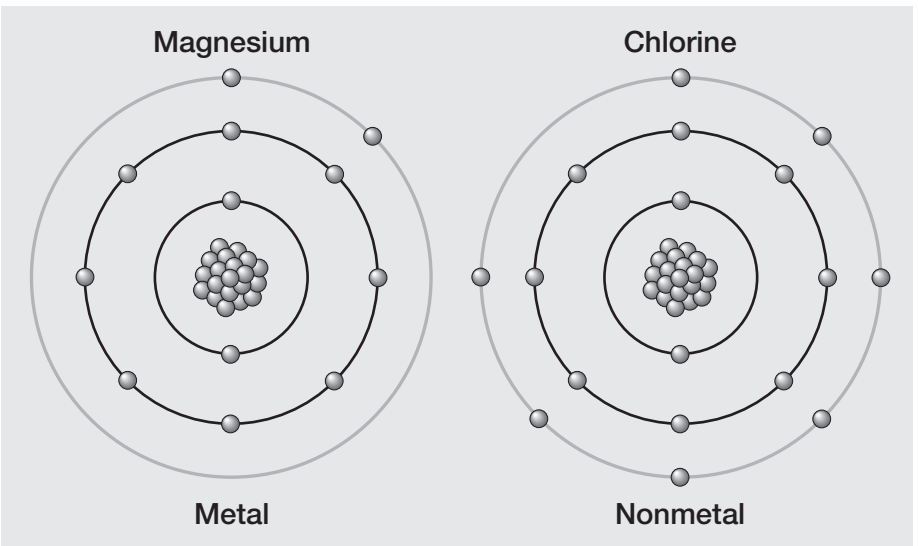


FIGURE 3-1 A voltaic pile.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

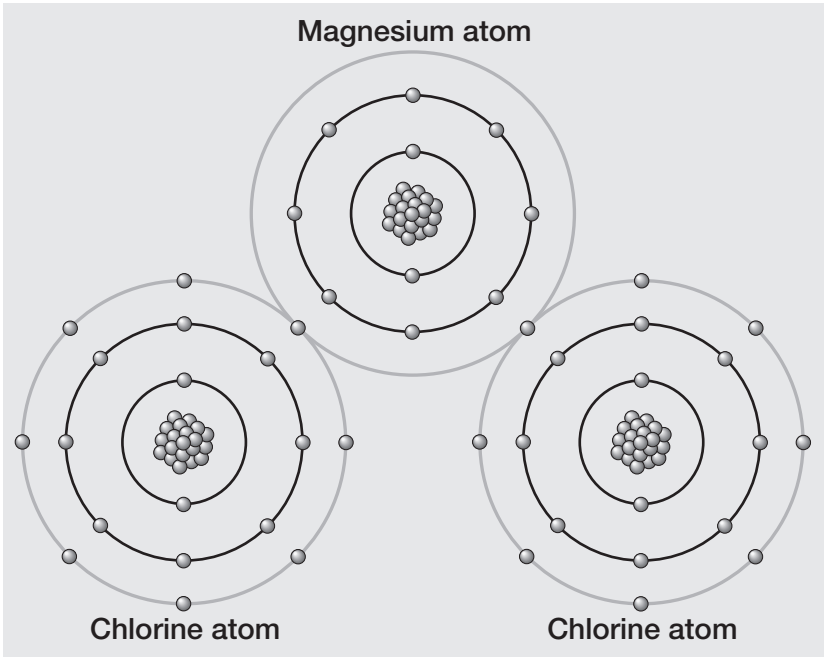


FIGURE 3-2 Schematic symbols used to represent a single cell and a battery.

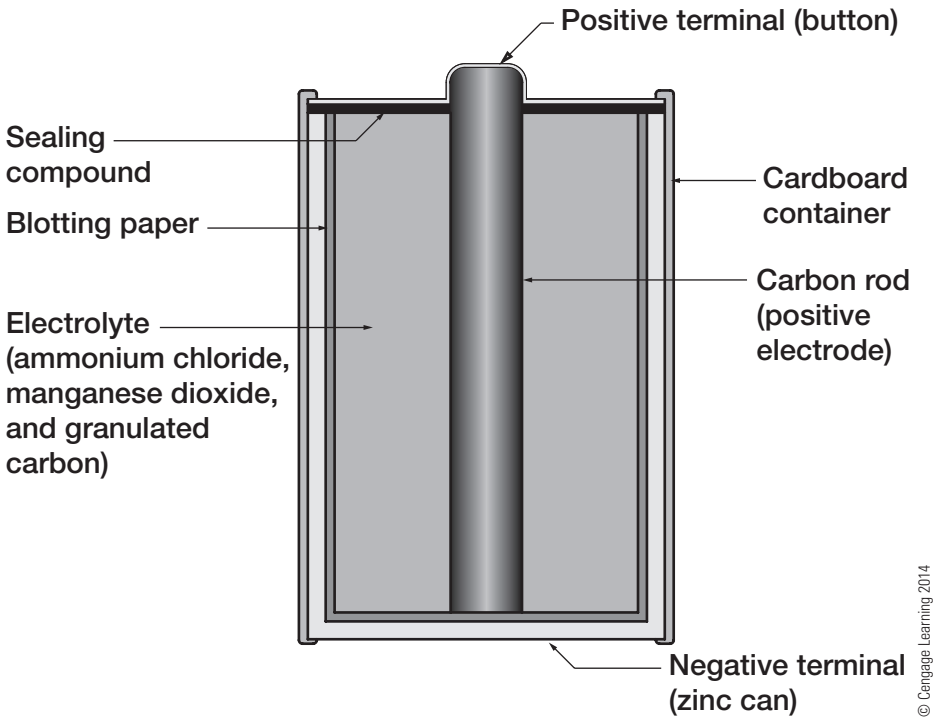


FIGURE 3-3 Construction of a basic carbon-zinc cell.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

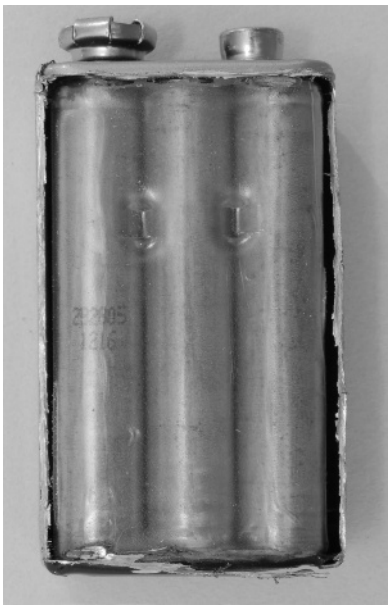
primary cells available and their voltage will vary depending on the materials from which they are made. The chart in FIGURE 3-4 lists different primary cells, the materials used in their construction, and the cell voltage.

Primary cells are often connected in series to increase the terminal voltage. A very common battery is the 9 V, FIGURE 3-5. The common 9-V battery is made by connecting six individual 1.5-V cells in series. When cells are connected in series their voltages will produce a total output voltage.

CELL	NEGATIVE PLATE	POSITIVE PLATE	ELECTROLYTE	VOLTS PER CELL
Carbon-zinc (Leclanche)	Zinc	Carbon, manganese dioxide	Ammonium chloride	1.5
Alkaline	Zinc	Manganese dioxide	Potassium hydroxide	1.5
Mercury	Zinc	Mercuric oxide	Potassium hydroxide	1.35
Silver-zinc	Zinc	Silver oxide	Potassium hydroxide	1.6
Zinc-air	Zinc	Oxygen	Potassium hydroxide	1.4
Edison-lalance	Zinc	Copper oxide	Sodium hydroxide	0.8

© Cengage Learning 2014

FIGURE 3-4 Primary cells.



© Cengage Learning 2014

FIGURE 3-5 A 9-V battery is made by connecting six individual cells together in series.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 3-6 Cells can be obtained in different sizes and styles.

Cells can also be obtained in different sizes and styles, FIGURE 3-6. Common alkaline cells can be obtained in sizes D, C, AA, and AAA. All of these cells have a voltage of 1.5 V. The difference is the amount of current they can produce and the amount of energy density. The amount of current a cell can produce is determined by the area of the cell plates. The larger the cell, the greater the plate surface area, and the more current it can produce. Also, the larger the cell the more energy density it contains. Assume that a D cell and a AA cell are used to power identical loads that have the same current requirement. The D cell will be able to power the load longer because it contains more material and therefore has a greater energy density.

The current capacity (energy density) of cells is measured in watt-hours. A chart showing the current capacity of different size alkaline-manganese cells is shown in FIGURE 3-7. Size is not the only factor that determines the energy density of a cell. Different types of cells contain different amounts of energy. A D-size alkaline cell contains more energy than a D-size carbon-zinc cell. Mercury cells contain more energy density than an equivalent size alkaline-manganese cell. A chart showing the watt-hours per cubic inch for different types of cells is shown in FIGURE 3-8.

ALKALINE-MANGANESE CELL SIZE	VOLUME IN CUBIC INCHES	WATT-HOURS PER CUBIC INCH
D cell	3.17	4.0
C cell	1.52	4.2
AA cell	0.44	4.9
AAA cell	0.20	5.1

© Cengage Learning 2014

FIGURE 3-7 Watt-hours per cubic inch for different size cells.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

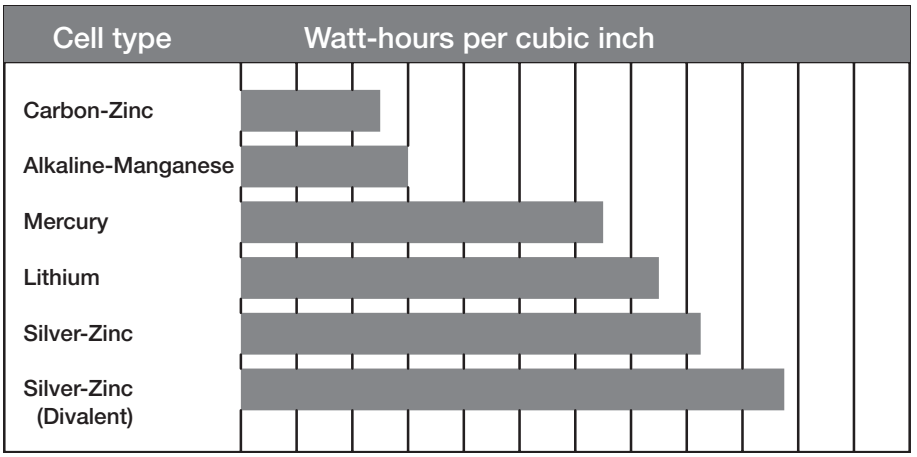


FIGURE 3-8 Watt-hours per cubic inch for different types of cells.

All batteries have some amount of internal resistance. If they did not have internal resistance they could produce an infinite amount of current. If an ammeter were connected directly to a C-size cell, for example, some amount of current would flow, FIGURE 3-9. The current is limited by the amount of internal resistance. The internal resistance is determined by several factors such as

- size of the cell,
- type of cell, and
- state of charge.

As a cell uses its stored energy, the internal resistance increases. This is the reason that the lamp of a flashlight will become dimmer as the cells become weaker. When internal resistance increases the output current is limited to a greater degree.

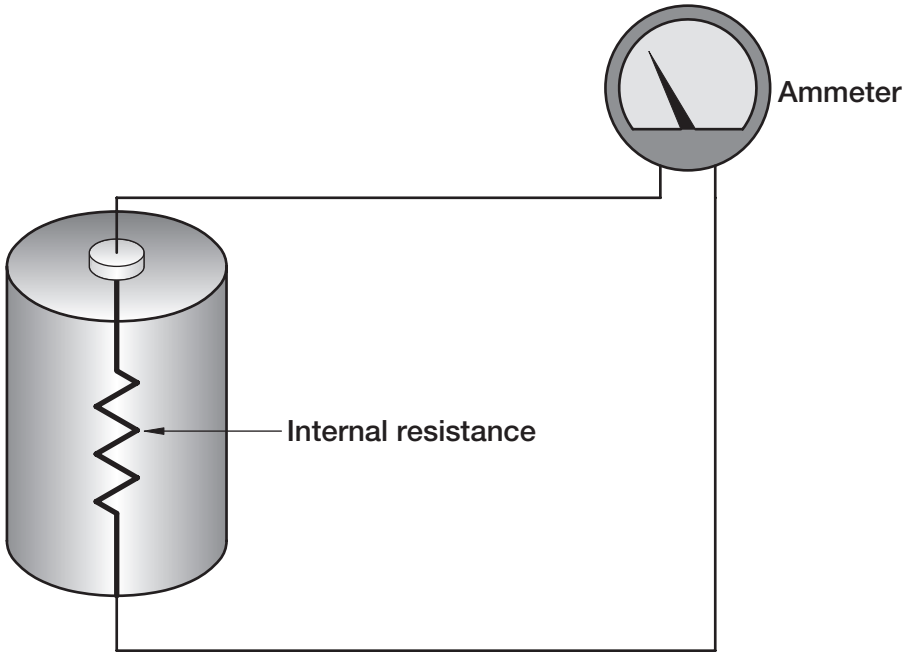
SECONDARY CELLS

Secondary cells can be recharged. Some common examples of secondary cells are lead-acid, nickel-cadmium (Ni-Cad), nickel-metal hydride (Ni-MH), and lithium-ion. Probably the most common type of secondary cell is the lead-acid. These cells are employed to make the batteries that start automobiles, operate trolling motors on fishing boats, and supply the power for electric fork trucks. Lead-acid cells produce 2 V per cell. Automobile batteries contain six cells connected in series to produce an output voltage of 12 V. Lead-acid batteries can produce a very high output current under a short-circuit condition. **Never short the terminals of**

KEY POINT

Never short the terminals of a lead-acid battery. It can cause the battery to explode.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 3-9 All batteries have some amount of internal resistance.

KEY POINT
Caution should be used when charging a lead-acid battery because it can produce hydrogen gas during the charging cycle. Hydrogen is the most explosive gas known.

a lead-acid battery. It can cause the battery to explode. The typical starting current for most automobiles will range from 200 to 250 A.

When charging a lead-acid battery, the charger must have a voltage greater than the terminal voltage of the battery. The positive lead of the charger is connected to the positive lead of the battery, and the negative lead of the charger is connected to the negative lead of the battery. **Caution should be used when charging a lead-acid battery because it can produce hydrogen gas during the charging cycle. Hydrogen is the most explosive gas known.** A lead-acid battery should never be charged at a rate greater than one-tenth the amp-hour rating. To do so will greatly shorten the life of the battery. Assume that a lead-acid battery has an amp-hour rating of 80 Ah. The charging current should not exceed 8 A (80/10). The amp-hour rating is determined by measuring the battery's ability to produce current for a 20-hour period at a temperature of 80°F. A battery with the ability to produce 5 A of current for 20 hours would have a rating of 100 Ah (5×20).

Marine batteries designed to produce smaller amounts of current over a long period of time will generally have an amp-hour rating. Lead-acid batteries intended to start automobiles, however, generally have a cold-cranking amps rating. The cold-cranking amps rating has nothing to do with

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

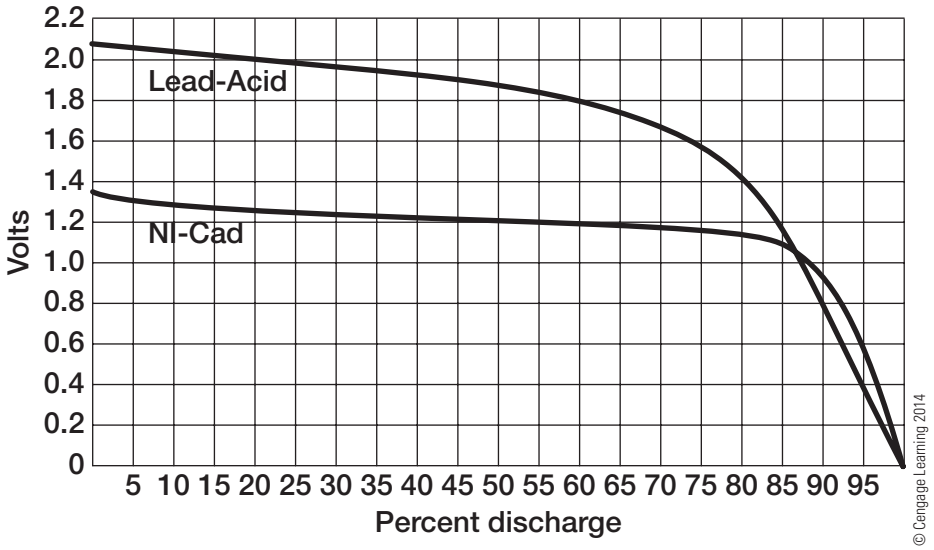


FIGURE 3-10 Typical characteristic curves of Ni-Cad and lead-acid batteries.

the amp-hour rating. The cold-cranking amps rating is the amount of current the battery can produce under a short-circuit condition at a temperature of 20°C (68°F).

Nickel-cadmium and nickel metal hydride cells have very similar operating characteristics. Both cells produce 1.2 V. The characteristic curve is basically the same for both types of cells. The characteristic curves of a nickel-cadmium cell and a lead-acid cell are shown in FIGURE 3-10. The characteristic curves reveal that the voltage of a lead-acid cell will drop at a proportional rate as it discharges. The voltage of the nickel-cadmium cell remains fairly constant until it reaches discharge and the voltage then drops rapidly.

Although nickel-cadmium and nickel-metal hydride cells are very similar, they do have some differences. The nickel-cadmium cell has a problem with memory. If the cell is used for only low currents and permitted to discharge only through part of a cycle and then recharged, over a long period of time it will develop a characteristic curve to match this cycle. Nickel-cadmium cells should be permitted to reach the end of their discharge curve before being recharged. The nickel-metal hydride cell does not exhibit as great a problem with memory accumulation. Nickel-metal hydride cells also have about 40% more energy density than nickel-cadmium cells. Both nickel-cadmium and nickel-metal hydride batteries are used in portable devices such as power tools, electric razors, electric toothbrushes, and rechargeable flashlights.

Lithium-ion cells are very popular for portable equipment such as notebook computers, video cameras, cell phones, and many others. They offer a very high energy density for their size and weight. They exhibit a voltage of

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

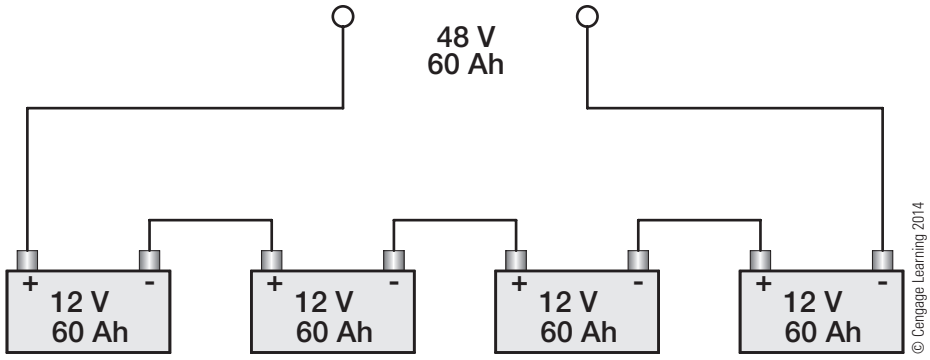


FIGURE 3-11 When batteries are connected in series, their voltages add and their amp-hour capacities remain the same.

3.6 V per cell, which is the same voltage that can be obtained by connecting three nickel-cadmium or nickel-metal hydride cells in series. Lithium-ion cells exhibit a weight-energy density that is about three times greater than a nickel-cadmium cell. Under proper charging conditions they can be recharged about 500 times. Unlike nickel-cadmium cells, lithium-ion cells do not have the problem of memory accumulation. They can be recharged to their full capacity each time they are charged.

BATTERY CONNECTIONS

When batteries are connected in series, their voltages will add but the amp-hour rating will remain the same. Four 12-V batteries are connected in series, FIGURE 3-11. Each battery has a current capacity of 60 Ah. The total output for this connection is 48 V (12×4) with a current capacity of 60 Ah. If the same four batteries are connected in parallel, FIGURE 3-12, the voltage will remain the same but the amp-hour capacity will add.

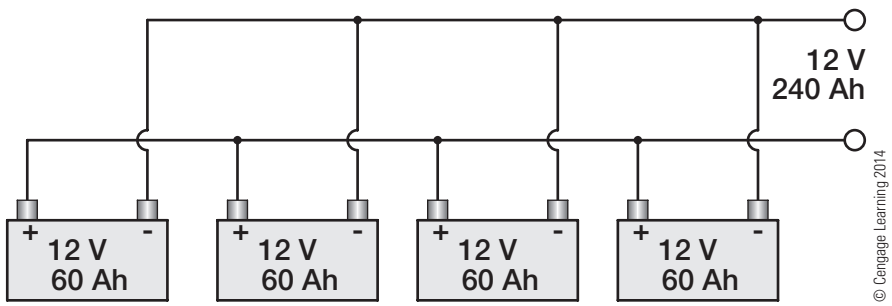


FIGURE 3-12 When batteries are connected in parallel, their voltage remains the same and their amp-hour capacities add.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

SOLAR CELLS

Although batteries are the largest source of electricity after alternators and generators, they are not the only source. One source of electricity is the **photovoltaic** cell, or solar cell. Solar cells are constructed from a combination of P- and N-type semiconductor material. Semiconductors are made from materials that contain four valence electrons. The most common semiconductor materials are silicon and germanium. Impurities must be added to the pure semiconductor material to form P- and N-type materials. If a material containing three valence electrons is added to a pure semiconductor material, P-type material is formed. P-type material has a lack of electrons. N-type material is formed when a material containing five valence electrons is added to a pure semiconductor material. N-type material has an excess of electrons.

photovoltaic
material or device that produces a voltage in the presence of light.

Light is composed of particles called **photons.** A photon is a small package of pure energy that contains no mass. When photons strike the surface of the photocell, the energy contained in the photon is given to a free electron. This causes the electron to cross the junction between the two types of semiconductor material producing a voltage, FIGURE 3-13.

photons
particles of light.

The amount of voltage produced by a solar cell is determined by the material from which it is made. Silicon solar cells produce an open circuit voltage of 0.5 V per cell in direct sunlight. The amount of current a cell can deliver is

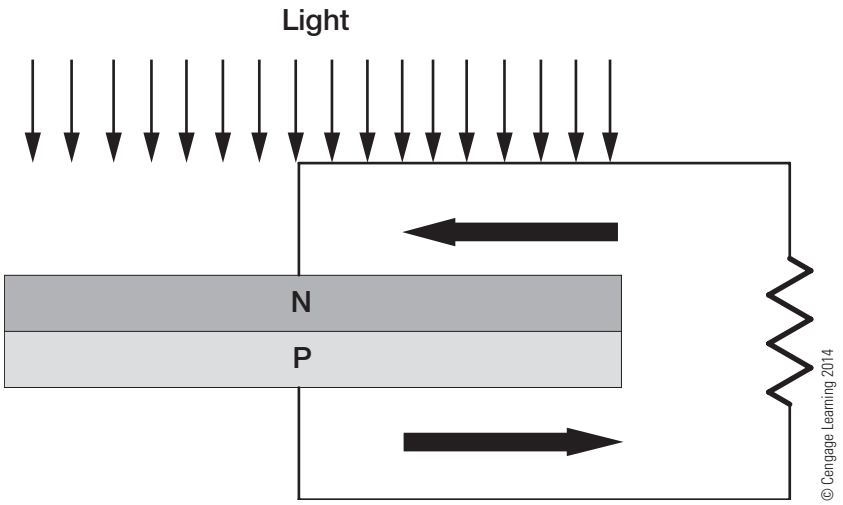
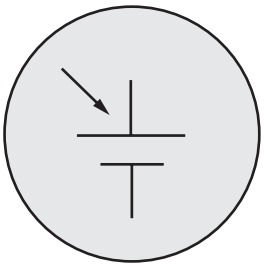


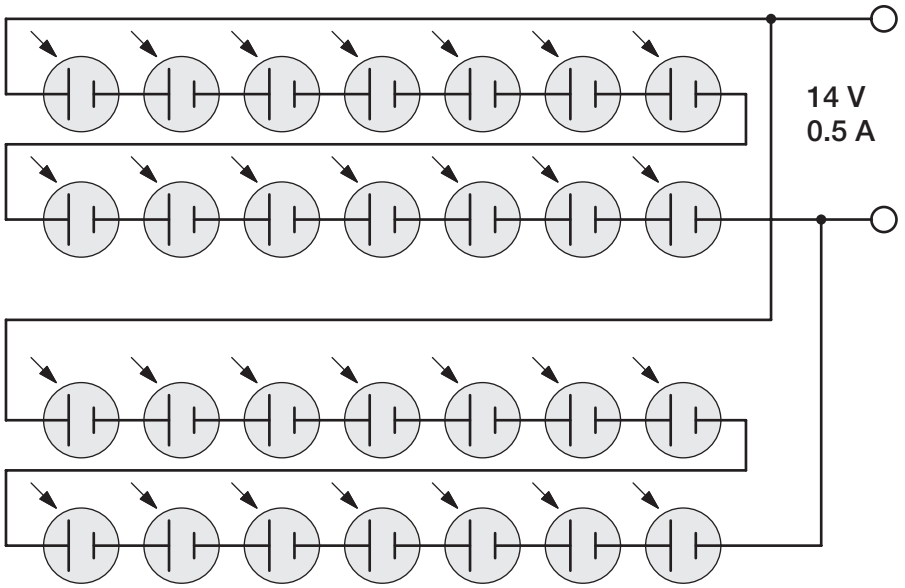
FIGURE 3-13 Solar cells are made from a combination of P- and N-type semiconductor material.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 3-14 Symbol for a solar cell.



© Cengage Learning 2014

FIGURE 3-15 Series-parallel connection of solar cells.

determined by the surface area of the cell. Since the solar cell produces a voltage in the presence of light, the schematic symbol for a solar cell is the same as that used to represent a single voltaic cell with the addition of an arrow to indicate it is receiving light, FIGURE 3-14.

It is often necessary to connect solar cells in series and/or parallel to obtain desired amounts of voltage and current. For example, assume that an array of photovoltaic cells is to be used to charge a 12-V lead-acid battery. The charging voltage is to be 14 V and the charging current should be 0.5 A. Now assume that each cell produces 0.5 V with a short-circuit current of 0.25 A. In order to produce 14 V, it will be necessary to connect 28 solar cells in series. This will produce an output of 14 V with a current capacity of 0.25 A. To produce an output of 14 V with a current capacity of 0.5 A, it will be necessary to connect a second set of 28 cells in series and parallel them with the first set, FIGURE 3-15.

THERMOCOUPLES

Seebeck effect
producing a voltage by heating the junction of two dissimilar metals.

In 1822, a German scientist named Seebeck discovered that when two dissimilar metals are joined at one end, and that junction is heated, a voltage is produced, FIGURE 3-16. This is known as the **Seebeck effect.** The device produced by the joining of two dissimilar metals for the purpose

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

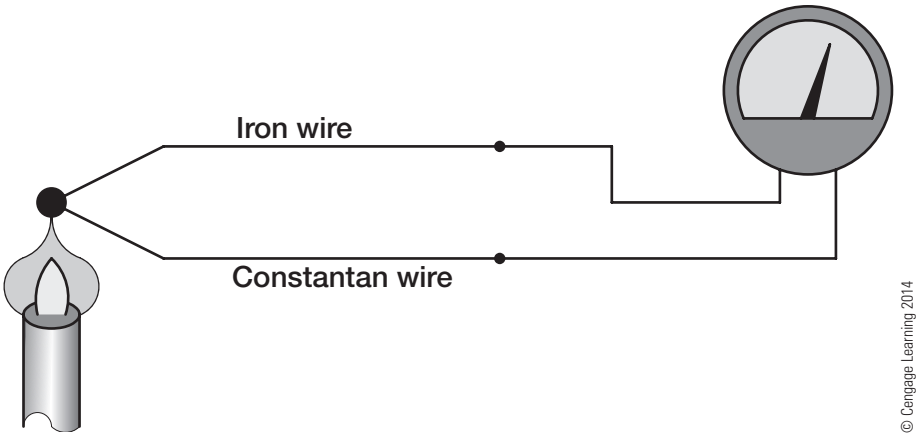


FIGURE 3-16 A thermocouple is made by forming a junction of two different types of metal.

of producing electricity with heat is called a thermocouple. The amount of voltage produced by a thermocouple is determined by

1. the type of materials used to produce the thermocouple; and
2. the temperature difference of the two junctions.

The chart in FIGURE 3-17 shows common types of thermocouples. The different metals used in the construction of thermocouples is shown as well as their normal temperature range.

The amount of voltage produced by a thermocouple is small, generally in the order of millivolts (1 mV = 0.001 V). The polarity of the voltage of some thermocouples is determined by the temperature. For example, a J-type thermocouple produces 0 V at about 32°F. At temperatures above 32°F, the iron wire is positive and the constantan wire is negative. At temperatures below 32°F, the iron wire becomes negative and the constantan wire becomes positive. At a temperature of +300°F, a J-type thermocouple will produce a voltage of about +7.9 mV. At a temperature of −300°F, it will produce a voltage of about −7.9 mV.

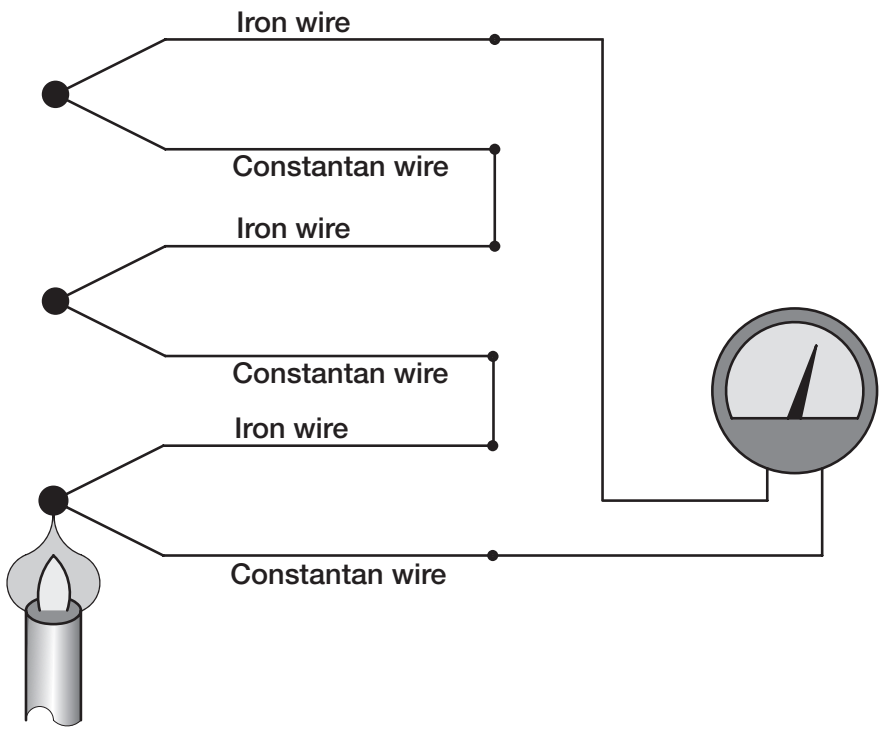
Since thermocouples produce such low voltages, they are often connected in series as shown in FIGURE 3-18. This connection is referred to as a thermopile. Thermocouples and thermopiles are generally used for making temperature measurements and are sometimes used to detect the presence of a pilot light in appliances that operate with natural gas. The thermocouple is heated by the pilot light. The current produced by the thermocouple is used to produce a magnetic field that holds a gas

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

TYPE	MATERIAL		DEGREES F	DEGREES C
J	Iron	Constantan	–328 to +32 +32 to +1,432	–200 to 0 0 to 778
K	Chromel	Alumel	–328 to +32 +32 to 2,472	–200 to 0 0 to 1,356
T	Copper	Constantan	–328 to +32 +32 to 752	–200 to 0 0 to 400
E	Chromel	Constantan	–328 to +32 +32 to 1,832	–200 to 0 0 to 1,000
R	Platinum 13% Rhodium	Platinum	+32 to +3,232	0 to 1,778
S	Platinum 10% Rhodium	Platinum	+32 to +3,232	0 to 1,778
B	Platinum 30% Rhodium	Platinum 6% Rhodium	+992 to +3,352	533 to 1,800

© Cengage Learning 2014

FIGURE 3-17 Thermocouple chart.



© Cengage Learning 2014

FIGURE 3-18 A thermopile is a series connection of thermocouples.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

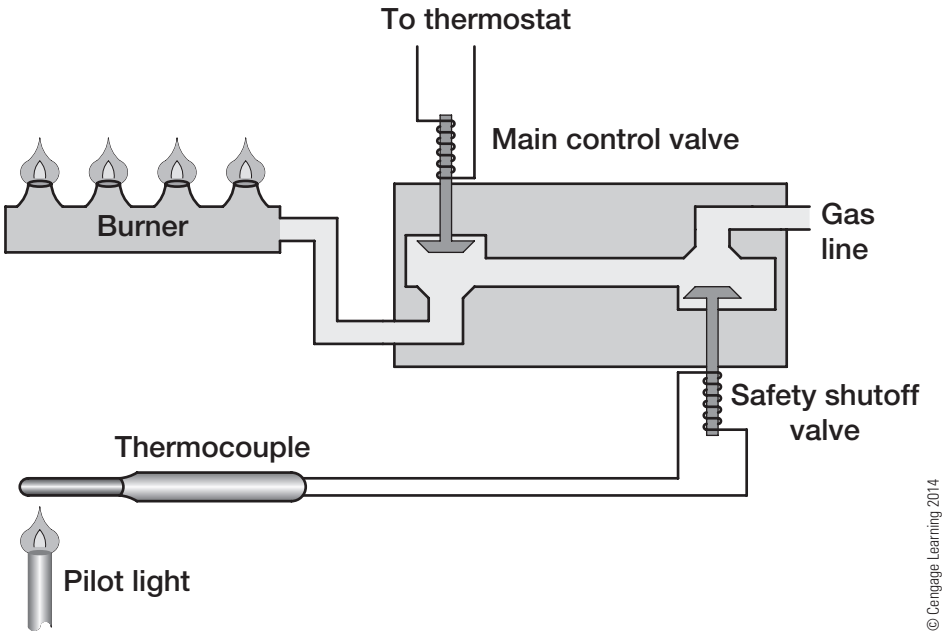


FIGURE 3-19 A thermocouple provides power to keep the safety shutoff valve open.

valve open to permit gas to flow to the main burner. If the pilot light should go out, the thermocouple ceases to produce current and the valve closes, FIGURE 3-19.

PIEZOELECTRICITY

piezo
producing electricity by placing certain materials under pressure.

The word **piezo,** pronounced pee-ay'-zo, is derived from the Greek word for pressure. Piezoelectricity is produced by some materials when they are placed under pressure. The pressure can be caused by compression, twisting, bending, or stretching. Rochelle salt (sodium potassium tartrate) is often used as the needle or stylus of a phonograph. Grooves in the record cause the crystal to be twisted back and forth, producing an alternating voltage. This voltage is amplified and is heard as music or speech. Rochelle salt crystals are also used as the pick up for microphones. The vibrations caused by sound waves produce stress on the crystals. This stress causes the crystals to produce an alternating voltage that can be amplified.

Another crystal used to produce the piezoelectric effect is barium titanate. Barium titanate can actually produce enough voltage and current to flash a small neon lamp when struck by a heavy object, FIGURE 3-20. Industry uses the crystal's ability to produce voltage in transducers for sensing pressure and mechanical vibration of machine parts. Barium titanate is also used in flintless cigarette lighters and gas grills to ignite the gas. They are characterized by

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

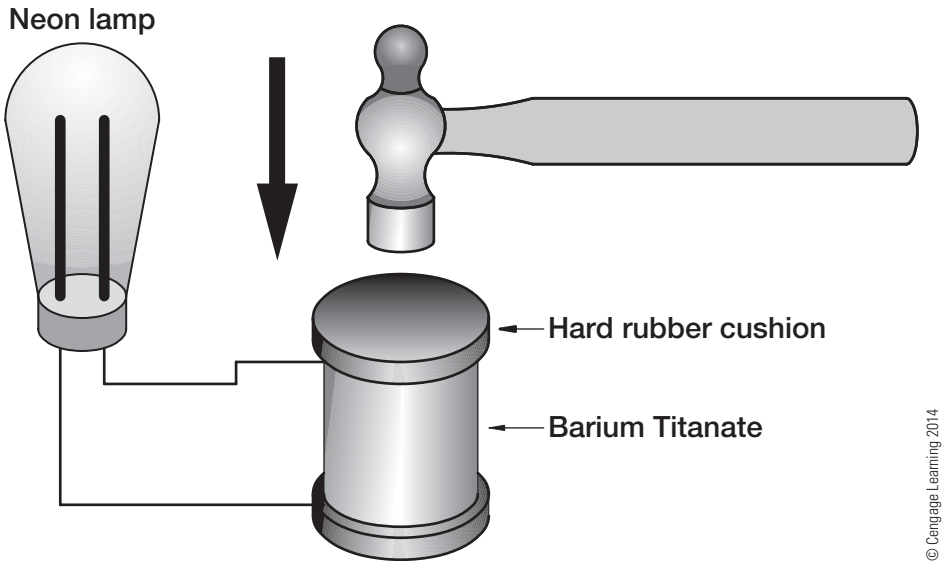


FIGURE 3-20 Voltage produced by piezoelectric effect.

a striking sound when a knob is turned or a button pushed. The striking sound is caused by a hammer striking the crystal.

Quartz crystal has been used for many years as the basis for crystal oscillators. In this application, an AC voltage close to the natural mechanical vibration frequency of a slice of quartz is applied to opposite surfaces of the crystal. This will cause the quartz to vibrate at its natural frequency. The frequency is extremely constant for a particular slice of quartz. Quartz crystals have been used to change the frequency range of two-way radios for many years.

STATIC CHARGES

static
stationary or not moving.

Static electrical charges are a common occurrence in everyday life. Almost everyone has received a shock after walking across a carpet and then touching a metal object, or sliding across seat covers in a car and touching the door handle, FIGURE 3-21. Almost everyone has combed their hair with a hard rubber or plastic comb and then used the comb to attract small pieces of paper or other lightweight objects. Static electric charges are the reason that clothes stick together when they are taken out of a clothes dryer. Lightning is without doubt the greatest display of a static electric discharge.

Although static charges can be a nuisance, they can also be beneficial. Copy machines, for example, operate on the principle of static electricity.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

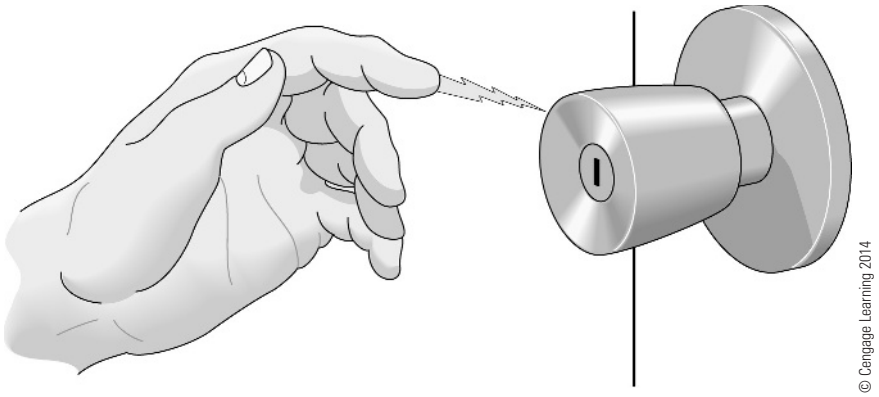
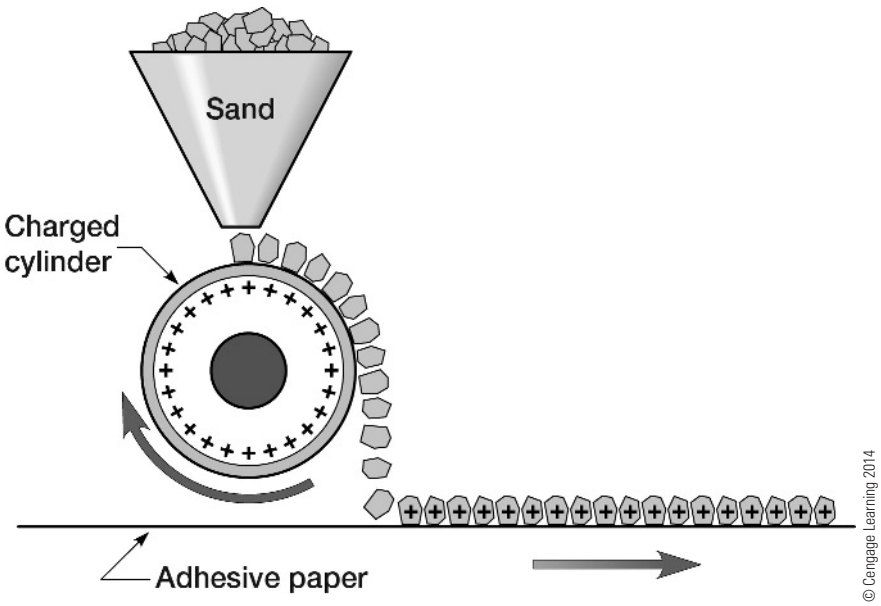

© Cengage Learning 2014

FIGURE 3-21 Static electric charges can cause a painful shock.



© Cengage Learning 2014

FIGURE 3-22 Grains of sand receive a charge to help them stand apart.

Grains of sand receive a static charge to make them stand apart and expose a sharper edge when sandpaper is made, FIGURE 3-22. Electronic air filters (precipitators) use static charges to attract small particles of smoke, dust, and pollen, FIGURE 3-23. The precipitator uses a high-voltage DC power supply to provide a set of wires with a positive charge, and a set of plates with a negative charge. As a blower circulates air through the unit, small particles receive

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

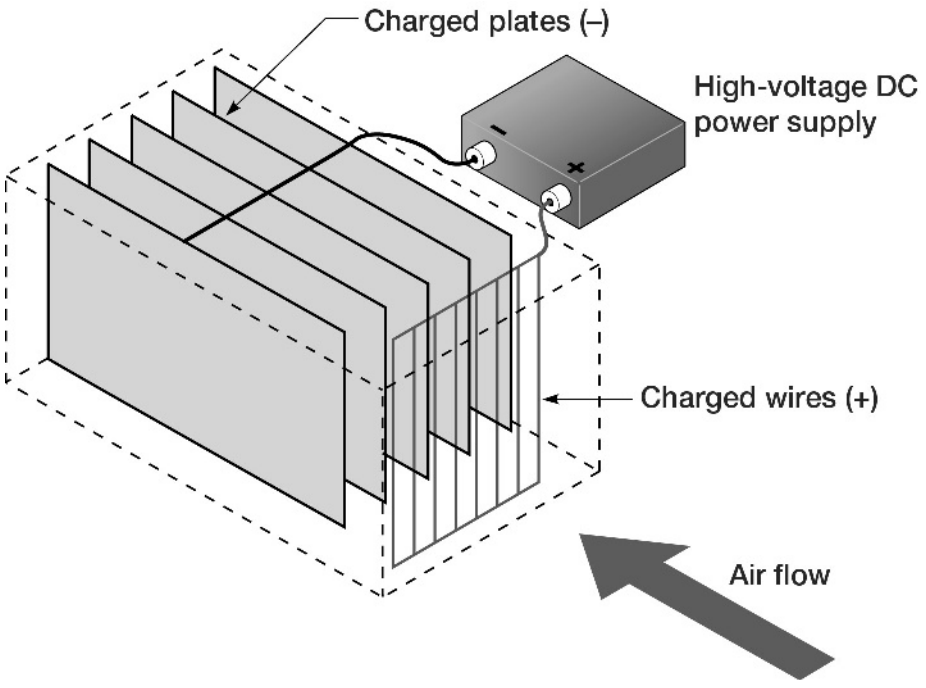


FIGURE 3-23 Electronic air cleaner.

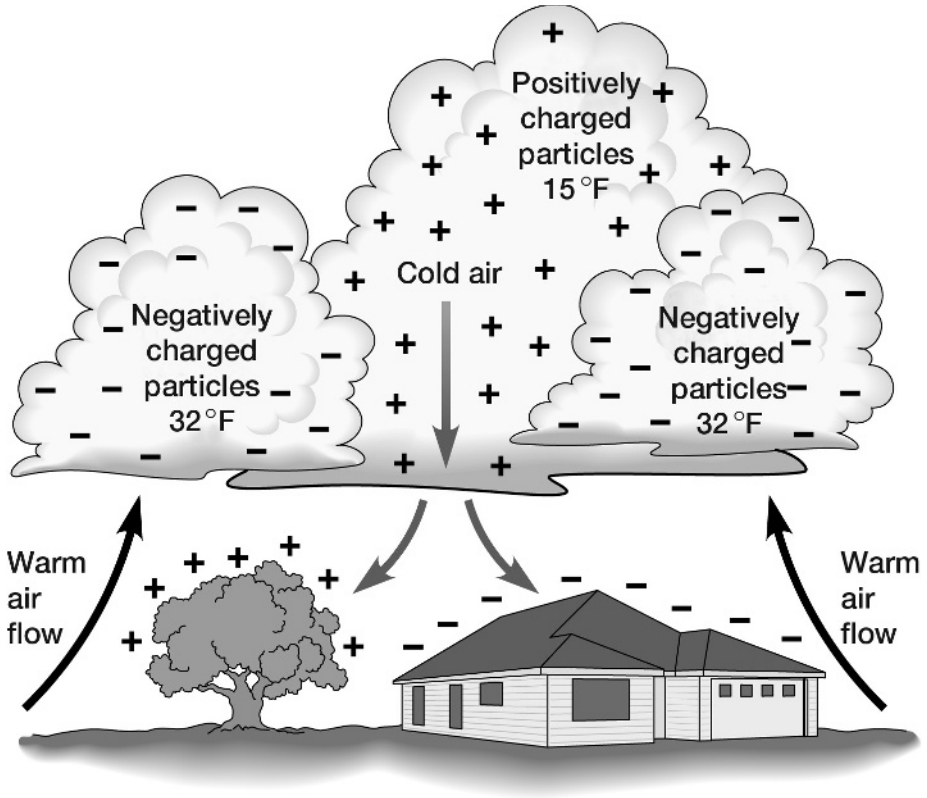
a positive charge as they move across the charged wires. The charged particles are then attracted to the negative plates. The negative plates hold the particles until the unit is turned off and the plates are cleaned.

The word *static* means not moving, or sitting still. Static electricity refers to electrons that are sitting still and not moving. Static electricity is, therefore, a charge and not a current. Static electric charges are built up on insulator materials because insulators are the only materials that can hold the electrons stationary and not permit them to flow to a different location. A static charge can be built up on a conductor only if the conductor is electrically insulated from surrounding objects. A static charge can be either positive or negative. If an object has a lack of electrons, it will have a positive charge, and if it has an excess of electrons, it will have a negative charge.

STATIC ELECTRICITY IN NATURE

When static electricity occurs in nature, it can be harmful. The best example of natural static electricity is lightning. A static charge builds up in clouds that contain a large amount of moisture as they move through the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

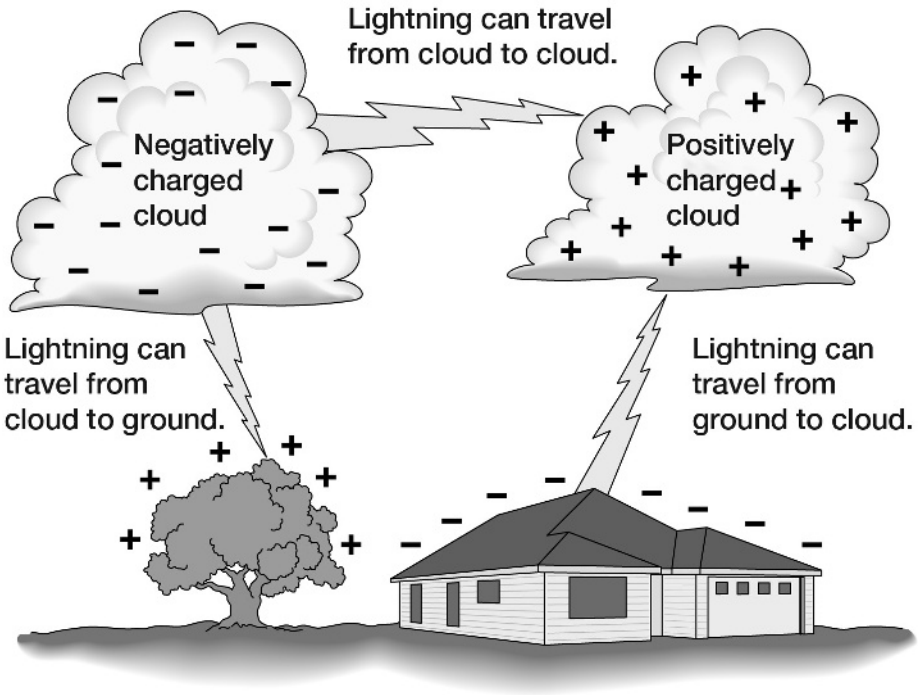


© Cengage Learning 2014

FIGURE 3-24 A typical thundercloud contains both negatively and positively charged particles.

air. It is theorized that the movement causes a static charge to build up on the surface of drops of water. Large drops become positively charged and small drops become negatively charged. FIGURE 3-24 illustrates a typical thundercloud. Notice that both positive and negative charges can be contained in the same cloud. Most lightning discharges take place within the cloud. Lightning discharges can also take place between different clouds, between a cloud and the ground, and between the ground and the cloud, FIGURE 3-25. Whether a lightning bolt travels from the cloud to the ground or from the ground to the cloud is determined by which contains the negative and positive charge. Current will always flow from negative to positive. If a cloud is negative and an object on the ground is positive, the lightning discharge will travel from the cloud to the ground. If the cloud has a positive charge and the object on the ground has a negative charge, the discharge will be from the ground to the cloud. A lightning bolt has an average voltage of about 15,000,000 V.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 3-25 Lightning travels from the most negatively charged object to the most positively charged object.

LIGHTNING PROTECTION

Lightning rods are sometimes used to help protect objects from lightning. Lightning rods work by providing an easy path to ground for current flow. If the protected object is struck by a lightning bolt, the lightning rod bleeds the lightning discharge to ground before harm can occur to the protected object, FIGURE 3-26. Lightning rods were first invented by Benjamin Franklin in the mid-1700s.

Another device used for lightning protection is the lightning arrestor. The lightning arrestor works very similarly to the lightning rod except that it is not designed to be struck by lightning itself, and it does not provide a direct path to ground. The lightning arrestor is grounded at one end, and the other end is brought close to but not touching the object to be protected. If the protected object is struck, the high voltage of the lightning arcs across to the lightning arrestor and bleeds to ground.

Power lines are often protected by lightning arrestors, which exhibit a very high resistance at the normal voltage of the line. If the power line is struck

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

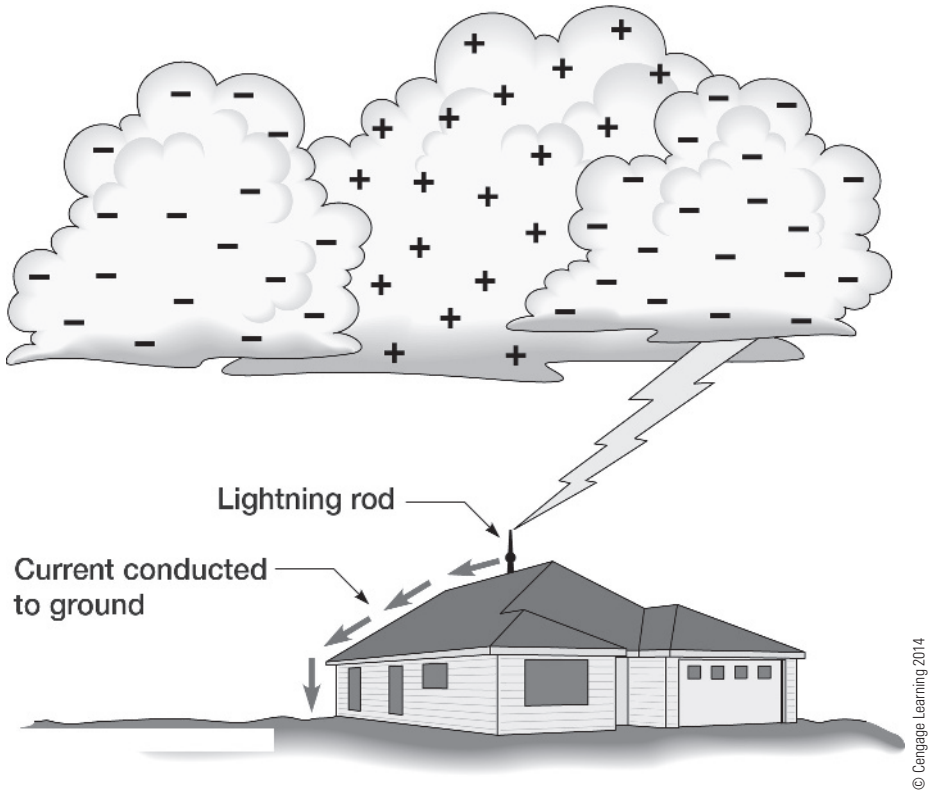


FIGURE 3-26 A lightning rod provides an easy path to ground.

by lightning, the increase in voltage causes the resistance of the arrestor to decrease and conduct the lightning discharge to ground.

Summary

1. Most of the electric power in the world is produced by alternators which work on the principle of electromagnetic induction.
2. Batteries are the second most common source of electric power.
3. Batteries can be divided into two basic types: primary and secondary.
4. Primary cells cannot be recharged.
5. The voltage of a cell is determined by the materials from which it is made.
6. The current density or current capacity of a cell is determined by the area of the cell plates.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

7. Secondary cells can be recharged.
8. Solar cells produce a voltage in direct sunlight.
9. The output voltage of a solar cell is determined by the materials from which it is made.
10. The output current of a solar cell is determined by the surface area of the plates.
11. Silicon solar cells produce 0.5 V in direct sunlight.
12. Thermocouples produce a voltage when one end of the junction is heated.
13. The voltage of a thermocouple is determined by the type of materials from which it is made and the temperature difference between the two junctions.
14. Different types of thermocouples operate at different temperature ranges.
15. Piezoelectricity is produced by pressure.
16. Static electricity is a charge, not a current.
17. Only insulators or insulated conductors can hold a static charge.
18. Static charges can be either positive or negative.
19. Lightning is an example of static electricity.
20. The average lightning bolt has a voltage of about 15,000,000 V.
21. Lightning rods and lightning arrestors are often employed to protect devices and objects from a lightning discharge.

Review Questions

1. What type of voltaic cell can be recharged?
2. What determines the amount of voltage produced by a voltaic cell?
3. Six 12-V lead-acid batteries are rated at 50 Ah each. If these batteries are connected in series, what is the output voltage and amp rating of the connection?
4. If the batteries in question 3 are connected in parallel, what would be the voltage and amp rating of the connection?
5. What determines the amount of current a voltaic cell can produce?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

6. What is the average output voltage of a silicon solar cell in direct sunlight?
7. Thirty silicon solar cells have a current capacity of 0.2 A each. If these cells are connected in series, what would be the output voltage and current capacity of the connection?
8. What is a photon?
9. Thermocouples exhibit the _____ effect.
10. What type of wire is used to make a J-type thermocouple?
11. In degrees C, what are the upper and lower operating limits of a T-type thermocouple?
12. What type of crystal is used to produce a high voltage when struck?
13. What type of materials are capable of holding a static charge?
14. If electrons are removed from an object, is the object now positively or negatively charged?
15. Can one thundercloud contain both positive and negative charges?
16. A thundercloud has a negative charge and an object on the ground has a positive charge. Will lightning travel from the cloud to the ground or from the ground to the cloud?
17. Name two devices used for lightning protection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 4

Magnetism

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the properties of permanent magnets.
- Discuss the difference between the axis poles of the earth and the magnetic poles of the earth.
- Discuss the operation of electromagnets.
- Determine the polarity of an electromagnet when the current direction is known.
- Discuss the different systems used to measure magnetism.
- Define terms used to describe magnetism and magnetic quantities.

Magnetism is one of the most important phenomena in the electrical field. It is the force used to produce most of the electrical power in the world. The force of magnetism has been known for over 2,000 years. It was first discovered by the Greeks when they found that a certain type of stone was attracted to iron. This stone was first found in Magnesia in Asia Minor and was named *magnetite.* The first compass was invented when it was noticed that a magnetite placed on a small piece of wood floating in water always aligned itself north and south, FIGURE 4-1. Due to their ability to always

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

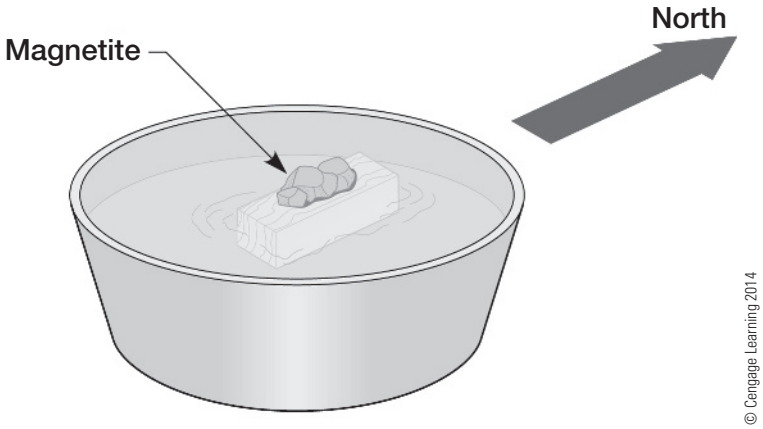


FIGURE 4-1 The first compass.

align themselves north and south, natural magnets become known as "leading stones" or **lodestones.** In the dark ages, the strange powers of the magnet were believed to be caused by evil spirits or the devil.

lodestones
natural magnets.

THE EARTH IS A MAGNET

The reason why the lodestone aligns itself north and south is because the earth itself contains magnetic poles. FIGURE 4-2 illustrates the position of the true north and south poles, or axes, of the earth and the position of the magnetic poles. Notice that the magnetic pole is not located at the true north pole of the earth. This is the reason why navigators must distinguish between true north and magnetic north. The angular difference between the two is known as *the angle of declination.* The illustration shows the magnetic lines of force to be only on each side of the earth. It should be understood that the lines actually surround the entire earth like a magnetic shell. Also notice that the magnetic north pole is located near the southern polar axis and the magnetic south pole is located near the northern polar axis. The reason why the *geographic poles* (axes) are called north and south is because the north pole of a compass needle points in the direction of the north geographic pole. Because unlike magnetic poles attract, the north magnetic pole of the compass needle is attracted to the south magnetic pole of the earth.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

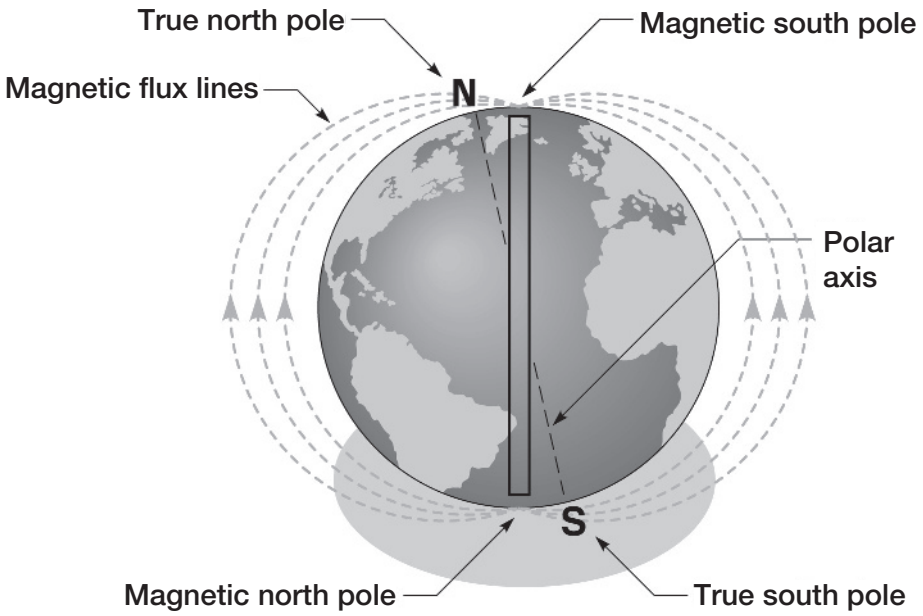


FIGURE 4-2 The earth is a magnet.

PERMANENT MAGNETS

permanent magnets
magnets that require no force to maintain their magnetic properties.

Permanent magnets are magnets that do not require any power or force to maintain their field. They are an excellent example of one of the basic laws of magnetism, which states that **energy is required to create a magnetic field, but no energy is required to maintain a magnetic field.** Manmade permanent magnets are much stronger and can retain their magnetism longer than natural magnets.

KEY POINT

Energy is required to create a magnetic field, but no energy is required to maintain a magnetic field.

THE ELECTRON THEORY OF MAGNETISM

electron spin patterns
the patterns that electrons spin.

There are actually only three substances that form natural magnets: iron, nickel, and cobalt. Our understanding of why these materials form magnets is the result of rather complex scientific investigations resulting in an explanation of magnetism based on **electron spin patterns.** It is believed that internal gravity causes electrons to spin on their axes as they orbit around the nucleus of the atom. This spinning motion causes each electron to become a tiny permanent magnet. Although all electrons spin, they do not all spin in the same direction. In most atoms, electrons that spin in opposite directions tend to form pairs, FIGURE 4-3. Since the electron pairs spin in opposite directions, their magnetic effect cancels each other out, as far as having any effect on distant objects. It would be very similar to

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

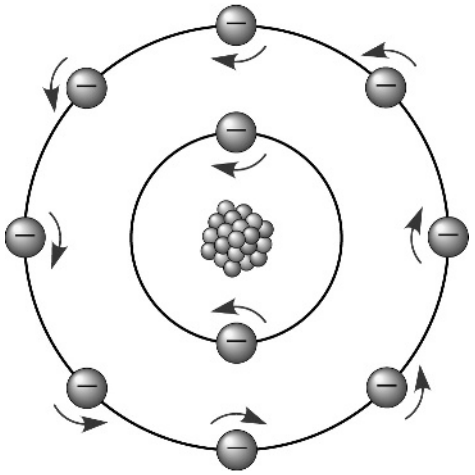
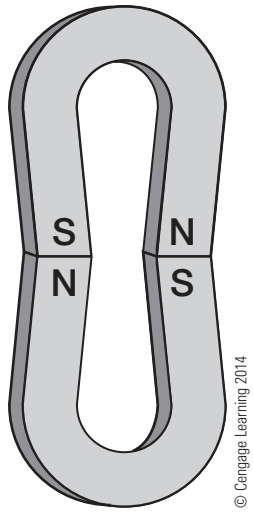

© Cengage Learning 2014

FIGURE 4-3 Electron pairs generally spin in opposite directions.



© Cengage Learning 2014

FIGURE 4-4 Two horseshoe magnets attract each other.

connecting two horseshoe magnets together. They would be strongly attracted to each other but would have little effect on surrounding objects, FIGURE 4-4.

An atom of iron contains twenty-six electrons. Of these twenty-six, twenty-two are paired and spin in opposite directions, canceling each other's magnetic effect. In the next-to-outermost shell, however, there are four electrons that are not paired and thus spin in the same direction. It is these electrons that account for the magnetic properties of iron. At a temperature of 1,420°F or 771.1°C, the electron spin patterns rearrange themselves and iron loses its magnetic properties.

When the atoms of most materials combine to form molecules, they arrange themselves in a manner that produces a total of eight valence electrons. The electrons form a spin pattern that cancels the magnetic field of the material. When the atoms of iron, nickel, and cobalt combine, however, this is not the case. Their electrons combine so that they share valence electrons in such a way that their spin patterns are in the same direction, causing their magnetic fields to add instead of cancel. The additive effect forms regions in the molecular structure of the metal called **magnetic domains** or **magnetic molecules.** These magnetic domains act like small permanent magnets.

magnetic domains magnetic regions inside a magnet.

A piece of nonmagnetized metal has its molecules in a state of disarray, as shown in FIGURE 4-5. When the metal is magnetized, its molecules align themselves in an orderly pattern, as shown in FIGURE 4-6. In theory, each molecule of a magnetic material is itself a small magnet. If a permanent magnet is cut into pieces, each piece is a separate magnet, FIGURE 4-7.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

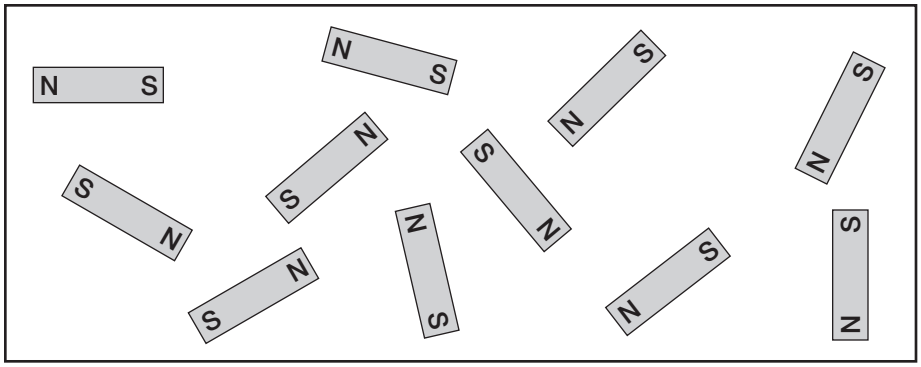


FIGURE 4-5 The molecules in a piece of nonmagnetized metal are disarrayed.

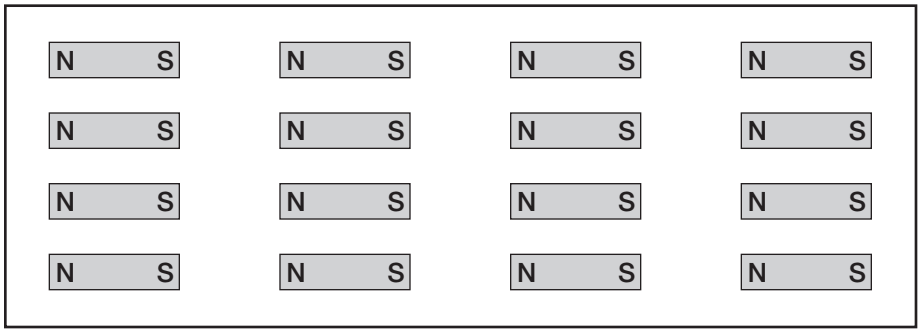


FIGURE 4-6 The molecules in a piece of magnetized metal are aligned in an orderly fashion.

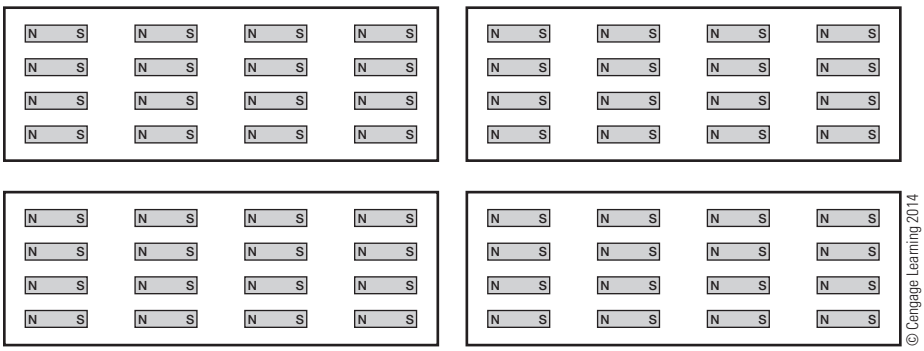


FIGURE 4-7 When a magnet is cut apart, each piece becomes a separate magnet.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

MAGNETIC MATERIALS

Magnetic materials can be divided into three basic classifications. These are:

Ferromagnetic — These materials are metals that are easily magnetized. Examples of these materials are iron, nickel, cobalt, and manganese.

Paramagnetic — These materials can be magnetized, but not as easily as ferromagnetic materials. Some examples of paramagnetic materials are platinum, titanium, and chromium.

Diamagnetic — These are materials that cannot be magnetized. The magnetic lines of force tend to go around them instead of through them. Some examples of these materials are copper, brass, and antimony.

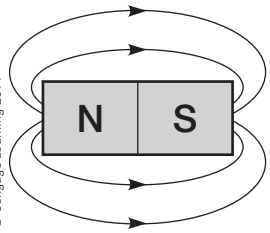
Some of the best materials for the production of permanent magnets are alloys. One of the best permanent magnet materials is Alnico 5, which is made from a combination of aluminum, nickel, cobalt, copper, and iron. Another type of permanent magnet material is made from a combination of barium ferrite and strontium ferrite. Ferrites can have an advantage in some situations because they are insulators and not conductors. They have a resistance of approximately one million ohms per centimeter. These two materials can be powdered. The powder is heated to the melting point and then rolled and heat treated, which changes the grain structure and magnetic properties of the material. This type of material has a property more like stone than metal and is known as a *ceramic magnet.* Ceramic magnets can be powdered and mixed with rubber or plastic or with liquids. Ceramic magnetic materials mixed with liquids can be used to make magnetic ink, which is used on checks. Another frequently used magnetic material is iron oxide, which is used to make magnetic recording tape and computer diskettes.

MAGNETIC LINES OF FORCE

Magnetic lines of force are called **flux.** The symbol used to represent flux is the Greek letter phi (Φ). Flux lines can be seen by placing a piece of cardboard on a magnet and sprinkling iron filings on the cardboard. The filings

flux
magnetic lines of force.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 4-8 Magnetic lines of force are called lines of flux.

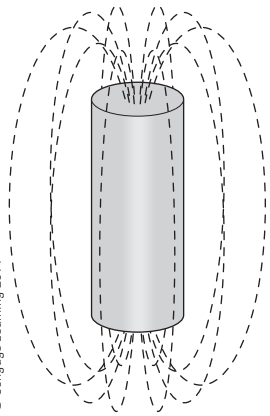
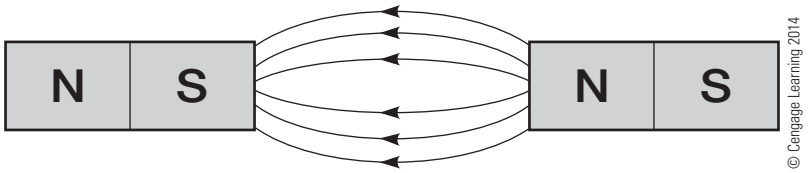

© Cengage Learning 2014

FIGURE 4-9 Magnetic lines of flux surround the entire magnet.

lines of flux
lines of magnetism.

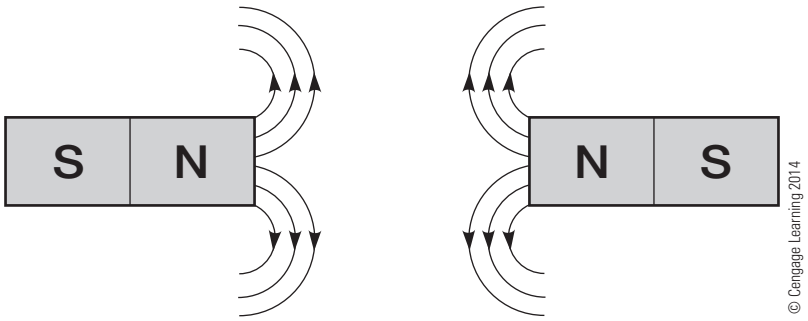
KEY POINT

Unlike poles attract and like poles repel.



© Cengage Learning 2014

FIGURE 4-10 Opposite magnetic poles attract each other.



© Cengage Learning 2014

FIGURE 4-11 Like magnetic poles repel each other.

will align themselves in a pattern similar to the one shown in FIGURE 4-8. It should be understood that the pattern produced by the iron filings forms a two-dimensional Figure. The flux lines actually surround the entire magnet, FIGURE 4-9. Magnetic **lines of flux** repel each other and never cross. Although magnetic lines of force do not flow, it is assumed they are oriented in a direction from north to south.

A basic law of magnetism states that **unlike poles attract and like poles repel.** FIGURE 4-10 illustrates what happens if a piece of cardboard is placed over two magnets with their north and south poles facing each other and iron filings are sprinkled on the cardboard. The filings form a pattern showing that the magnetic lines of force are attracted to each other. FIGURE 4-11 illustrates the pattern formed by the iron filings when the cardboard is placed over two magnets with like poles facing each other. The filings show that the magnetic lines of force repel each other.

If the opposite poles of two magnets are brought close to each other, they will be attracted to each other, as shown in FIGURE 4-12. If like poles of the two magnets are brought together, they will repel each other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

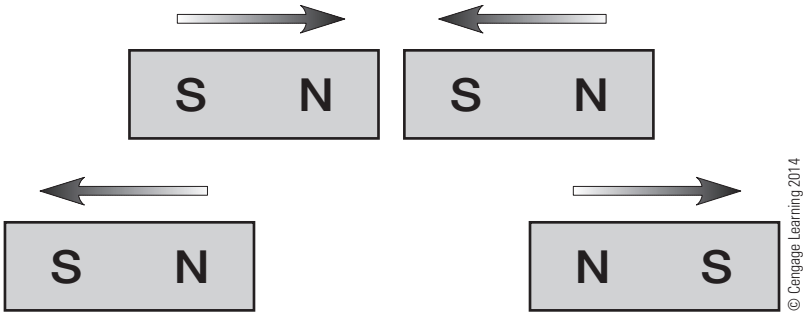


FIGURE 4-12 Opposite poles of a magnet attract and like poles repel.

ELECTROMAGNETS

A basic law of physics states that **whenever an electric current flows through a conductor, a magnetic field is formed around the conductor. Electromagnets** depend on electric current flow to produce a magnetic field. They are generally designed to produce a magnetic field only as long as the current is flowing and thus do not retain their magnetism when current flow stops. Electromagnets operate on the principle that current flowing through a conductor produces a magnetic field around the conductor, FIGURE 4-13. If the conductor is wound into a coil, as shown in FIGURE 4-14, the magnetic lines of force add to produce a stronger magnetic field. A coil with ten turns of wire will produce a magnetic field that is ten times stronger than the magnetic field around a single conductor.

Another factor that affects the strength of an electromagnetic field is the amount of current flowing through the wire. An increase in current flow will cause an increase in magnetic field strength. The two factors that determine the number of flux lines produced by an electromagnet are the number of turns of wire and the amount of current flow through the wire. The strength of an electromagnet is proportional to its **ampere-turns.**

KEY POINT
Whenever an electric current flows through a conductor, a magnetic field is formed around the conductor.

electromagnets
magnets that depend on electricity.

ampere-turns
basic unit for the measurement of magnetism (the product of turns of wire and current flow).

MAGNETIC INDUCTION

Magnetic induction is one of the most important concepts in the electrical field. It is the basic operating principle underlying alternators, generators, transformers, and most alternating current motors. It is imperative that anyone desiring to work in the electrical field have an understanding of the principles involved.

As stated, one of the basic laws of electricity is that whenever current flows through a conductor, a magnetic field is created around the conductor

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

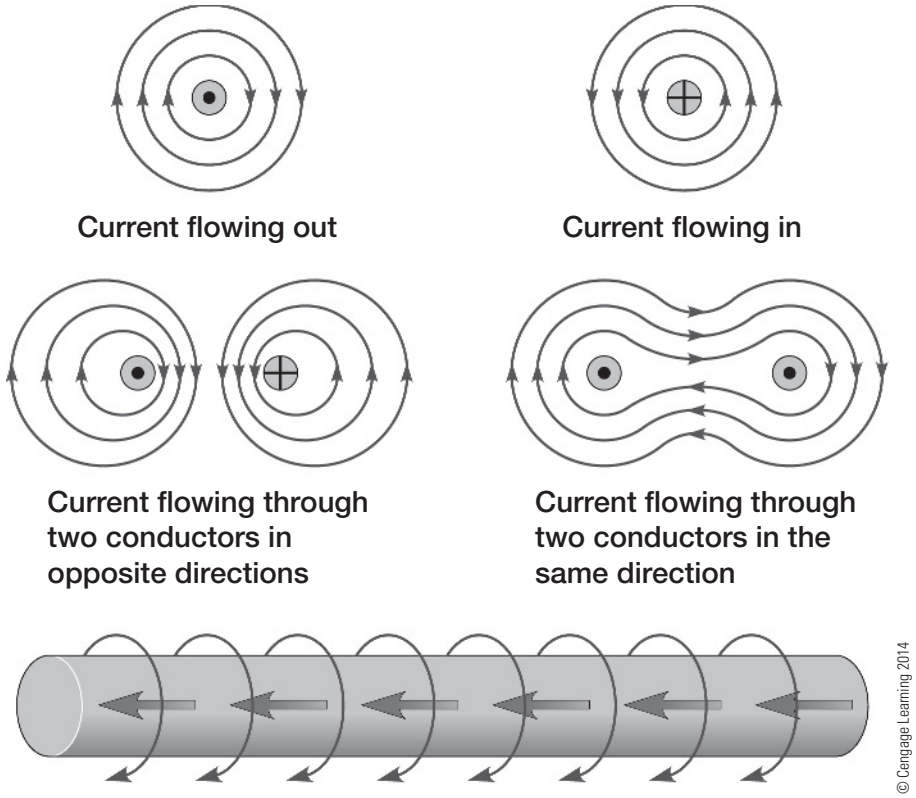


FIGURE 4-13 Current flowing through a conductor produces a magnetic field around the conductor.

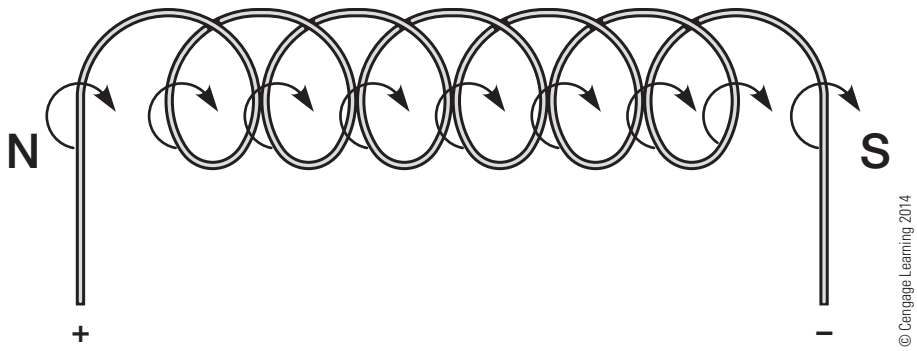


FIGURE 4-14 Winding the wire into a coil increases the strength of the magnetic field.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

(see Figure 4-13). The direction of current flow determines the polarity of the magnetic field, and the amount of current determines the strength of the magnetic field.

That basic law in reverse is the principle of **magnetic induction,** which states that **whenever a conductor cuts through magnetic lines of flux, a voltage is induced into the conductor.** The conductor in FIGURE 4-15 is connected to a zero-center microammeter, creating a complete circuit. When the conductor is moved downward through the magnetic lines of flux, the induced voltage will cause electrons to flow in the direction indicated by the arrows. This flow of electrons causes the pointer of the meter to be deflected from the center-zero position.

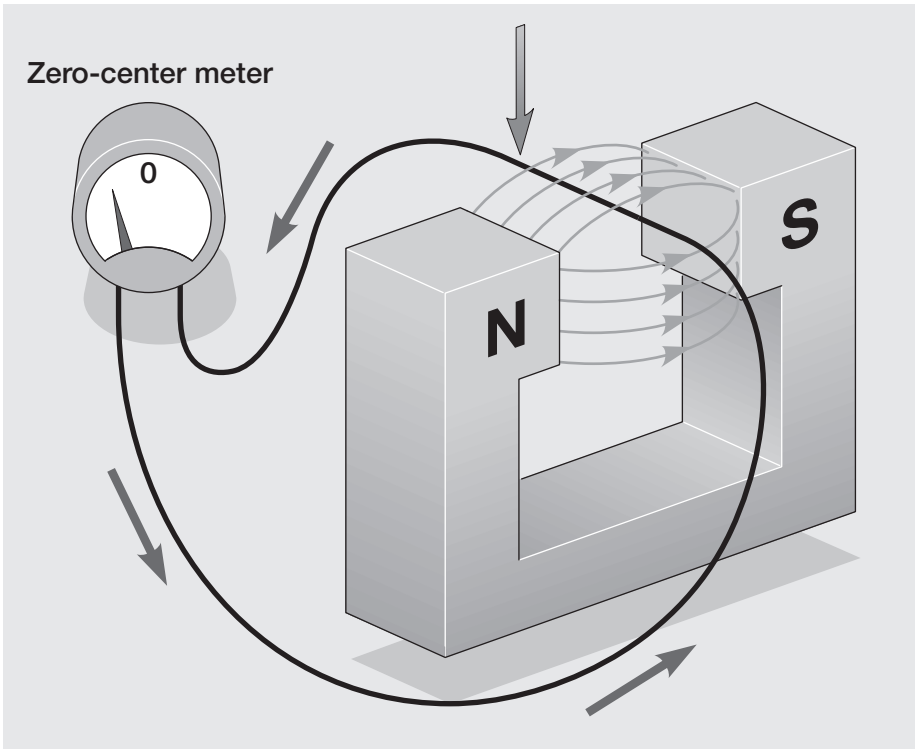
magnetic induction voltage will be induced in a conductor when it cuts magnetic lines of force.

KEY POINT

The principle of magnetic induction states that whenever a conductor cuts through magnetic lines of flux, a voltage is induced into the conductor.

If the conductor is moved upward, the polarity of induced voltage will be reversed and the current will flow in the opposite direction (FIGURE 4-16). The pointer will be deflected in the opposite direction.

The polarity of the induced voltage can also be changed by reversing the polarity of the magnetic field (FIGURE 4-17). In this example, the

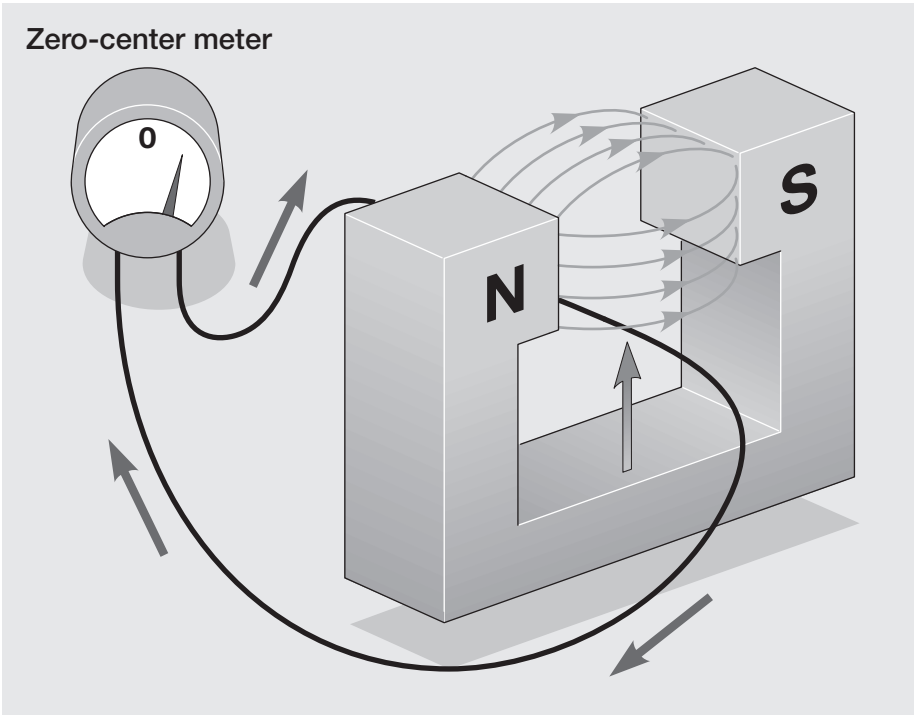


© Cengage Learning 2014

FIGURE 4-15 A voltage is induced when a conductor cuts magnetic lines of flux.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

KEY POINT
The polarity of the induced voltage is determined by the polarity of the magnetic field in relation to the direction of movement.



© Cengage Learning 2014

FIGURE 4-16 Reversing the direction of movement reverses the polarity of the voltage.

left-hand generator rule
a rule to determine polarity in a generator.

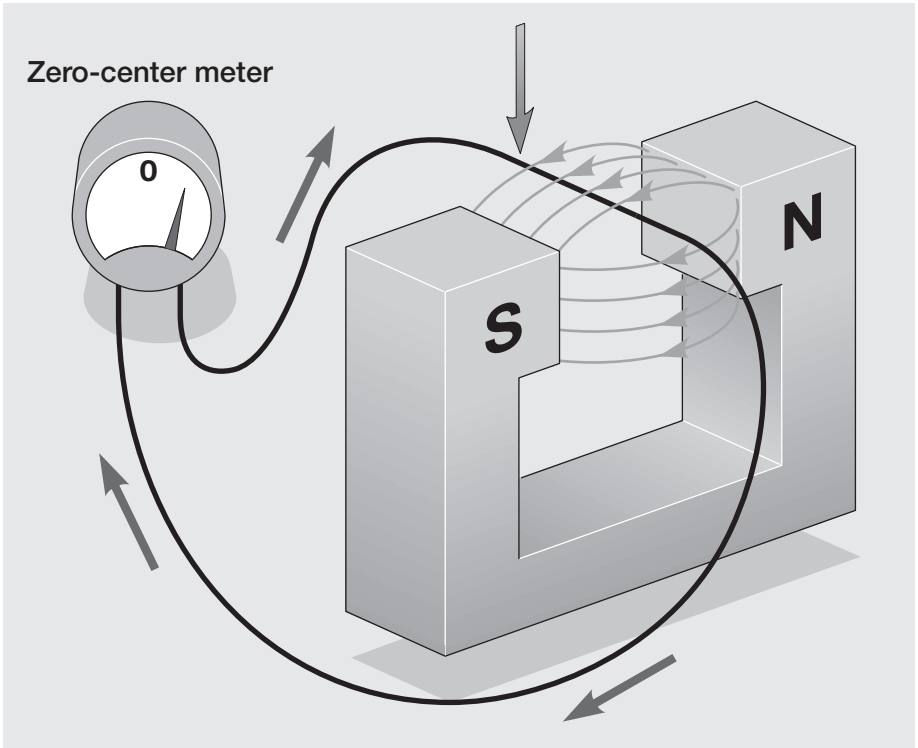
KEY POINT
The forefinger points in the direction of the field flux. The thumb points in the direction of thrust, and the center finger shows the direction of the current induced into the armature.

conductor is again moved downward through the lines of flux, but the polarity of the magnetic field has been reversed. Therefore the polarity of the induced voltage will be the opposite of that in Figure 4-15, and the pointer of the meter will be deflected in the opposite direction. It can be concluded that the polarity of the induced voltage is determined by **the polarity of the magnetic field in relation to the direction of movement.**

FLEMING'S LEFT-HAND GENERATOR RULE

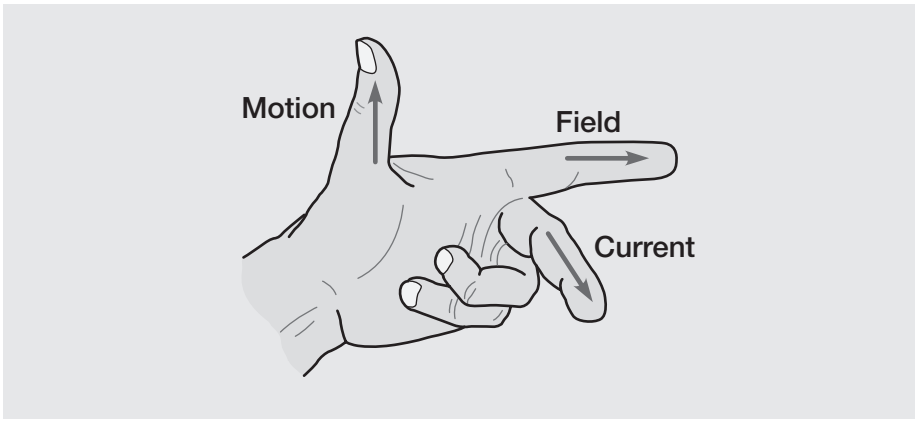
Fleming's **left-hand generator rule** can be used to determine the relationship of the motion of the conductor in a magnetic field to the direction of the induced current. To use the left-hand rule, place the thumb, forefinger, and center finger at right angles to each other as shown in FIGURE 4-18. **The forefinger points in the direction of the field flux,** assuming that magnetic lines of force are in a direction of north to south. **The thumb points in the**

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 4-17 Reversing the polarity of the magnetic field reverses the polarity of the voltage.



© Cengage Learning 2014

FIGURE 4-18 Left-hand generator rule.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

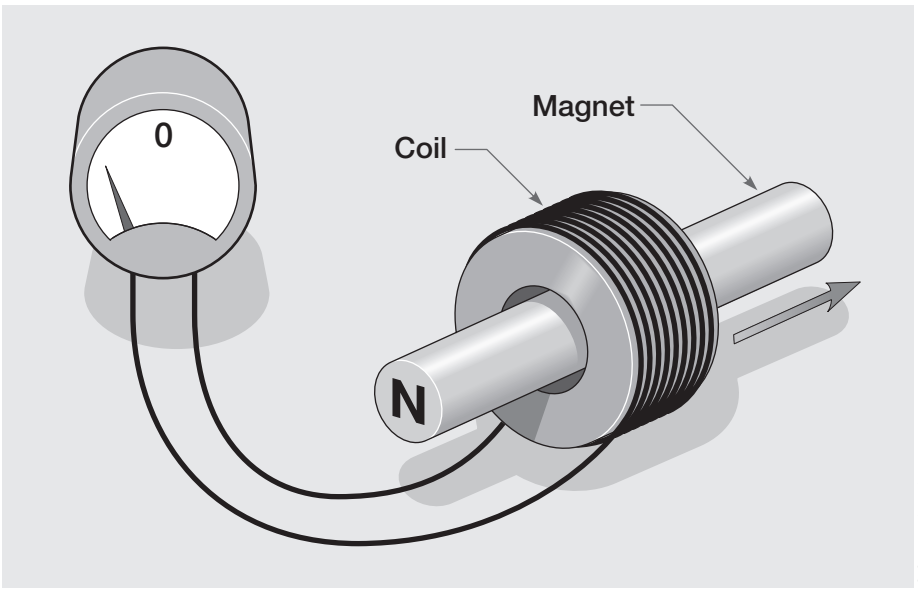
direction of thrust, or movement of the conductor, **and the center finger shows the direction of the current induced into the armature.** An easy method of remembering which finger represents which quantity is shown below.

THumb = **TH**rust
Forefinger = **F**lux
Center finger = **C**urrent

The left-hand rule can be used to clearly illustrate that if the polarity of the magnetic field is changed or if the direction of armature rotation is changed, the direction of induced current will change also.

MOVING MAGNETIC FIELDS

The important factors concerning magnetic induction are conductor, a magnetic field, and relative motion. In practice, it is often desirable to move the magnet instead of the conductor. Most alternating current generators or alternators operate on this principle. In FIGURE 4-19, a coil of wire is held stationary while a magnet is moved through the coil. As the magnet is moved, the lines of flux cut through the windings of the coil and induce a voltage into them.



© Cengage Learning 2014

FIGURE 4-19 Voltage is induced by a moving magnetic field.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

DETERMINING THE AMOUNT OF INDUCED VOLTAGE

Three factors determine the amount of voltage that will be induced in a conductor:

1. **the number of turns of wire,**
2. **the strength of the magnetic field** (flux density), and
3. **the speed of the cutting action.**

In order to induce 1 V in a conductor, the conductor must cut 100,000,000 lines of magnetic flux in 1 s. In magnetic measurement, 100,000,000 lines of flux are equal to one **weber (Wb).** Therefore, if a conductor cuts magnetic lines of flux at a rate of 1 Wb/s, a voltage of 1 V will be induced. A simple one-loop generator is shown in FIGURE 4-20. The loop is attached to a rod that is free to rotate. This assembly is suspended between the poles of two stationary magnets. If the loop is turned, the conductor cuts through magnetic lines of flux and a voltage is induced into the conductor.

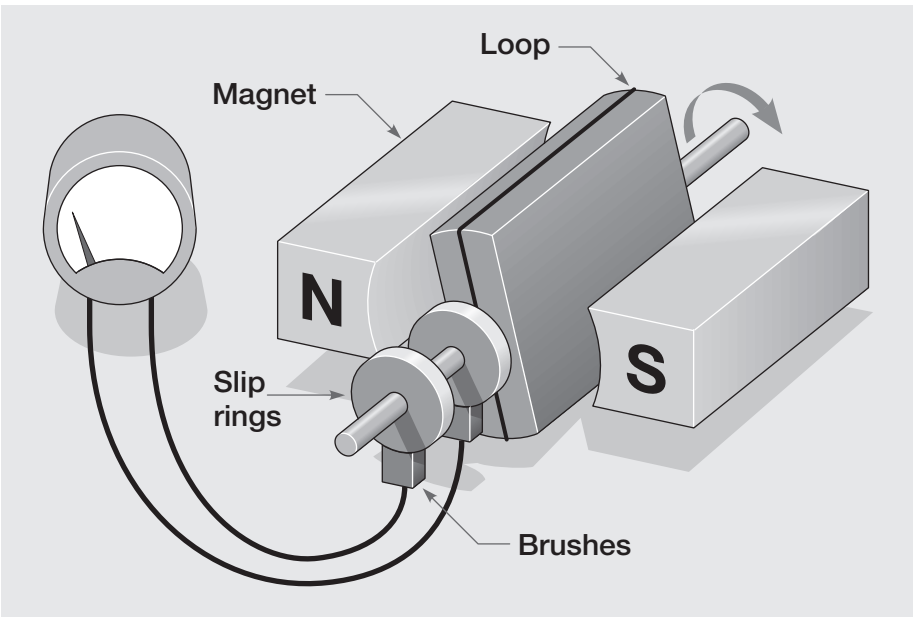
If the speed of rotation is increased, the conductor cuts more lines of flux per second, and the amount of induced voltage increases. If the speed of rotation remains constant and the strength of the magnetic field is increased, there will be more lines of flux per square inch. When there are more lines of

turns of wire
the number of turns of wire.

strength of magnetic field
flux density of the magnetic field.

speed
rate of cutting action.

weber (Wb)
measure of magnetic lines of flux in the meter-kilogram-second (MKS) system (1 weber = 100 million [1×10^8] lines of flux).



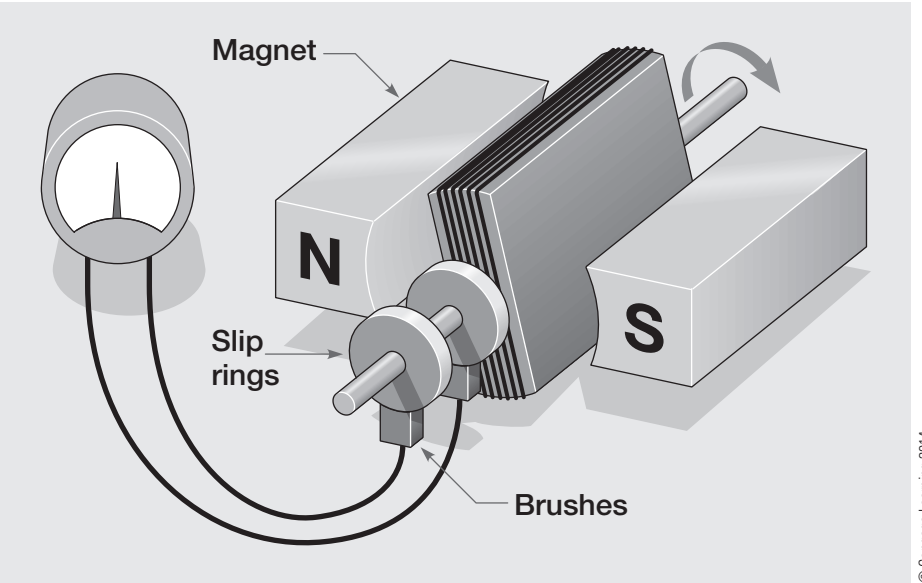
© Cengage Learning 2014

FIGURE 4-20 A single-loop generator.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Lenz's Law
a law concerning induced voltage.

KEY POINT
This law stipulates that the polarity of an induced emf will be such that any resulting current will have a magnetic field (flux) that opposes the original action (change in flux) that produced the induced current. In other words, the induced voltage always opposes the original change in current. That is why the induced voltage is known as the counter-emf (cemf), or back-emf.



© Cengage Learning 2014

FIGURE 4-21 Increasing the number of turns increases the induced voltage.

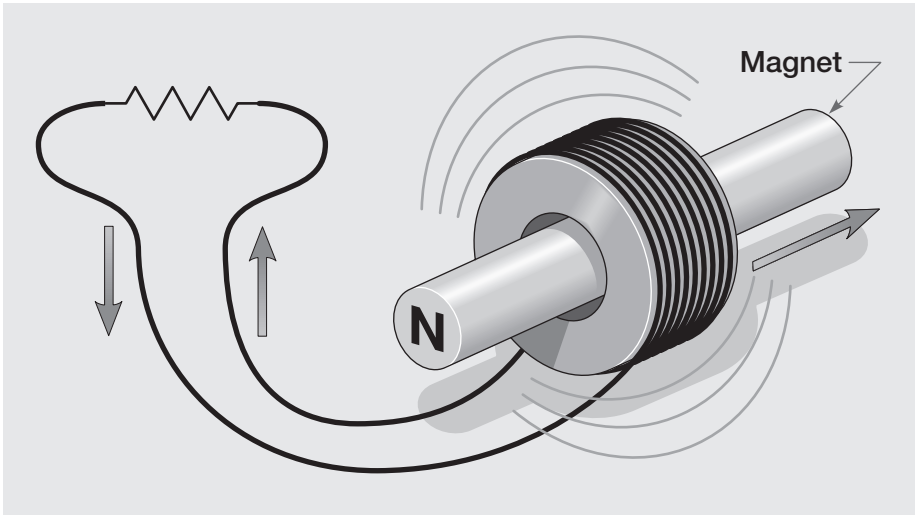
flux, the number of lines cut per second increases and the induced voltage increases. If more turns of wire are added to the loop (FIGURE 4-21), more flux lines are cut per second and the amount of induced voltage increases again. Adding more turns has the effect of connecting single conductors in series, and the amount of induced voltage in each conductor adds.

LENZ'S LAW

When a voltage is induced in a coil and there is a complete circuit, current will flow through the coil (FIGURE 4-22). When current flows through the coil, a magnetic field is created around the coil. This magnetic field develops a polarity opposite that of the moving magnet. The magnetic field developed by the induced current acts to attract the moving magnet and pull it back inside the coil.

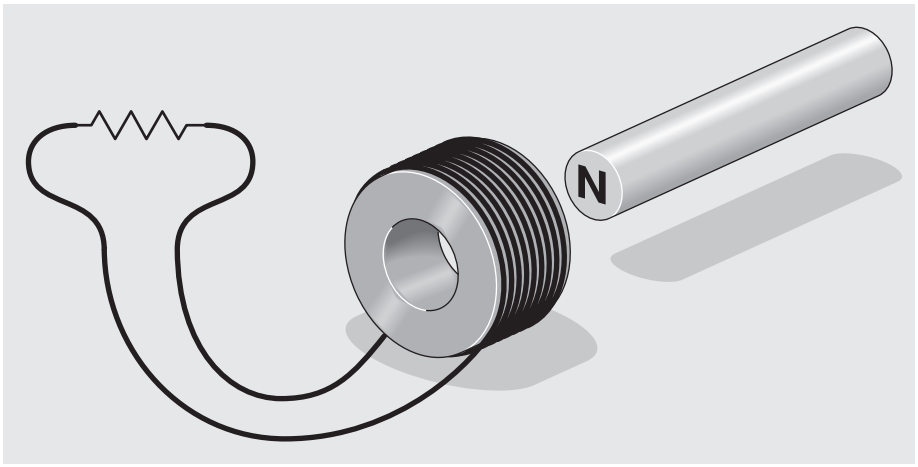
If the direction of motion is reversed, the polarity of the induced current is reversed, and the magnetic field created by the induced current again opposes the motion of the magnet. This principle was first noticed by Heinrich Lenz many years ago and is summarized in **Lenz's Law,** which states that **an induced voltage or current opposes the motion that causes it.** From this basic principle, other laws concerning inductors have been developed. One is that **inductors always oppose a change of current.** The coil in FIGURE 4-23, for example, has no induced voltage and therefore no induced current. If the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 4-22 An induced current produces a magnetic field around the coil.



© Cengage Learning 2014

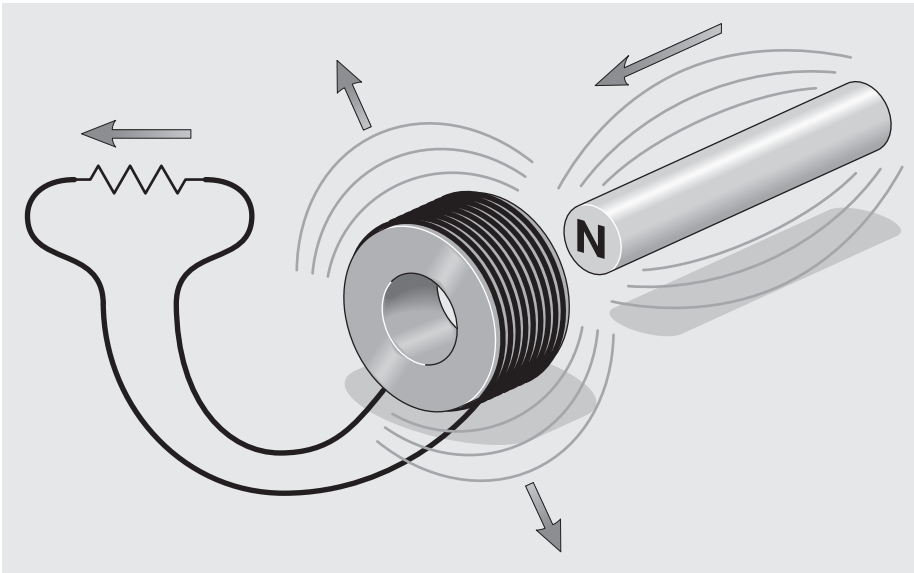
FIGURE 4-23 No current flows through the coil.

magnet is moved toward the coil, however, magnetic lines of flux will begin to cut the conductors of the coil, and a current will be induced in the coil. The induced current causes magnetic lines of flux to expand outward around the coil (FIGURE 4-24). As this expanding magnetic field cuts through the conductors of the coil, a voltage is induced in the coil. The polarity of the voltage is such that it opposes the induced current caused by the moving magnet.

KEY POINT

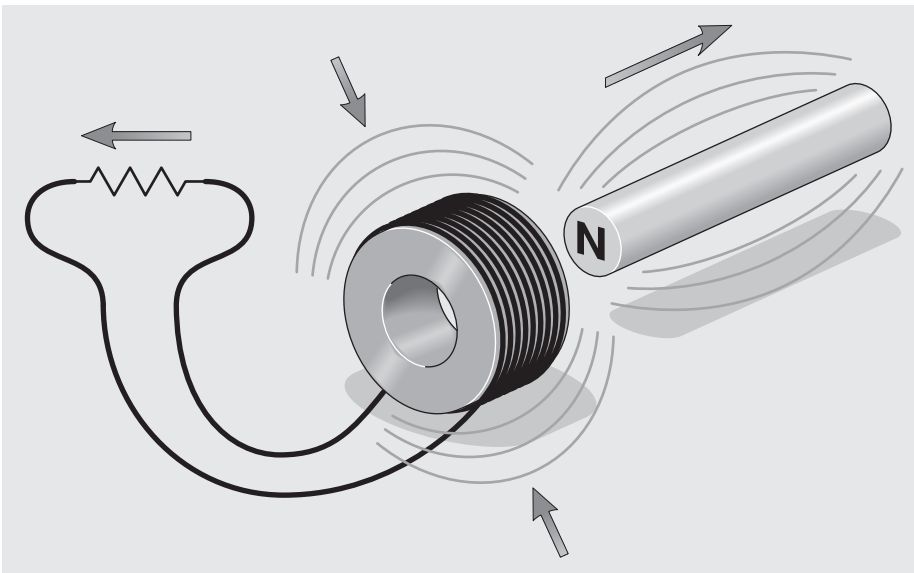
Inductors always oppose a change of current.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 4-24 Induced current produces a magnetic field around the coil.



© Cengage Learning 2014

FIGURE 4-25 The induced voltage forces current to flow in the same direction.

If the magnet is moved away, the magnetic field around the coil will collapse and induce a voltage in the coil (FIGURE 4-25). Since the direction of movement of the collapsing field has been reversed, the induced voltage will be opposite in polarity, forcing the current to flow in the same direction.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

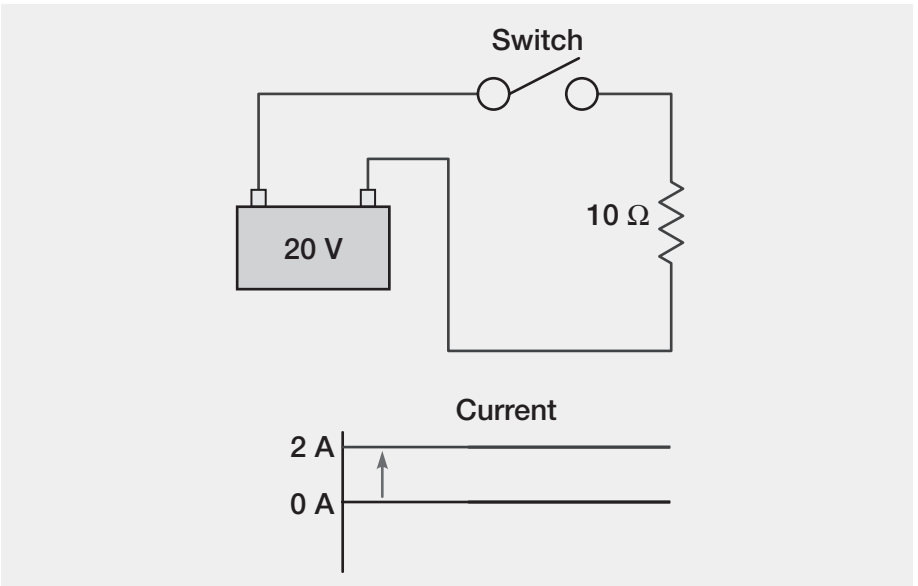
RISE TIME OF CURRENT IN AN INDUCTOR

When a resistive load is suddenly connected to a source of direct current (FIGURE 4-26), the current will instantly rise to its maximum value. The resistor shown in Figure 4-26 has a value of 10 Ω and is connected to a 20-V source. When the switch is closed the current will instantly rise to a value of 2 A (20 V/10 Ω = 2 A).

If the resistor is replaced with an inductor that has a wire resistance of 10 Ω and the switch is closed, the current cannot instantly rise to its maximum value of 2 A (FIGURE 4-27). As current begins to flow through an inductor, the expanding magnetic field cuts through the conductors, inducing a voltage into them. In accord with Lenz's Law, the induced voltage is opposite in polarity to the applied voltage. The induced voltage, therefore, acts like a resistance to hinder the flow of current through the inductor (FIGURE 4-28).

The induced voltage is proportional to the rate of change of current (speed of the cutting action). When the switch is first closed, current flow through the coil tries to rise instantly. This extremely fast rate of current change induces maximum voltage in the coil. As the current flow approaches its maximum Ohm's Law value, in this Example 2-A, the rate of change becomes less and the amount of induced voltage decreases.

KEY POINT
The induced voltage is proportional to the rate of change of current.



© Cengage Learning 2014

FIGURE 4-26 The current rises instantly in a resistive circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

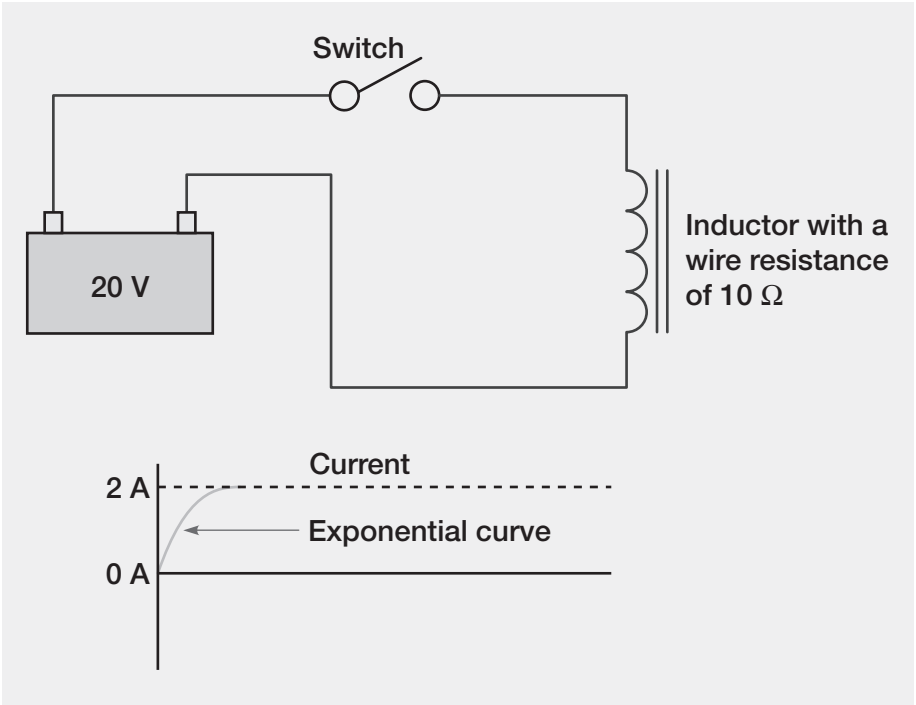


FIGURE 4-27 Current rises through an indicator at an exponential rate.

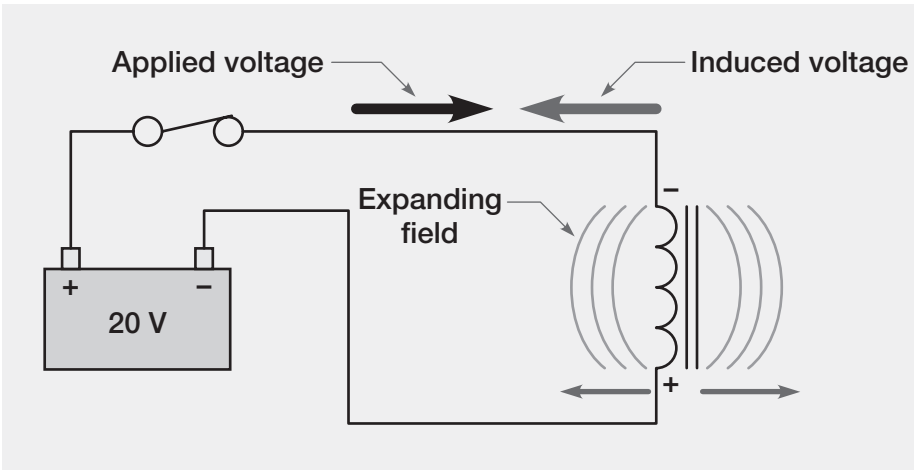


FIGURE 4-28 The applied voltage is opposite in polarity to the induced voltage.

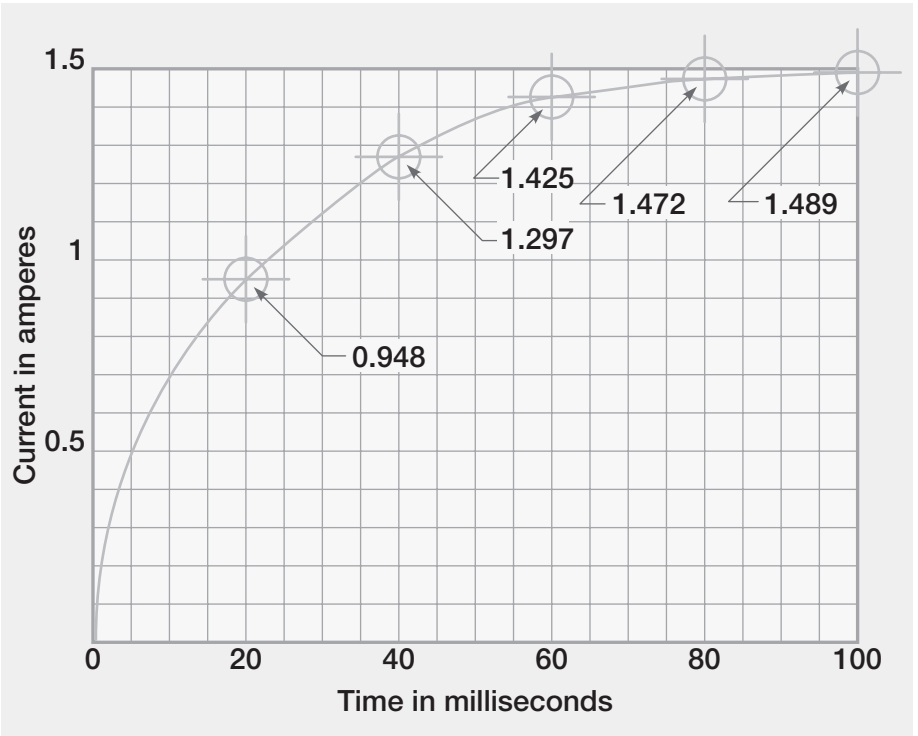
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

THE EXPONENTIAL CURVE

exponential curve
a natural curve.

The **exponential curve** describes a rate of certain occurrences. The curve is divided into five time constants. Each time constant is equal to 63.2% of some value. An exponential curve is shown in FIGURE 4-29. In this example, current must rise from 0 to a value of 1.5 A at an exponential rate. In this example, 100 ms are required for the current to rise to its full value. Since the current requires a total of 100 ms to rise to its full value, each time constant is 20 ms (100 ms/5 time constants = 20 ms per time constant). During the first time constant, the current will rise from 0 to 63.2% of its total value, or 0.948 A ($1.5 \times 0.632 = 0.948$). During the second time constant the current will rise to a value of 1.297 A, and during the third time constant the current will reach a total value of 1.425 A.

Because the current increases at a rate of 63.2% during each time constant, it is theoretically impossible to reach the total value of 1.5 A. After five time constants, however, the current has reached approximately 99.3% of the maximum value and for all practical purposes is considered to be complete.



© Cengage Learning 2014

FIGURE 4-29 An exponential curve.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

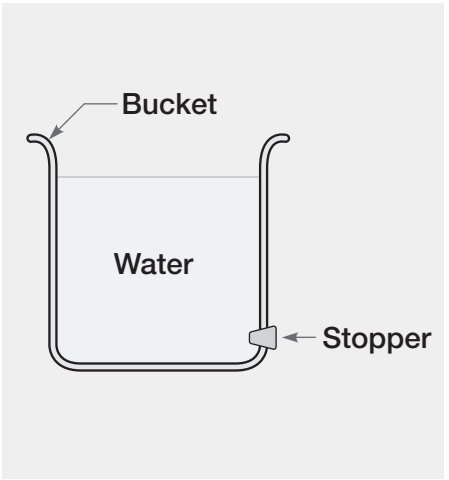


FIGURE 4-30 Exponential curves can be found in nature.

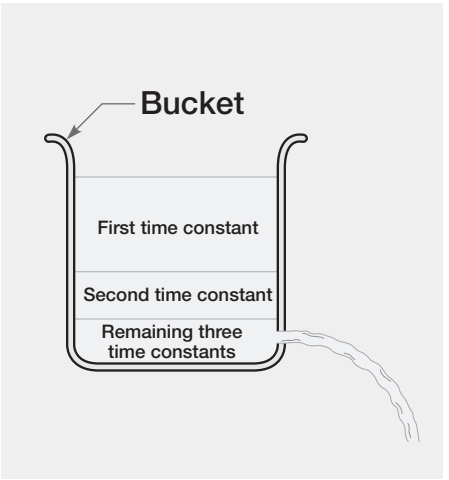


FIGURE 4-31 Water flows from a bucket at an exponential rate.

The exponential curve can often be found in nature. If clothes are hung on a line to dry, they will dry at an exponential rate. Another example of the exponential curve can be seen in FIGURE 4-30. In this example, a bucket has been filled to a certain mark with water. A hole has been cut at the bottom of the bucket and a stopper placed in the hole. When the stopper is removed from the bucket, water will flow out at an exponential rate. Assume, for example, it takes 5 min for the water to flow out of the bucket. Exponential curves are always divided into five time constants, so in this case each time constant has a value of 1 min. In FIGURE 4-31, if the stopper is removed and water is permitted to drain from the bucket for a period of 1 min before the stopper is replaced, during that first time constant 63.2% of the water in the bucket will drain out. If the stopper is again removed for a period of 1 min, 63.2% of the water remaining in the bucket will drain out. Each time the stopper is removed for a period of one time constant, the bucket will lose 63.2% of its remaining water.

henry (H)
basic unit of inductance.

KEY POINT
A coil has an inductance of one henry when a current change of one ampere per second results in an induced voltage of one volt.

INDUCTANCE

Inductance is measured in units called the **henry (H)** and is represented by the letter L. **A coil has an inductance of one henry when a current change of one ampere per second results in an induced voltage of one volt.**

The amount of inductance a coil will have is determined by its physical properties and construction. A coil wound on a nonmagnetic core material such as wood or plastic is referred to as an *air core* inductor. If the coil is

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

wound on a core made of magnetic material such as silicon steel or soft iron it is referred to as an *iron core* inductor. Iron core inductors produce more inductance with fewer turns than air core inductors because of the good magnetic path provided by the core material. Iron core inductors cannot be used for high-frequency applications, however, because of **eddy current** loss and **hysteresis loss** in the core material.

eddy current
circular induced current contrary to the main currents. Eddy currents are a source of heat and power loss in magnetically operated devices.

hysteresis loss
power loss in a conductive material due to molecular friction. Hysteresis loss is proportional to frequency.

Another factor that determines inductance is how far the windings are separated from each other. If the turns of wire are far apart they will have less inductance than turns wound closer together (FIGURE 4-32).

The inductance of a coil can be determined using the formula

$$L = \frac{0.4\pi N^2 \mu A}{l}$$

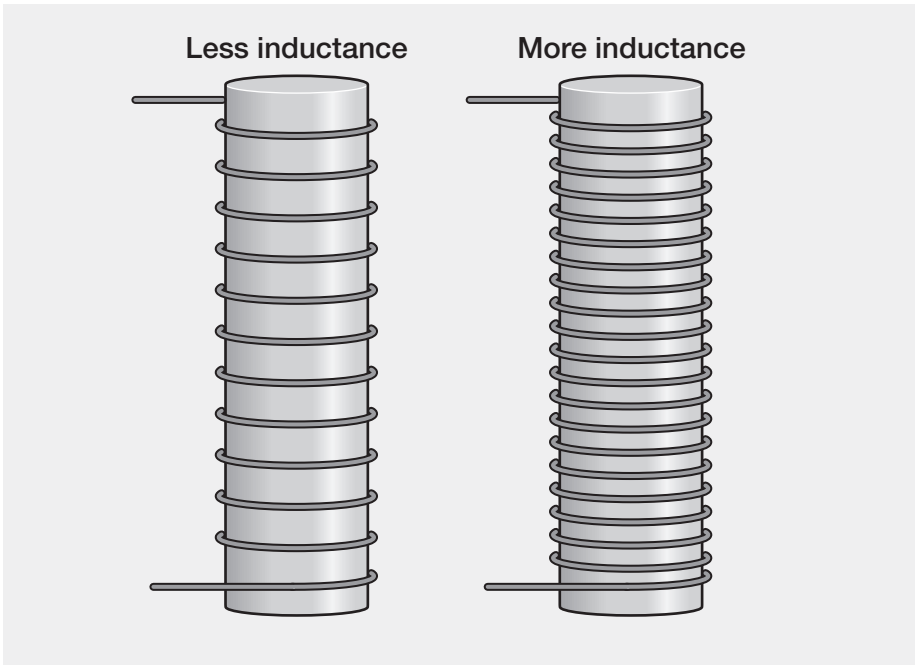
where

L = inductance in henrys

π = 3.1416

N = number of turns of wire

μ = permeability of the core material



© Cengage Learning 2014

FIGURE 4-32 Inductance is determined by the physical construction of the coil.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

A = cross-sectional area of the core

l = length of the core

The formula indicates that the inductance is proportional to the number of turns of wire, the type of core material used, and the cross-sectional area of the core, but inversely proportional to core length. An inductor is basically an electromagnet that changes its polarity at regular intervals. Because the inductor is an electromagnet, the same factors that affect magnets affect inductors. The permeability of the core material is just as important to an inductor as it is to any other electromagnet. Flux lines pass through a core material with a high permeability (such as silicon, steel, or soft iron) better than through a material with a low permeability (such as brass, copper, or aluminum). Once the core material has become saturated, however, the permeability value becomes approximately 1 and an increase in turns of wire has only a small effect on the value of inductance.

CORE MATERIAL

When a coil is wound around a nonmagnetic material such as wood or plastic, it is known as an *air core* magnet. When a coil is wound around a magnetic material such as iron or soft steel, it is known as an *iron core* magnet. The addition of magnetic material to the center of the coil can greatly increase the strength of the magnet. If the core material causes the magnetic field to become fifty times stronger, the core material has a **permeability** of 50, FIGURE 4-33. Permeability is a measure of a material's ability to become magnetized. The number of flux lines produced is proportional to the ampere-turns. The magnetic core material provides an easy path for the flow of magnetic lines, in much the same way that a conductor provides an easy path for the flow of electrons. This permits the flux lines to be concentrated in a smaller area, which increases the number of lines per square inch or square centimeter. It is very similar to a person using a garden hose with an adjustable nozzle attached. The nozzle can be adjusted to permit the water to spray in a fine mist, which covers a large area, or spray in a concentrated stream.

permeability
measurement of a material's ability to conduct magnetic lines of flux. The standard is air, which has a permeability of 1.

Another common magnetic measurement is **reluctance.** Reluctance is resistance to magnetism. A material such as soft iron or steel has a high permeability and low reluctance because it is easily magnetized. A material such as copper has a low permeability and high reluctance.

reluctance
resistance to magnetism.

If the current flow in an electromagnet is continually increased, the magnet will eventually reach a point at which its strength will increase only slightly with an increase in current. When this condition occurs, the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

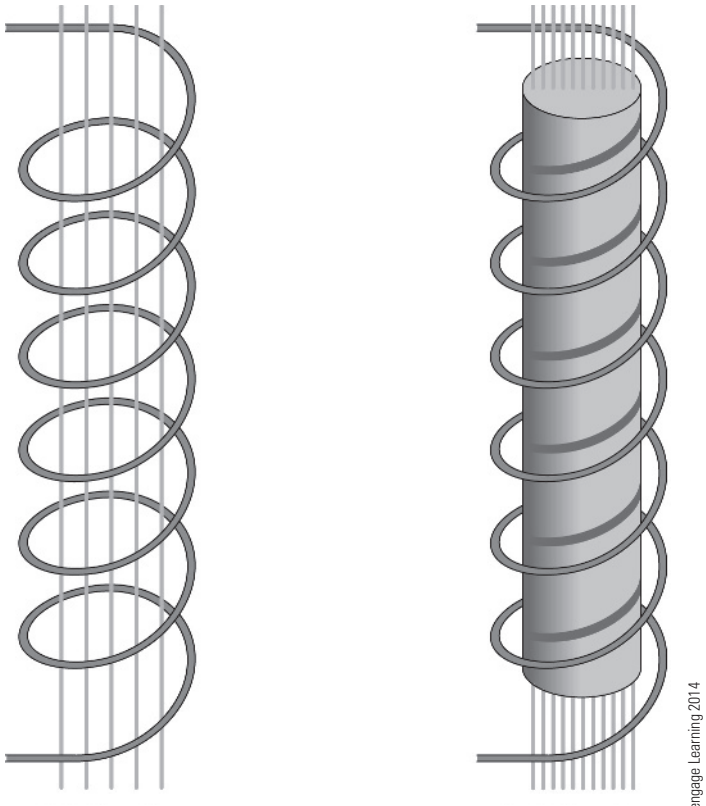


FIGURE 4-33 An iron core increases the number of flux lines per square inch.

magnetic material is at a point of **saturation.** Saturation occurs when all the molecules of the magnetic material are lined up. Saturation is similar to pouring five gallons of water into a five-gallon bucket. Once the bucket is full, it cannot hold any more water. If it became necessary to construct a stronger magnet, a larger piece of core material would be required.

saturation
maximum amount of magnetic flux a material can hold.

When the current flow through the coil of a magnet is stopped, there may be some magnetism left in the core material. The amount of magnetism left in a material after the magnetizing force has stopped is called **residual magnetism.** If the residual magnetism of a piece of core material is hard to remove, the material has a high *coercive force*. Coercive force is a measure of a material's ability to retain magnetism. A high coercive force is desirable in materials that are intended to be used as permanent magnets. A low coercive force is generally desirable for materials intended to be used as electromagnets. Coercive force is measured by determining the amount of

residual magnetism
amount of magnetism left in an object after the magnetizing force has been removed.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

current flow through the coil in the reverse direction that is required to remove the residual magnetism. Another term that is used to describe a material's ability to retain magnetism is *retentivity*.

MAGNETIC MEASUREMENT

The terms used to measure the strength of a magnetic field are determined by the system that is being used. There are three different systems used to measure magnetism: the *English* system, the *CGS* system, and the *MKS* system.

THE ENGLISH SYSTEM

In the English system of measure, magnetic strength is measured in a term called flux density. Flux density is measured in lines per square inch. The Greek letter phi (Φ) is used to measure flux. The letter B is used to represent flux density. The following formula is used to determine flux density.

$$\text{B (flux density)} = \frac{\Phi \text{ (flux lines)}}{\text{A (area)}}$$

magnetomotive force (mmf)
magnetic force produced by current flowing through a conductor or coil.

In the English system, the term used to describe the total force producing a magnetic field, or flux, is **magnetomotive force (mmf)**. Magnetomotive force can be computed using the formula

$$\text{mmf} = \Phi \times \text{rel (reluctance)}$$

The following formula can be used to determine the strength of the magnet:

$$\text{Pull (in pounds)} = \frac{\text{B} \times \text{A}}{72{,}000{,}000}$$

where

B = flux density in lines per square inch
A = area of the magnet

THE CGS SYSTEM (CENTIMETER-GRAM-SECOND)

In the CGS system of measurement, one magnetic line of force is known as a *maxwell*. A *gauss* represents a magnetic force of one maxwell per square centimeter. In the English system, magnetomotive force is measured in ampere-turns. In the CGS system, *gilberts* are used to represent the same measurement. Since the main difference between these two systems of measurement is that one uses English units of measure and the other uses metric units of measure, a conversion factor can be used to help convert one set of units to the other.

$$1 \text{ gilbert} = 1.256 \text{ ampere-turns}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

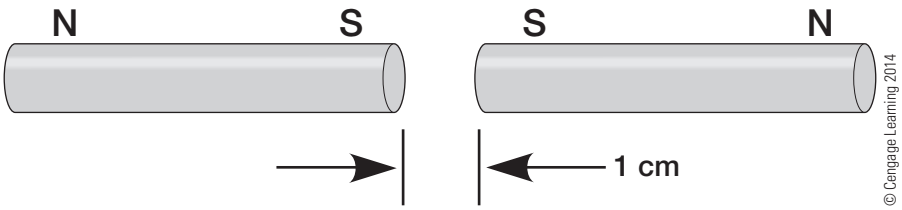


FIGURE 4-34 A unit magnetic pole produces a force of one dyne.

THE MKS SYSTEM (METER-KILOGRAM-SECOND)

The MKS system uses metric units of measure also. In this system, the main unit of magnetic measurement is the *dyne*. The dyne is a very weak amount of force. One dyne is equal to 1/27,800 of an ounce, or it requires 27,800 dynes to equal a force of one ounce. In the MKS system, a standard called the *unit magnetic pole* is used. In FIGURE 4-34, two magnets are separated by a distance of 1 centimeter (cm). These magnets repel each other with a force of 1 dyne. When two magnets separated by a distance of 1 cm exert a force on each other of 1 dyne, they are considered to be a unit magnetic pole. Magnetic force can then be determined using the following formula:

$$\text{Force (in dynes)} = \frac{M_1 \times M_2}{D}$$

where

M_1 = strength of first magnet, in unit magnetic poles
M_2 = strength of second magnet, in unit magnetic poles
D = distance between the poles, in centimeters

MAGNETIC POLARITY

The polarity of an electromagnet can be determined using the **left-hand rule.** When the fingers of the left hand are placed around the windings in the direction of electron current flow, the thumb will point to the north magnetic pole, FIGURE 4-35. If the direction of current flow is reversed, the polarity of the magnetic field will reverse also.

left-hand rule
rule for determining the polarity of a magnet.

DEMAGNETIZING

When an object is to be **demagnetized,** its molecules must be disarranged as they are in a nonmagnetized material. This can be done by placing the

demagnetized
removing magnetism from object.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

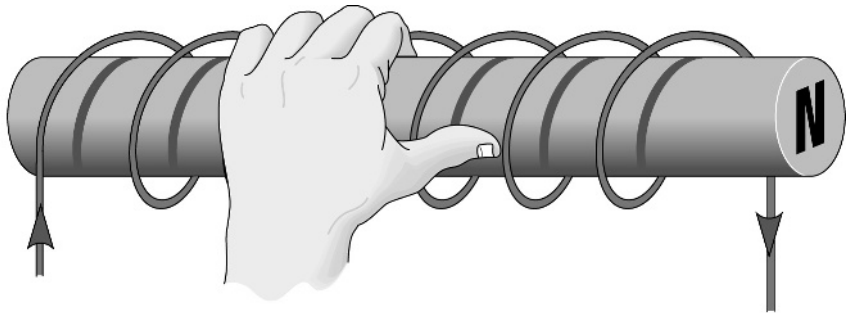


FIGURE 4-35 The left-hand rule can be used to determine the polarity of an electromagnet.

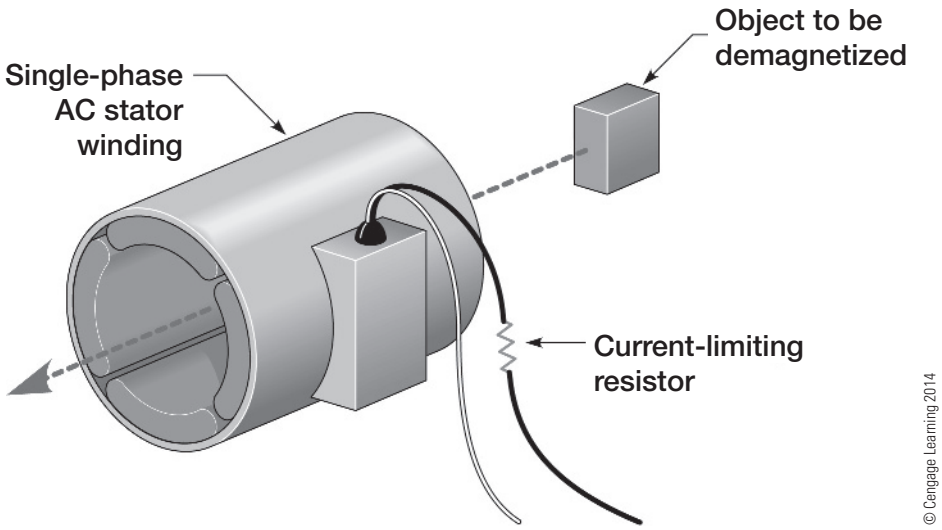


FIGURE 4-36 Demagnetizing an object.

object in the field of a strong electromagnet connected to an alternating current line. Since the magnet is connected to AC current, the polarity of the magnetic field reverses each time the current changes direction. The molecules of the object to be demagnetized are, therefore, aligned first in one direction and then in the other. If the object is pulled away from the AC magnetic field, the effect of the field becomes weaker as the object is moved farther away, FIGURE 4-36. This causes the molecules of the object to be left in a state of disarray. The ease or difficulty with which an object can be demagnetized depends on the strength of the AC magnetic field and the coercive force of the object.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

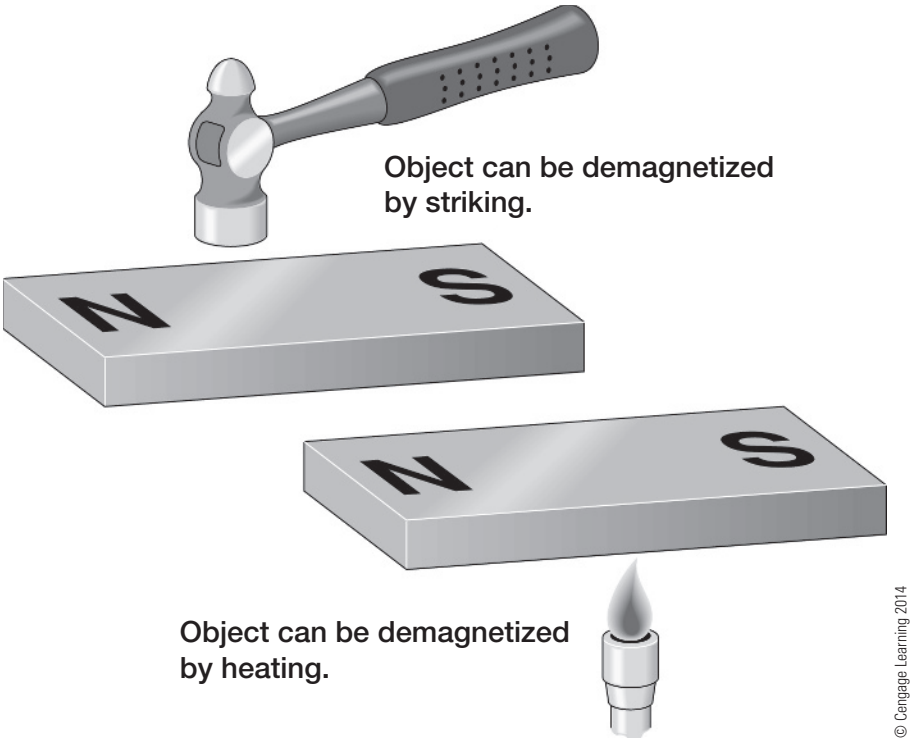


FIGURE 4-37 Other methods for demagnetizing objects.

There are two other ways in which an object can be demagnetized, FIGURE 4-37. If a magnetized object is struck, the vibration will often cause the molecules to rearrange themselves in a disordered fashion. It may be necessary to strike the object several times. Heating an object also will demagnetize it. When the temperature becomes high enough, the molecules will rearrange themselves in a disordered fashion.

MAGNETIC DEVICES

A list of all the devices that operate on magnetism would be very long indeed. Some of the more common devices are electromagnets, measuring instruments, inductors, transformers, and motors.

THE SPEAKER

The speaker is a common device that operates on the principle of magnetism, FIGURE 4-38. The speaker produces sound by moving a cone, which causes a displacement of air. The tone is determined by how fast the cone vibrates. Low or bass sounds are produced by vibrations in the range of 20 cycles per

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

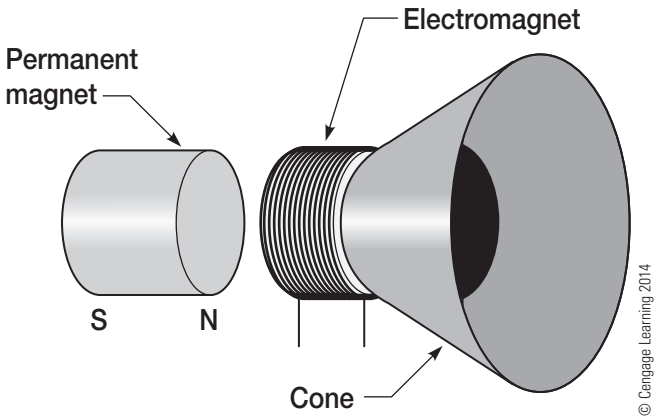


FIGURE 4-38 A speaker uses both an electromagnet and a permanent magnet.

second. High sounds are produced when the speaker vibrates in the range of 20,000 cycles per second.

The speaker uses two separate magnets. One is a permanent magnet, and the other is an electromagnet. The permanent magnet is held stationary, and the electromagnet is attached to the speaker cone. When current flows through the coil of the electromagnet, a magnetic field is produced. The polarity of the field is determined by the direction of current flow. When the electromagnet becomes a north polarity, it is repelled away from the permanent magnet. This causes the speaker cone to move outward, which causes a displacement of air. When the current flow reverses through the coil, the electromagnet becomes a south polarity and is attracted to the permanent magnet. This causes the speaker cone to move inward and again displace air. The tone of the speaker determines the number of times per second the current through the coil reverses.

Summary

1. Early natural magnets were known as lodestones.
2. The earth has a north and a south magnetic pole.
3. The magnetic poles of the earth and the axis poles are not the same.
4. Like poles of a magnet repel each other and unlike poles attract each other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. Some materials have the ability to become better magnets than others.

6. Three basic types of magnetic material are:

   A. ferromagnetic
   B. paramagnetic
   C. diamagnetic

7. When current flows through a wire, a magnetic field is created around the wire.

8. The direction of current flow through the wire determines the polarity of the magnetic field.

9. The strength of an electromagnet is determined by the ampere-turns.

10. The type of core material used in an electromagnet can determine its strength.

11. Three different systems used to measure magnetic values are:

    A. the English System
    B. the CGS System
    C. the MKS System

12. An object can be demagnetized by placing it in an AC magnetic field and pulling it away, by striking, and by heating.

13. When a conductor is cut by a magnetic field a voltage is induced into the conductor.

14. Three factors that determine the amount of induced voltage are:

    A. strength of the magnetic field
    B. number of turns of wire (sometimes stated as length of conductor)
    C. speed of the cutting action

15. The polarity of the induced voltage is determined by the polarity of the magnetic field and the direction of conductor movement.

16. Lenz's Law states that an induced voltage or current opposes the motion that causes it.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Review Questions

1. Is the north magnetic pole of the earth a north polarity or a south polarity?
2. What were early natural magnets known as?
3. The south pole of one magnet is brought close to the south pole of another magnet. Will the magnets repel or attract each other?
4. How can the polarity of an electromagnet be determined if the direction of current flow is known?
5. Define the following terms.
   A. flux density
   B. permeability
   C. reluctance
   D. saturation
   E. coercive force
   F. residual magnetism
6. A force of one ounce is equal to how many dynes?
7. A weber is defined as _____ lines of magnetic flux.
8. A coil contains 50 loops of wire and cuts through magnetic lines of flux at a rate of 20 webers per second. How much voltage is induced into the coil?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 5

Series Circuits

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the properties of series circuits.
- Compute values of voltage, current, and resistance for series circuits.
- List rules for solving electrical values of series circuits.

Electrical circuits can be divided into three major types: the series, the parallel, and the combination. Combination circuits are circuits that contain both series and parallel paths. The first type to be discussed is the **series circuit.**

series circuit
circuit that contains only one path for current flow.

SERIES CIRCUIT

A series circuit is a circuit that has only one path for current flow, FIGURE 5-1. Since there is only one path for current flow, the current is the same at any point in the circuit. Imagine that an electron leaves the negative terminal of the battery. This electron must flow through each resistor before it can complete the circuit to the positive battery terminal.

KEY POINT
A series circuit is a circuit that has only one path for current flow.

One of the best examples of a series-connected device is a fuse or circuit breaker, FIGURE 5-2. Since **fuses** and **circuit breakers** are connected in series with the rest of the circuit, all the circuit current must flow through them. If the current becomes excessive, the fuse or circuit breaker will open and disconnect the rest of the circuit from the power source.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

fuses
device used to protect a circuit or electrical device from excessive current. Fuses operate by melting a metal link when the current becomes excessive.

circuit breakers
device designed to open under an abnormal amount of current flow. The device is not damaged and may be used repeatedly. It is rated by voltage, current, and horsepower.

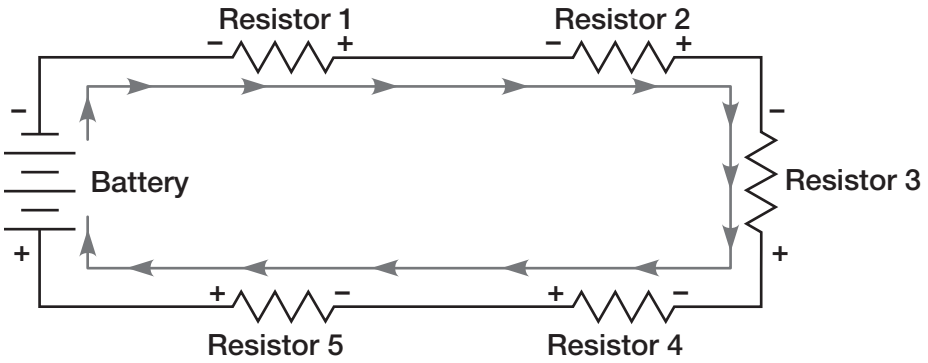


FIGURE 5-1 In a series circuit, there is only one path for current flow.

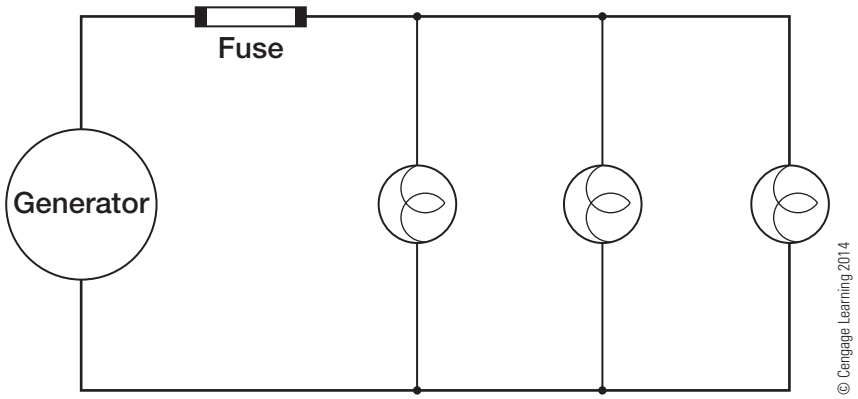


FIGURE 5-2 All the current must flow through the fuse.

KEY POINT
In a series circuit, the sum of all the voltage drops across all the resistors must equal the voltage applied to the circuit.

VOLTAGE DROPS IN A SERIES CIRCUIT

Voltage is the force that pushes the electrons through a resistance. The amount of voltage required is determined by the amount of current flow and resistance. If a voltmeter is connected across a resistor, FIGURE 5-3, the amount of voltage necessary to push the current through that resistor will be indicated by the meter. This is known as **voltage drop.** It is similar to pressure drop in a water system. **In a series circuit, the sum of all the voltage drops across all the resistors must equal the voltage applied to the circuit.** The amount of voltage drop across each resistor will be proportional to its resistance and the circuit current.

voltage drop
amount of voltage required to cause an amount of current to flow through a certain resistance.

In the circuit shown in FIGURE 5-4, four resistors are connected in series. It is assumed that each resistor has the same value. The circuit is connected to a 24-V battery. Since each resistor has the same value, the voltage drop across each will be 6 V (24 V/4 resistors = 6 V). Note that each resistor will have the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

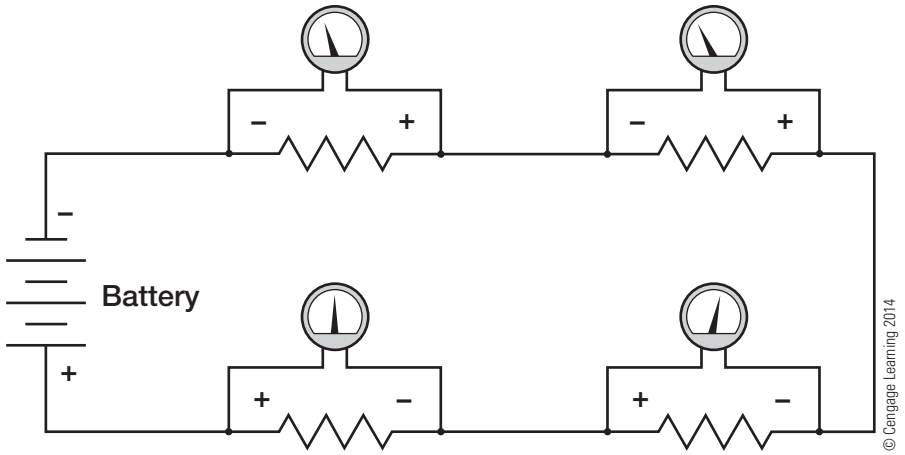


FIGURE 5-3 The voltage drops in a series circuit must equal the applied voltage.

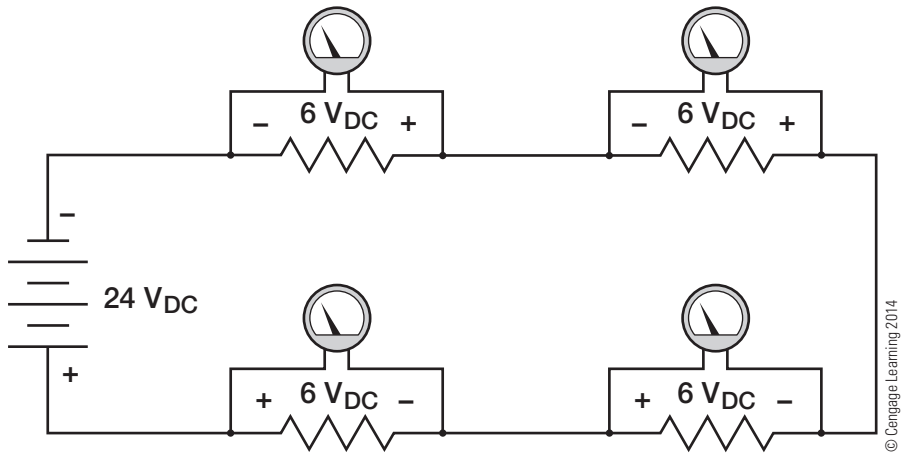


FIGURE 5-4 The voltage drop across each resistor is proportional to its resistance.

same voltage drop only if each resistor is the same value. The circuit shown in FIGURE 5-5 illustrates a series circuit comprised of resistors having different values. Notice that the voltage drop across each resistor is proportional to its resistance. Also notice that the sum of the voltage drops will equal the applied voltage of 24 V.

RESISTANCE IN A SERIES CIRCUIT

Since there is only one path for the current to flow through a series circuit, it must flow through each resistor in the circuit (FIGURE 5-1). Each resistor limits or impedes the flow or current in the circuit. Therefore, the total amount of

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

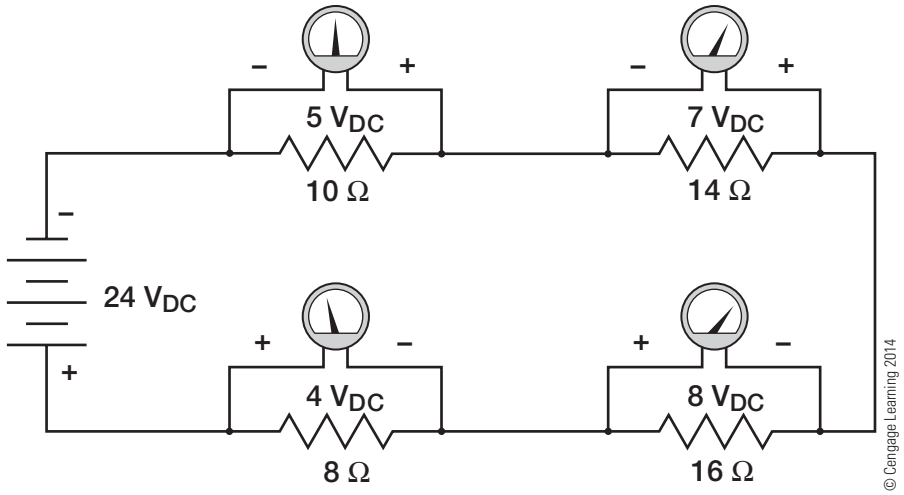


FIGURE 5-5 Series circuit with four resistors having different voltage drops.

series resistance
In a series circuit the total resistance is the sum of all circuit resistances.

series resistance offered to the flow of current is proportional to the sum of all the resistors in the circuit.

CALCULATING SERIES CIRCUIT VALUES

There are three rules that can be used with Ohm's Law for finding values of voltage, current, resistance, and power in any series circuit.

1. The current is the same at any point in the circuit.
2. The total resistance is the sum of the individual resistors.
3. The applied voltage is equal to the sum of the voltage drops across all resistors.

The circuit shown in FIGURE 5-6 shows the values of current flow, voltage drop, and resistance for each of the resistors. Notice that the total resistance (R_T) of the circuit can be found by adding the values of the resistors **(resistance adds).**

$$R_{T(total)} = R_1 + R_2 + R_3$$
$$R_T = 20\ \Omega + 10\ \Omega + 30\ \Omega$$
$$R_T = 60\ \Omega$$

Ohm's Law
the basis of almost all physical laws concerning electricity.

The amount of current flow in the circuit can be found by using **Ohm's Law.**

$$I = \frac{E}{R}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

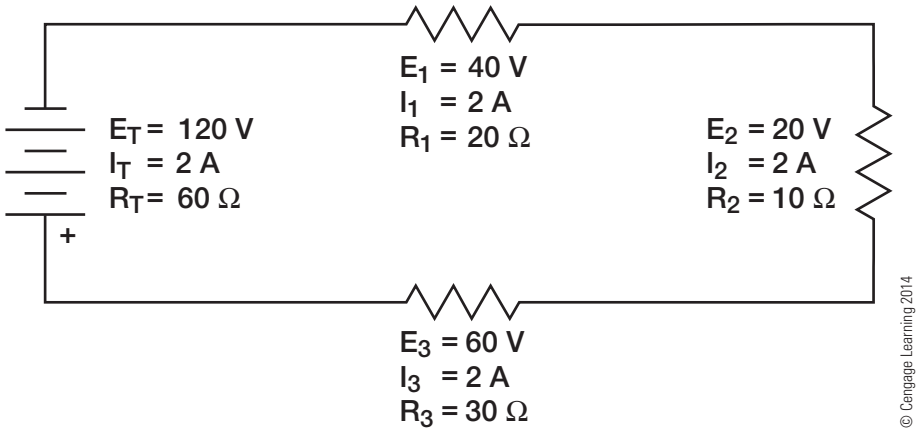


FIGURE 5-6 Series circuit values.

$$I = \frac{120}{60}$$

$$I = 2 \text{ A}$$

A current of 2 A flows through each resistor in the circuit.

$$(I_{T(total)} = I_1 = I_2 = I_3)$$

Since the amount of current flowing through resistor R_1 is known, the voltage drop across the resistor can be found using Ohm's Law.

$$E_1 = I_1 \times R_1$$

$$E_1 = 2 \text{ A} \times 20\ \Omega$$

$$E_1 = 40 \text{ V}$$

This means that it takes 40 V to push 2 A of current through 20 Ω of resistance. If a voltmeter is connected across resistor R_1, it would indicate a value of 40 V, FIGURE 5-7. This is the amount of voltage drop across resistor R_1. The voltage drop across resistors R_2 and R_3 can be found in the same way.

$$E_2 = I_2 \times R_2$$

$$E_2 = 2 \text{ A} \times 10\ \Omega$$

$$E_2 = 20 \text{ V}$$

$$E_3 = I_3 \times R_3$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

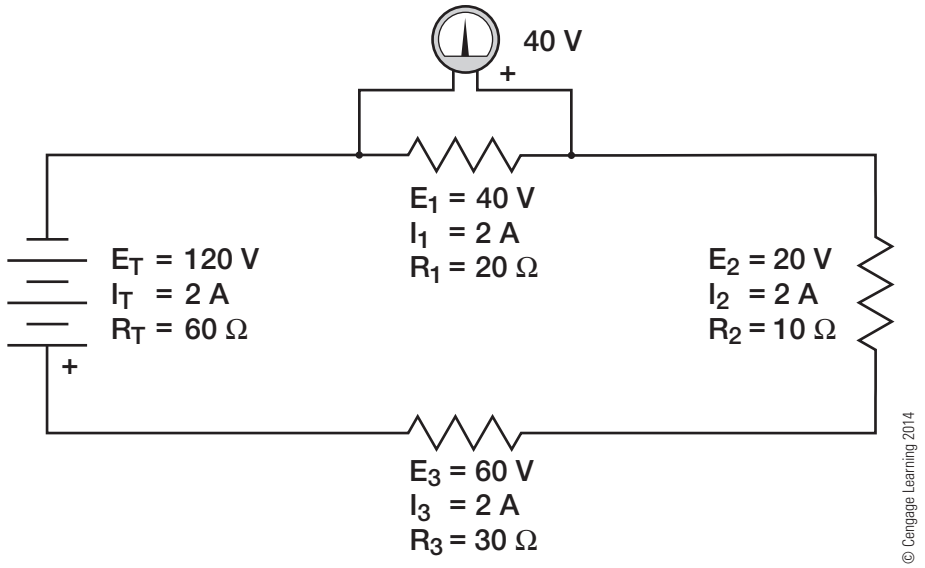


FIGURE 5-7 The voltmeter indicates a voltage drop of 40 V.

$$E_3 = 2\ A \times 30\ \Omega$$

$$E_3 = 60\ V$$

If the voltage drop across all the resistors is added, it equals the total applied voltage (E_T).

$$(E_{T(total)} = E_1 + E_2 + E_3)$$

$$E_T = 40\ V + 20\ V + 60\ V$$

$$E_T = 120\ V$$

SOLVING CIRCUITS

In the following problems, circuits will be shown that have missing values. The missing values can be found by using the rules for series circuits and Ohm's Law.

EXAMPLE 1: The first step in finding the missing values in the circuit shown in FIGURE 5-8 is to find the total resistance. This can be done by using the third rule of series circuits, which states that resistances add to equal the total resistance of the circuit.

$$R_T = R_1 + R_2 + R_3 + R_4$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

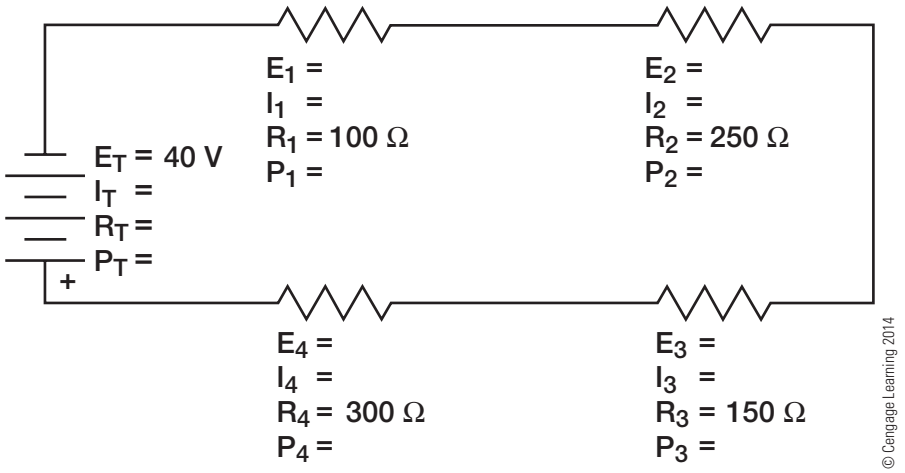


FIGURE 5-8 Series circuit, Example 1.

$$R_T = 100\ \Omega + 250\ \Omega + 150\ \Omega + 300\ \Omega$$

$$R_T = 800\ \Omega$$

Now that the total voltage and total resistance are known, the current flow through the circuit can be found using Ohm's Law.

$$I = \frac{E}{R}$$

$$I = \frac{40}{800}$$

$$I = 0.050\ A$$

The second rule of series circuits states that current remains the same at any point in the circuit. Therefore, 0.050 A flows through each resistor in the circuit, FIGURE 5-9. The voltage drop across each resistor can now be found using Ohm's Law, FIGURE 5-10.

$$E_1 = I_1 \times R_1$$

$$E_1 = 0.050 \times 100$$

$$E_1 = 5\ V$$

$$E_2 = I_2 \times R_2$$

$$E_2 = 0.050 \times 250$$

$$E_2 = 12.5\ V$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

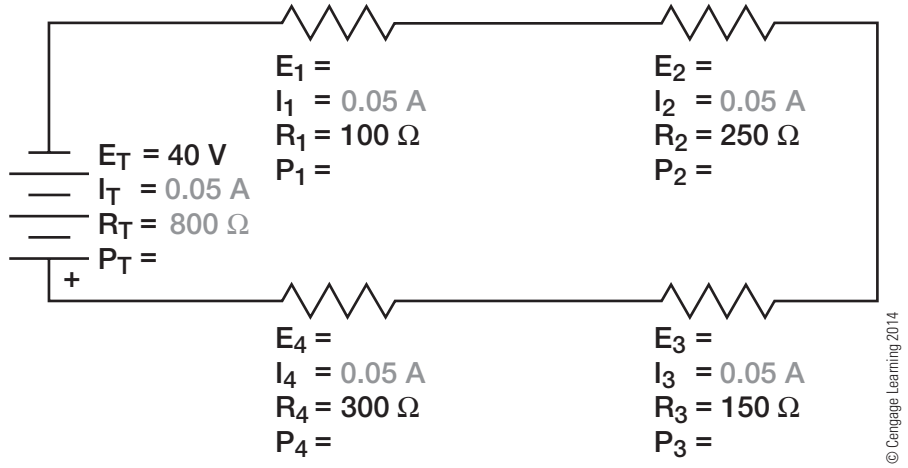


FIGURE 5-9 In a series circuit, the current is the same at any point.

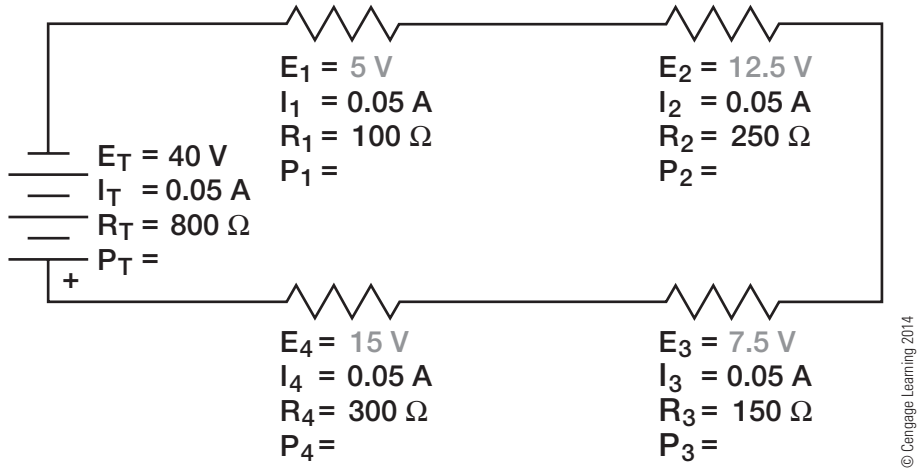


FIGURE 5-10 The voltage drop across each resistor can be found using Ohm's Law.

$$E_3 = I_3 \times R_3$$
$$E_3 = 0.050 \times 150$$
$$E_3 = 7.5 \text{ V}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.050 \times 300$$
$$E_4 = 15 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Several formulas can be used to determine the amount of power dissipated (changed into heat energy) by each resistor. The power dissipation of resistor R_1 will be found using the formula:

$$P_1 = E_1 \times I_1$$
$$P_1 = 5 \times 0.05$$
$$P_1 = 0.25 \text{ W}$$

The amount of power dissipation for resistor R_2 will be computed using the formula:

$$P_2 = \frac{E_2^2}{R_2}$$
$$P_2 = \frac{156.25}{250}$$
$$P_2 = 0.625 \text{ W}$$

The amount of power dissipation for resistor R_3 will be computed using the formula:

$$P_3 = I_3^2 \times R_3$$
$$P_3 = 0.0025 \times 150$$
$$P_3 = 0.375 \text{ W}$$

The amount of power dissipation for resistor R_4 will be found using the formula:

$$P_4 = E_4 \times I_4$$
$$P_4 = 15 \times 0.05$$
$$P_4 = 0.75 \text{ W}$$

A good rule to remember when calculating values of electrical circuits is that **the total power used in a circuit is equal to the sum of the power used by all parts.** This means that the total power can be found in any kind of a circuit (series, parallel, or combination) by adding the power dissipation of each part. The total power for this circuit can be found using the formula:

$$P_T = P_1 + P_2 + P_3 + P_4$$
$$P_T = 0.25 + 0.625 + 0.375 + 0.75$$
$$P_T = 2 \text{ W}$$

KEY POINT

The total power used in a circuit is equal to the sum of the power used by all parts.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

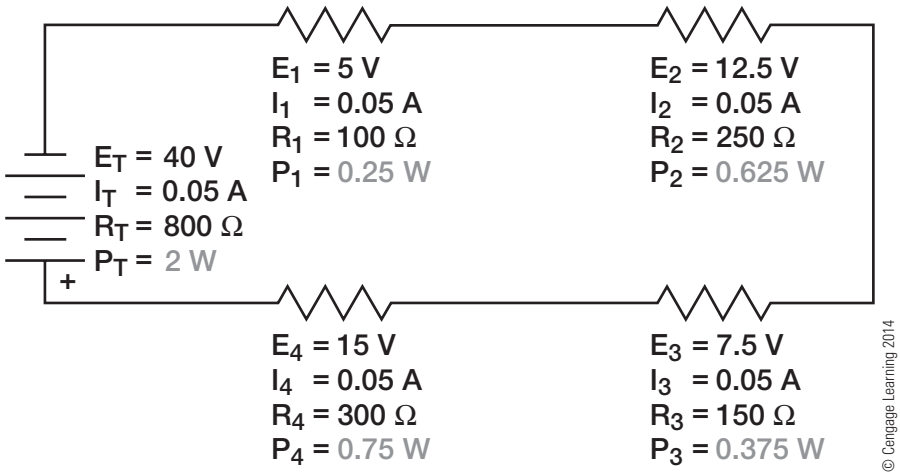


FIGURE 5-11 The final values for the circuit in Example 1.

Now that all the missing values have been found, FIGURE 5-11, the circuit can be checked by using the first rule of series circuits, which states that voltage drops add to equal the applied voltage.

$$E_T = E_1 + E_2 + E_3 + E_4$$
$$E_T = 5 + 12.5 + 7.5 + 15$$
$$E_T = 40 \text{ V}$$

EXAMPLE 2: The second circuit to be solved is shown in FIGURE 5-12. In this circuit the total resistance is known, but the value of resistor R_2 is not. The third rule of series circuits states that resistance adds to equal the total resistance of the circuit. Since the total resistance is known, the missing resistance of R_2 can be found by adding the value of the other resistors and subtracting their sum from the total resistance of the circuit, FIGURE 5-13.

$$R_2 = R_T - (R_1 + R_3 + R_4)$$
$$R_2 = 6000 - (1000 + 2000 + 1200)$$
$$R_2 = 6000 - 4200$$
$$R_2 = 1800\ \Omega$$

The amount of current flow in the circuit can be found using Ohm's Law.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

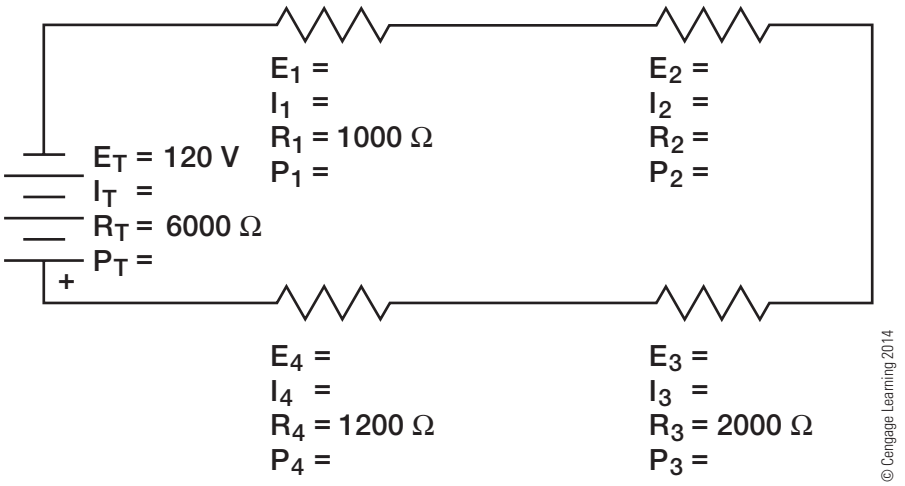


FIGURE 5-12 Series circuit, Example 2.

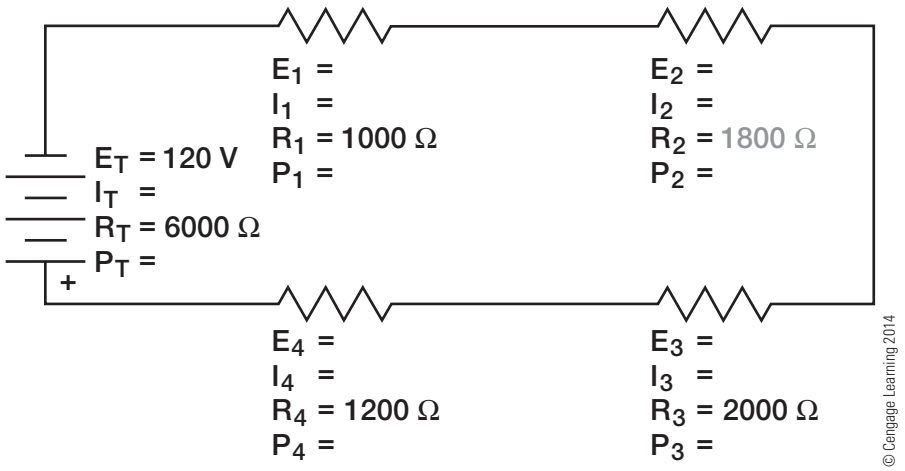


FIGURE 5-13 The missing resistor value.

$$I = \frac{E}{R}$$

$$I = \frac{120}{6000}$$

$$I = 0.020 \text{ A}$$

Since the amount of current flow is the same through all elements of a series circuit, FIGURE 5-14, the voltage drop across each resistor can be found using Ohm's Law, FIGURE 5-15.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

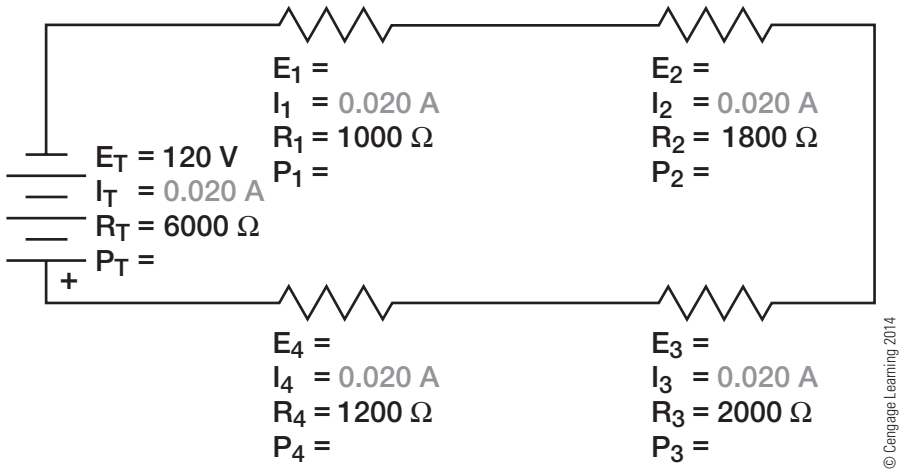


FIGURE 5-14 The current is the same through each circuit element.

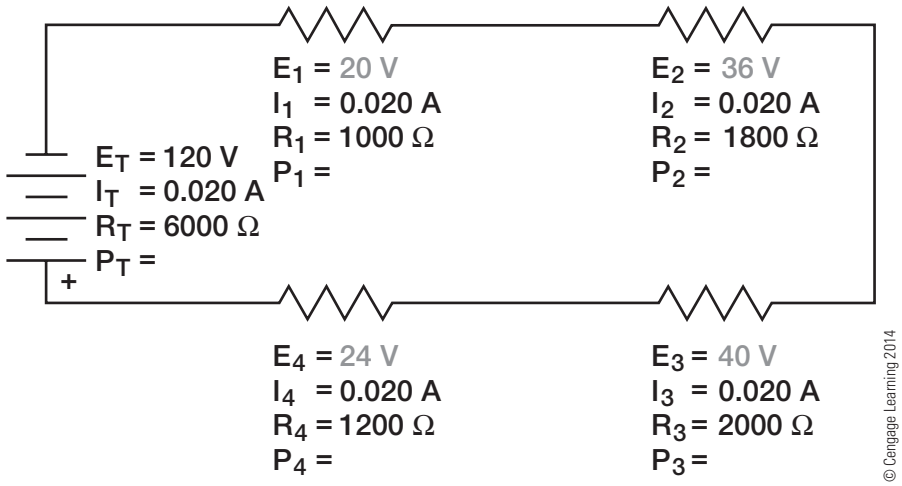


FIGURE 5-15 The voltage drops across each resistor.

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.020 \times 1000$$
$$E_1 = 20 \text{ V}$$

$$E_2 = I_2 \times R_2$$
$$E_2 = 0.020 \times 1800$$
$$E_2 = 36 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$E_3 = I_3 \times R_3$$
$$E_3 = 0.020 \times 2000$$
$$E_3 = 40 \text{ V}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.020 \times 1200$$
$$E_4 = 24 \text{ V}$$

The first rule of series circuits can be used to check the answers.

$$E_T = E_1 + E_2 + E_3 + E_4$$
$$E_T = 20 + 36 + 40 + 24$$
$$E_T = 120 \text{ V}$$

The amount of power dissipation for each resistor in the circuit can be computed in the same manner as in circuit one. The power dissipated by resistor R_1 will be computed using the formula:

$$P_1 = E_1 \times I_1$$
$$P_1 = 20 \times 0.02$$
$$P_1 = 0.4 \text{ W}$$

The amount of power dissipation for resistor R_2 will be found by using the formula:

$$P_2 = \frac{E_2^2}{R_2}$$

$$P_2 = \frac{1296}{1800}$$

$$P_2 = 0.72 \text{ W}$$

The power dissipation of resistor R_3 will be found using the formula:

$$P_3 = I_3^2 \times R_3$$
$$P_3 = 0.0004 \times 2000$$
$$P_3 = 0.8 \text{ W}$$

The power dissipation of resistor R_4 will be computed using the formula:

$$P_4 = E_4 \times I_4$$
$$P_4 = 24 \times 0.02$$
$$P_4 = 0.48 \text{ W}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

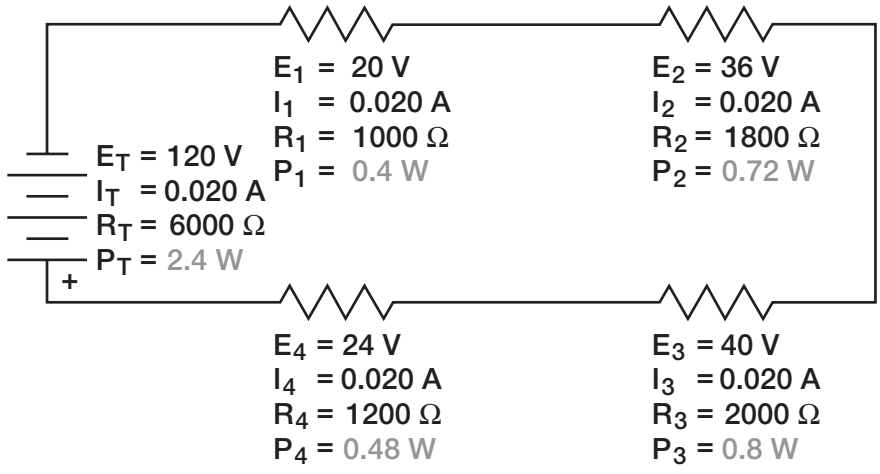


FIGURE 5-16 The remaining unknown values for the circuit in Example 2.

The total power will be computed using the formula:

$$P_T = E_T \times I_T$$

$$P_T = 120 \times 0.02$$

$$P_T = 2.4 \text{ W}$$

The circuit with all computed values is shown in FIGURE 5-16.

EXAMPLE 3: In the circuit shown in FIGURE 5-17, resistor R_1 has a voltage drop of 6.4 V, resistor R_2 has a power dissipation of 0.102 W, resistor R_3 has a power dissipation of 0.154 W, resistor R4 has a power dissipation of 0.307 W, and the total power consumed by the circuit is 0.768 W.

The only value that can be found with the given quantities is the amount of power dissipated by resistor R_1. Since the total power is known and the power dissipated by all other resistors is known, the power dissipated by resistor R_1 can be found by subtracting the power dissipated by resistors R_2, R_3, and R_4 from the total power used in the circuit.

$$P_1 = P_T - (P_2 + P_3 + P_4)$$

or

$$P_1 = P_T - P_2 - P_3 - P_4$$

$$P_1 = 0.768 - 0.102 - 0.154 - 0.307$$

$$P_1 = 0.205 \text{ W}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

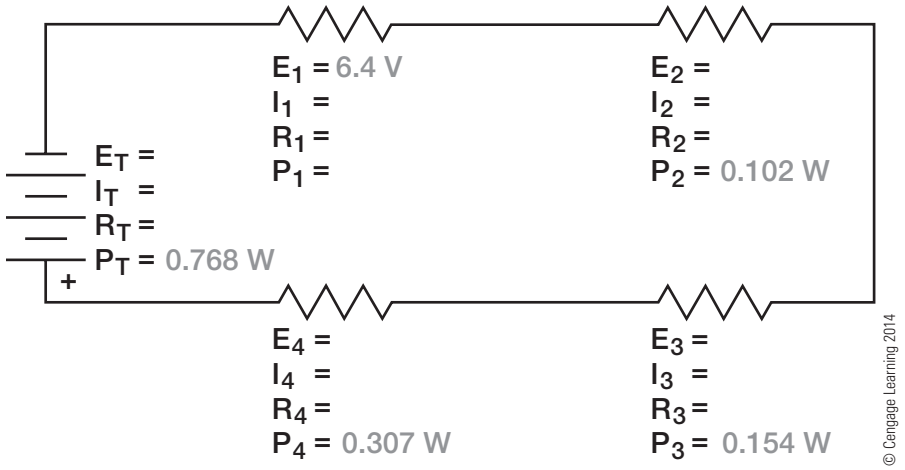


FIGURE 5-17 Series circuit, Example 3.

Now that the amount of power dissipated by resistor R_1 and the amount of voltage dropped across R_1 are known, the current flow through resistor R_1 can be found using the formula:

$$I = \frac{P}{E}$$

$$I = \frac{0.205}{6.4}$$

$$I = 0.032 \text{ A}$$

Since the current in a series circuit must be the same at any point in the circuit, it must be the same through all circuit components, FIGURE 5-18.

Now that the power dissipation of each resistor and the amount of current flowing through each resistor are known, the voltage drop of each resistor can be computed, FIGURE 5-19.

$$E_2 = \frac{P_2}{I_2}$$

$$E_2 = \frac{0.102}{0.032}$$

$$E_2 = 3.2 \text{ V}$$

$$E_3 = \frac{P_3}{I_3}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

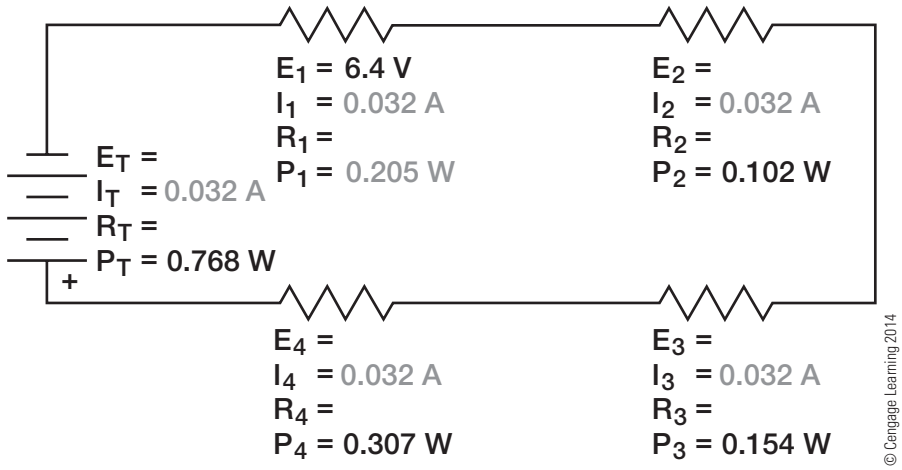


FIGURE 5-18 The current flow in the circuit in Example 3.

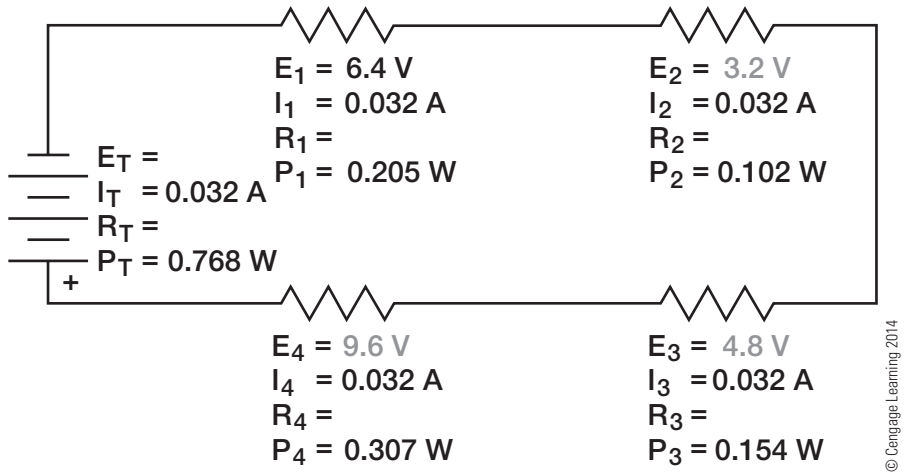


FIGURE 5-19 The voltage drops across each resistor.

$$E_3 = \frac{0.154}{0.032}$$

$$E_3 = 4.8 \text{ V}$$

$$E_4 = \frac{P_4}{I_4}$$

$$E_4 = \frac{0.307}{0.032}$$

$$E_4 = 9.6 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Ohm's Law can now be used to find the ohmic value of each resistor in the circuit, FIGURE 5-20.

$$R_1 = \frac{E_1}{I_1}$$

$$R_1 = \frac{6.4}{0.032}$$

$$R_1 = 200\ \Omega$$

$$R_2 = \frac{E_2}{I_2}$$

$$R_2 = \frac{3.2}{0.032}$$

$$R_2 = 100\ \Omega$$

$$R_3 = \frac{E_3}{I_3}$$

$$R_3 = \frac{4.8}{0.032}$$

$$R_3 = 150\ \Omega$$

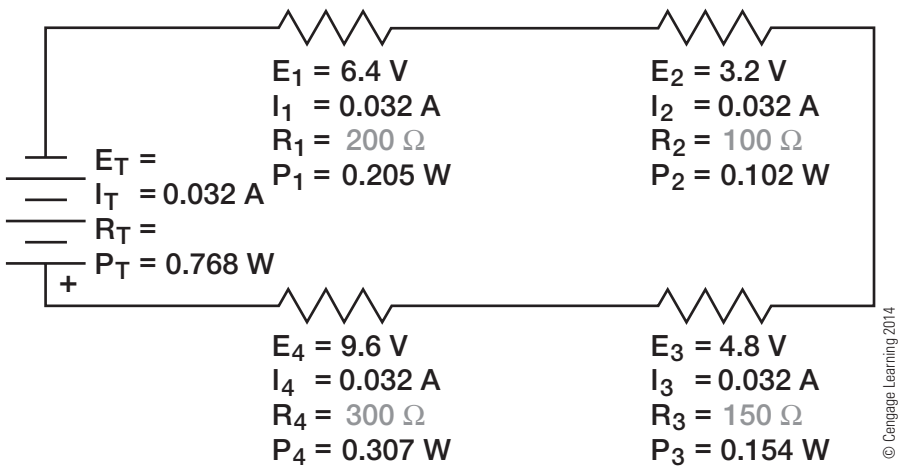


FIGURE 5-20 The ohmic value of each resistor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$R_4 = \frac{E_4}{I_4}$$

$$R_4 = \frac{9.6}{0.032}$$

$$R_4 = 300\ \Omega$$

The voltage applied to the circuit can be found by adding the voltage drops across each resistor, FIGURE 5-21.

$$E_T = E_1 + E_2 + E_3 + E_4$$

$$E_T = 6.4 + 3.2 + 4.8 + 9.6$$

$$E_T = 24\ V$$

The total resistance of the circuit can be found in a similar manner. The total resistance is equal to the sum of all the resistive elements in the circuit.

$$R_T = R_1 + R_2 + R_3 + R_4$$

$$R_T = 200 + 100 + 150 + 300$$

$$R_T = 750\ \Omega$$

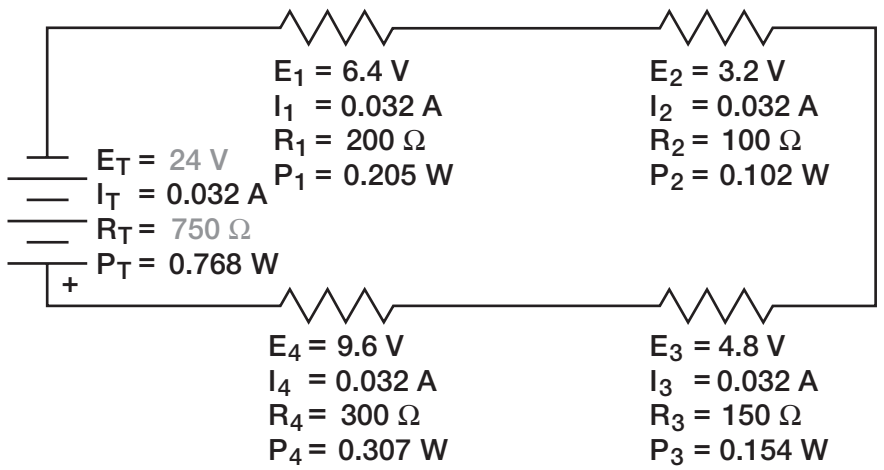


FIGURE 5-21 The applied voltage and the total resistance.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

VOLTAGE DIVIDERS

voltage divider
a series circuit used to provide different voltages across certain points.

One common use for series circuits is the construction of voltage dividers. A **voltage divider** works on the principle that the sum of the voltage drops across a series circuit must equal the applied voltage. Voltage dividers are used to provide different voltages across certain points, FIGURE 5-22. If a voltmeter is connected between points A and B, a voltage of 20 V will be seen. If the voltmeter is connected between points B and D, a voltage of 80 V will be seen.

Voltage dividers can be constructed to produce any voltage desired. For example, assume that a voltage divider is connected to a source of 120 V and is to provide voltage drops of 36 V, 18 V, and 66 V. Notice that the sum of the voltage drops equals the applied voltage. The next step is to decide how much current is to flow through the circuit. Since there is only one path for current flow, the current will be the same through each resistor. In this circuit, a current flow of 15 mA (0.015 A) will be used. The resistance value of each resistor can now be determined.

$$R = \frac{E}{I}$$

$$R_1 = \frac{36}{0.015}$$

$$R_1 = 2.4\ \text{k}\Omega\ (2400\ \Omega)$$

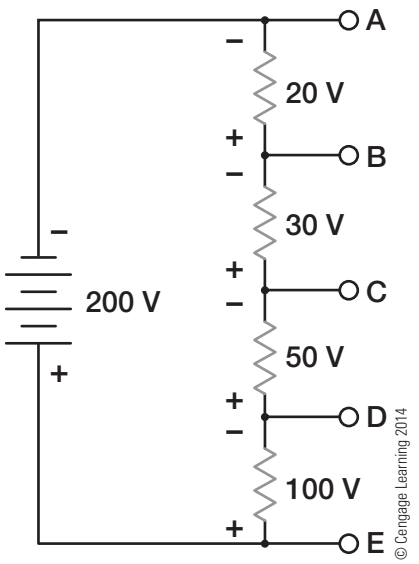


FIGURE 5-22 Series circuit used as a voltage divider.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$R_2 = \frac{18}{0.015}$$

$$R_2 = 1.2\ \text{k}\Omega\ (1200\ \Omega)$$

$$R_3 = \frac{66}{0.015}$$

$$R_3 = 4.4\ \text{k}\Omega\ (4400\ \Omega)$$

VOLTAGE POLARITY

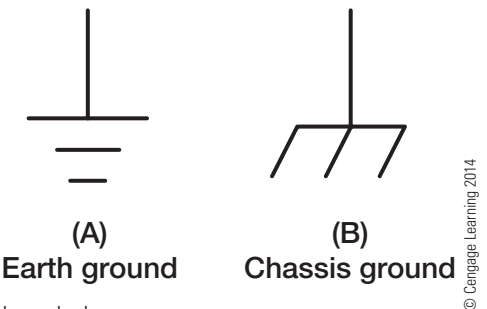
It is often necessary to know the polarity of the voltage developed across a resistor. **Voltage polarity** can be determined by observing the direction of current flow through the circuit. In the circuit shown in FIGURE 5-22 it will be assumed that the current flows from the negative terminal of the battery to the positive terminal. Point A is connected to the negative battery terminal and point E is connected to the positive terminal. If a voltmeter is connected across terminals A and B, terminal B will be positive with respect to A. If a voltmeter is connected across terminals B and C, however, terminal B will be negative with respect to terminal C. Notice that terminal B is located closer to the negative terminal of the battery. This means that electrons flow through the resistor in a direction that makes terminal B more negative than C. Terminal C would be negative with respect to terminal D for the same reason.

USING GROUND AS A REFERENCE

Two symbols are used to represent ground, FIGURE 5-23. The symbol shown in FIGURE 5-23A is an **earth ground** symbol. It symbolizes a **ground point**

earth ground
grounding a circuit directly to the earth via a grounding rod.

ground point
point where a circuit is connected to ground.



© Cengage Learning 2014

FIGURE 5-23 Ground symbols.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

that is made by physically driving an object, such as a rod or pipe, into the ground. The symbol shown in FIGURE 5-23B symbolizes a **chassis ground.** This is a point that is used as a common connection for other parts of a circuit but is not actually driven into the ground. Although the symbol shown in FIGURE 5-23B is the accepted symbol for a chassis ground, the symbol shown in FIGURE 5-23A is also often used to represent a chassis ground.

chassis ground
grounding a circuit to the case or chassis of a piece of equipment.

An excellent example of using ground as a common connection can be found in the electrical system of an automobile. The negative terminal of the battery is grounded to the frame or chassis of the vehicle. This does not mean that the frame of the automobile is connected directly to earth ground. The chassis is insulated from the ground by rubber tires. In the case of an automobile electrical system, the chassis of the vehicle is the negative side of the circuit. An electrical circuit using ground as a common connection point is shown in FIGURE 5-24. This circuit is an electronic burglar alarm. Notice the numerous ground points in the schematic. In practice, when the circuit is connected, all the ground points will be connected.

In voltage divider circuits, ground is often used to provide a common reference point to produce voltages that are above and below ground, FIGURE 5-25. An above-ground voltage is a voltage that is positive with respect to ground. A below-ground voltage is negative with respect to ground. In Figure 5-25, one terminal of a zero-center voltmeter is connected to ground. If the probe is connected to point A, the pointer of the voltmeter will give a negative indication for voltage. If the probe is connected to point B, the pointer will indicate a positive voltage.

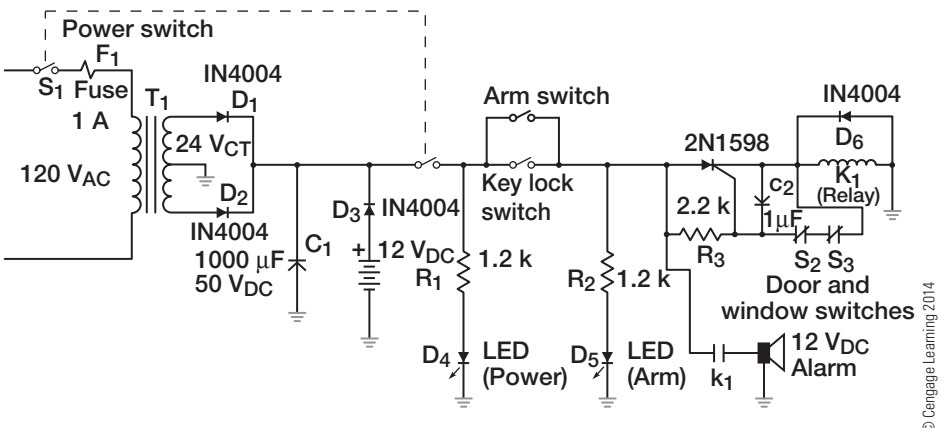


FIGURE 5-24 Burglar alarm with battery backup.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

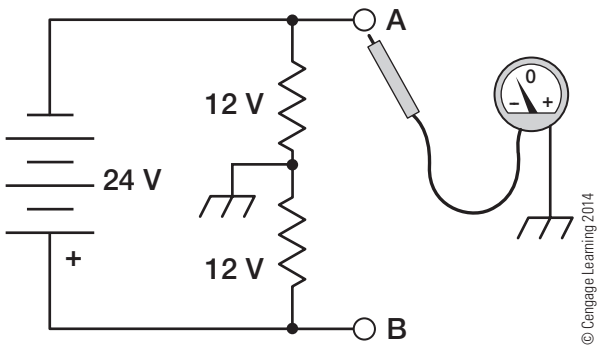


FIGURE 5-25 A common ground used to produce above- and below-ground voltage.

Summary

1. Series circuits have only one path for current flow.
2. The individual voltage drops in a series circuit can be added to equal the applied voltage.
3. The current is the same at any point in a series circuit.
4. The individual resistors can be added to equal the total resistance of the circuit.
5. Fuses and circuit breakers are connected in series with the devices they are intended to protect.
6. The total power in any circuit is equal to the sum of the power dissipated by all parts of the circuit.

Review Questions

1. A series circuit has individual resistor values of 200 Ω, 86 Ω, 91 Ω, 180 Ω, and 150 Ω. What is the total resistance of the circuit?
2. A series circuit contains four resistors. The total resistance of the circuit is 360 Ω. Three of the resistors have values of 56 Ω, 110 Ω, and 75 Ω. What is the value of the fourth resistor?
3. A series circuit contains five resistors. The total voltage applied to the circuit is 120 V. Four resistors have voltage drops of 35 V, 28 V, 22 V, and 15 V. What is the voltage drop of the fifth resistor?
4. A circuit has three resistors connected in series. The resistance of resistor R_2 is 220 Ω, and it has a voltage drop of 44 V. What is the current flow through resistor R_3?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. A circuit has four resistors connected in series. If each resistor has a voltage drop of 60 V, what is the voltage applied to the circuit?
6. Define a series circuit.
7. State the three rules for series circuits.
8. A series circuit has resistance values of 160 Ω, 100 Ω, 82 Ω, and 120 Ω. What is the total resistance of this circuit?
9. If a voltage of 24 V is applied to the circuit in question 8, what will be the total amount of current flow in the circuit?
10. What will be the voltage drop across each of the resistors?

A. 160 Ω_____V

B. 100 Ω_____V

C. 82 Ω_____V

D. 120 Ω_____V

Practice Problems

CIRCUITS

1. Find the missing values in the circuit shown in FIGURE 5-26.

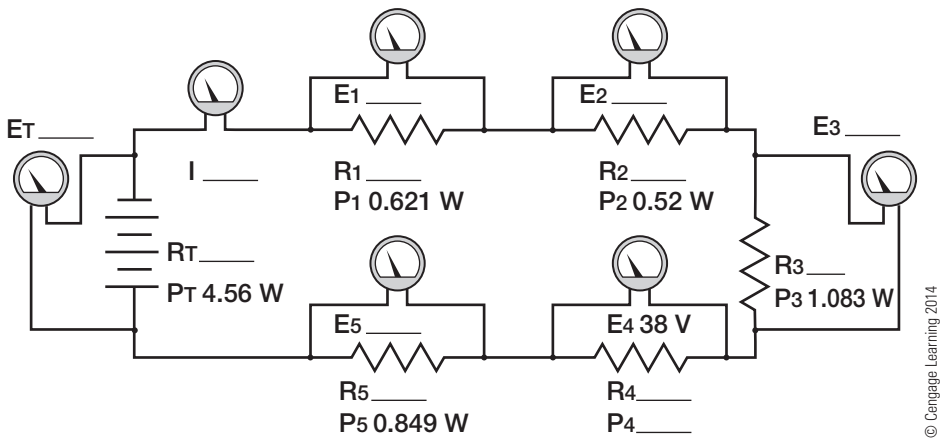


FIGURE 5-26 Practice Problem 1.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

2. Find the missing values in the circuit shown in FIGURE 5-27.

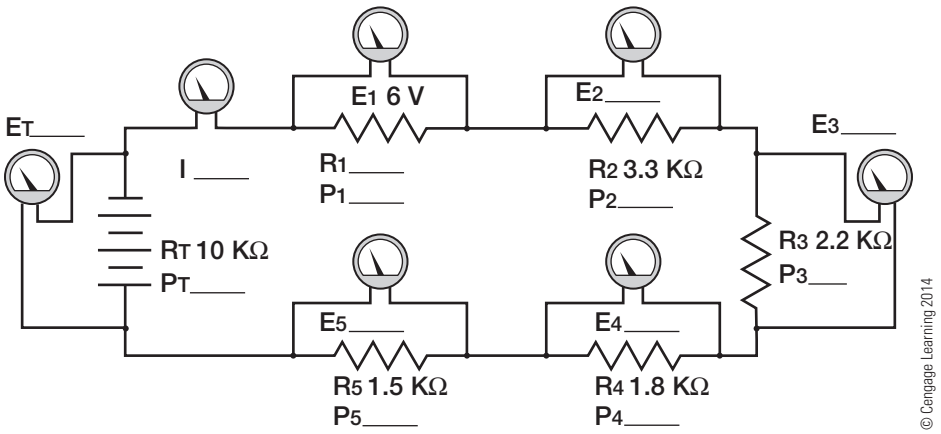


FIGURE 5-27 Practice Problem 2.

3. Find the missing values in the circuit shown in FIGURE 5-28.

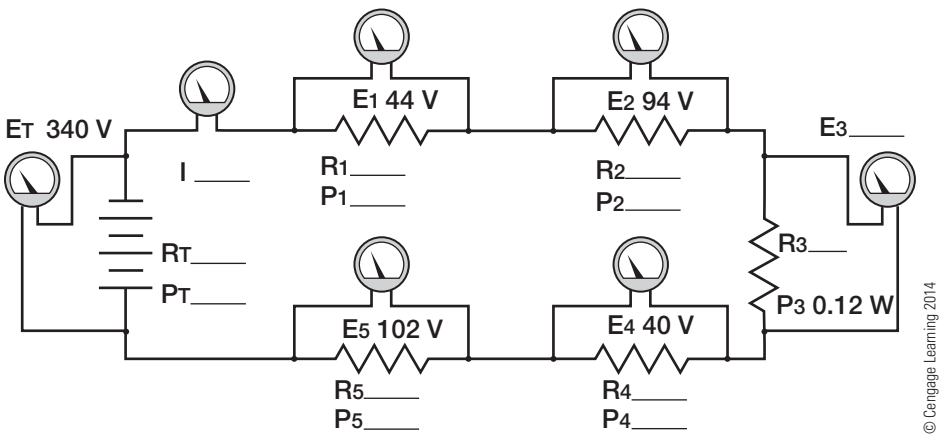


FIGURE 5-28 Practice Problem 3.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

4. Find the missing values in the circuit shown in FIGURE 5-29.

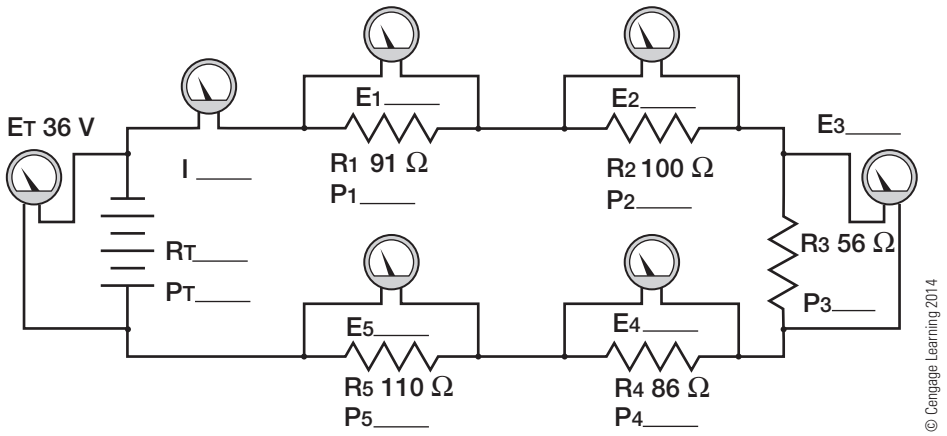


FIGURE 5-29 Practice Problem 4.

5. Find the missing values in the circuit shown in FIGURE 5-30.

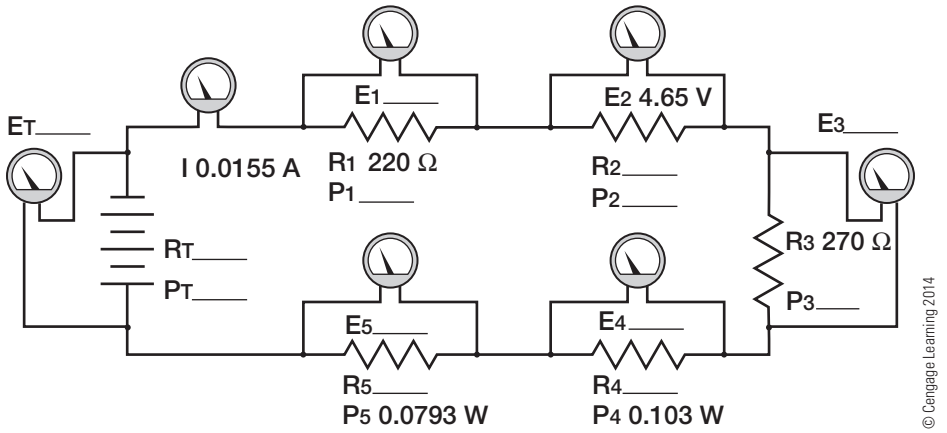


FIGURE 5-30 Practice Problem 5.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 6

Parallel Circuits

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the characteristics of a parallel circuit.
- State three rules for parallel circuits.
- Solve the missing values in a parallel circuit using the three rules and Ohm's Law.

parallel circuits circuit that contains more than one path for current flow.

Parallel circuits are probably the type of circuit with which most people are familiar. Most devices such as lights and receptacles in homes and office buildings are connected in parallel. Imagine if the lights in your home were wired in series. All the lights in the home would have to be turned on in order for any light to operate, and if one were to burn out, all the lights would go out. The same is true for receptacles. If receptacles were connected in series, some device would have to be connected into each receptacle before power could be supplied to any other device.

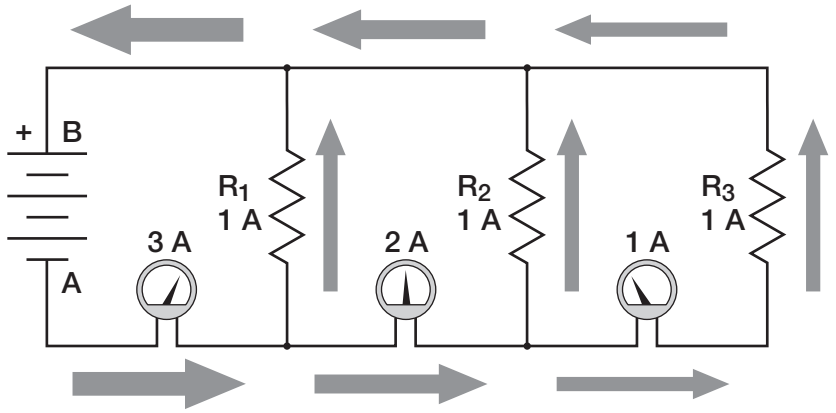
KEY POINT Parallel circuits are circuits that have more than one path for current flow.

PARALLEL CIRCUIT VALUES

TOTAL CURRENT

Parallel circuits are circuits that have more than one path for current flow, FIGURE 6-1. If it is assumed that current leaves terminal A and returns to

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 6-1 Parallel circuits provide more than one path for current flow.

terminal B, it can be seen that there are three separate paths that can be taken by the electrons. In FIGURE 6-1, 3 A of current leaves terminal A. One ampere flows through resistor R_1 and 2 A flows to resistors R_2 and R_3. At the junction of resistors R_2 and R_3, 1 A flows through resistor R_2 and 1 A flows to resistor R_3. Notice that the power supply, terminals A and B, must furnish all the current that flows through each individual resistor or **circuit branch.** One of the rules for parallel circuits states that **the total current flow in the circuit is equal to the sum of the currents through all of the branches. This is known as current adds.**

VOLTAGE DROP

FIGURE 6-2 shows another parallel circuit and gives the values of voltage and current for each individual resistor or branch. Notice that the voltage drop across each resistor is the same. If the circuit is traced, it can be seen that each resistor is connected directly to the power source. A second rule for parallel circuits states that **the voltage drop across any branch of a parallel circuit is the same as the applied voltage.** For this reason, most electrical circuits in homes are connected in parallel. Each lamp and receptacle is supplied with 120 V, FIGURE 6-3.

TOTAL RESISTANCE

In the circuit shown in FIGURE 6-4, three separate resistors have values of 15 Ω, 10 Ω, and 30 Ω. The total resistance of the circuit, however, is 5 Ω. **The total resistance of a parallel circuit is always less than the resistance of the lowest-value resistor, or branch, in the circuit.** This is because there is more than one path for current flow. Each time another element is connected in parallel, there is less opposition to the flow of current through the entire circuit. Imagine a water system consisting of a holding tank, a pump, and return

circuit branch
a circuit that branches off the main circuit.

KEY POINT
the total current flow in the circuit is equal to the sum of the currents through all of the branches. This is known as current adds.

KEY POINT
The voltage drop across any branch of a parallel circuit is the same as the applied voltage.

KEY POINT
The total resistance of a parallel circuit is always less than the resistance of the lowest-value resistor, or branch, in the circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

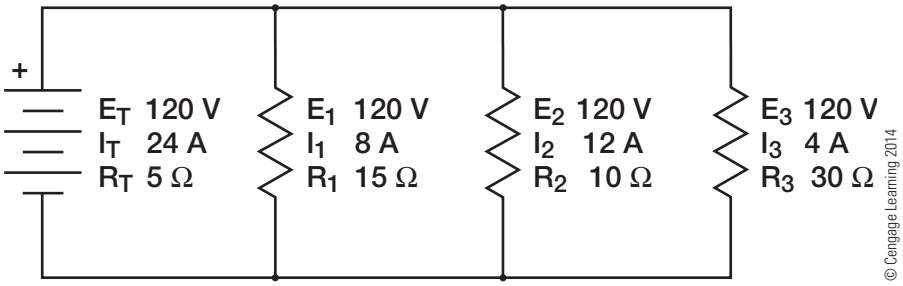


FIGURE 6-2 Parallel circuit values.

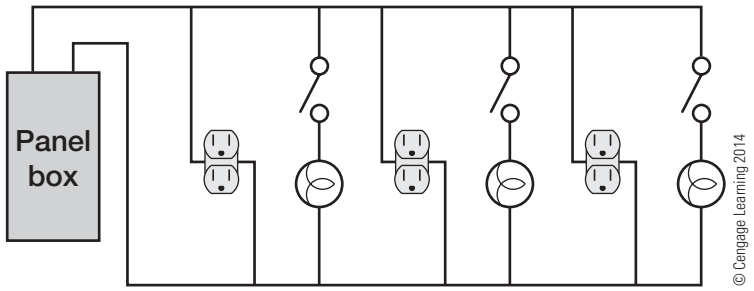


FIGURE 6-3 Lights and receptacles are connected in parallel.

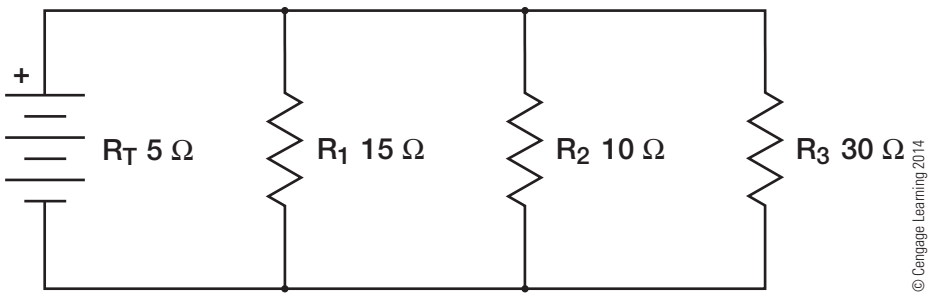


FIGURE 6-4 Total resistance is always less than the resistance of any single branch.

lines to the tank, FIGURE 6-5. Although large return pipes have less resistance to the flow of water than small pipes, the small pipes do provide a return path to the holding tank. Each time another return path is added, regardless of size, there is less resistance to flow and the rate of flow increases.

load
the amount of power a power source must provide.

This concept often causes confusion concerning the definition of **load** among students of electricity. Students often think that an increase of resistance constitutes an increase of load. The reason for this is that in a laboratory exercise, students often see the circuit current increase each time a

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

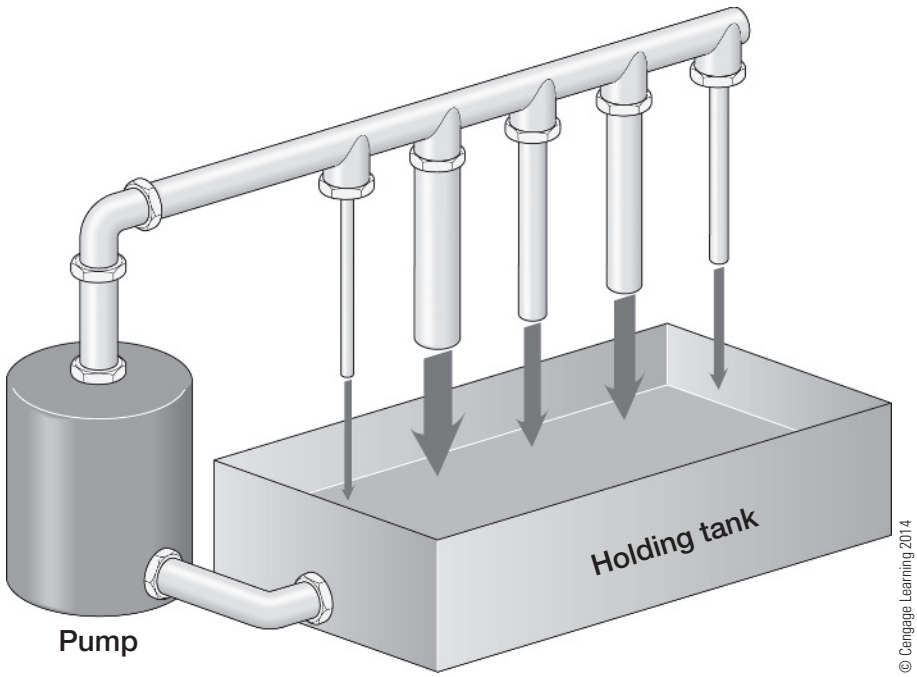


FIGURE 6-5 Each new path reduces the total resistance to the flow of water.

resistive element is connected to the circuit. They conclude that an increase of resistance must, therefore, cause an increase of current. This conclusion is, of course, completely contrary to Ohm's Law, which states that an increase of resistance must cause a proportional decrease of current. The false concept that an increase of resistance causes an increase of current can be overcome once the student understands that if the resistive elements are being connected in parallel, the circuit resistance is actually being decreased and not increased.

PARALLEL RESISTANCE FORMULAS

RESISTORS OF EQUAL VALUE

Three formulas can be used to determine the total resistance of a parallel circuit. The first formula shown can be used only when all the resistors in the circuit are of equal value. This formula states that **when all resistors are of equal value, the total resistance is equal to the value of one individual resistor, or branch, divided by the number (N) of resistors, or branches.**

$$R_T = \frac{R}{N}$$

KEY POINT when all resistors are of equal value, the total resistance is equal to the value of one individual resistor, or branch, divided by the number (N) of resistors, or branches.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

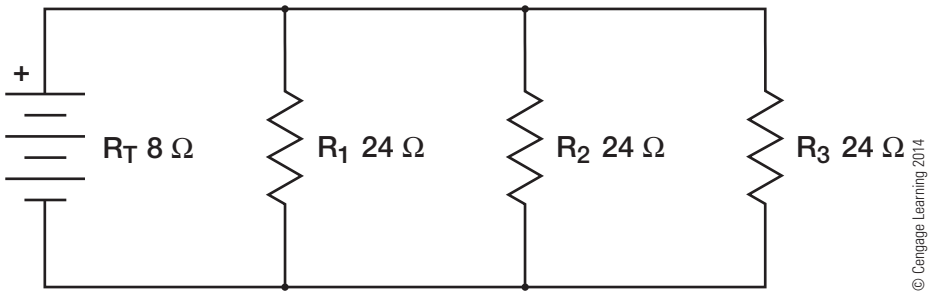


FIGURE 6-6 Finding the total resistance when all resistors have the same value.

Assume that three resistors, each having a value of 24 Ω, are connected in parallel, FIGURE 6-6. The total resistance of this circuit can be found by dividing the resistance of one single resistor by the total number of resistors.

$$R_T = \frac{R}{N}$$

$$R_T = \frac{24}{3}$$

$$R_T = 8\ \Omega$$

Product over Sum

The second formula used to determine the total resistance in a parallel circuit divides the product of two resistors by their sum. This is commonly referred to as the **product over sum method.**

product over sum method
one method of determining total resistance connected in parallel.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

In the circuit shown in FIGURE 6-7, three branches having single resistors with values of 20 Ω, 30 Ω, and 60 Ω are connected in parallel. To find the total resistance of the circuit using the previous formula, find the total resistance of the first two branches in the circuit, FIGURE 6-8.

$$R_T = \frac{R_2 \times R_3}{R_2 + R_3}$$

$$R_T = \frac{30 \times 60}{30 + 60}$$

$$R_T = \frac{1800}{90}$$

$$R_T = 20\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

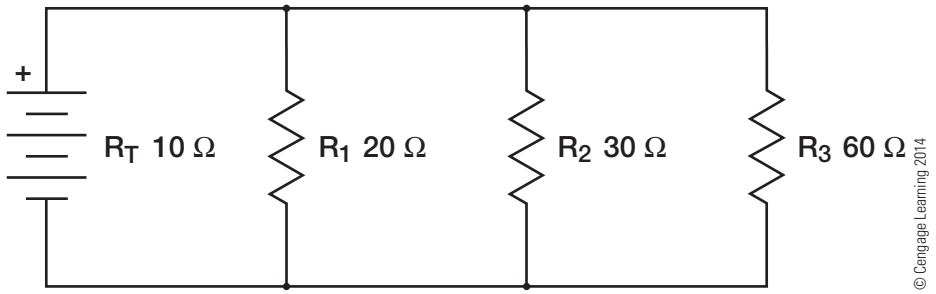


FIGURE 6-7 Finding the total resistance of a parallel circuit by dividing the product of two resistors by their sum.

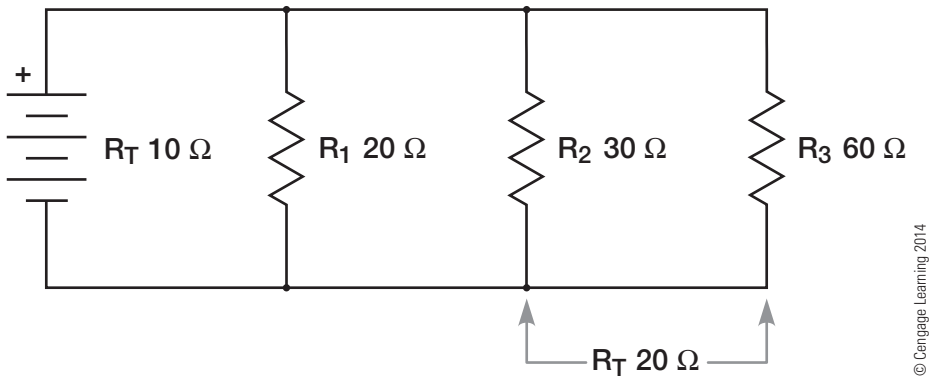


FIGURE 6-8 Finding the total resistance of the first two branches.

The total resistance of the last two resistors in the circuit is 20 Ω. This 20 Ω, however, is connected in parallel with a 20 Ω resistor. The total resistance of the last two resistors is now used to substitute for the value of R_2 in the formula, and the value of the next resistor is used to substitute for the value of R_1, FIGURE 6-9.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{20 \times 20}{20 + 20}$$

$$R_T = \frac{400}{40}$$

$$R_T = 10\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

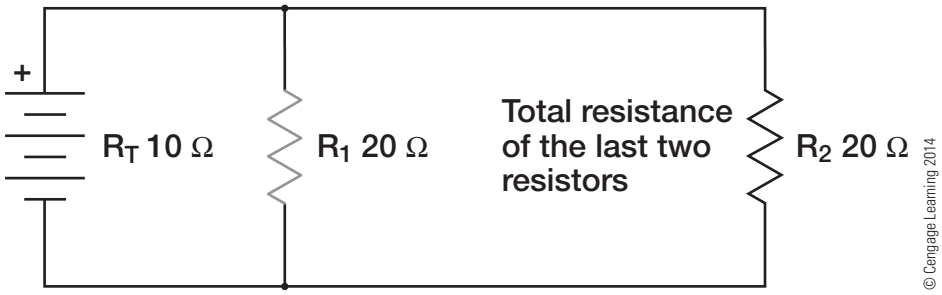


FIGURE 6-9 The total value of the last two resistors is used as resistor 2.

RECIPROCAL FORMULA

reciprocal formula one of the methods of determining total resistance connected in parallel.

The third formula used to find the total resistance of a parallel circuit is often referred to as the **reciprocal formula.**

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}$$

Notice that this formula actually finds the reciprocal of the total resistance, instead of the total resistance. To make the formula equal to the total resistance it can be rewritten as follows:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}}$$

The value R_N stands for R number and means the number of resistors in the circuit. If the circuit has twenty-five resistors connected in parallel, for example, the last resistor in the formula would be R_{25}.

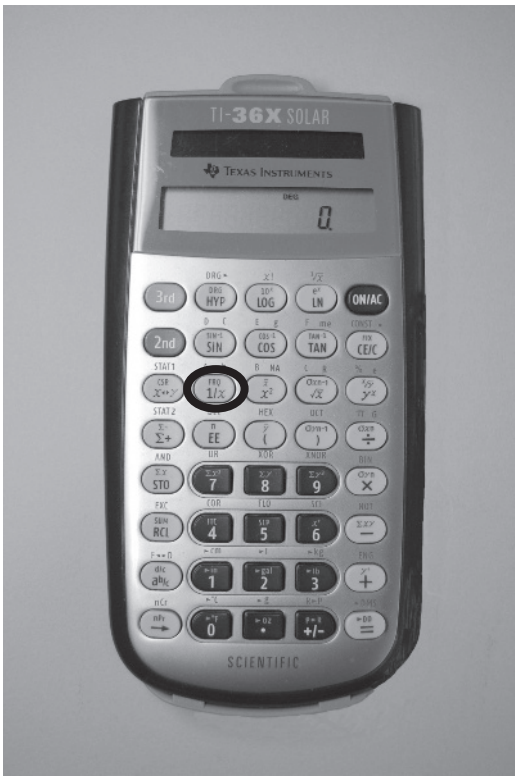
KEY POINT

The total resistance of a parallel circuit is the reciprocal of the sum of the reciprocals of the individual branches.

This formula is referred to as the reciprocal formula because the reciprocal of any number is that number divided into 1. The reciprocal of 4, for example, is 0.25 because $1/4 = 0.25$. A third rule of parallel circuits is **the total resistance of a parallel circuit is the reciprocal of the sum of the reciprocals of the individual branches.**

Before the invention of handheld calculators, the slide rule was often employed to help with the mathematical calculations in electrical work. At that time, the product over sum method of finding total resistance was the most popular. Since the invention of calculators, however, the reciprocal formula has become the most popular because scientific calculators have a reciprocal key (1/X), FIGURE 6-10, which makes computing total resistance using the reciprocal method very easy.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 6-10 Most scientific calculators contain a reciprocal key.

In FIGURE 6-11, three resistors having values of 150 Ω, 300 Ω, and 100 Ω are connected in parallel. The total resistance will be found using the reciprocal formula.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}}$$

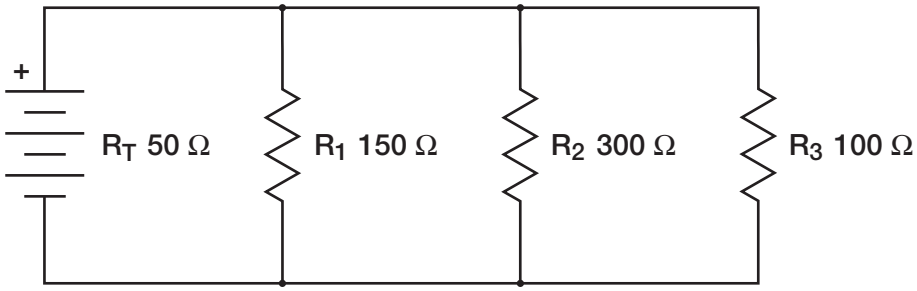
$$R_T = \frac{1}{\frac{1}{150} + \frac{1}{300} + \frac{1}{100}}$$

$$R_T = \frac{1}{0.006667 + 0.003333 + 0.01}$$

$$R_T = \frac{1}{0.02}$$

$$R_T = 50\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



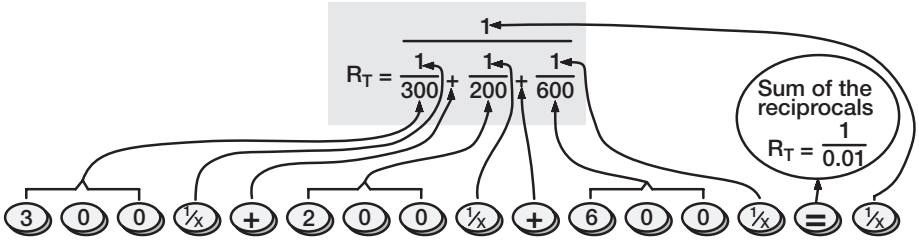
© Cengage Learning 2014

FIGURE 6-11 Finding the total resistance using the reciprocal method.



© Cengage Learning 2014

FIGURE 6-12 Determining total resistance with a scientific calculator.



© Cengage Learning 2014

FIGURE 6-13 The key sequence follows the formula.

To find the total resistance of the circuit in FIGURE 6-11 using a scientific calculator, press the keys in the sequence shown in FIGURE 6-12. Notice in FIGURE 6-13 that the sequence of key punches exactly follows the formula.

SOLVING CIRCUIT VALUES

EXAMPLE 1: In the circuit shown in FIGURE 6-14, three resistors having values of 300 Ω, 200 Ω, and 600 Ω are connected in parallel. Total current flow through the circuit is 0.6 A. Find all of the missing values in the circuit.

Solution:

The first step is to find the total resistance of the circuit. The reciprocal formula will be used.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

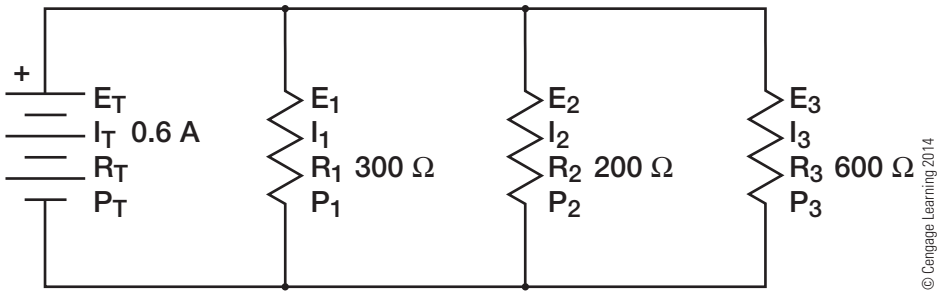


FIGURE 6-14 Parallel circuit, Example 1.

$$R_T = \frac{1}{\frac{1}{300} + \frac{1}{200} + \frac{1}{600}}$$

$$R_T = \frac{1}{0.003333 + 0.005 + 0.001667}$$

$$R_T = \frac{1}{0.01}$$

$$R_T = 100\ \Omega$$

Now that the total resistance of the circuit is known, the voltage applied to the circuit can be found by using the total current value and Ohm's Law.

$$E_T = I_T \times R_T$$

$$E_T = 0.6 \times 100$$

$$E_T = 60\ V$$

One of the rules for parallel circuits states that the voltage across all of the parts of a parallel circuit are the same as the total voltage. Therefore, the voltage drop across each resistor is 60 V, FIGURE 6-15.

$$E_T = E_1 = E_2 = E_3$$

Since the voltage drop and resistance of each resistor is known, Ohm's Law can be used to determine the amount of current flow through each resistor, FIGURE 6-16.

$$I_1 = \frac{E_1}{R_1}$$

$$I_1 = \frac{60}{300}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

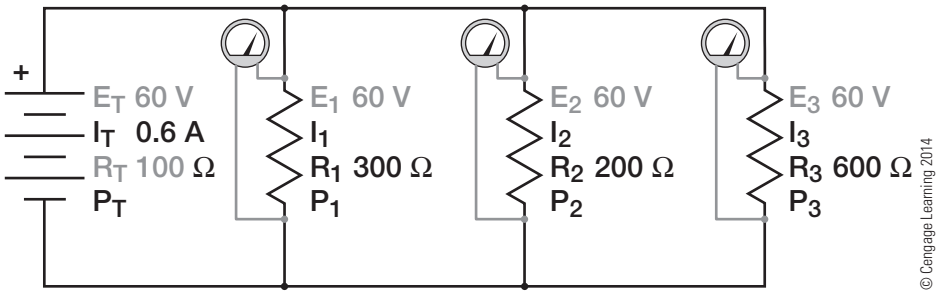


FIGURE 6-15 The voltage is the same across all branches of a parallel circuit.

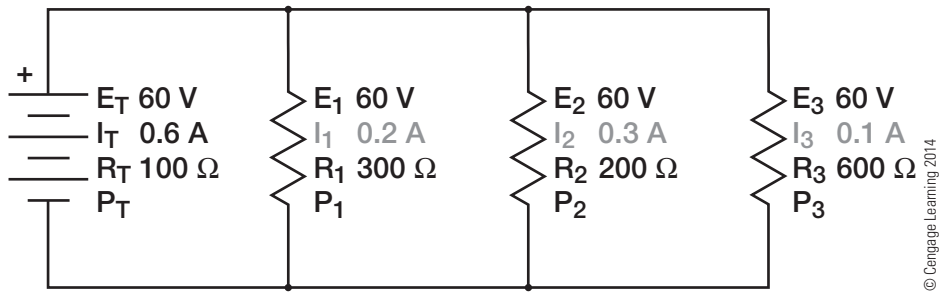


FIGURE 6-16 Ohm's Law is used to compute the amount of current through each branch.

$$I_1 = 0.2 \text{ A}$$

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{60}{200}$$

$$I_2 = 0.3 \text{ A}$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{60}{600}$$

$$I_3 = 0.1 \text{ A}$$

The amount of power (watts) used by each resistor can be found by using Ohm's Law. A different formula will be used to find the amount of electrical energy converted into heat by each of the resistors.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$P_1 = \frac{E_1^2}{R_1}$$

$$P_1 = \frac{60 \times 60}{300}$$

$$P_1 = 12 \text{ W}$$

$$P_2 = I_2^2 \times R_2$$

$$P_2 = 0.3 \times 0.3 \times 200$$

$$P_2 = 18 \text{ W}$$

$$P_3 = E_2 \times I_3$$

$$P_3 = 60 \times 0.1$$

$$P_3 = 6 \text{ W}$$

In Unit 5, it was stated that the total amount of power in a circuit is equal to the sum of the power used by all the parts. This is true for any type of circuit. Therefore, the total amount of power used by this circuit can be found by taking the sum of the power used by all resistors, FIGURE 6-17.

$$P_T = P_1 + P_2 + P_3$$

$$P_T = 12 + 18 + 6$$

$$P_T = 36 \text{ W}$$

EXAMPLE 2: In the circuit shown in FIGURE 6-18, three resistors are connected in parallel. Two of the resistors have a value of 900 Ω and 1800 Ω. The value of resistor R_2 is unknown. The total resistance of the circuit is 300 Ω. Resistor R_2 has a current flow through it of 0.2 A. Find the missing circuit values.

Solution:

The first step in solving this problem is to find the missing resistor value. This can be done by changing the reciprocal formula as shown:

$$\frac{1}{R_2} = \frac{1}{R_T} - \frac{1}{R_1} - \frac{1}{R_3}$$

or

$$R_2 = \frac{1}{\frac{1}{R_T} - \frac{1}{R_1} - \frac{1}{R_3}}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

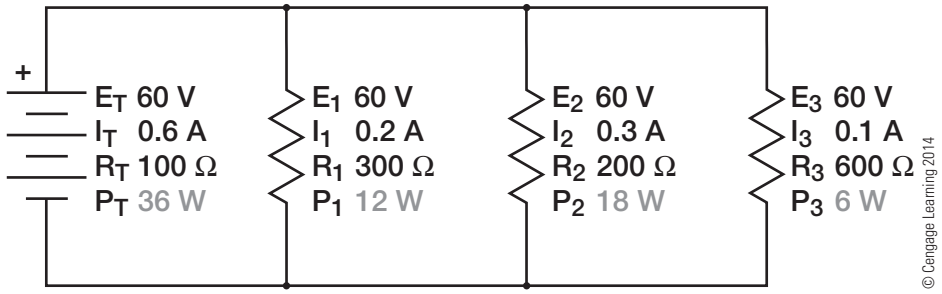


FIGURE 6-17 Finding the amount of power used by the circuit.

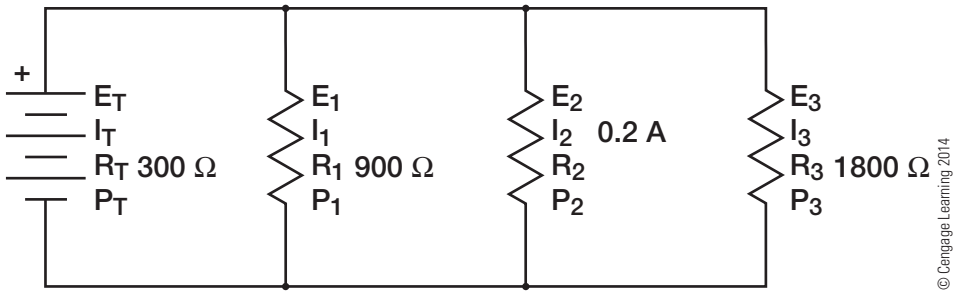


FIGURE 6-18 Parallel circuit, Example 2.

One of the rules for parallel circuits states that the reciprocal of the total resistance is equal to the sum of the reciprocals of the individual resistors. Therefore, the reciprocal of any individual resistor is equal to the difference between the reciprocal of the total resistance and the sum of the reciprocals of the other resistors in the circuit.

$$R_2 = \frac{1}{\frac{1}{R_T} - \frac{1}{R_1} - \frac{1}{R_3}}$$

$$R_2 = \frac{1}{\frac{1}{300} - \frac{1}{900} - \frac{1}{1800}}$$

$$R_2 = \frac{1}{0.003333 - 0.001111 - 0.0005556}$$

$$R_2 = \frac{1}{0.001666}$$

$$R_2 = 600\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Now that the resistance of resistor R_2 has been found, the voltage drop across resistor R_2 can be determined using the current flow through the resistor and Ohm's Law, FIGURE 6-19.

$$E_2 = I_2 \times R_2$$

$$E_2 = 0.2 \times 600$$

$$E_2 = 120 \text{ V}$$

If 120 V is dropped across resistor R_2, the same voltage is dropped across each component of the circuit.

$$E_2 = E_T = E_1 = E_3$$

Now that the voltage drop across each part of the circuit is known and the resistance is known, the current flow through each branch can be determined using Ohm's Law, FIGURE 6-20.

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{120}{300}$$

$$I_T = 0.4 \text{ A}$$

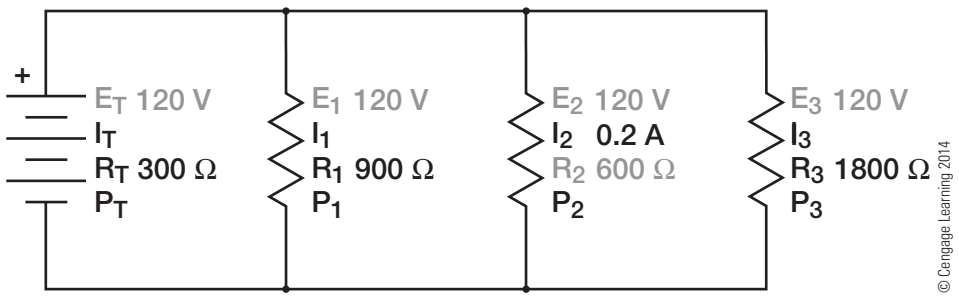


FIGURE 6-19 Finding the missing resistor value.

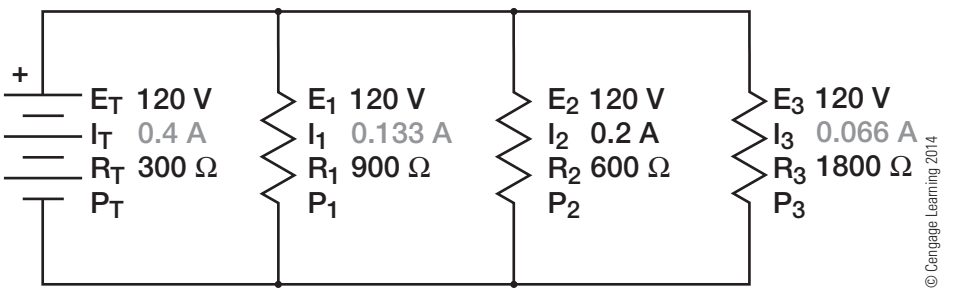


FIGURE 6-20 Determining the current using Ohm's Law.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$I_1 = \frac{E_1}{R_1}$$

$$I_1 = \frac{120}{900}$$

$$I_1 = 0.1333 \text{ A}$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{120}{1800}$$

$$I_3 = 0.0666 \text{ A}$$

The amount of power used by each resistor can be found using Ohm's Law, FIGURE 6-21.

$$P_1 = \frac{E_1^2}{R_1}$$

$$P_1 = \frac{120 \times 120}{900}$$

$$P_1 = 16 \text{ W}$$

$$P_2 = I_2^2 \times R_2$$

$$P_2 = 0.2 \times 0.2 \times 600$$

$$P_2 = 24 \text{ W}$$

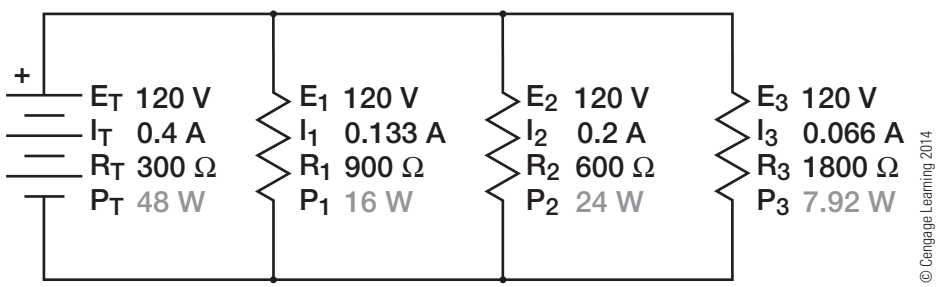


FIGURE 6-21 Computing values of power for the circuit in Example 2.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$P_3 = E_3 \times I_3$$
$$P_3 = 120 \times 0.066$$
$$P_3 = 7.92 \text{ W}$$

$$P_T = E_T \times I_T$$
$$P_T = 120 \times 0.4$$
$$P_T = 48 \text{ W}$$

If the wattage values of the three resistors are added to compute total power for the circuit, it will be seen that their total is 47.92 W instead of the computed 48 W. The small difference in answers is caused by the rounding off of other values. In this instance, the current of resistor R_3 was rounded from 0.066666666 to 0.066.

EXAMPLE 3: In the circuit shown in FIGURE 6-22, three resistors are connected in parallel. Resistor R_1 is producing 0.075 W of heat, R_2 is producing 0.45 W of heat, and R_3 is producing 0.225 W of heat. The circuit has a total current of 0.05 A.

Solution:

Since the amount of power dissipated by each resistor is known, the total power for the circuit can be found by taking the sum of the power used by each component.

$$P_T = P_1 + P_2 + P_3$$
$$P_T = 0.075 + 0.45 + 0.225$$
$$P_T = 0.75 \text{ W}$$

Now that the amount of total current and total power for the circuit is known, the applied voltage can be found using Ohm's Law, FIGURE 6-23.

$$E_T = \frac{P_T}{I_T}$$
$$E_T = \frac{0.75}{0.05}$$
$$E_T = 15 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

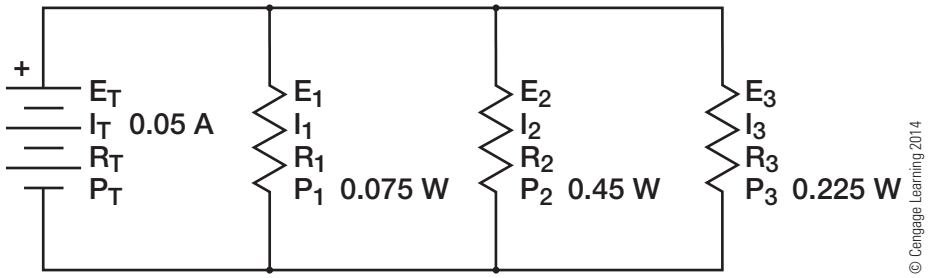


FIGURE 6-22 Parallel circuit, Example 3.

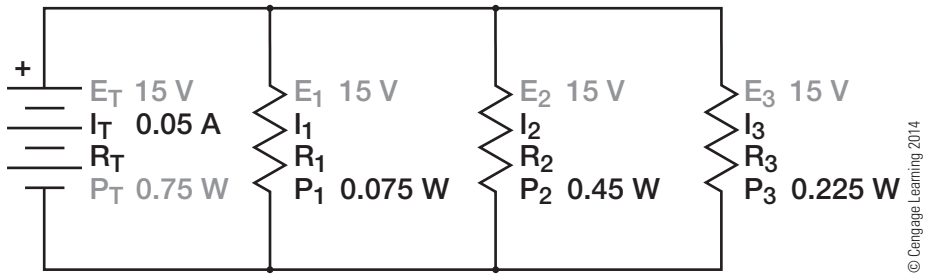


FIGURE 6-23 Computing the applied voltage for the circuit, Example 3.

The amount of current flow through each resistor can now be found using Ohm's Law, FIGURE 6-24.

$$I_1 = \frac{P_1}{E_1}$$

$$I_1 = \frac{0.075}{15}$$

$$1_1 = 0.005 \text{ A}$$

$$I_2 = \frac{P_2}{E_2}$$

$$I_2 = \frac{0.45}{15}$$

$$I_2 = 0.03 \text{ A}$$

$$I_3 = \frac{P_3}{E_3}$$

$$I_3 = \frac{0.225}{15}$$

$$I_3 = 0.015 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

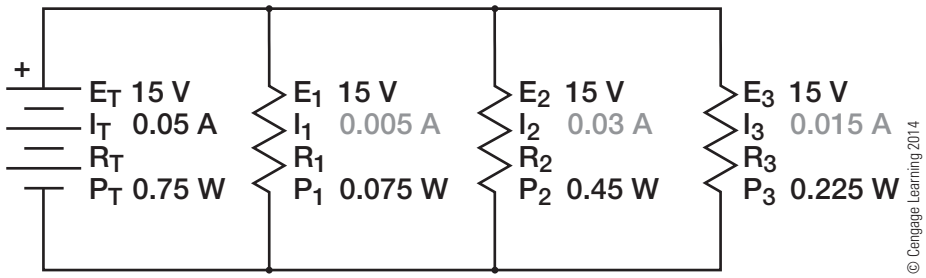


FIGURE 6-24 Finding the current through each branch.

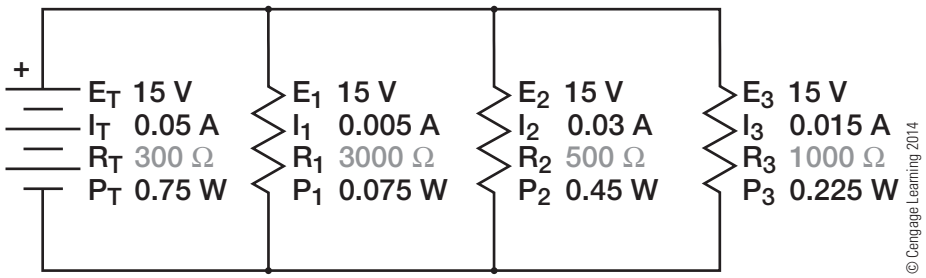


FIGURE 6-25 Computing the remaining values for the circuit, Example 3.

All resistance values for the circuit can now be found using Ohm's Law, FIGURE 6-25.

$$R_1 = \frac{E_1}{I_1}$$

$$R_1 = \frac{15}{0.005}$$

$$R_1 = 3000\ \Omega$$

$$R_2 = \frac{E_2}{I_2}$$

$$R_2 = \frac{15}{0.03}$$

$$R_2 = 500\ \Omega$$

$$R_3 = \frac{E_3}{I_3}$$

$$R_3 = \frac{15}{0.015}$$

$$R_3 = 1000\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$R_T = \frac{E_T}{I_T}$$

$$R_T = \frac{15}{0.05}$$

$$R_T = 300\ \Omega$$

Summary

1. A parallel circuit is characterized by the fact that it has more than one path for current flow.
2. Three rules for solving parallel circuits are:
   A. The total current is the sum of the currents through each individual branch of the circuit.
   B. The voltage is the same across any part of the circuit.
   C. The reciprocal of total resistance is the sum of the reciprocals of each individual branch.
3. Circuits in homes are connected in parallel.
4. The total power in a parallel circuit is equal to the sum of the power dissipation by each component.

Review Questions

1. What characterizes a parallel circuit?
2. Why are circuits in homes connected in parallel?
3. State three rules concerning parallel circuits.
4. A parallel circuit contains four branches. One branch has a current flow of 0.8 A, another has a current flow of 1.2 A, the third has a current flow of 0.25 A, and the fourth has a current flow of 1.5 A. What is the total current flow in the circuit?
5. Four resistors having a value of 100 Ω each are connected in parallel. What is the total resistance of the circuit?
6. A parallel circuit has three branches. An ammeter is connected in series with the output of the power supply and indicates a total current flow of 2.8 A. If branch 1 has a current flow of 0.9 A and

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

branch 2 has a current flow of 1.05 A, what is the current flow through branch 3?

7. Four resistors having values of 270 Ω, 330 Ω, 510 Ω, and 430 Ω are connected in parallel. What is the total resistance of the circuit?
8. A parallel circuit contains four resistors. The total resistance of the circuit is 120 Ω. Three of the resistors have values of 820 Ω, 750 Ω, and 470 Ω. What is the value of the fourth resistor?

Practice Problems

PARALLEL CIRCUITS

1. Find the missing values in the circuit shown in FIGURE 6-26.

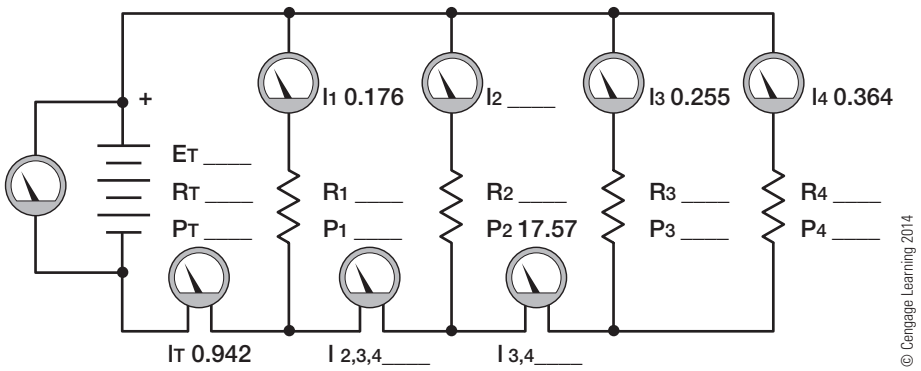


FIGURE 6-26 Practice Problem 1.

2. Find the missing values in the circuit shown in FIGURE 6-27.

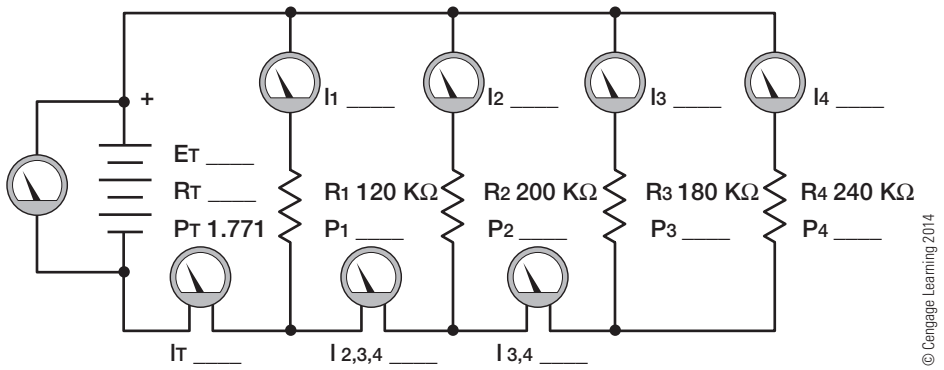


FIGURE 6-27 Practice Problem 2.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

3. Find the missing values in the circuit shown in FIGURE 6-28.

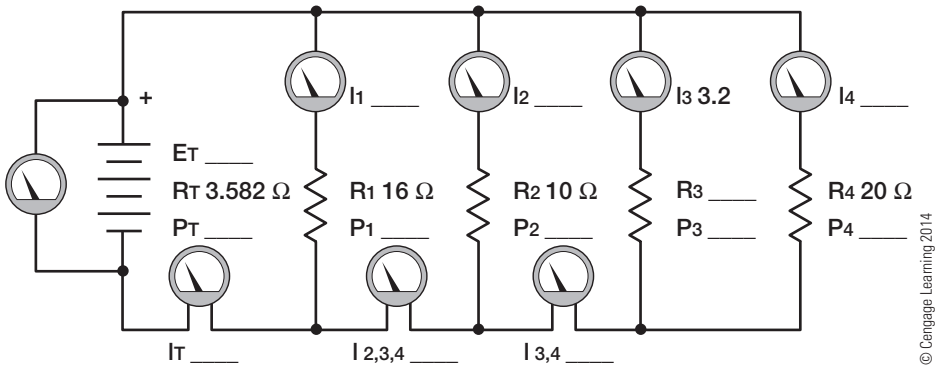


FIGURE 6-28 Practice Problem 3.

4. Find the missing values in the circuit shown in FIGURE 6-29.

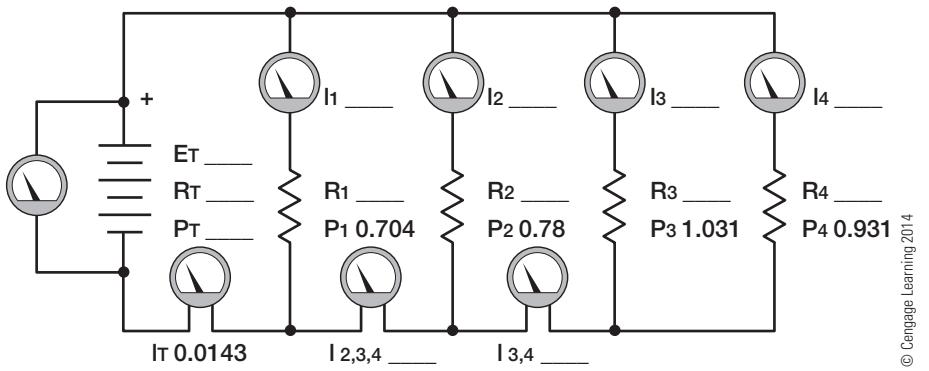


FIGURE 6-29 Practice Problem 4.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. Find the missing values in the circuit shown in FIGURE 6-30.

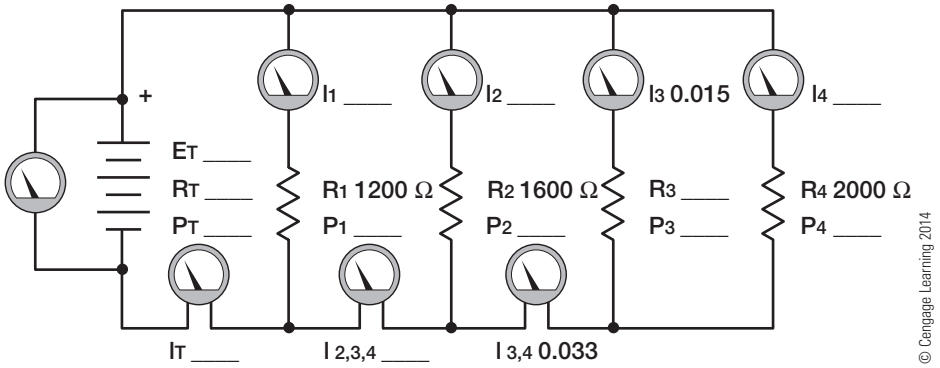


FIGURE 6-30 Practice Problem 5.

6. Find the missing values in the circuit shown in FIGURE 6-31.

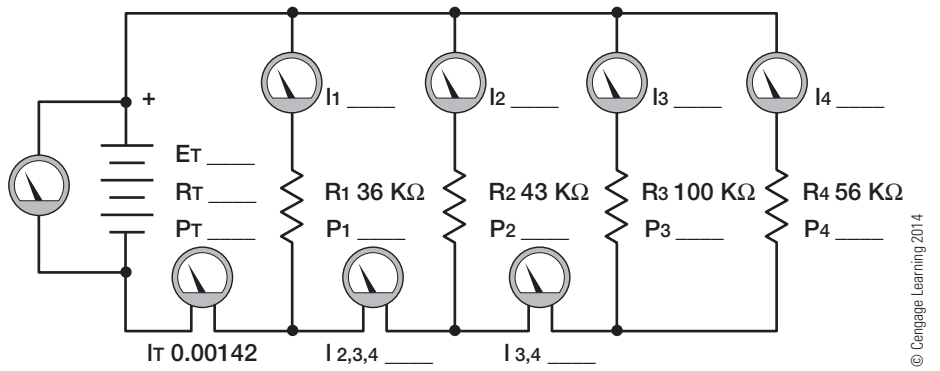


FIGURE 6-31 Practice Problem 6.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

7. Find the missing values in the circuit shown in FIGURE 6-32.

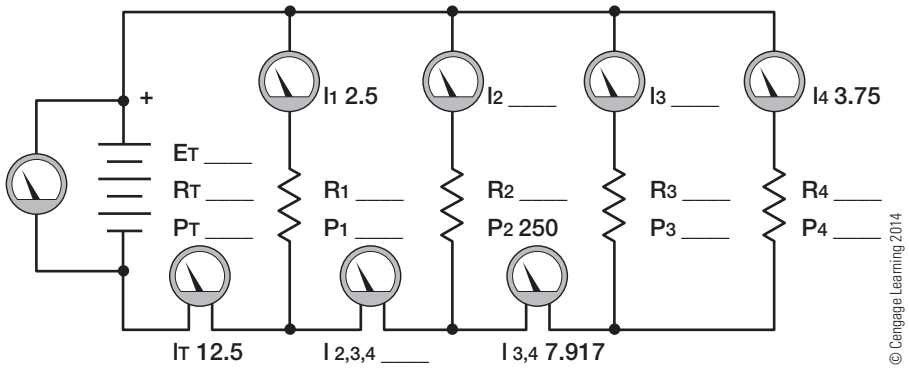


FIGURE 6-32 Practice Problem 7.

8. Find the missing values in the circuit shown in FIGURE 6-33.

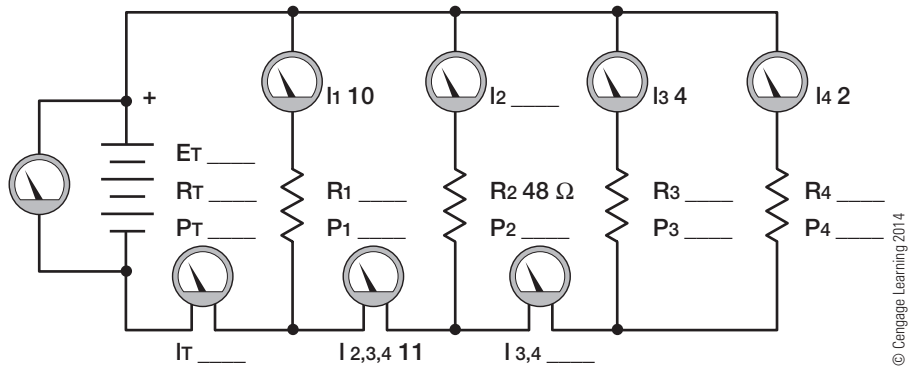


FIGURE 6-33 Practice Problem 8.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

9. Find the missing values in the circuit shown in FIGURE 6-34.

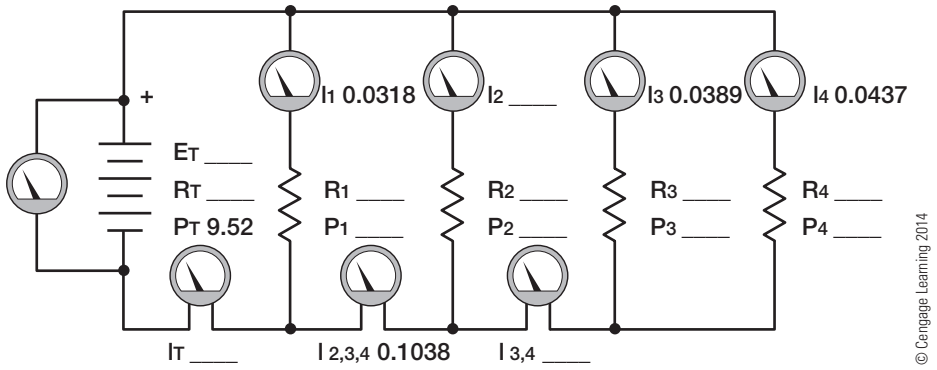


FIGURE 6-34 Practice Problem 9.

10. Find the missing values in the circuit shown in FIGURE 6-35.

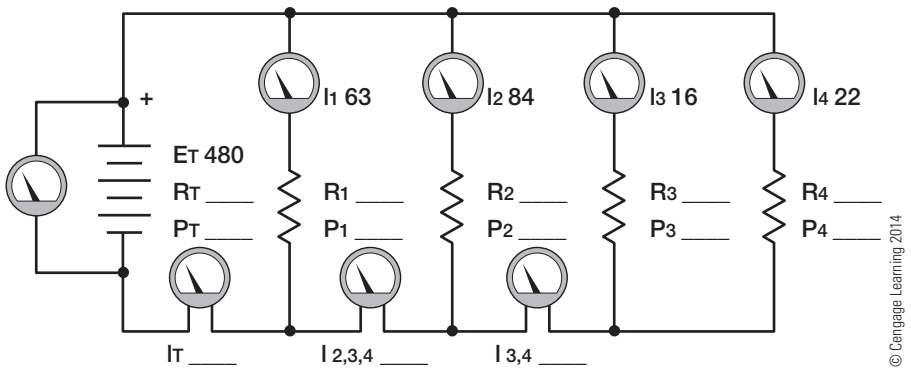


FIGURE 6-35 Practice Problem 10.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 7

Combination Circuits

OBJECTIVES: After studying this unit, you should be able to:

- Define a combination circuit.
- List the rules for parallel circuits.
- List the rules for series circuits.
- Solve combination circuits using the rules for parallel circuits, the rules for series circuits, and Ohm's Law.

Combination circuits contain a combination of both series and parallel elements. A simple combination circuit is shown in FIGURE 7-1. To determine which components are in parallel and which are in series, trace the flow of current through the circuit. Remember, a series circuit is one that has only one path for current flow, and a parallel circuit has more than one path for current flow. Series elements can be identified by the fact that all the circuit current must pass through them. In parallel elements, the circuit current will divide and part will flow through each element.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

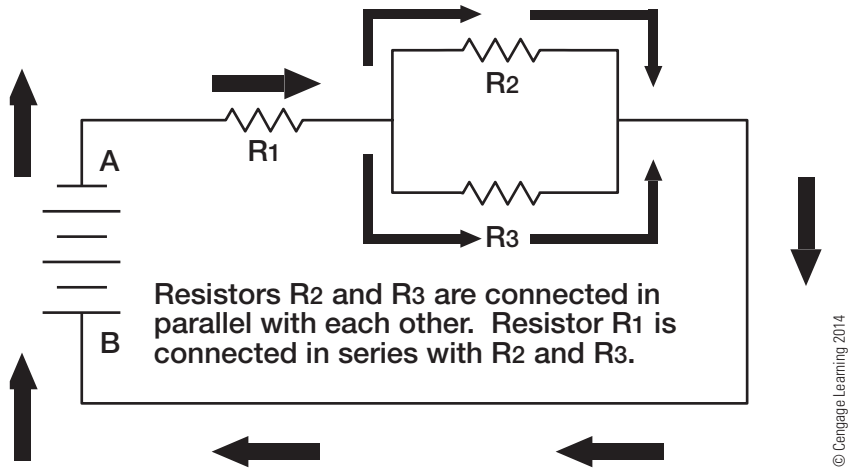


FIGURE 7-1 A simple combination circuit.

COMBINATION CIRCUITS

EXAMPLE 1: In FIGURE 7-1, it will be assumed that the current will flow from point A to point B. To identify the series and parallel elements, **trace the current path.** All the current in the circuit must flow through resistor R_1. Resistor R_1 is, therefore, in series with the rest of the circuit. When the current reaches the junction point of resistors R_2 and R_3, however, it splits. A junction point where two or more branches are connected is often referred to as a **node.** Part of the current flows through resistor R_2 and part flows through resistor R_3. These two resistors are in parallel because this circuit contains both series and parallel elements, it is a **combination circuit.**

node
a point at which connections are joined.

combination circuit
a circuit that contains both series and parallel elements.

SOLVING COMBINATION CIRCUITS

The circuit shown in FIGURE 7-2 contains four resistors with values of 325 Ω, 275 Ω, 150 Ω, and 250 Ω. The circuit has a total current flow of 1 A. To determine which resistors are in series or parallel, the path for current flow will be traced through the circuit. When the path of current flow is traced, it can be seen that there are two separate paths by which current can flow from the negative terminal to the positive terminal. One path is through resistors R_1 and R_2, and the other path is through resistors R_3 and R_4. These two paths are, therefore, in parallel. However, the same current must flow through resistors R_1 and R_2. These two resistors are in series. The same is true for resistors R_3 and R_4.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

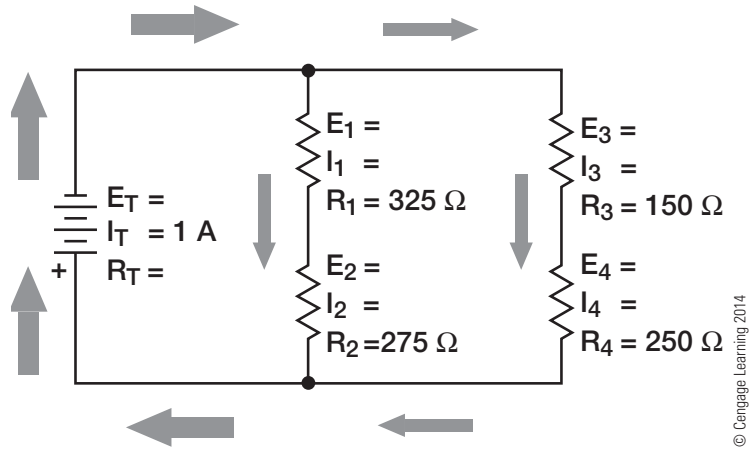


FIGURE 7-2 Tracing the current paths through combination circuit 1.

When solving the unknown values in a combination circuit, use series circuit rules for those sections of the circuit that are connected in series and parallel circuit rules for those sections connected in parallel. The circuit rules are as follows:

SERIES CIRCUITS

1. The current is the same at any point in the circuit.
2. The total resistance is the sum of the individual resistors.
3. The sum of the voltage drops of the individual resistors must equal the applied voltage.

PARALLEL CIRCUITS

1. The voltage is the same across any circuit branch.
2. The total current is the sum of the current flowing through the individual circuit paths.
3. The reciprocal of the total resistance is equal to the sum of the reciprocals of the branch resistances.

SIMPLIFYING THE CIRCUIT

simple parallel circuit a circuit that contains only elements connected in parallel.

The circuit shown in FIGURE 7-2 can be reduced or simplified to a **simple parallel circuit** as shown in FIGURE 7-3. Since resistors R_1 and R_2 are connected in series, their values can be added to form one equivalent resistor,

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

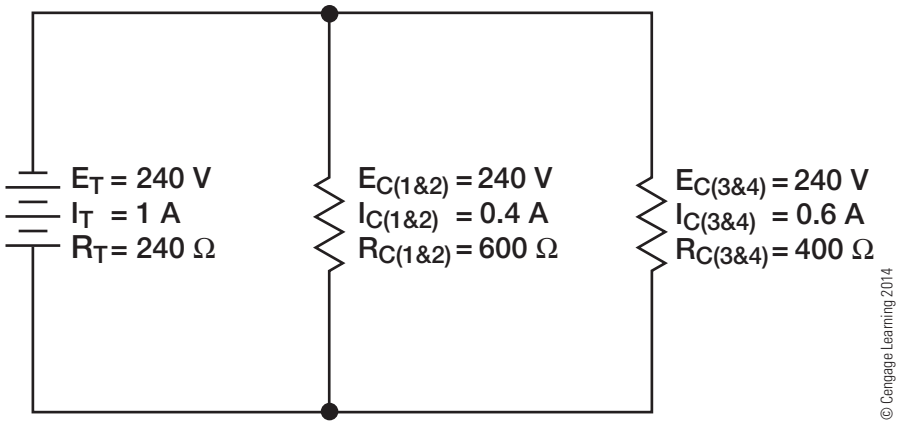


FIGURE 7-3 Simplifying combination circuit 1.

[$R_{C(1\&2)}$], which stands for combination of resistors 1 and 2. The same is true for resistors R_3 and R_4. Their values are added to form resistor $R_{C(3\&4)}$. Now that the circuit has been reduced to a simple parallel circuit, the total resistance can be found.

$$R_T = \frac{1}{\frac{1}{R_{c(1\&2)}} + \frac{1}{R_{c(3\&4)}}}$$

$$R_T = \frac{1}{\frac{1}{600} + \frac{1}{400}}$$

$$R_T = \frac{1}{0.0016667 + 0.0025}$$

$$R_T = \frac{1}{0.0041667}$$

$$R_T = 240\ \Omega$$

Now that the total resistance has been found, the other circuit values can be computed. The applied voltage can be found using Ohm's Law.

$$E_T = I_T \times R_T$$

$$E_T = 1 \times 240$$

$$E_T = 240\ \text{V}$$

One of the rules for parallel circuits states that the voltage is the same across each branch of the circuit. For this reason, the voltage drops across resistors

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$R_{C(1\&2)}$ and $R_{C(3\&4)}$ are the same. Since the voltage drop and the resistance are known, Ohm's Law can be used to find the current flow through each branch.

$$I_{C(1\&2)} = \frac{E_{C(1\&2)}}{R_{C(1\&2)}}$$

$$I_{C(1\&2)} = \frac{240}{600}$$

$$I_{C(1\&2)} = 0.4 \text{ A}$$

$$I_{C(3\&4)} = \frac{E_{C(3\&4)}}{R_{C(3\&4)}}$$

$$I_{C(3\&4)} = \frac{240}{400}$$

$$I_{C(3\&4)} = 0.6 \text{ A}$$

These values can now be used to solve the missing values in the original circuit. Resistor $R_{C(1\&2)}$ is actually a combination of resistors R_1 and R_2. The values of voltage and current that apply to $R_{C(1\&2)}$ therefore apply to resistors R_1 and R_2. Resistors R_1 and R_2 are connected in series. One of the rules for a series circuit states that the current is the same at any point in the circuit. Since 0.4 A of current flows through resistor $R_{C(1\&2)}$, the same amount of current flows through resistors R_1 and R_2. Now that the current flow through these two resistors is known, the voltage drop across each can be computed using Ohm's Law.

$$E_1 = I_1 \times R_1$$

$$E_1 = 0.4 \times 325$$

$$E_1 = 130 \text{ V}$$

$$E_2 = I_2 \times R_2$$

$$E_2 = 0.4 \times 275$$

$$E_2 = 110 \text{ V}$$

These values of voltage and current can now be added to the circuit in Figure 7-2 to produce the circuit shown in FIGURE 7-4.

The values of voltage and current for resistor $R_{C(3\&4)}$ apply to resistors R_3 and R_4. The same amount of current that flows through resistor $R_{C(3\&4)}$ flows through resistors R_3 and R_4. The voltage across these two resistors can now be computed using Ohm's Law.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

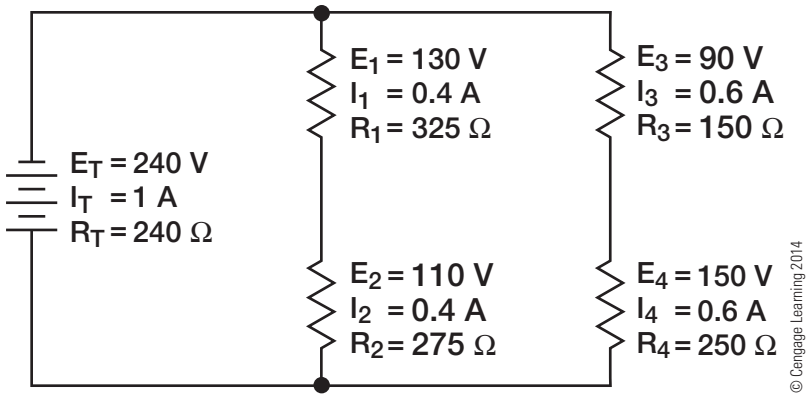


FIGURE 7-4 Finding all the missing values for combination circuit 1.

$$E_3 = I_3 \times R_3$$
$$E_3 = 0.6 \times 150$$
$$E_3 = 90 \text{ V}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.6 \times 250$$
$$E_4 = 150 \text{ V}$$

EXAMPLE 2: The second circuit to be discussed is shown in FIGURE 7-5. The first step in finding the missing values is to trace the current path through the circuit to determine which resistors are in series and which are connected in parallel. All the current must flow through resistor R_1. Resistor R_1 is, therefore, in series with the rest of the circuit. When the current reaches the junction of resistors R_2 and R_3, it divides, and part flows through each resistor. Resistors R_2 and R_3 are in parallel. All the current must then flow through resistor R_4 to the junction of resistors R_5 and R_6. The current path is divided between these two resistors. Resistors R_5 and R_6 are connected in parallel. All the circuit current must then flow through resistor R_7.

SIMPLIFYING THE CIRCUIT

The next step in solving this circuit is to **reduce** it to a simpler circuit. If the total resistance of the first **parallel block** formed by resistors R_2 and R_3 and R_3 is found, this block can be replaced by a single resistor.

reduce
to make smaller.

parallel block
components connected in parallel.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

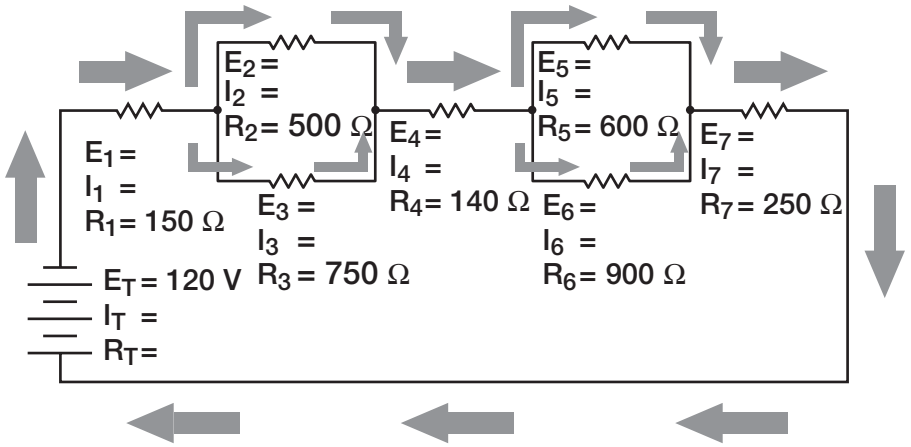


FIGURE 7-5 Tracing the flow of current through combination circuit 2.

$$R_T = \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{1}{0.002 + 0.0013333}$$

$$R_T = \frac{1}{0.0033333}$$

$$R_T = 300\ \Omega$$

The equivalent resistance of the second parallel block can be computed in the same way.

$$R_T = \frac{1}{\frac{1}{R_5} + \frac{1}{R_6}}$$

$$R_T = \frac{1}{\frac{1}{600} + \frac{1}{900}}$$

$$R_T = \frac{1}{0.0016667 + 0.0011111}$$

$$R_T = \frac{1}{0.00277778}$$

$$R_T = 360\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

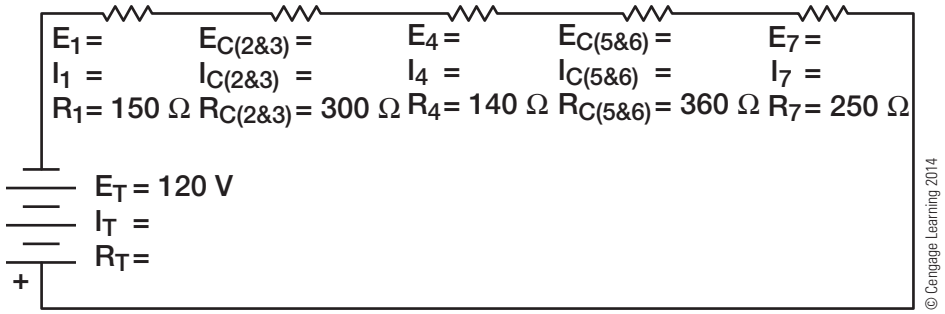


FIGURE 7-6 Simplifying combination circuit 2.

Now that the total resistance of the second parallel block is known, you can **redraw** the circuit as a simple series circuit as shown in FIGURE 7-6. The first parallel block has been replaced with a single resistor of 300-Ω labeled $R_{C(2\&3)}$, and the second parallel block has been replaced with a single 360-Ω resistor labeled $R_{C(5\&6)}$. Ohm's Law can be used to find the missing values in this series circuit.

redraw
draw the circuit in its simpler form.

One of the rules for series circuits states that the total resistance of a series circuit is equal to the sum of the individual resistors. R_T (total resistance of the circuit) can be computed by adding the resistance of all resistors.

$$R_T = R_1 + R_{C(2\&3)} + R_4 + R_{C(5\&6)} + R_7$$
$$R_T = 150 + 300 + 140 + 360 + 250$$
$$R_T = 1200\ \Omega$$

Since the total voltage and total resistance are known, the total current flow through the circuit can be computed.

$$I_T = \frac{E_T}{R_T}$$
$$I_T = \frac{120}{1200}$$
$$I_T = 0.1\ \text{A}$$

The first rule of series circuits states that the current is the same at any point in the circuit. The current flow through each resistor is, therefore, 0.1 A. The voltage drop across each resistor can now be computed using Ohm's Law.

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.1 \times 150$$
$$E_1 = 15\ \text{V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$E_{c(2\&3)} = I_{c(2\&3)} \times R_{c(2\&3)}$$
$$E_{c(2\&3)} = 0.1 \times 300$$
$$E_{c(2\&3)} = 30 \text{ V}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.1 \times 140$$
$$E_4 = 14 \text{ V}$$

$$E_{c(5\&6)} = I_{c(5\&6)} \times R_{c(5\&6)}$$
$$E_{c(5\&6)} = 0.1 \times 360$$
$$E_{c(5\&6)} = 36 \text{ V}$$

$$E_7 = I_7 \times R_7$$
$$E_7 = 0.1 \times 250$$
$$E_7 = 25 \text{ V}$$

The series circuit with all solved values is shown in FIGURE 7-7. These values can now be used to solve missing parts in the original circuit.

Resistor $R_{C(2\&3)}$ is actually the parallel block containing resistors R_2 and R_3. The values for $R_{C(2\&3)}$, therefore, apply to this parallel block. One of the rules for a parallel circuit states that the voltage drop of a parallel circuit is the same at any point in the circuit. Since 30 V is dropped across resistor $R_{C(2\&3)}$, the same 30 V is dropped across resistors R_2 and R_3, FIGURE 7-8. The current flow through these resistors can now be computed using Ohm's Law.

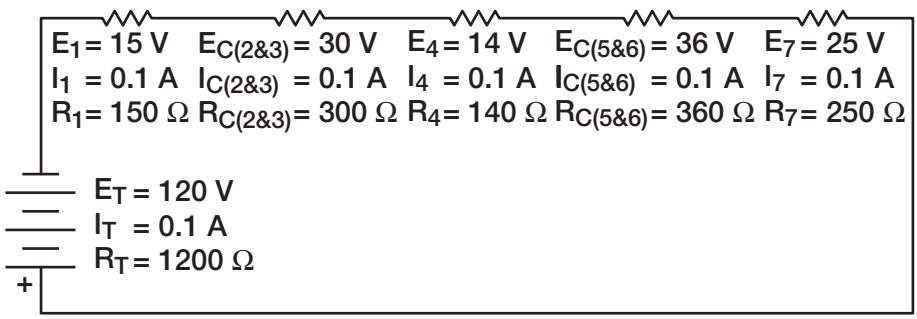


FIGURE 7-7 The simplified circuit with all values solved.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

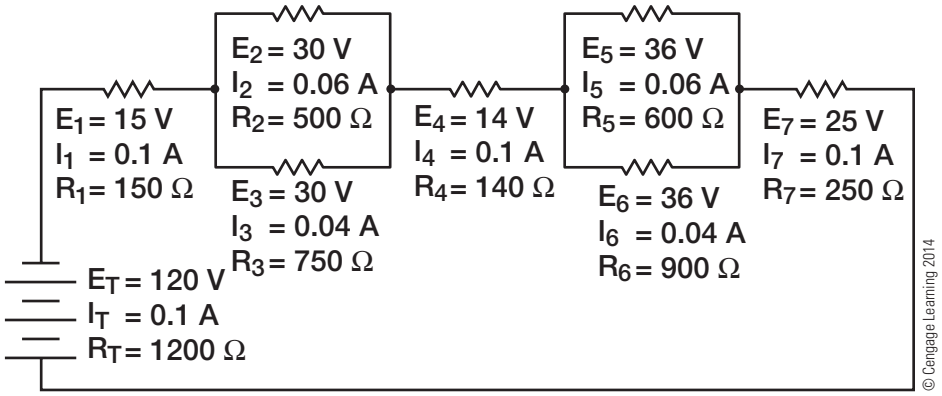


FIGURE 7-8 All values solved for combination circuit 2.

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{30}{500}$$

$$I_2 = 0.06 \text{ A}$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{30}{750}$$

$$I_3 = 0.04 \text{ A}$$

The values of resistor $R_{C(5\&6)}$ can be applied to the parallel block composed of resistors R_5 and R_6. $E_{C(5\&6)}$ is 36 V. This is the voltage drop across resistors R_5 and R_6. The current flow through these two resistors can be computed using Ohm's Law.

$$I_5 = \frac{E_5}{R_5}$$

$$I_5 = \frac{36}{600}$$

$$I_5 = 0.06 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$I_6 = \frac{E_6}{R_6}$$

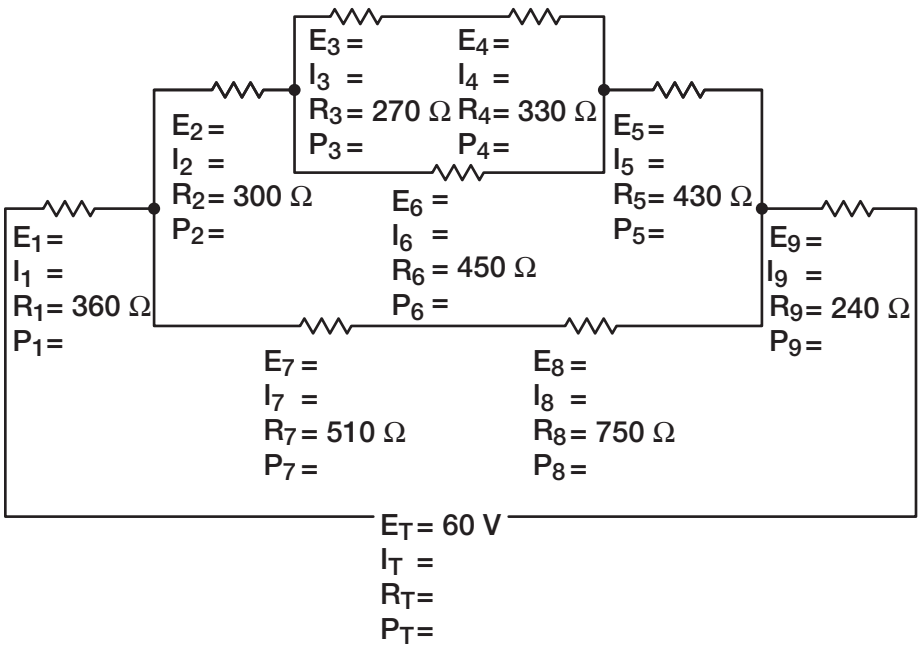
$$I_6 = \frac{36}{900}$$

$$I_6 = 0.04 \text{ A}$$

EXAMPLE 3: Both of the preceding circuits were solved by first determining which parts of the circuit were in series and which were in parallel. The circuits were then reduced to a simple series or parallel circuit. This same procedure can be used for any combination circuit. The circuit shown in FIGURE 7-9 will be reduced to a simpler circuit first. Once the values of the simple circuit are found, they can be placed back in the original circuit to find other values.

Solution:

The first step will be to reduce the top part of the circuit to a single resistor. This part consists of resistors R_3 and R_4. Since these two resistors are connected in series, their values can be added to form one single resistor. This combination will form R_{C1}, FIGURE 7-10.



© Cengage Learning 2014

FIGURE 7-9 Circuit 3.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

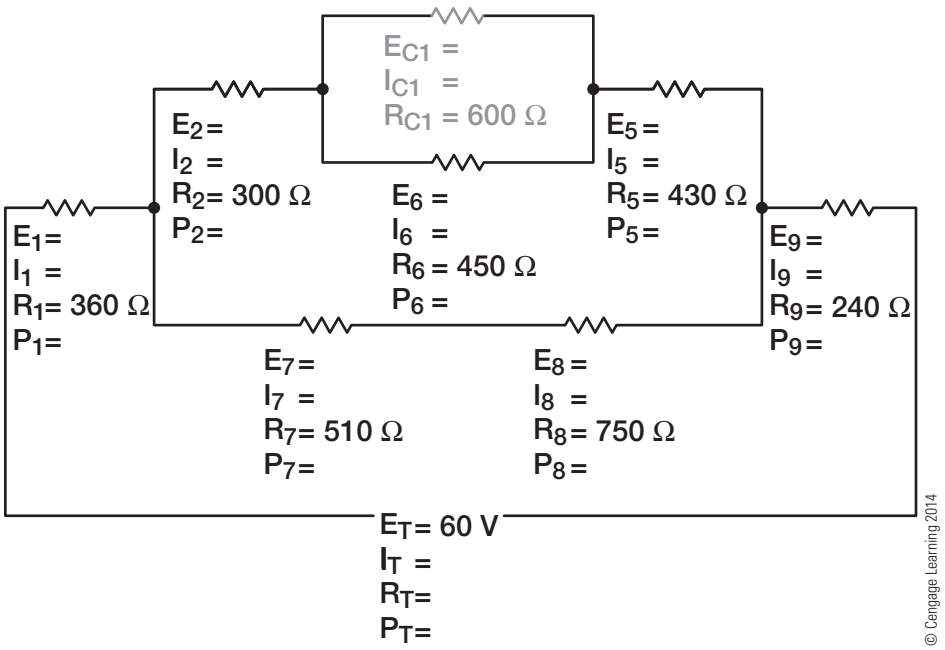


FIGURE 7-10 Resistors R_1 and R_2 are combined to form R_{c1}.

$$R_{C1} = R_3 + R_4$$
$$R_{C1} = 270 + 330$$
$$R_{C1} = 600\ \Omega$$

The top part of the circuit is now formed by resistors R_{C1} and R_6. These two resistors are in parallel. If their total resistance is computed, they can be changed into one single resistor with a value of 257.143 Ω. This combination will become resistor R_{C2}, FIGURE 7-11.

$$R_{C2} = \frac{1}{\frac{1}{R_{C1}} + \frac{1}{R_6}}$$
$$R_{C2} = \frac{1}{\frac{1}{600} + \frac{1}{450}}$$
$$R_T = 257.143\ \Omega$$

The top of the circuit now consists of resistors R_2, R_{C2}, and R_5. These three resistors are connected in series with each other. They can be combined to form resistor R_{C3} by adding their resistances together, FIGURE 7-12.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

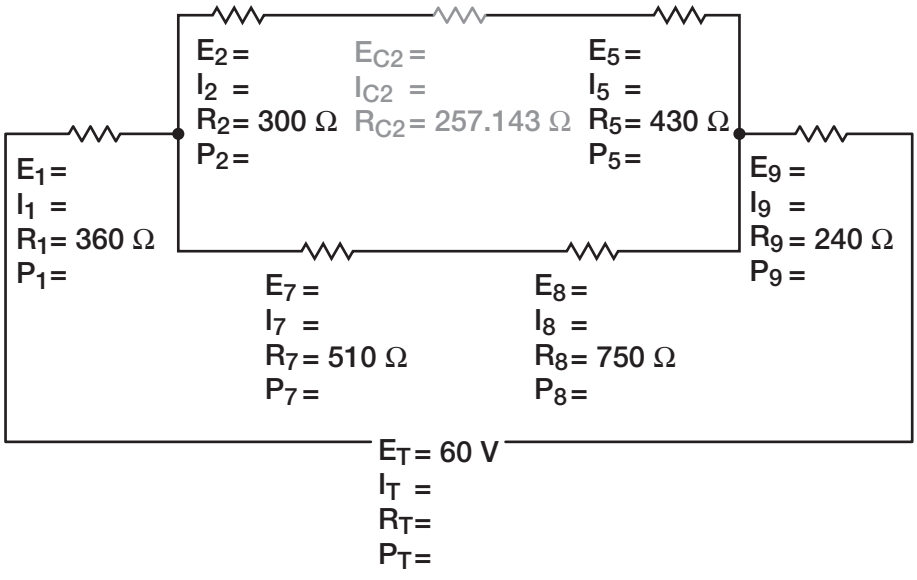


FIGURE 7-11 Resistors R_{c1} and R_6 are combined to form R_{c2}.

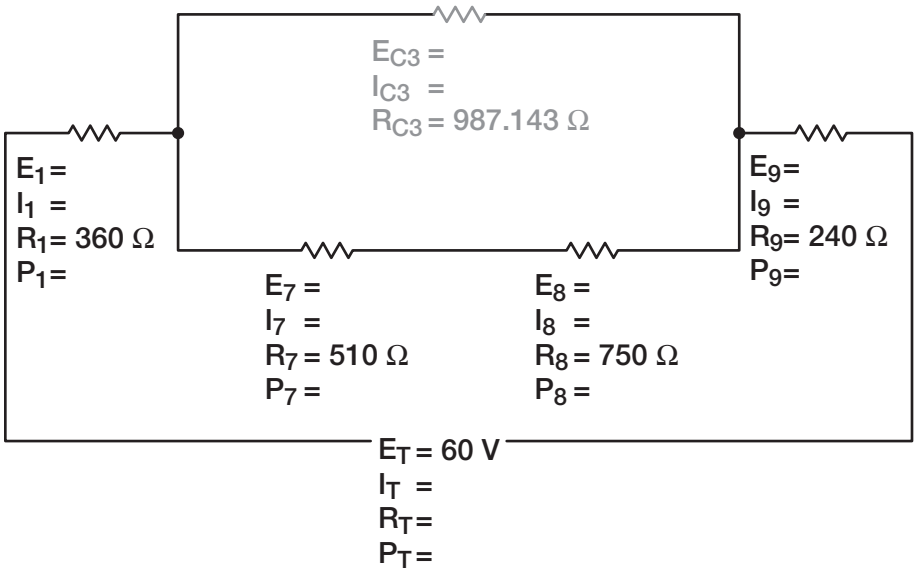


FIGURE 7-12 Resistors R_2, R_{c2}, and R_5 are combined to form R_{c3}.

$$R_{c3} = R_2 + R_{C2} + R_5$$
$$R_{c3} = 300 + 257.143 + 430$$
$$R_{c3} = 987.143\ \Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

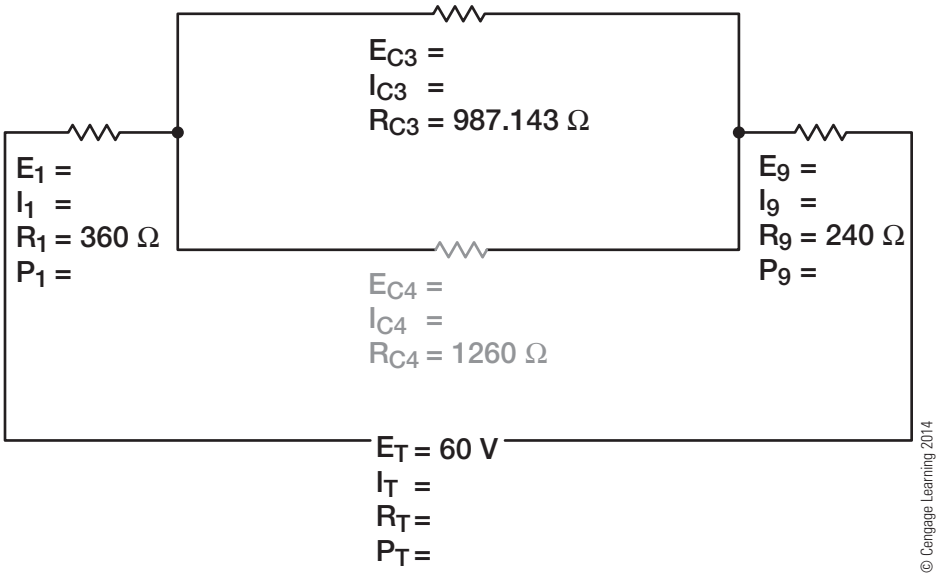


FIGURE 7-13 Resistors R_7 and R_8 are combined to form R_{c4}.

Resistors R_7 and R_8 are connected in series also. These two resistors will be added to form resistor R_{C4}, FIGURE 7-13.

$$R_{c4} = R_7 + R_8$$

$$R_{c4} = 510 + 750$$

$$R_{c4} = 1260\ \Omega$$

Resistors R_{C3} and R_{C4} are connected in parallel. Their total resistance can be computed to form resistor R_{C5}, FIGURE 7-14.

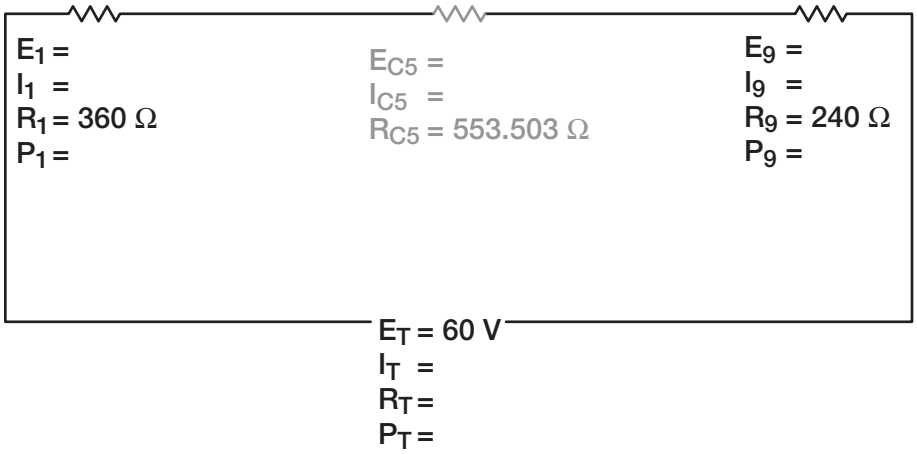
$$R_{C5} = \frac{1}{\frac{1}{R_{C3}} + \frac{1}{R_{C4}}}$$

$$R_{C5} = \frac{1}{\frac{1}{987.143} + \frac{1}{1260}}$$

$$R_{c5} = 553.503\ \Omega$$

The circuit has now been reduced to a simple series circuit containing three resistors. The total resistance of the circuit can be computed by adding resistors R_1, R_{C5}, and R_9.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 7-14 Resistors R_{c3} and R_{c4} are combined to form R_{c5}.

$$R_T = R_1 + R_{c5} + R_9$$
$$R_T = 360 + 553.503 + 240$$
$$R_T = 1153.503\ \Omega$$

Now that the total resistance and total voltage are known, the total circuit current and total circuit power can be computed using Ohm's Law.

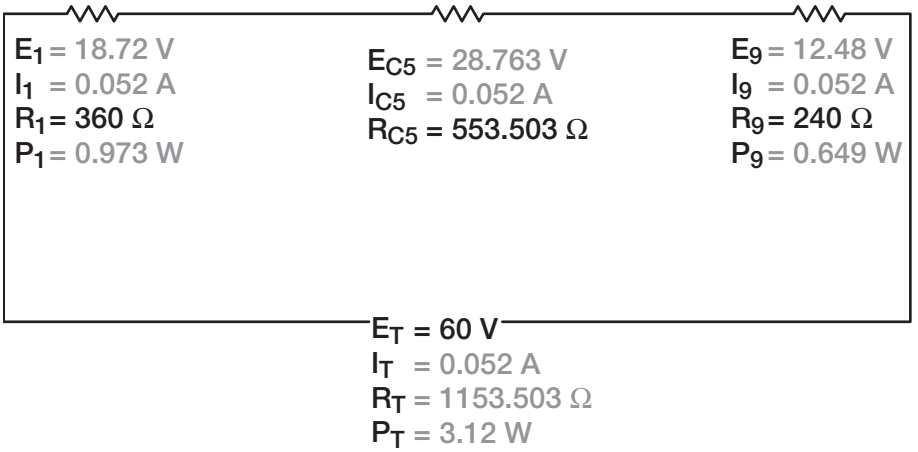
$$I_T = \frac{E_T}{R_T}$$
$$I_T = \frac{60}{1153.503}$$
$$I_T = 0.052\ \text{A}$$

$$P_T = E_T \times I_T$$
$$P_T = 60 \times 0.052$$
$$P_T = 3.12\ \text{W}$$

Ohm's Law can now be used to find the missing values for resistors R_1, R_{C5}, and R_9, FIGURE 7-15.

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.052 \times 360$$
$$E_1 = 18.72\ \text{V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 7-15 Missing values are found for the first part of the circuit.

$$P_1 = E_1 \times I_1$$
$$P_1 = 18.72 \times 0.052$$
$$P_1 = 0.973 \text{ W}$$

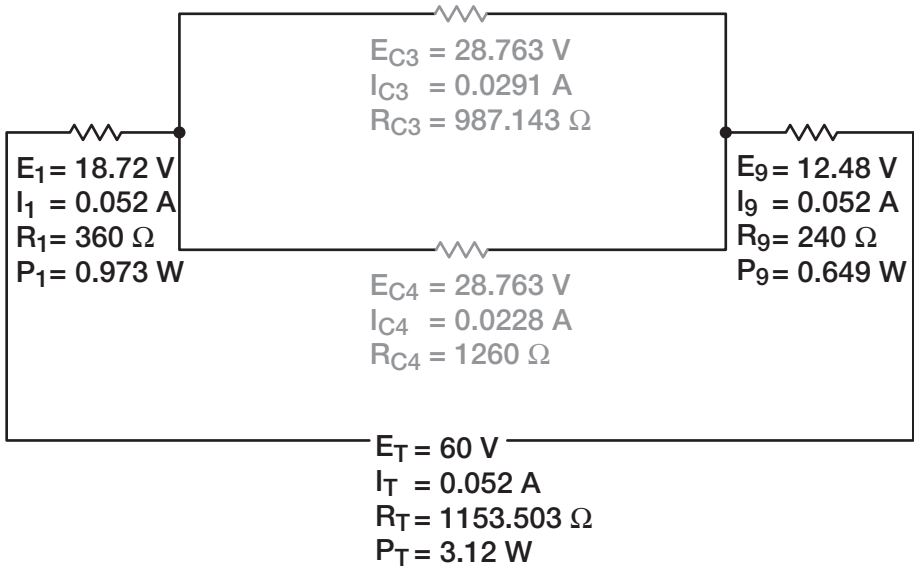
$$E_{c5} = I_{c5} \times R_{c5}$$
$$E_{c5} = 0.052 \times 553.143$$
$$E_{c5} = 28.763 \text{ V}$$

$$E_9 = I_9 \times R_9$$
$$E_9 = 0.052 \times 240$$
$$E_9 = 12.48 \text{ V}$$

Resistor RC5 is actually the combination of resistors R_{C3} and R_{C4}. The values of R_{C5}, therefore, apply to resistors R_{C3} and R_{C4}. Since these two resistors are connected in parallel with each other, the voltage drop across them will be the same. Each will have the same voltage drop as resistor R_{C5}, FIGURE 7-16. Ohm's Law can now be used to find the remaining values of R_{C3} and R_{C4}.

$$I_{c4} = \frac{E_{c4}}{R_{c4}}$$
$$I_{c4} = \frac{28.763}{1260}$$
$$I_{c4} = 0.0228 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 7-16 Solving the values for resistors R_{c3} and R_{c4}.

$$I_{c3} = \frac{E_{c3}}{R_{c3}}$$

$$I_{c3} = \frac{28.763}{987.143}$$

$$I_{c3} = 0.0291 \text{ A}$$

Resistor R_{C4} is the combination of resistors R_7 and R_8. So, the values of resistor R_{C4} apply to resistors R_7 and R_8. Since resistors R_7 and R_8 are connected in series, the current flow will be the same through both, FIGURE 7-17. Ohm's Law can now be used to compute the remaining values for these two resistors.

$$E_7 = I_7 \times R_7$$

$$E_7 = 0.0228 \times 510$$

$$E_7 = 11.268 \text{ V}$$

$$P_7 = E_7 \times I_7$$

$$P_7 = 11.268 \times 0.0228$$

$$P_7 = 0.265 \text{ W}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

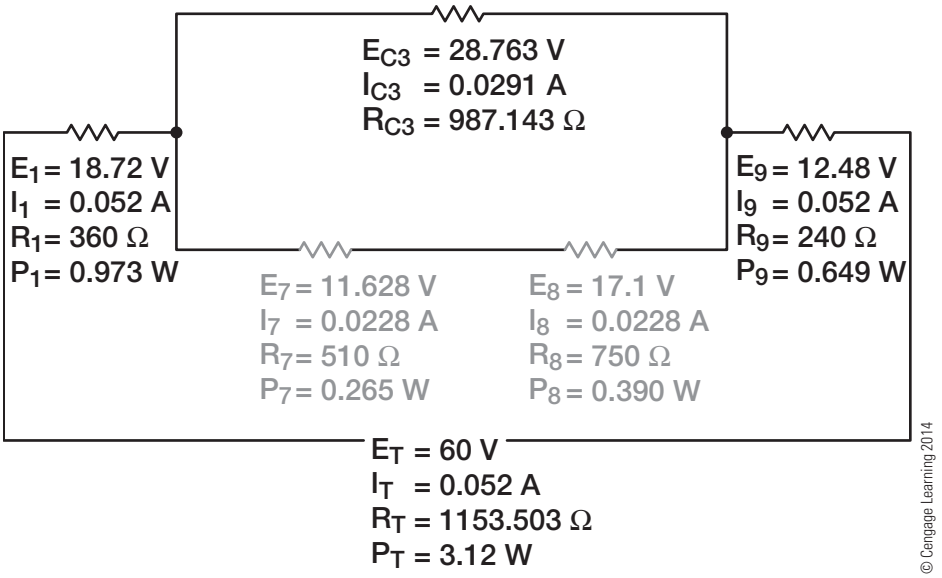


FIGURE 7-17 Solving the values for resistors R_7 and R_8.

$$E_8 = I_8 \times R_8$$
$$E_8 = 0.0228 \times 750$$
$$E_8 = 17.1 \text{ V}$$

$$P_8 = E_8 \times I_8$$
$$P_8 = 17.1 \times 0.0228$$
$$P_8 = 0.390 \text{ W}$$

Resistor R_{C3} is the combination of resistors R_2, R_{C2}, and R_5. Since these resistors are connected in series, the current flow through each will be the same as the current flow through R_{C3}. The remaining values can now be computed using Ohm's Law, FIGURE 7-18.

$$E_{c2} = I_{c2} \times R_{c2}$$
$$E_{c2} = 0.0292 \times 257.143$$
$$E_{c2} = 7.509 \text{ V}$$

$$E_2 = I_2 \times R_2$$
$$E_2 = 0.0292 \times 300$$
$$E_2 = 8.76 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

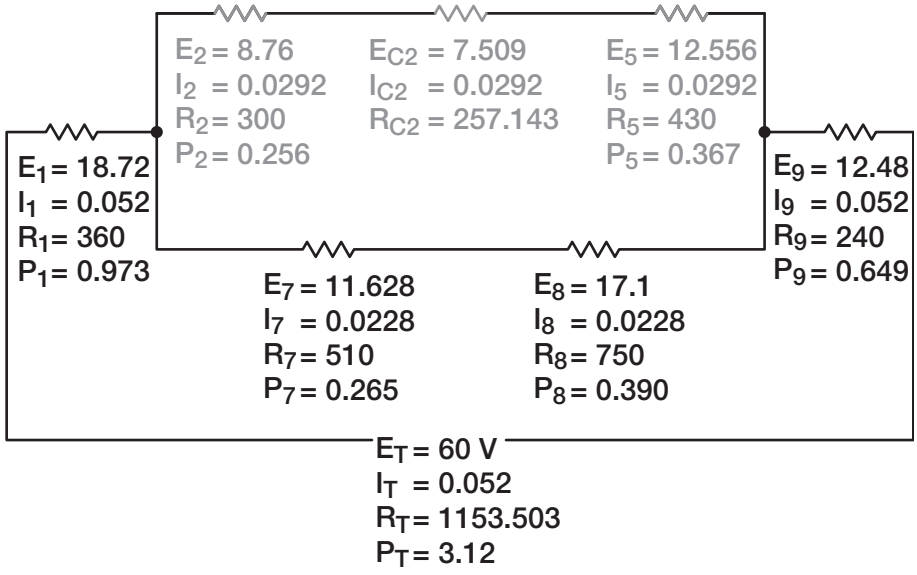


FIGURE 7-18 Determining values for R_2, R_{c2}, and R_5.

$$P_2 = E_2 \times I_2$$
$$P_2 = 8.76 \times 0.292$$
$$P_2 = 0.256 \text{ W}$$

$$E_5 = I_5 \times R_5$$
$$E_5 = 0.0292 \times 430$$
$$E_5 = 12.556 \text{ V}$$

$$P_5 = E_5 \times I_5$$
$$P_5 = 12.556 \times 0.0292$$
$$P_5 = 0.367 \text{ W}$$

Resistor R_{C2} is the combination of resistors R_{C1} and R_6. Resistors R_{C1} and R_6 are connected in parallel and will, therefore, have the same voltage drop as resistor R_{C2}. Ohm's Law can be used to compute the remaining values for R_{C2} and R_6, FIGURE 7-19.

$$I_{c1} = \frac{E_{c1}}{R_{c1}}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

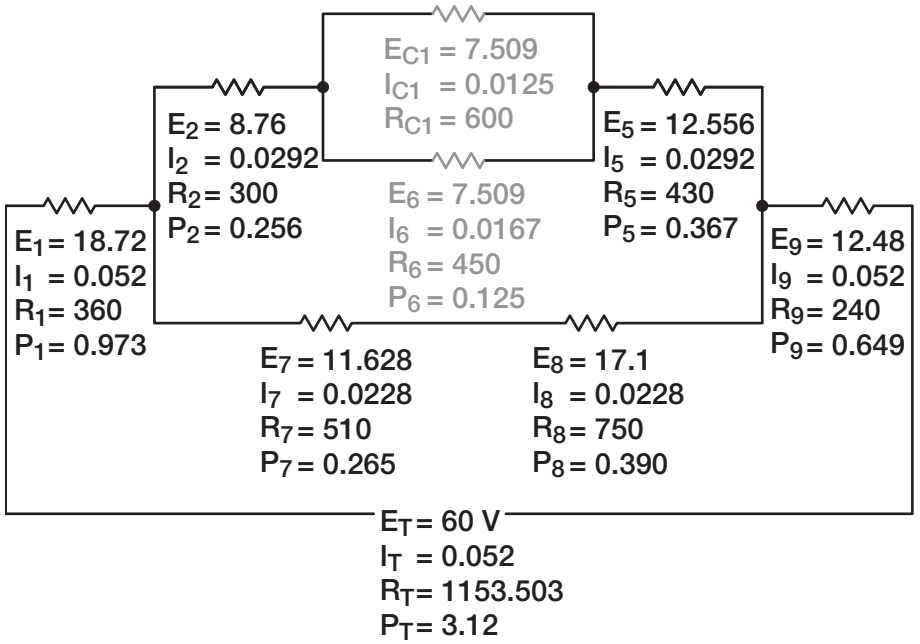


FIGURE 7-19 Computing the missing values for R_{c1} and R_6.

$$I_{c1} = \frac{7.509}{600}$$

$$I_{c1} = 0.0125 \text{ A}$$

$$I_6 = \frac{E_6}{R_6}$$

$$I_6 = \frac{7.509}{450}$$

$$I_6 = 0.0167 \text{ A}$$

$$P_6 = E_6 \times I_6$$

$$P_6 = 7.509 \times 0.0167$$

$$P_6 = 0.125 \text{ W}$$

Resistor R_{C1} is the combination of resistors R_3 and R_4. Since these two resistors are connected in series, the amount of current flow through resistor R_{C1} will be the same as the flow through R_3 and R_4. The remaining values of the circuit can now be found using Ohm's Law, FIGURE 7-20.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

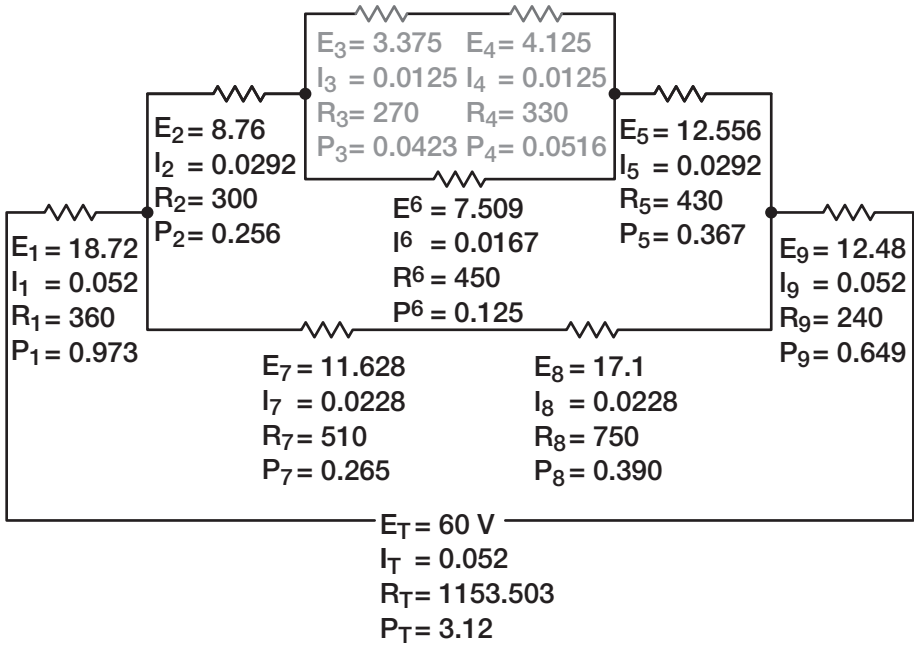


FIGURE 7-20 Computing the values for R_3 and R_4.

$$E_3 = I_3 \times R_3$$
$$E_3 = 0.0125 \times 270$$
$$E_3 = 3.375 \text{ V}$$

$$P_3 = E_3 \times I_3$$
$$P_3 = 3.375 \times 0.0125$$
$$P_3 = 0.0423 \text{ W}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.0125 \times 330$$
$$E_4 = 4.125 \text{ V}$$

$$P_4 = E_4 \times I_4$$
$$P_4 = 4.125 \times 0.0125$$
$$P_4 = 0.0516 \text{ W}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Summary

1. Combination circuits are circuits that contain both series and parallel branches.
2. The three rules for series circuits are:
   A. The current is the same at any point in a series circuit.
   B. The total resistance is the sum of each individual resistor.
   C. The applied voltage is equal to the sum of the voltage drops across each individual component.
3. The three rules for parallel circuits are:
   A. The voltage is the same across any branch of a parallel circuit.
   B. The total current is the sum of the individual currents through each path in the circuit.
   C. The reciprocal of the total resistance is the sum of the reciprocals of the branch resistances.
4. Solving combination circuits is generally easier if the circuit is reduced to simpler circuits.

Review Questions

1. Refer to FIGURE 7-2. Replace the values shown with the listed values. Solve for all of the unknown values.

   $I_T = 0.6$ A
   $R_1 = 470\ \Omega$
   $R_2 = 360\ \Omega$
   $R_3 = 510\ \Omega$
   $R_4 = 430\ \Omega$

2. Refer to FIGURE 7-5. Replace the values shown with the listed values. Solve for all of the unknown values.

   $E_T = 63$ V
   $R_1 = 1{,}000\ \Omega$
   $R_2 = 2{,}200\ \Omega$
   $R_3 = 1{,}800\ \Omega$
   $R_4 = 910\ \Omega$
   $R_5 = 3{,}300\ \Omega$
   $R_6 = 4{,}300\ \Omega$
   $R_7 = 860\ \Omega$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Practice Problems

1. Refer to the circuit shown in FIGURE 7-21. Determine the amount of resistance that would be measured across the points indicated.

A-B _____ Ω A-C _____ Ω A-D _____ Ω
B-C _____ Ω B-D _____ Ω C-D _____ Ω

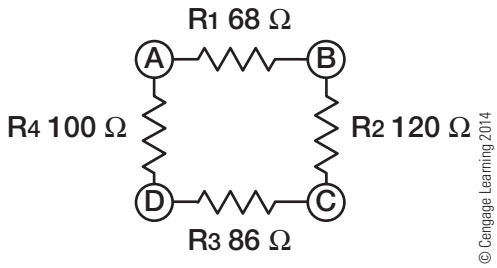


FIGURE 7-21 Practice Problem 1.

2. Refer to the circuit shown in FIGURE 7-22. Determine the amount of resistance that would be measured across the points indicated.

A-B _____ Ω A-C _____ Ω A-D _____ Ω
B-C _____ Ω B-D _____ Ω C-D _____ Ω

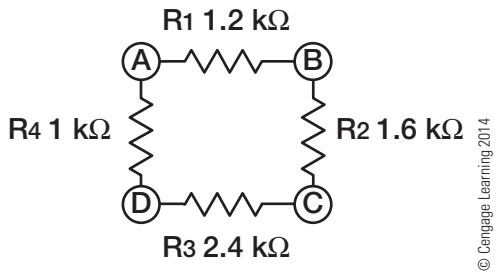


FIGURE 7-22 Practice Problem 2.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

3. Refer to the circuit shown in FIGURE 7-23. Determine the amount of resistance that would be measured across the points indicated.

A-B _____ Ω A-C _____ Ω A-D _____ Ω
B-C _____ Ω B-D _____ Ω C-D _____ Ω

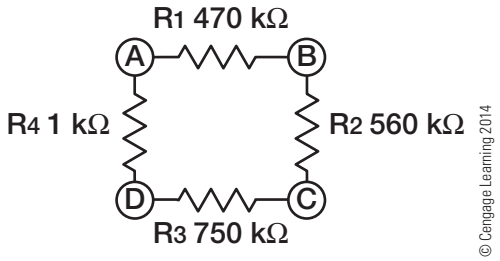


FIGURE 7-23 Practice Problem 3.

4. Refer to the circuit shown in FIGURE 7-24. Determine the amount of resistance that would be measured across the points indicated.

A-B _____ Ω A-C _____ Ω A-D _____ Ω
B-C _____ Ω B-D _____ Ω C-D _____ Ω

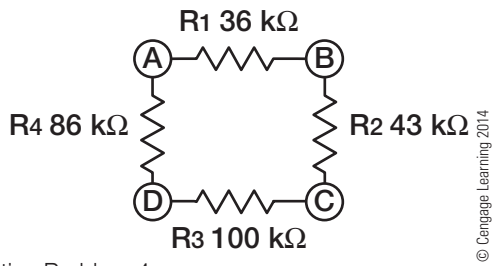


FIGURE 7-24 Practice Problem 4.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. Find all the missing values in the circuit shown in FIGURE 7-25.

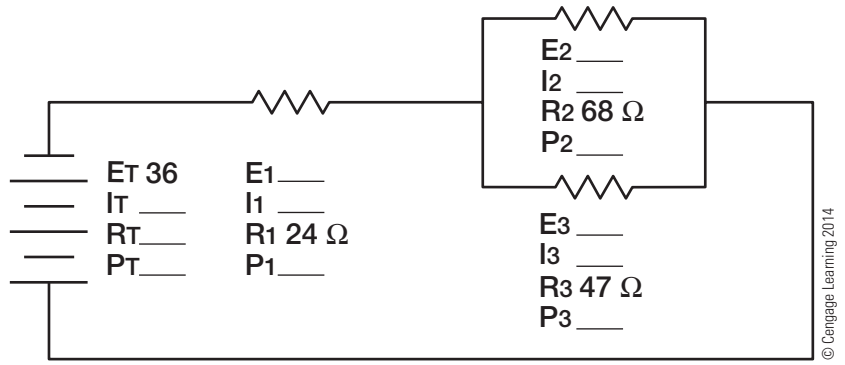


FIGURE 7-25 Practice Problem 5.

6. Find all the missing values in the circuit shown in FIGURE 7-26.

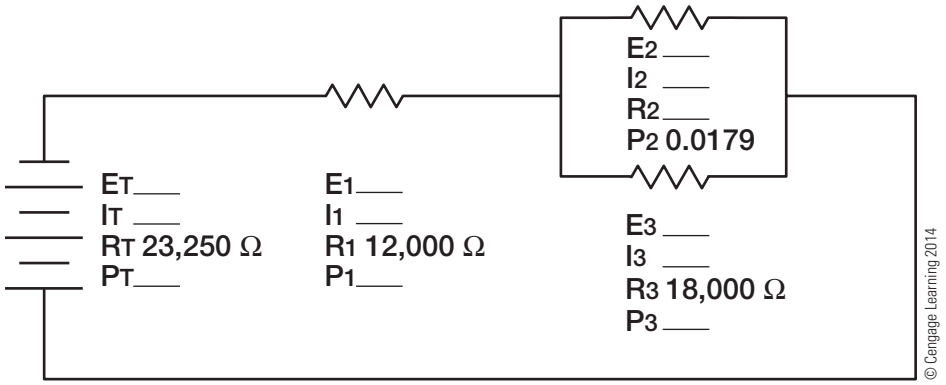


FIGURE 7-26 Practice Problem 6.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

7. Find all the missing values in the circuit shown in FIGURE 7-27.

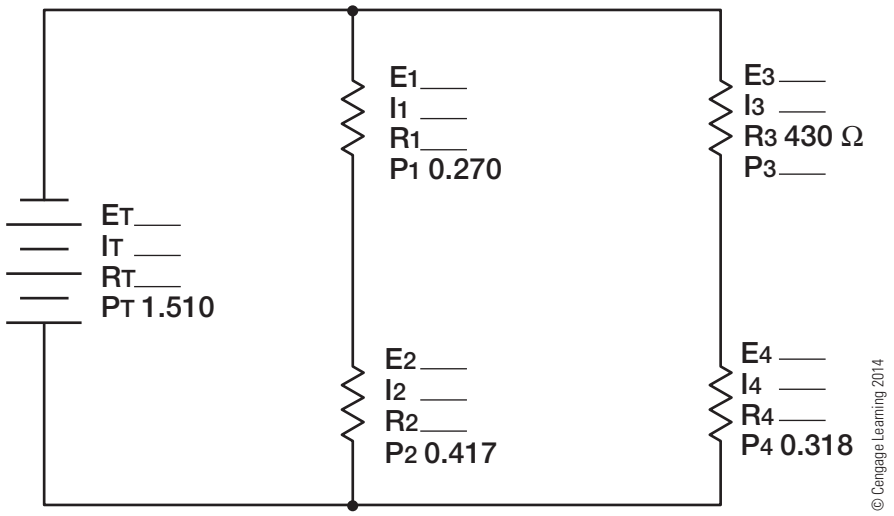


FIGURE 7-27 Practice Problem 7.

8. Find all the missing values in the circuit shown in FIGURE 7-28.

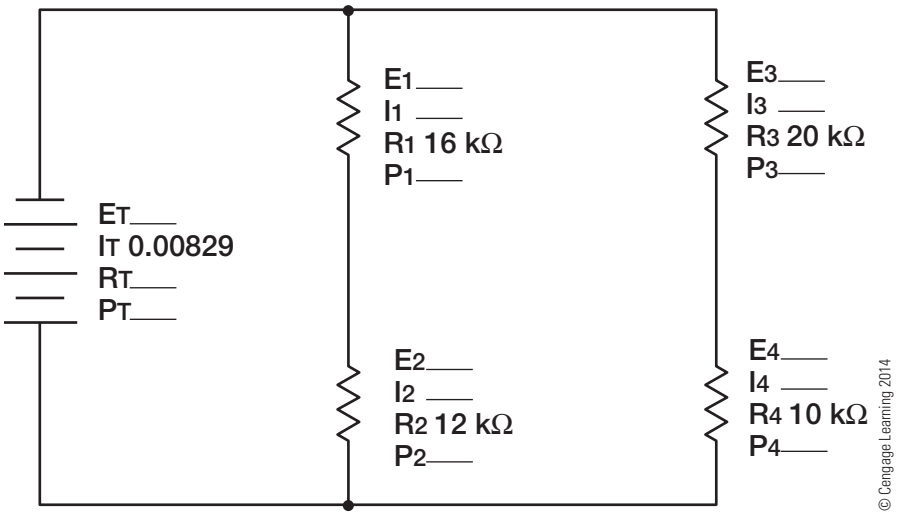


FIGURE 7-28 Practice Problem 8.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

9. Find all the missing values in the circuit shown in FIGURE 7-29.

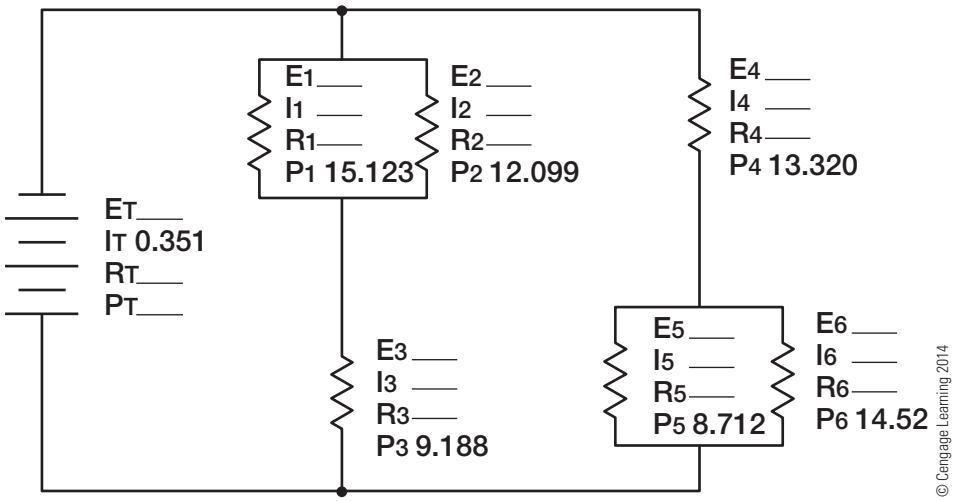


FIGURE 7-29 Practice Problem 9.

10. Find all the missing values in the circuit shown in FIGURE 7-30.

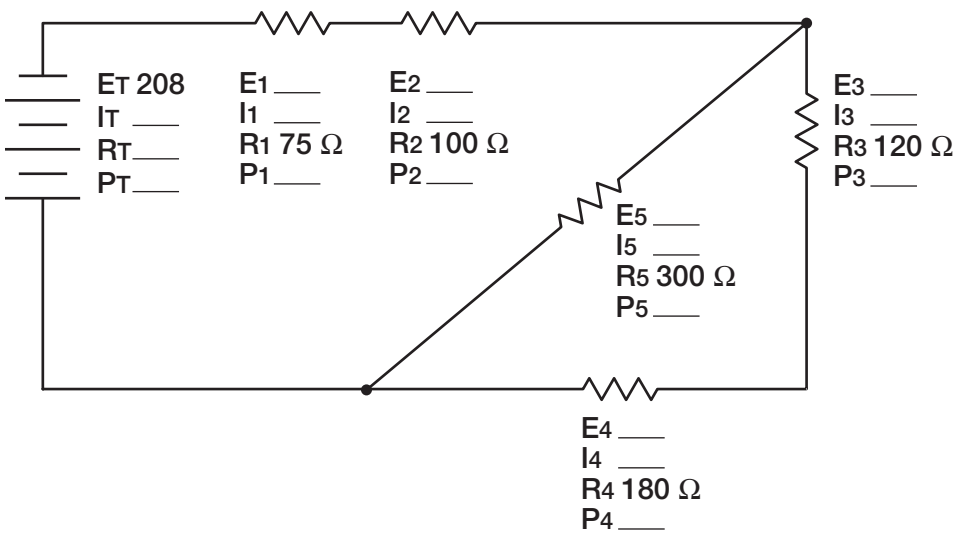


FIGURE 7-30 Practice Problem 10.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 8

Measuring Instruments

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the operation of a d'Arsonval meter movement.
- Discuss the operation of a moving iron type of movement.
- Connect a voltmeter to a circuit.
- Connect and read an analog multimeter.
- Connect an ammeter.
- Measure resistance using an ohmmeter.

Anyone desiring to work in the electrical and electronics field must become proficient with the common instruments used to measure electrical quantities. These instruments are the voltmeter, ammeter, and ohmmeter. Without meters it would be impossible to make meaningful interpretations of what is happening in a circuit. Meters can be divided into two general types, analog and digital.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

ANALOG METERS

analog meters
voltmeter that uses a meter movement to indicate the voltage value. Analog meters use a pointer and scale.

d'Arsonval movement
meter movement using a permanent magnet and a coil of wire; this is the basic meter movement used in many analog-type voltmeters, ammeters, and ohmmeters.

moving coil meter
A moving coil meter is a d'Arsonval type movement.

galvanometers
meter movement requiring microamperes to cause a full-scale deflection. Many galvanometers utilize a zero center, which permits them to measure both positive and negative values.

Analog meters are characterized by the fact that they use a pointer and scale to indicate their value, FIGURE 8-1. There are different types of analog meter movements. One of the most common is the **d'Arsonval movement** shown in FIGURE 8-2. This type of movement is often referred to as a **moving coil** type meter. A coil of wire is suspended between the poles of a permanent magnet. The coil is suspended either by jeweled movements similar to those used in watches or by taut bands. The taut band type offers less turning friction than the jeweled movement. These meters can be made to operate on very small amounts of current and are often referred to as **galvanometers.**

PRINCIPLE OF OPERATION

Analog meters operate on the principle that like magnetic poles repel each other. As current passes through the coil, a magnetic field is created around the coil. The direction of current flow through the meter is such that the same polarity of magnetic pole is created around the coil as that of the permanent magnet. This causes the coil to be deflected away from the pole of the magnet. A spring is used to retard the turning of the coil. The distance the coil turns against the spring is proportional to the strength of the magnetic field developed in the coil. If a pointer is added to the coil and a scale placed behind the pointer, a meter movement is created.



© Cengage Learning 2014

FIGURE 8-1 An analog meter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

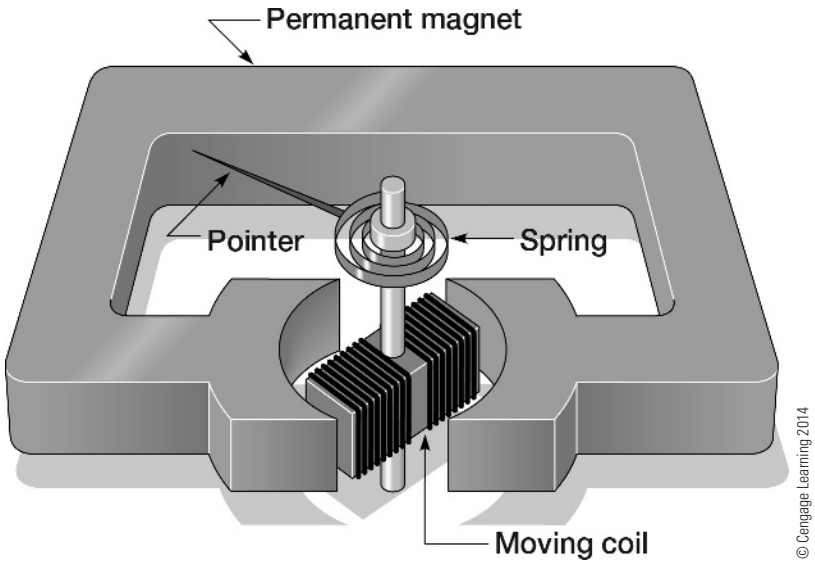


FIGURE 8-2 Basic d'Arsonval meter movement.

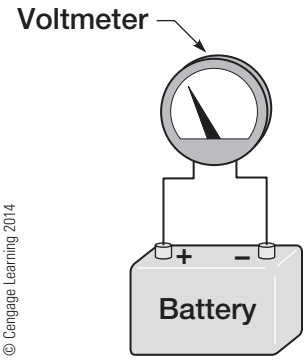
Since the turning force of this meter depends on the repulsion of magnetic fields, it will operate on DC current only. If a 60-Hz AC current is connected to the moving coil, the magnetic polarity will change sixty times per second and the net turning force will be zero. For this reason, a DC voltmeter will indicate zero if connected to an AC line. When this type of movement is to be used to measure AC values, the current must be rectified or changed into DC before it is applied to the meter, FIGURE 8-3.

ANALOG VOLTMETERS

voltmeter
instrument used to measure a level of voltage.

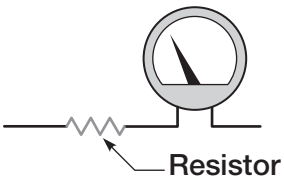
The **voltmeter** is designed to be connected directly across the source of power. FIGURE 8-4 shows an analog voltmeter being used to test the voltage of a battery. Notice that the leads of the meter are connected directly across the source of voltage. A voltmeter can be connected directly across the power source because it has a very high resistance connected in series with the meter movement, FIGURE 8-5. The industrial standard for an analog type voltmeter is 20,000 Ω per volt for DC and 5,000 Ω per volt for AC. Assume the voltmeter shown in Figure 8-5 is an AC meter and has a full-scale range of 300 V. The meter circuit (meter plus resistor) would, therefore, have a resistance of 1,500,000 Ω (300 V × 5,000 Ω per volt = 1,500,000 Ω).

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



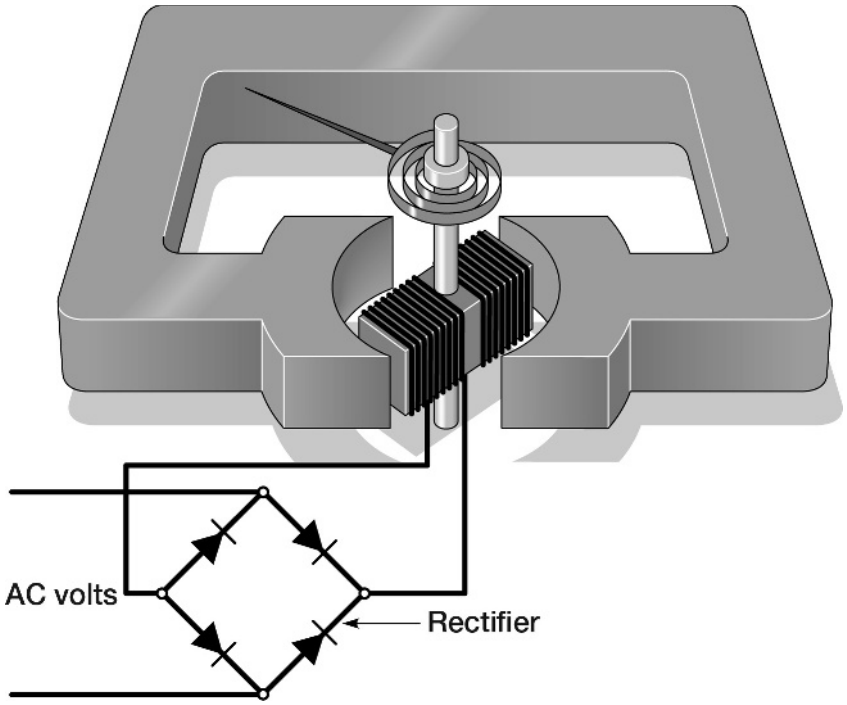
© Cengage Learning 2014

FIGURE 8-4 A voltmeter connects directly across the power source.



© Cengage Learning 2014

FIGURE 8-5 A resistor connects in series with the meter.



© Cengage Learning 2014

FIGURE 8-3 A rectifier changes AC voltage into DC voltage.

MULTIRANGE VOLTMETERS

multirange voltmeters
voltmeters that contain more than one range of voltages.

Most voltmeters are **multirange voltmeters,** which means that they are designed to use one meter movement to measure several ranges of voltage. For example, one meter may have a selector switch that permits full-scale ranges to be selected. These ranges may be 3-V full scale, 12-V full scale, 30-V full scale, 60-V full scale, 120-V full scale, 300-V full scale, and 600-V full scale. The reason for making a meter with these many scales is to make the device as versatile as possible. If it is necessary to check for a voltage of 480 V, the meter can be set on the 600-V range. If it became necessary to check a 24-V system, this would be very difficult to do on the 600-V range. If the meter is set on the 30-V range, it becomes a simple matter to test for a voltage of 24 V. The meter shown in Figure 8-1 has multirange selection for voltage.

When the selector switch of this meter is turned, steps of resistance are inserted in the circuit to increase the range, or removed from the circuit to decrease the range. The meter shown in FIGURE 8-6 has four range settings for full-scale voltage: 30 V, 60 V, 300 V, and 600 V. Notice that when the higher voltage settings are selected, more resistance is inserted in the circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

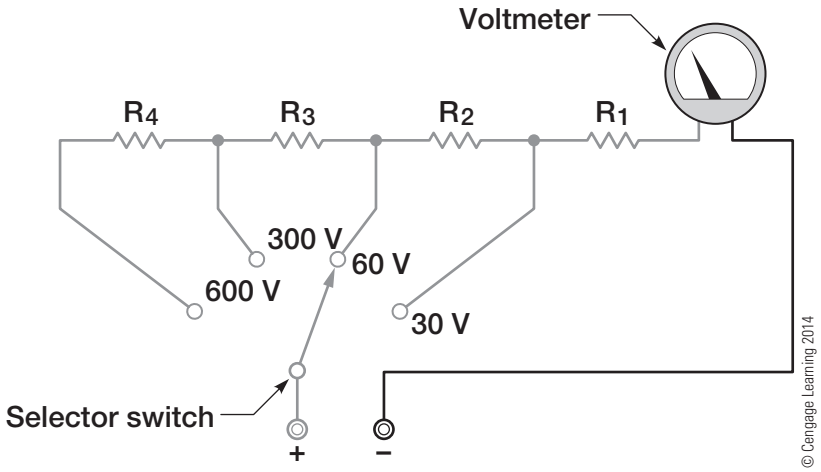


FIGURE 8-6 A rotary selector switch is used to change the full range setting.

READING A METER

Learning to read the scale of a multimeter takes time and practice. Most people use meters every day without thinking about it. A very common type of meter used daily by most people is shown in FIGURE 8-7. The meter illustrated is a speedometer similar to those seen in automobiles. This meter is designed to measure speed. It is calibrated in miles per hour. The speedometer shown has a full-scale value of 80 mph. If the pointer is positioned as shown in Figure 8-7, most people will know instantly that the speed of the automobile is 55 mph.

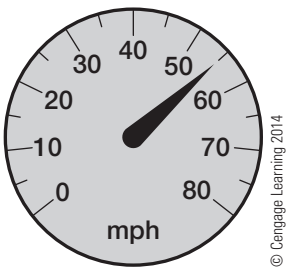


FIGURE 8-7 A speedometer.

FIGURE 8-8 illustrates another common meter used by most people. This meter is used to measure the amount of fuel in the tank of the automobile. Most people can glance at the pointer of the meter and know that the meter is indicating that there is one-quarter of a tank of fuel remaining. Now assume that the tank has a capacity of 20 gallons. The meter is indicating that there are a total of 5 gallons of fuel remaining in the tank.

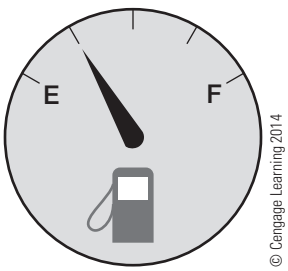


FIGURE 8-8 A fuel gauge.

Learning to read the scale of a multimeter is similar to learning to read a speedometer or fuel gauge. The meter scale shown in FIGURE 8-9 has several scales used to measure different quantities and values. The top of the scale is used to measure resistance or ohms. Notice that the scale begins with infinity at the left and ends with zero at the right. Ohmmeters will be covered later in this unit. The second scale is labeled AC-DC and is used to measure voltage. Notice that this scale has three different full-scale values. The top scale is 0–300, the second scale is 0–60, and the third scale is 0–12. The scale used is determined by the setting of the range control switch. The third set of

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

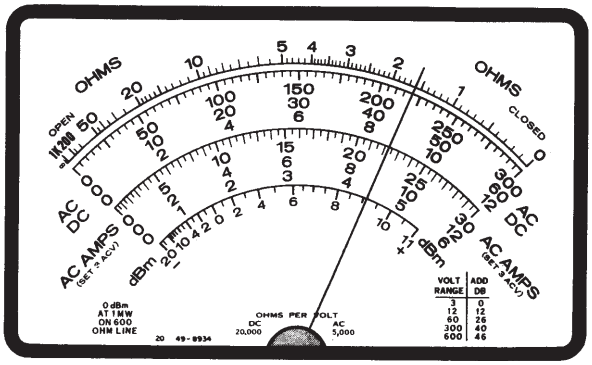


FIGURE 8-9 A typical multimeter.

scales is labeled AC amperes. This scale is used with a clamp-on ammeter attachment that can be used with some meters. The last scale is labeled dBm and is used to measure decibels.

READING A VOLTMETER

Notice that the three voltmeter scales use the primary numbers 3, 6, and 12 and are in multiples of 10 of these numbers (300 is a multiple of 3 and 60 is a multiple of 6). Since the numbers are in multiples of 10, it is easy to multiply or divide the readings in your head by moving a decimal point. Remember that any number can be multiplied by 10 by moving the decimal point one place to the right, and any number can be divided by 10 by moving the decimal point one place to the left. For example, if the selector switch is set to permit the meter to indicate a voltage of 3-V full scale, the 300-V scale would be used and the reading would be divided by 100. The reading can be divided by 100 by moving the decimal point two places to the left. In FIGURE 8-10, the meter

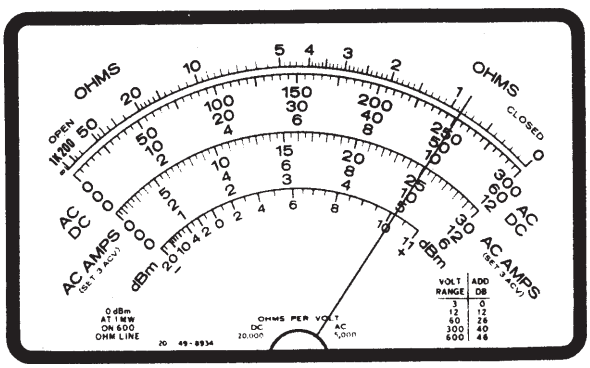
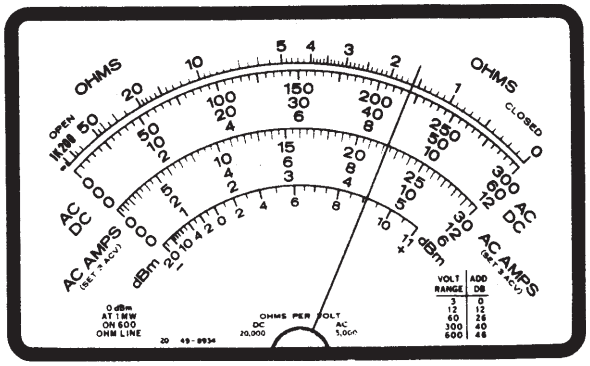


FIGURE 8-10 Reading the meter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 8-11 Reading the meter.

is indicating a voltage of 2.5 V if the selector switch is set for 3-V full scale. The pointer is indicating a value of 250. Moving the decimal point two places to the left will give a reading of 2.5 V. If the selector switch is set for a full-scale value of 30 V, the meter shown in Figure 8-10 would be indicating a value of 25 V. This reading is obtained by dividing the scale by 10, and moving the decimal point one place to the left.

Now assume that the meter has been set to have a full-scale value of 600 V. The meter shown in FIGURE 8-11 is indicating a voltage of 440 V. Since the full-scale value of the meter is set for 600 V, use the 60-V range and multiply the reading on the meter by 10. Do this by moving the decimal point one place to the right. The pointer in Figure 8-11 is indicating a value of 44. If this value is multiplied by 10, the correct reading becomes 440 V.

Three distinct steps should be followed when reading a meter. This is especially true for someone who has not had a great deal of experience reading a multimeter. These steps are as follows:

1. *Determine what the meter indicates.* Is the meter set to read a value of DC voltage, DC current, AC voltage, AC current, or ohms? It is impossible to read a meter if you don't know what it is used to measure.
2. *Determine the full-scale value of the meter.* The advantage of a multimeter is that it has the ability to measure a wide range of values and quantities. After it has been determined what quantity the meter is set to measure, it must then be determined what the range of the meter is. There is a great deal of difference in reading when the meter is set to indicate a value of 600-V full scale and when it is set for 30-V full scale.
3. *Read the meter.* The last step is to determine what the meter is indicating. It may be necessary to determine the value of the hash

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

marks on the meter face for the range for which the selector switch is set. If the meter in Figure 8-9 is set for 300-V full scale, each hash mark has a value of 5 V. If the full-scale value of the meter is 60-V, however, each hash mark has a value of 1 V.

THE AMMETER

ammeter
instrument used to measure the flow of current.

The **ammeter,** unlike the voltmeter, is a very low-impedance device. The ammeter must be connected in series with the load to permit the load to limit the current flow, FIGURE 8-12. An ammeter has a typical impedance of less than 0.1 Ω. If this meter is connected in parallel with the power supply, the impedance of the ammeter is the only thing to limit the amount of current flow in the circuit. Assume that an ammeter with a resistance of 0.1 Ω is connected across a 240-V AC line. The current flow in this circuit would be 2400 A (240/.1 = 2400). The blinding flash of light would be followed by the destruction of the ammeter. Ammeters connected directly into the circuit, as shown in Figure 8-12, are referred to as in-line ammeters. FIGURE 8-13 shows an ammeter of this type.

AMMETER SHUNTS

ammeter shunt
a low value resistance designed to shunt most the current away from the meter movement.

DC ammeters are constructed by connecting a common moving coil type of meter across a shunt. An **ammeter shunt** is a low-resistance device used to conduct most of the circuit current away from the meter movement. Since the meter movement is connected in parallel with the shunt, the voltage drop across the shunt is the voltage applied to the meter. Most ammeter shunts

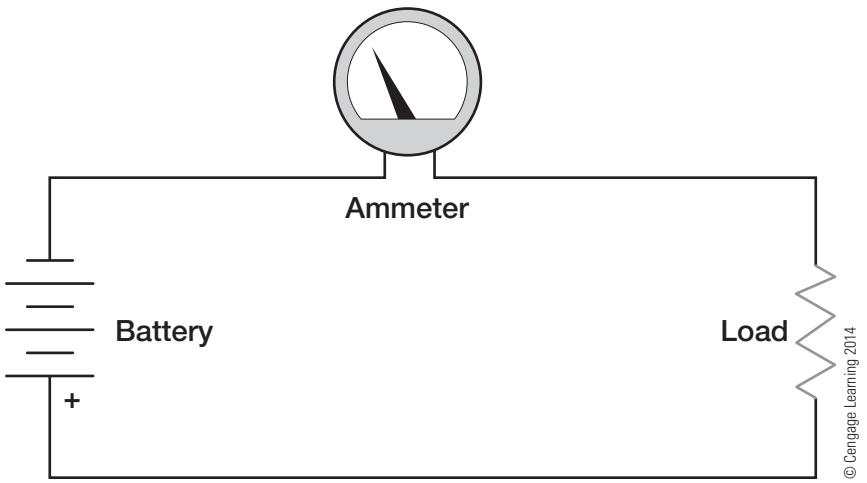
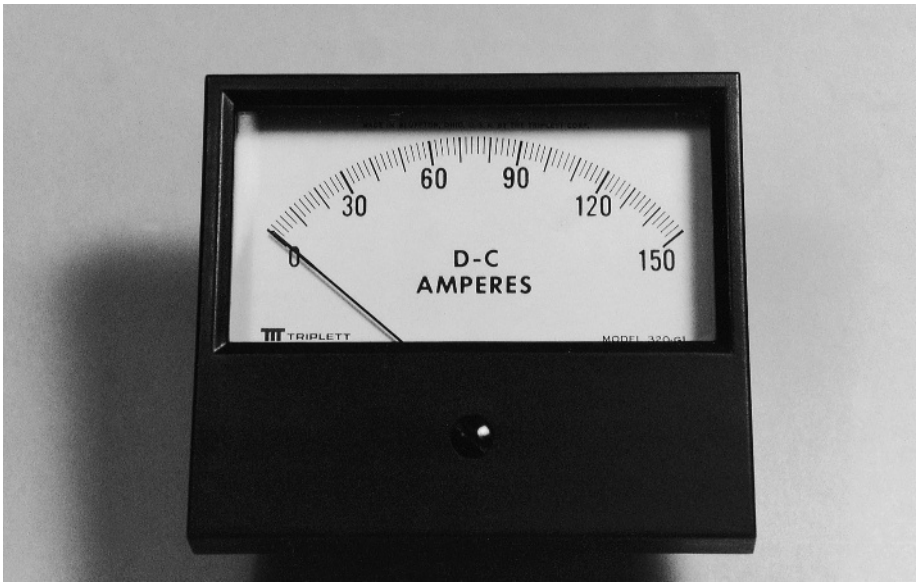


FIGURE 8-12 An ammeter connects in series with the load.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 8-13 In-line ammeter.

are manufactured to have a voltage drop of 50 millivolts (mV). If a 50-mV meter movement is connected across the shunt as shown in FIGURE 8-14, the pointer will move to the full-scale value when the rated current of the shunt is flowing. In the example shown, the ammeter shunt is rated to have a 50-mV drop when 10 A of current are flowing in the circuit. Since the meter movement has a full-scale voltage of 50 mV, it will indicate the full-scale value when 10 A of current are flowing through the shunt. An ammeter shunt is shown in FIGURE 8-15.

Ammeter shunts can be purchased to indicate different values. If the same 50-mV movement is connected across a shunt designed to drop 50 mV when 100 A of current flow through it, the meter will now have a full-scale value of 100 A.

The resistance of an ammeter shunt can be computed using Ohm's Law. The resistance of a shunt designed to have a voltage drop of 50 mV when 100 A of current flows through it is:

$$R = \frac{E}{I}$$

$$R = \frac{0.050}{100}$$

$$R = 0.0005\ \Omega, \text{ or } 0.5\ m\Omega$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

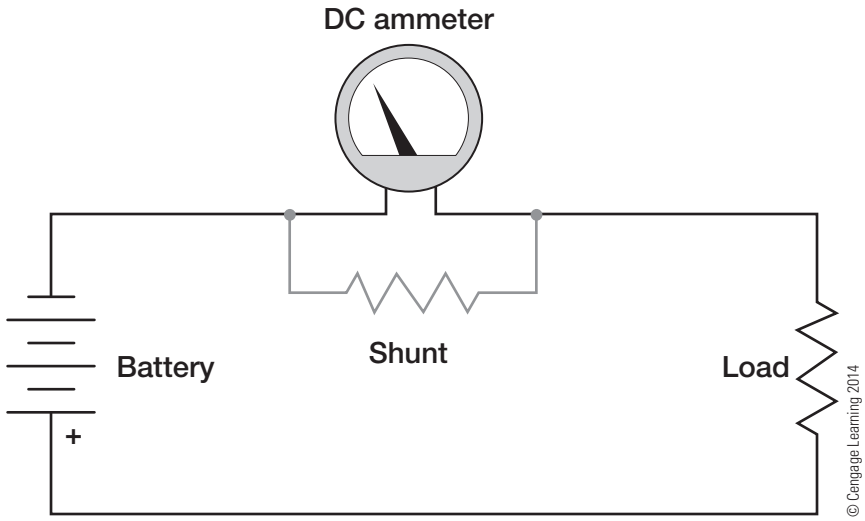


FIGURE 8-14 A shunt is used to set the value of the ammeter.

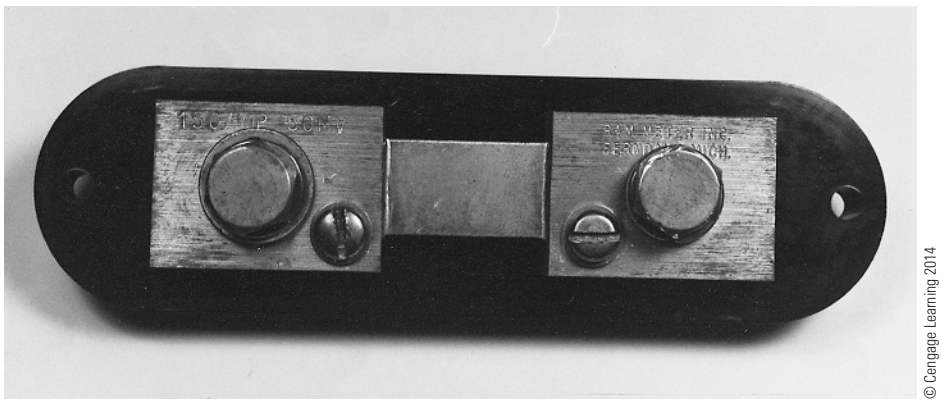


FIGURE 8-15 Ammeter shunt.

In the previous problem, no consideration was given to the electrical values of the meter movement. The reason is that the amount of current needed to operate the meter movement is so small compared to the 100-A circuit current, it could have no meaningful effect on the resistance value of the shunt. When computing the value for a low-current shunt, however, the meter values must be taken into consideration.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

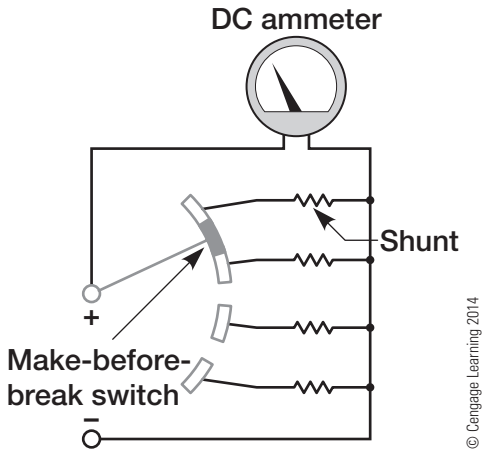


FIGURE 8-16 A make-before-break switch is used to change meter shunts.

MULTIRANGE AMMETERS

multirange ammeters
ammeters that contain more than one range.

Many ammeters, called **multirange ammeters,** are designed to operate on more than one range. This is done by connecting the meter movement to different shunts. **When a multirange meter is used, care must be taken that the shunt is never disconnected from the meter.** Disconnection would cause the meter movement to be inserted in series with the circuit, and full-circuit current would flow through the meter. Two basic methods are used for connecting shunts to a meter movement. One method is to use a make-before-break switch. This type of switch is designed so that it will make contact with the next shunt before it breaks connection with the shunt to which it is connected, FIGURE 8-16. This method does, however, present a problem: contact resistance. Notice in Figure 8-16 that the rotary switch is in series with the shunt resistors. This causes the contact resistance to be added to the shunt resistance, and can cause inaccuracy in the meter reading.

KEY POINT
When a multirange meter is used, care must be taken that the shunt is never disconnected from the meter.

THE AYRTON SHUNT

Ayrton shunt
a type of ammeter shunt.

The second method is to use an **Ayrton shunt,** FIGURE 8-17. In this type of circuit, connection is made to different parts of the shunt, and the meter movement is never disconnected from the shunt. Also, notice that the switch connections are made external to the shunt and meter. This prevents contact resistance from affecting the accuracy of the meter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

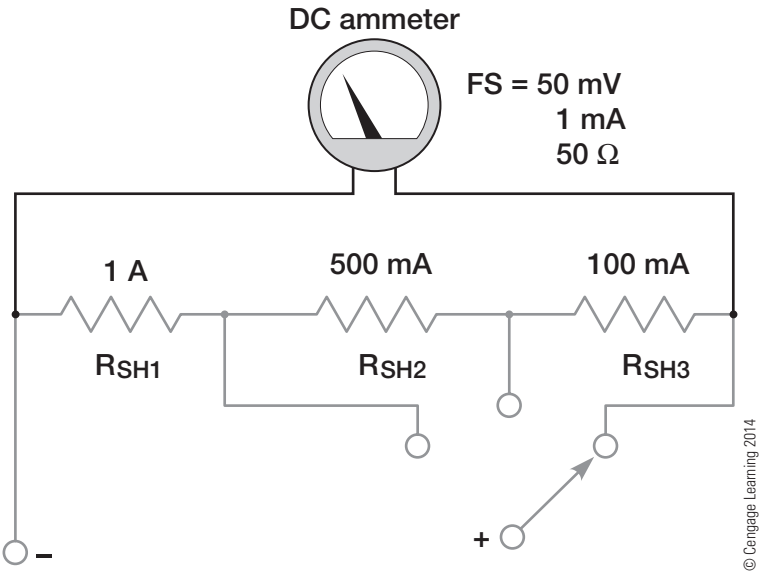


FIGURE 8-17 An Ayrton shunt.

ALTERNATING CURRENT AMMETERS

current transformer
electrical device that changes one value of AC voltage into another value of AC voltage.

Shunts can be used with alternating current (AC) ammeters to increase their range but cannot be used to decrease their range. Most AC ammeters use a **current transformer** instead of shunts to change scale values. This type of ammeter is shown in FIGURE 8-18. The primary of the transformer is connected in series with the load, and the ammeter is connected to the

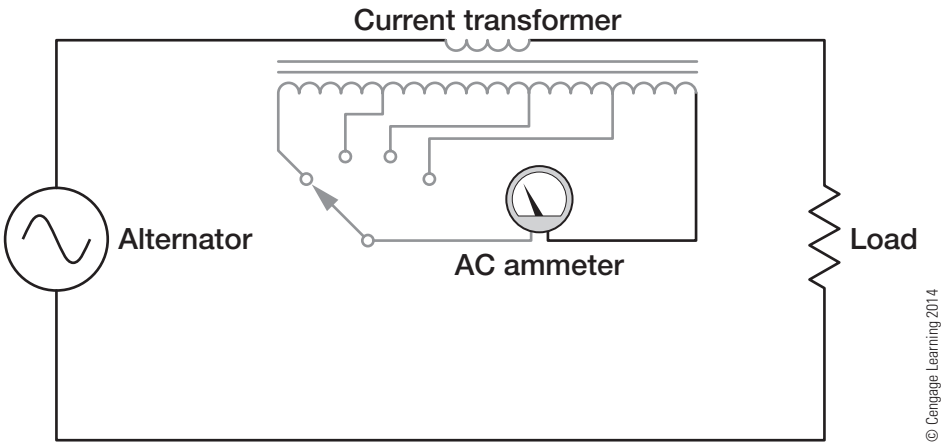
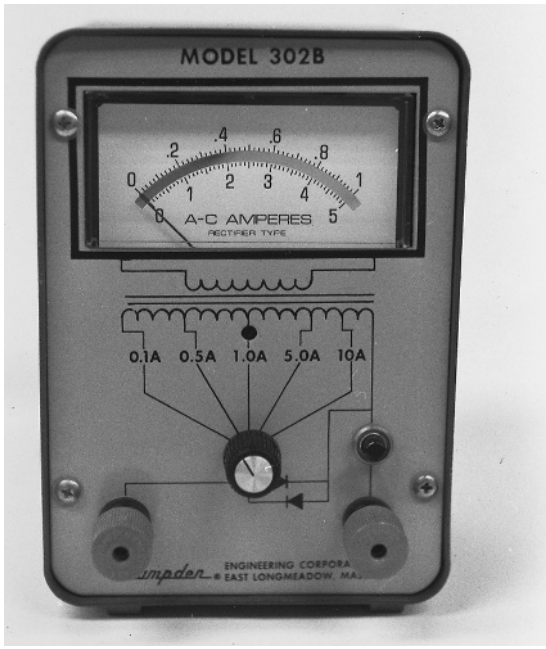


FIGURE 8-18 A current transformer is used to change the range of an AC ammeter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 8-19 Multirange AC ammeter.

secondary of the transformer. Notice that the range of the meter is changed by selecting different taps on the secondary of the current transformer. The different taps on the transformer provide different turns ratios between the primary and secondary of the transformer. An ammeter of this type is shown in FIGURE 8-19.

CURRENT TRANSFORMERS

When a large amount of AC current must be measured, a different type of current transformer (CT) is connected in the power line. These transformers have ratios that start at 200:5 and can have ratios of several thousand to five. These current transformers, generally referred to in industry as *CTs*, have a standard secondary current rating of 5-A AC. They are designed to be operated with a 5-A AC ammeter connected directly to their secondary winding, which produces a short circuit. CTs are designed to operate with the secondary winding shorted. **The secondary winding of a CT should never be opened when power is being applied to the primary. This will cause the transformer to produce a step-up in voltage that could be high enough to kill anyone who comes in contact with it.**

KEY POINT

The secondary winding of a CT should never be opened when power is being applied to the primary. This will cause the transformer to produce a step-up in voltage that could be high enough to kill anyone who comes in contact with it.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 8-20 Current transformer with a ratio of 600:5.

A current transformer is basically a toroid transformer. A toroid transformer is constructed with a hollow core similar to a donut, FIGURE 8-20. When current transformers are used, the main power line is inserted through the opening in the transformer, FIGURE 8-21. The power line acts as the primary of the transformer and is considered to be one turn.

The turns ratio of the transformer can be changed by looping the power wire through the opening in the transformer to produce a primary winding of more than one turn. For example, assume a current transformer has a ratio of 600:5. If the primary power wire is inserted through the opening, it will require a current of 600 A to deflect the meter full scale. If the primary power conductor is looped around and inserted through the window a second time, the primary now contains two turns of wire instead of one, FIGURE 8-22. It now requires 300 A of current flow in the primary to deflect the meter full scale. If the primary conductor is looped through the opening a third time, it would require only 200 A of current flow to deflect the meter full scale.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

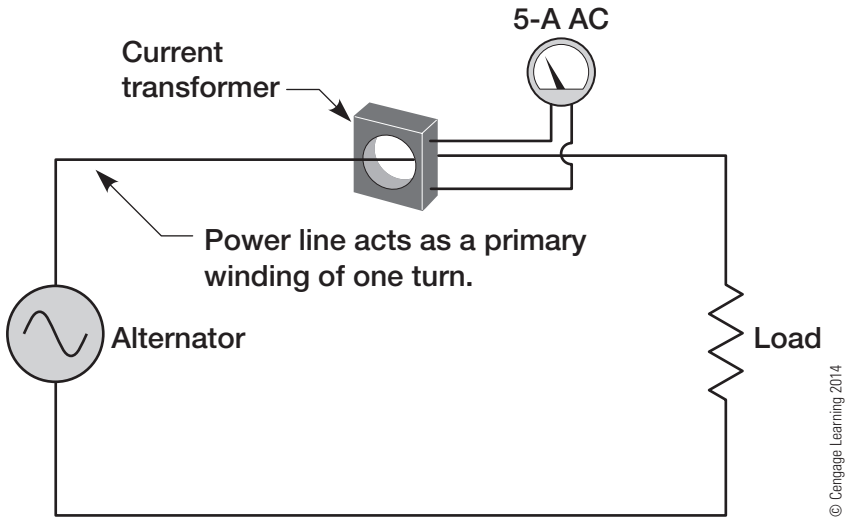


FIGURE 8-21 The main power line is run through the opening of the current transformer.

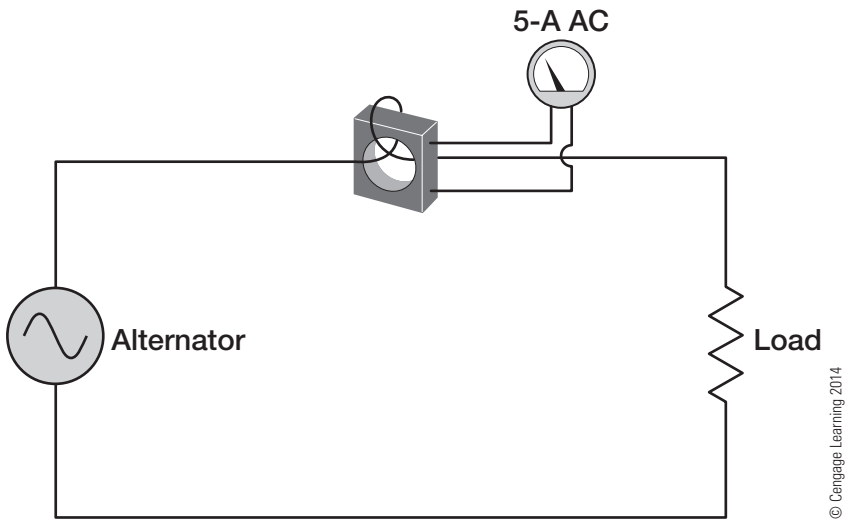


FIGURE 8-22 The primary conductor loops through the current transformer to produce a second turn, which changes the ratio.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CLAMP-ON AMMETERS

clamp-on ammeter
an ammeter that does not have to be physically connected into the circuit.

Many electricians use a type of AC ammeter called a **clamp-on ammeter,** FIGURE 8-23. To use this type of meter, the jaw of the meter is clamped around one of the conductors supplying power to the load, FIGURE 8-24. The meter is clamped around only one of the lines. If the meter is clamped around more than one line, the magnetic fields of the wires cancel each other and the meter indicates zero.

The clamp-on meter also uses a current transformer to operate. The jaw of the meter is part of the core material of the transformer. When the meter is connected around the current-carrying wire, the changing magnetic field produced by the AC current induces a voltage into the current transformer. The strength and frequency of the magnetic field determines the amount of voltage induced in the current transformer. Because 60 Hz is a standard frequency throughout the country, the amount of induced voltage is proportional to the strength of the magnetic field.

The clamp-on ammeter can be used with different range settings by changing the turns ratio of the secondary of the transformer, just as is done on the in-line ammeter. The primary of the transformer is the conductor around



© Cengage Learning 2014

FIGURE 8-23 Clamp-on AC ammeter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

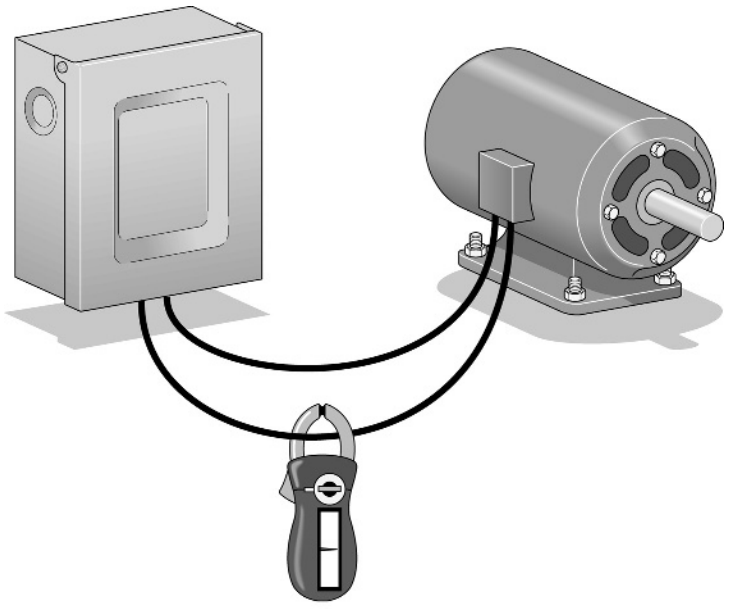


FIGURE 8-24 The clamp-on ammeter connects around only one conductor.

which the movable jaw is connected. If the ammeter is connected around one wire, the primary has one turn of wire compared to the turns of the secondary. The turns ratio can be changed in the same manner as the ratio of the CT. If two turns of wire are wrapped around the jaw of the ammeter, FIGURE 8-25, the primary winding now contains two turns instead of one, and the turns ratio of the transformer is changed. The ammeter will now indicate double the amount of current in the circuit. The reading on the scale of the meter would have to be divided by two to get the correct reading. The ability to change the turns ratio of a clamp-on ammeter can be useful for measuring low currents. Changing the turns ratio is not limited to wrapping two turns of wire around the jaw of the ammeter. Any number of turns can be wrapped around the jaw, and the reading will be divided by that number.

A problem with many clamp-on type ammeters is that their lowest scale value is too high to accurately measure low current values. For example, an ammeter with a full-scale range of 0–6 A would not be able to accurately measure a current flow of 0.2 A. The answer to this problem is to wrap many turns of wire around the jaw of the ammeter to change the secondary scale value. If ten turns of wire are wrapped around the jaw of a 0- to 6-A meter, the meter will now indicate a full-scale value of 0.6 A. The meter could now

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

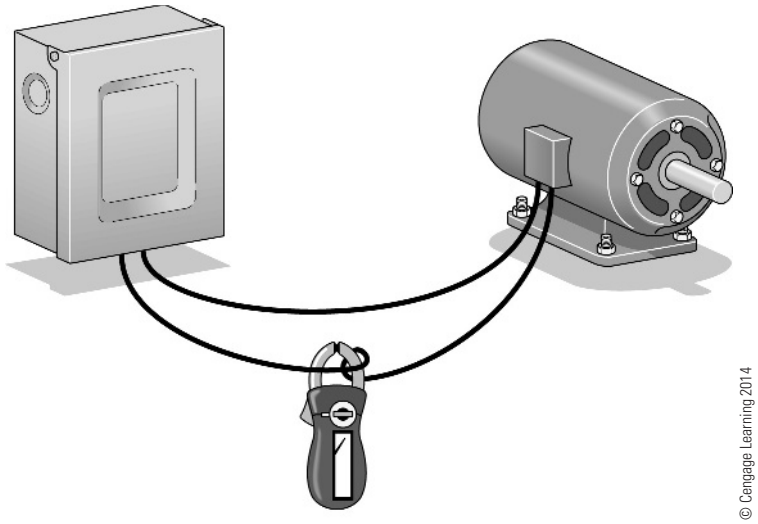


FIGURE 8-25 Looping the conductor around the jaw of the ammeter changes the ratio.

accurately measure a current of 0.2 A. In the field, however, it is not often that there is enough slack wire to make ten wraps around the jaw of an ammeter. A simple device can be constructed to overcome this problem. Assume that ten turns of wire are wound around a piece of non-conductive material, such as a piece of plastic pipe, FIGURE 8-26. Plastic tape is then used to prevent the wire from slipping off the plastic core. If alligator clips are attached to the ends of the wire, the device can be inserted in series with the load in a similar manner to using an in-line ammeter. The jaw of the ammeter can then be inserted through the opening in the plastic pipe, FIGURE 8-27. The current value is then read by moving the decimal one place to the left. A full-scale value of 0–6 A becomes a full-scale value of 0–0.6 A, and a 0 to 30-A scale becomes a 0 to 3-A scale.

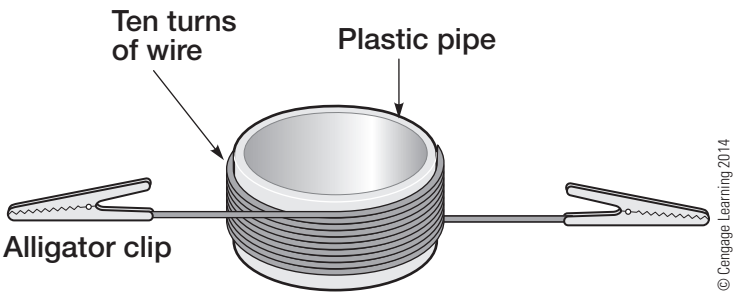


FIGURE 8-26 Ten turns of wire are wrapped around a plastic pipe and two alligator clips are attached.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

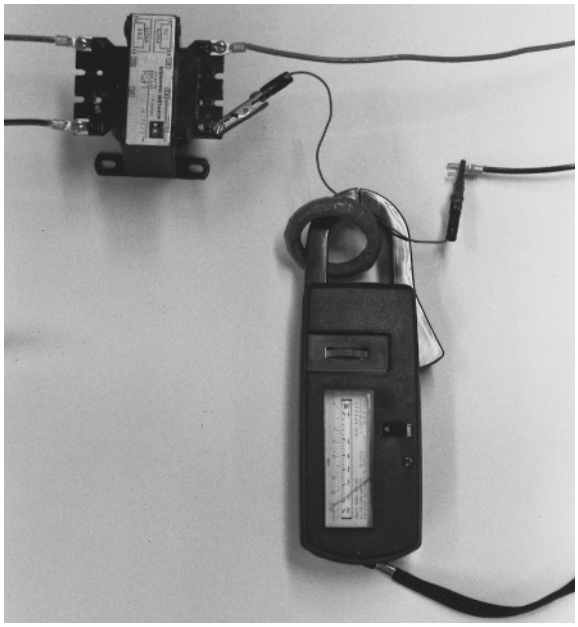

© Cengage Learning 2014

FIGURE 8-27 A simple device for increasing the range of a clamp-on ammeter.

DC-AC CLAMP-ON AMMETERS

Most clamp-on ammeters that have the ability to measure both direct and alternating current do not operate on the principle of the current transformer. Current transformers depend on induction, which means that the current in the line must change direction periodically to provide a change of magnetic field polarity. It is the continuous change of field strength and direction that permits the current transformer to operate. The current in a DC circuit is unidirectional and does not change polarity, so it would not permit the current transformer to operate.

DC-AC clamp-on ammeters, FIGURE 8-28, use the *Hall effect* as the basic principle of operation. The Hall effect was discovered by Edward H. Hall at Johns Hopkins University in 1879. Hall originally used a piece of pure gold to produce the Hall effect, but today a semiconductor material is used because it has better operating characteristics and is less expensive. The device is often referred to as a *Hall generator.* FIGURE 8-29 illustrates the operating principle of the Hall generator. A constant current generator is used to supply a continuous current to the semiconductor chip. The leads of a zero-center voltmeter are connected across the opposite sides of the chip. As long as the current flows through the center of the semiconductor chip, there is no potential difference or voltage developed across the chip.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

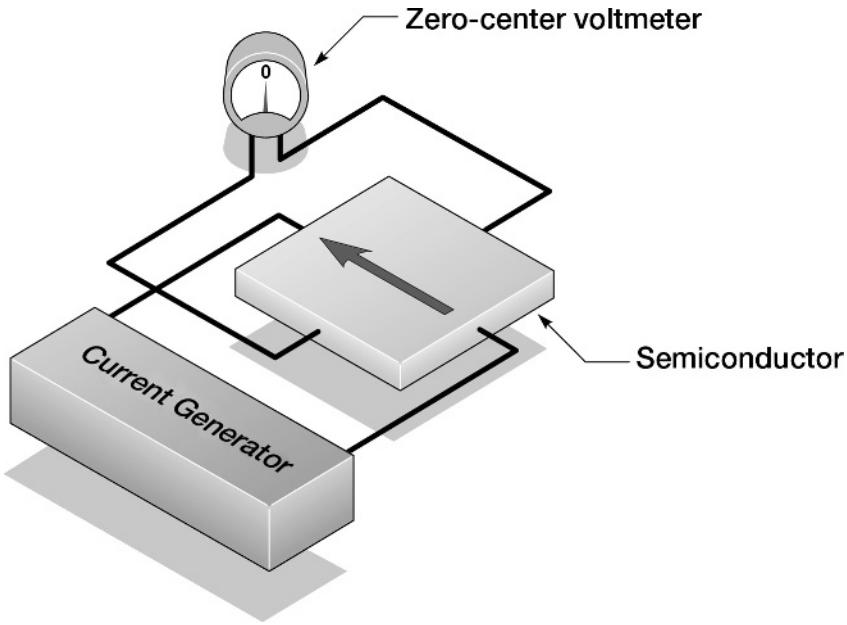


© Cengage Learning 2014

© Cengage Learning 2014

(A) (B)

FIGURE 8-28 DC-AC clamp-on ammeter. Digital clamp-on ammeter.



© Cengage Learning 2014

FIGURE 8-29 Basic Hall generator.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

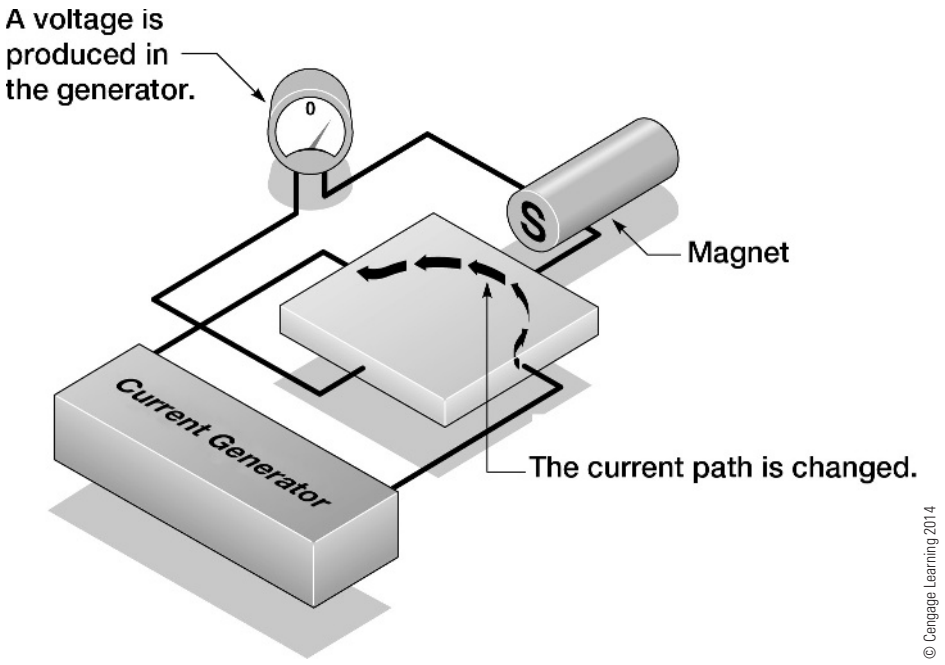


FIGURE 8-30 The presence of a magnetic field causes the Hall generator to produce a voltage.

If a magnetic field comes near the chip, FIGURE 8-30, the electron path is distorted and the current no longer flows through the center of the chip. A voltage across the sides of the chip is produced. The voltage is proportional to the amount of current flow and the amount of current distortion. Since the current remains constant and the amount of distortion is proportional to the strength of the magnetic field, the voltage produced across the chip is proportional to the strength of the magnetic field.

If the polarity of the magnetic field should be reversed, FIGURE 8-31, the current path would be distorted in the opposite direction, producing a voltage of the opposite polarity. Notice that the Hall generator produces a voltage in the presence of a magnetic field. It makes no difference whether the field is moving or stationary. The Hall effect can, therefore, be used to measure direct or alternating current.

THE OHMMETER

The **ohmmeter** is used to measure resistance. The common VOM (volt-ohm-milliammeter) contains an ohmmeter. The ohmmeter has the only scale on a VOM that is nonlinear. The scale numbers increase in value as they progress

ohmmeter
device used to measure resistance.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

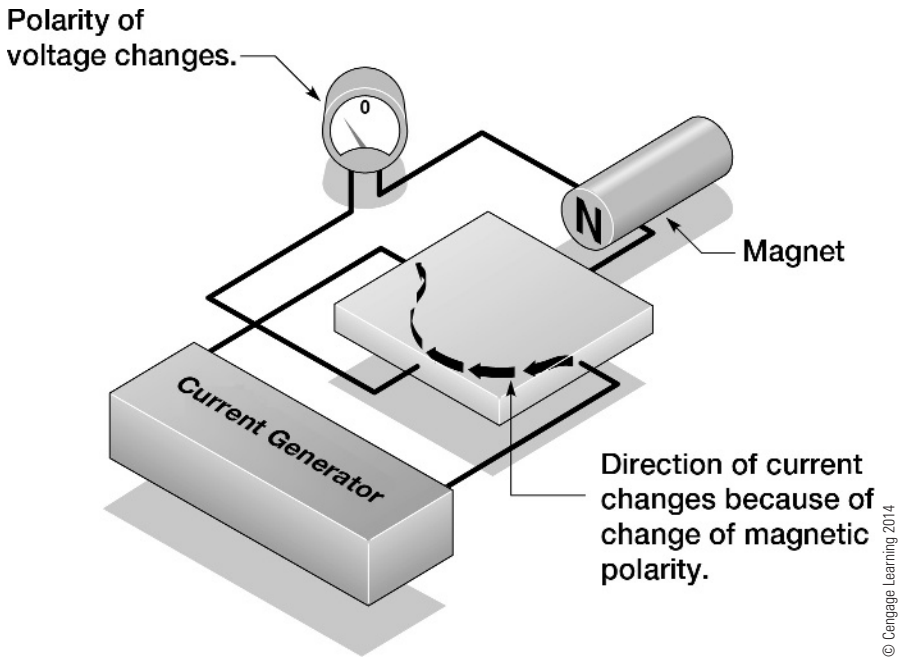


FIGURE 8-31 If the polarity of the magnetic field changes, the polarity of the voltage changes.

from right to left. There are two basic types of analog ohmmeters, the series and the shunt. The series ohmmeter is used to measure high values of resistance, and the shunt type is used to measure low values of resistance. Regardless of the type used, the meter must provide its own power source to measure resistance. The power is provided by batteries located inside the instrument.

THE SERIES OHMMETER

A schematic for a basic series ohmmeter is shown in FIGURE 8-32. It is assumed that the meter movement has a resistance of 1,000 Ω and requires a current of 50 μA to deflect the meter full scale. The power source will be a 3-V battery. A fixed resistor with a value of 54 kΩ, R_1 is connected in series with the meter movement, and a variable resistor with a value of 10 kΩ, R_2 is connected in series with the meter and R_1. These resistance values were chosen to ensure there would be enough resistance in the circuit to limit the current flow through the meter movement to 50 μA. If Ohm's Law is used to compute the resistance needed (3 V/0.000050 A = 60,000 Ω), it will be seen that a value of 60 kΩ is needed. This circuit contains a total of 65,000 Ω (1,000 [meter] + 54,000 + 10,000). The circuit resistance can be changed by adjusting

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

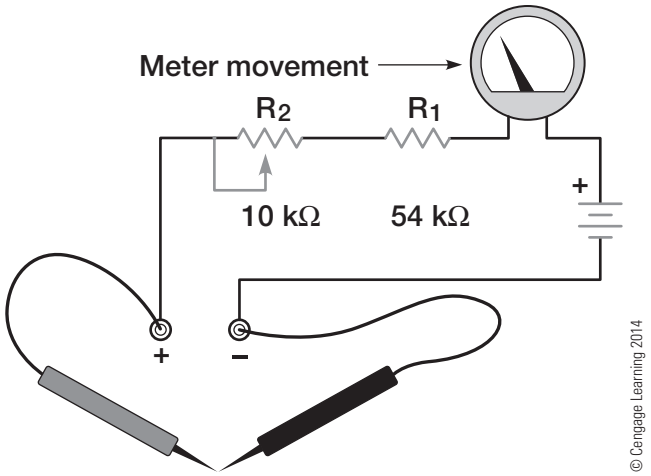


FIGURE 8-32 Basic series ohmmeter.

the variable resistor to a value as low as 55,000 Ω, however, to compensate for the battery as it ages and becomes weaker.

When resistance is to be measured, the meter must first be zeroed. This is done with the ohms-adjust control, the variable resistor located on the front of the meter. To zero the meter, connect the leads together, Figure 8-32, and turn the ohms-adjust knob until the meter indicates zero at the far right end of the scale, FIGURE 8-33. When the leads are separated, the meter will again indicate infinity resistance at the left side of the meter scale. When the leads are connected across a resistance, the meter will again go up the scale. Since resistance has been added to the circuit, less than 50 μA of current will flow, and

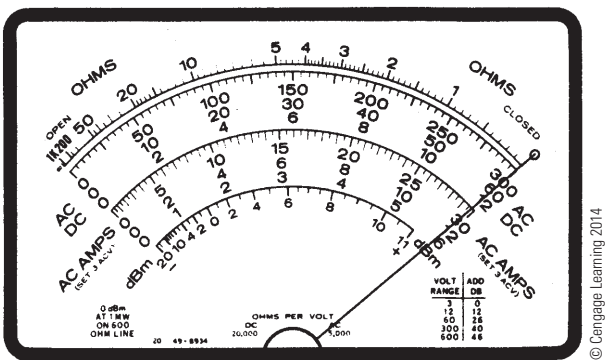
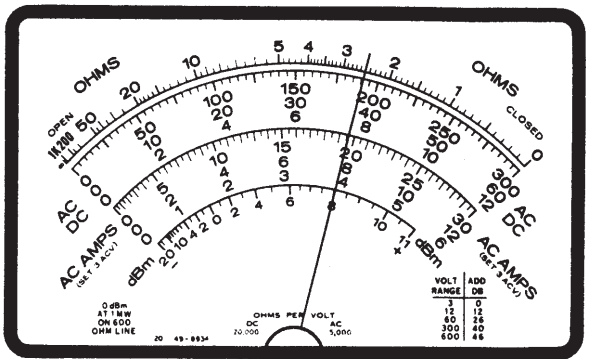


FIGURE 8-33 Adjusting the ohmmeter to zero.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 8-34 Reading the ohmmeter.

the meter will indicate some value other than zero. FIGURE 8-34 shows a meter indicating a resistance of 25 Ω, assuming the range setting is R_X1.

KEY POINT
An ohmmeter should always be readjusted to zero when the scale is changed.

Ohmmeters can have different range settings, such as R_X1, R_X100, R_X1000, or $R_x10{,}000$. These different scales can be obtained by adding different values of resistance in the meter circuit and resetting the meter to zero. **An ohmmeter should always be readjusted to zero when the scale is changed.** On the R_X1 setting, the resistance is measured straight off the resistance scale located at the top of the meter. If the range is set for R_X1000, however, the reading must be multiplied by 1,000. The ohmmeter reading shown in Figure 8-34 would be indicating a resistance of 25,000 Ω if the range had been set for R_X1000. Notice that the ohmmeter scale is read backward from the other scales: zero ohms is located on the far right side of the scale and maximum ohms is located at the far left side. It generally takes a little time and practice to read the ohmmeter properly.

SHUNT-TYPE OHMMETERS

As stated previously, the shunt-type ohmmeter is used for measuring low values of resistance. It operates on the same basic principle as an ammeter shunt. When using a shunt-type ohmmeter, place the unknown value of resistance in parallel with the meter movement. This causes part of the circuit current to bypass the meter, FIGURE 8-35.

DIGITAL METERS

DIGITAL OHMMETERS

Digital ohmmeters display the resistance in figures instead of using a meter movement. When using a digital ohmmeter, care must be taken to notice the scale indication on the meter. For example, most digital meters will display

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

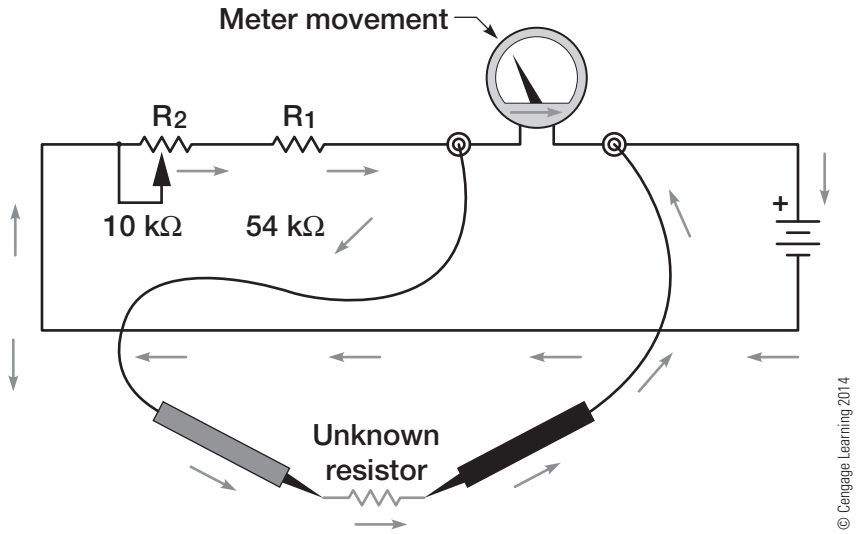


FIGURE 8-35 Shunt type ohmmeter.

a K on the scale to indicate kilohms or an M to indicate megohms (kilo means 1,000 and mega means 1,000,000). If the meter is showing a resistance of 0.200 K, it means 0.200 × 1000 or 200 Ω. If the meter indicates 1.65 M, it means 1.65 × 1,000,000 or 1,650,000 Ω.

Appearance is not the only difference between analog and digital ohmmeters. Their operating principle is different also. Analog meters operate by measuring the amount of current change in the circuit when an unknown value of resistance is added. Digital ohmmeters measure resistance by measuring the amount of voltage drop across an unknown resistance. In the circuit shown in FIGURE 8-36, a constant current generator is used to supply a known amount of current to a resistor, R_x. It will be assumed that the amount of current supplied is 1 mA. The voltage drop across the resistor is proportional to the resistance of the resistor and the amount of current flow. For example, assume the value of the unknown resistor is 4,700 Ω. The voltmeter would indicate a drop of 4.7 V when 1 mA of current flowed through the resistor. The scale factor of the ohmmeter can be changed by changing the amount of current flow through the resistor. Digital ohmmeters generally exhibit an accuracy of about 1%.

The ohmmeter, whether digital or analog, must never be connected to a circuit when the power is turned on. Since the ohmmeter uses its own internal power supply, it has a very low operating voltage. Connecting a meter to power when it is set in the ohms position will probably damage or destroy the meter.

KEY POINT

The ohmmeter, whether digital or analog, must never be connected to a circuit when the power is turned on.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

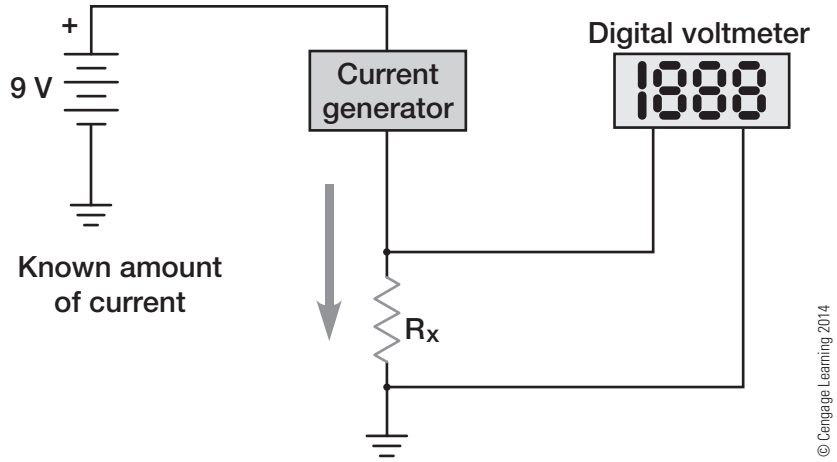


FIGURE 8-36 Digital ohmmeters operate by measuring the voltage drop across a resistor when a known amount of current flows through it.

DIGITAL MULTIMETERS

Digital multimeters have become increasingly popular in the past few years. The most apparent difference between digital meters and analog meters is that digital meters display their reading in discrete digits instead of with a pointer and scale. A digital multimeter is shown in FIGURE 8-37. Some digital meters have a range switch similar to the range switch used with analog meters. This switch sets the full range value of the meter. Many digital meters have voltage range settings from 200 mV to 2,000 V. The lower ranges are used for accuracy. For example, assume it is necessary to measure a voltage of 16 V. The meter will be able to make a more accurate measurement when set on the 20-V range than when set on the 2,000-V range.

Some digital meters do not contain a range-setting control. These meters are known as autoranging meters. They contain a function control switch that permits selection of the electrical quantity to be measured, such as AC volts, DC volts, ohms, and so on. When the meter probes are connected to the object to be tested, the meter automatically selects the proper range and displays the value.

Analog meters change scale value by inserting or removing resistance from the meter circuit, Figure 8-6. The typical resistance of an analog meter is 20,000 Ω per volt for DC and 5,000 Ω per volt for AC. If the meter is set for a full-scale value of 60 V, there will be 1.2 MΩ of resistance connected in series with the meter if it is being used to measure DC ($60 \times 20{,}000 = 1{,}200{,}000$) and 300 kΩ if it is being used to measure AC ($60 \times 5000 = 300{,}000$). The impedance of the meter is of little concern if it is used to measure circuits

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 8-37 Digital multimeter.

that are connected to a high current source. For example, assume the voltage of a 480-V panel is to be measured with a multimeter that has a resistance of 5,000 Ω per volt. If the meter is set on the 600-V range, the resistance connected in series with the meter is 3 MΩ (600 × 5000 = 3,000,000). This will permit a current of 160 μA to flow in the meter circuit (480/3,000,000 = 0.000160). The 160 μA of current are not enough to affect the circuit being tested.

Now assume that this meter is to be used to test a 24-V circuit that has a current flow of 100 μA. If the 60-V range is used, the meter circuit contains a resistance of 300 kΩ (60 × 5000 = 300,000). This means that a current of 80 μA will flow when the meter is connected to the circuit (24/300,000 = 0.000080). The connection of the meter to the circuit has changed the entire circuit operation. This is known as the *loading effect.*

Digital meters do not have a loading effect. Most digital meters have an input impedance of about 10 MΩ on all ranges. This impedance is accomplished by using field effect transistors (FETs) and a voltage divider circuit. A simple schematic for this circuit is shown in FIGURE 8-38. Notice that the meter input is connected across 10 MΩ of resistance regardless of the range setting of the meter. If this meter is used to measure the voltage of the 24-V circuit, a current of 2.4 μA will flow through the meter. This is not enough current to upset the rest of the circuit, and voltage measurements can be made accurately.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

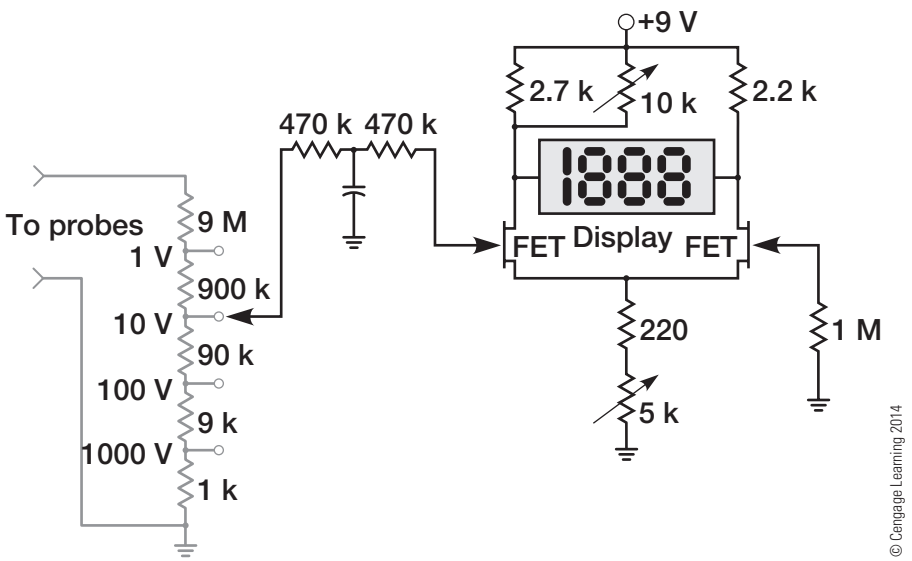


FIGURE 8-38 Digital voltmeter.

THE LOW-IMPEDANCE VOLTAGE TESTER

Another device used to test voltage is often referred to as a voltage tester. This device does measure voltage, but it does not contain a meter movement or digital display. It contains a coil and a plunger. The coil produces a magnetic field that is proportional to the voltage to which the tester is connected. The higher the voltage to which the tester is connected, the stronger the magnetic field becomes. The plunger must overcome the force of a spring as it is drawn into the coil, FIGURE 8-39. The plunger acts as a pointer to indicate the amount of voltage to which the tester is connected. The tester has an impedance of approximately 5,000 Ω and can generally be used to measure voltages as high as 600 V. **The low-impedance voltage tester has a very large current draw compared with other types of voltmeters and should never be used to test low-power circuits.**

KEY POINT
The low-impedance voltage tester has a very large current draw compared with other types of voltmeters and should never be used to test low-power circuits.

The relatively high current draw of the voltage tester can be an advantage when testing certain types of circuits. This is true because it is not susceptible to giving the misleading voltage readings caused by high impedance ground paths or feedback voltages that affect other types of voltmeters. An example of this advantage is shown in FIGURE 8-40. A transformer is used to supply power to a load. Notice that neither the output side of the transformer nor the load are connected to ground. If a high impedance voltmeter is used to measure between one side of the transformer and a grounded point, it will most likely indicate some amount of voltage. This is because that ground can act

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

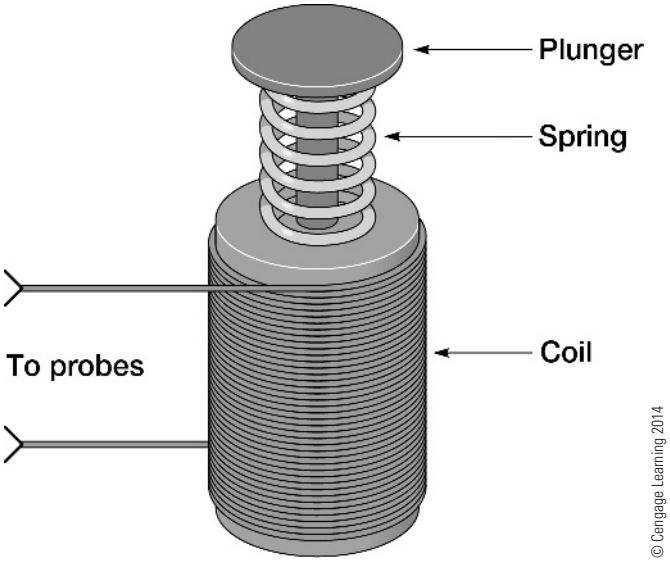


FIGURE 8-39 Low-impedance voltage tester.

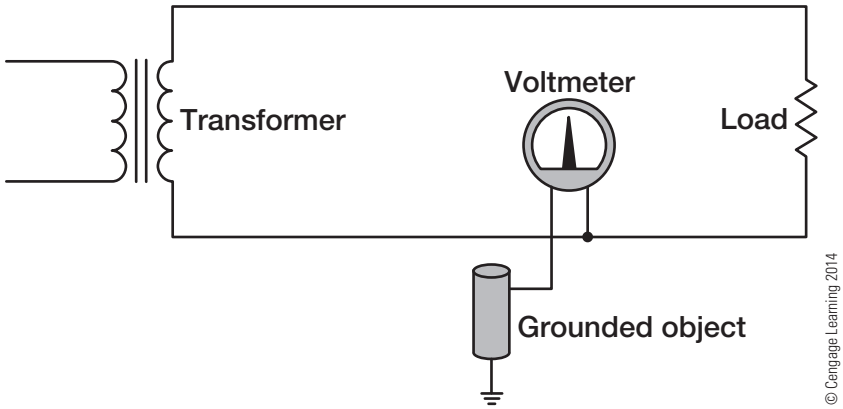


FIGURE 8-40 High-impedance ground paths can produce misleading voltage readings.

as a large capacitor and permit a small amount of current to flow through the circuit created by the meter. This high-impedance ground path can support only a few microamperes of current flow, but it is enough to operate the meter movement. If a voltage tester is used to make the same measurement, it will not show a voltage because there cannot be enough current flow to attract the plunger. A voltage tester is shown in FIGURE 8-41.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



Courtesy Schneider Electric

FIGURE 8-41 Low-impedance voltage tester.

THE WATTMETER

wattmeter
measures the true power in a circuit.

The **wattmeter** is used to measure the power in a circuit. This meter differs from the d'Arsonval type of meter because it does not contain a permanent magnet. This meter contains a set of electromagnets and a moving coil, FIGURE 8-42. The electromagnets are connected in series with the load in the same manner that an ammeter is connected. The moving coil has resistance connected in series with it, and is connected directly across the power source in the same manner as a voltmeter, FIGURE 8-43.

Since the electromagnet is connected in series with the load, the current flow through the load determines the magnetic field strength of the stationary magnet. The magnetic field strength of the moving coil is determined by the amount of line voltage. The turning force of the coil is proportional to the strength of these two magnetic fields. The deflection of

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

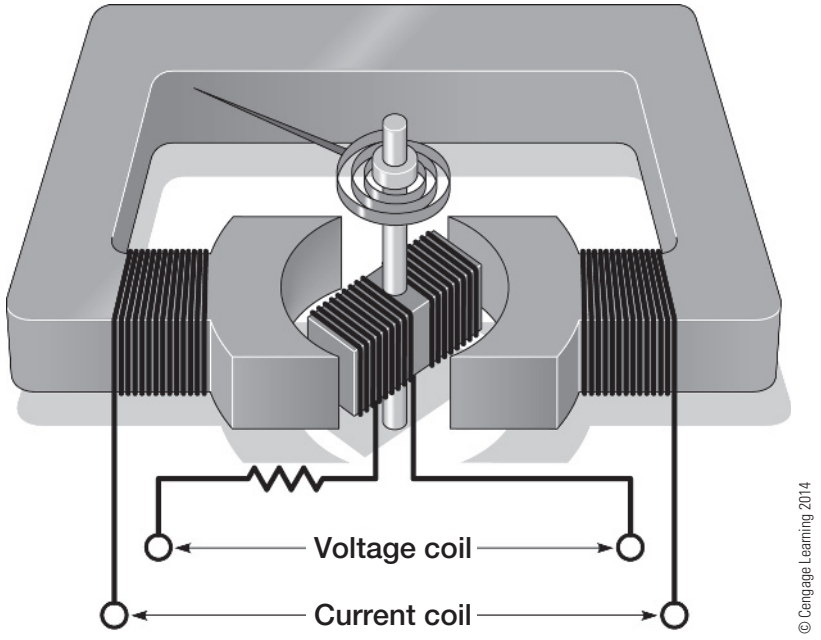


FIGURE 8-42 A dynamic wattmeter contains two coils—one for voltage and the other for current.

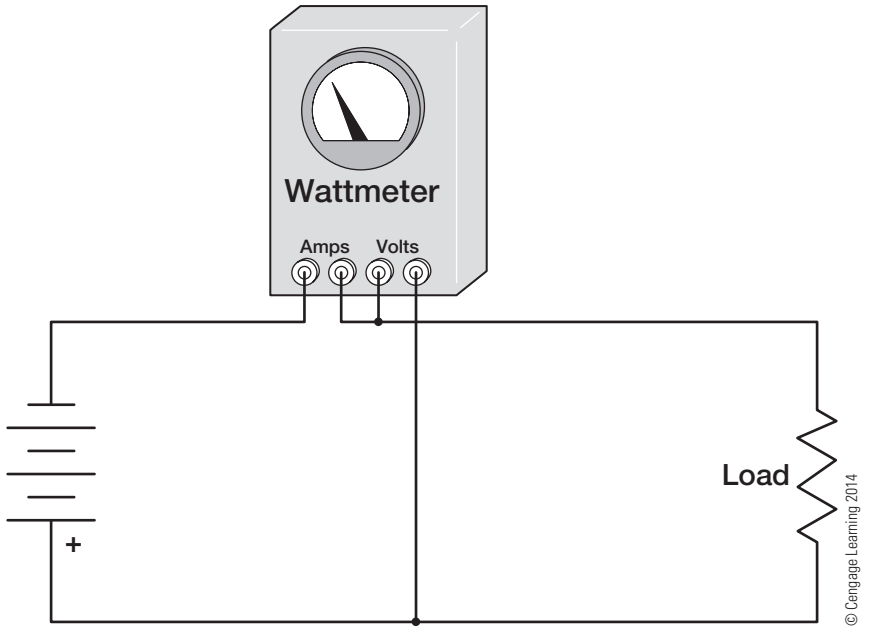


FIGURE 8-43 The current section of the wattmeter is connected in series with the load, and the voltage section is connected in parallel with the load.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

the meter against the spring is proportional to the amount of current flow and voltage.

Since the wattmeter contains an electromagnet instead of a permanent magnet, the polarity of the magnetic field is determined by the direction of current flow. The same is true of the polarity of the moving coil connected across the source of voltage. If the wattmeter is connected into an AC circuit, the polarity of both coils will reverse at the same time, producing a continuous torque. For this reason, the wattmeter can be used to measure power in either a direct or alternating current circuit. It should be noted, however, that if the connection of the stationary coil or the moving coil should be reversed, the meter will attempt to read backward.

ELECTRONIC WATTMETERS

The wattmeter previously described is generally referred to as a *dynamic wattmeter.* Many manufacturers use an electronic circuit to determine watts because of the expense of producing dynamic wattmeters. This circuit is connected to a standard d'Arsonval meter movement that has been scaled to indicate watts. The advantage of an electronic wattmeter is that it costs much less. The disadvantage of an electronic wattmeter is that it cannot be connected into a DC circuit; it can be used in AC circuits only.

RECORDING METERS

There are occasions when it becomes necessary to make a recording of an electrical value over a long period of time. Recording meters produce a graph of metered values during a certain length of time. They are used to detect spike voltages, or currents of short duration, or sudden drops in voltage current, or power. Recording meters can show the amount of voltage or current, its duration, and the time of occurrence. Some meters have the ability to store information in memory over a period of several days. This information can be recalled later by the service technician. Two types of recording meters are shown in FIGURE 8-44A and FIGURE 8-44B.

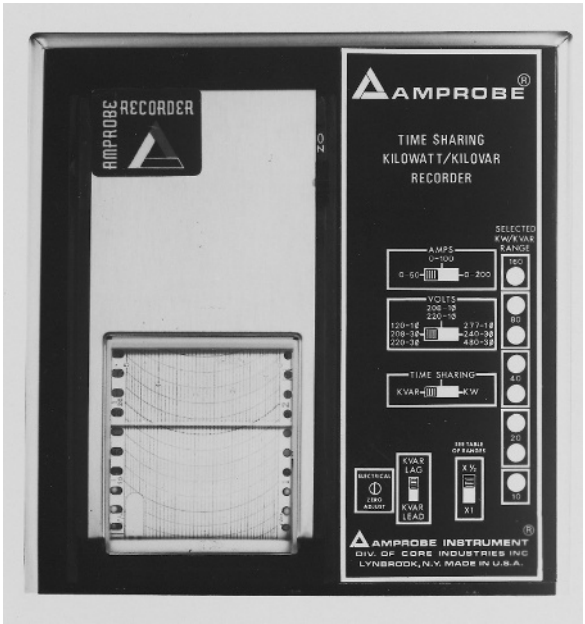
BRIDGE CIRCUITS

bridge circuit
circuit that consists of four sections connected in series to form a closed loop.

Wheatstone bridge
a device for measuring resistance.

One of the most common devices used to measure values of resistance, inductance, and capacitance accurately is a **bridge circuit.** A bridge is constructed by connecting four components to form a parallel-series circuit. All four components are of the same type, such as four resistors, four inductors, or four capacitors. The bridge used to measure resistance is called a **Wheatstone bridge.** The basic circuit for a Wheatstone bridge is shown in FIGURE 8-45. The bridge operates on the principle that the sum of the voltage

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



Courtesy of Amprobe Instrument®

(A)



Courtesy of Amprobe Instrument®

(B)

FIGURE 8-44 Recording-type meters.

drops in a series circuit must equal the applied voltage. A galvanometer is used to measure the voltage between points B and D. The galvanometer can be connected to different values of resistance or directly between points B and D. Values of resistance are used to determine the sensitivity of the meter circuit. When the meter is connected directly across the two points, its sensitivity is maximum.

In FIGURE 8-45, assume the battery has a voltage of 12 V, and that resistors R_1 and R_2 are precision resistors that have the same value of resistance. Since resistors R_1 and R_2 are connected in series and have the same value, each will have a voltage drop equal to one-half of the applied voltage or 6 V. This means that point B is 6 V more negative than point A, and 6 V more positive than point C.

Resistors R_V (variable) and R_X (unknown) are connected in series. Resistor R_X represents the unknown value of resistance to be measured. Resistor R_V can be adjusted for different resistive values. If the value of R_V should be greater than the value of R_X, the voltage at point D will be more positive than the voltage at point B. This will cause the pointer of the zero-center galvanometer to move in one direction. If the value of R_V is less than R_X, the voltage at point D will be more negative than the voltage at point B, causing the point

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

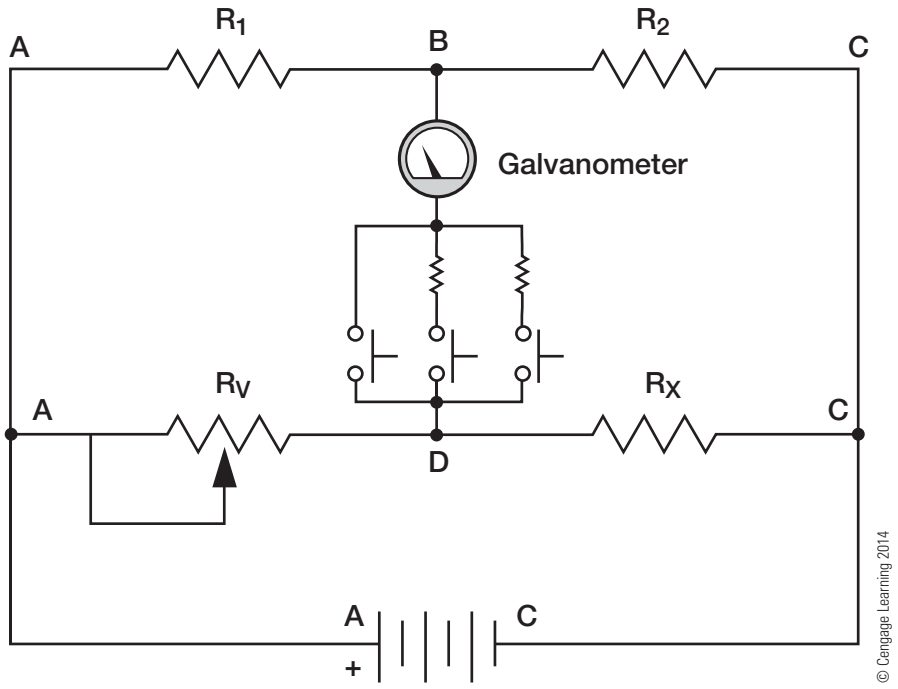


FIGURE 8-45 The Wheatstone bridge circuit is used to make accurate measurements of resistance and operates on the principle that the sum of the voltage drops in a series circuit must equal the applied voltage.

to move in the opposite direction. When the value of R_V becomes equal to R_X, the voltage at point D will become equal to the voltage at point B. When this occurs, the galvanometer will indicate zero. A Wheatstone bridge is shown in FIGURE 8-46.

THE OSCILLOSCOPE

Many of the electronic control systems in today's industry produce voltage pulses that are meaningless to a VOM. In many instances, it is necessary to know not only the amount of voltage present at a particular point, but also the length or duration of the pulse and its frequency. Some pulses may be less than one volt and last for only a millisecond. A VOM would be useless for measuring such a pulse. It is therefore necessary to use an oscilloscope to learn what is actually happening in the circuit.

oscilloscope
voltmeter that displays a waveform of voltage in proportion to its amplitude with respect to time.

The oscilloscope is a powerful tool in the hands of a trained technician. The first thing to understand is that an **oscilloscope** is a voltmeter. It does not measure current, resistance, or watts. The oscilloscope measures an amount of voltage during a period of time and produces a two-dimensional image.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



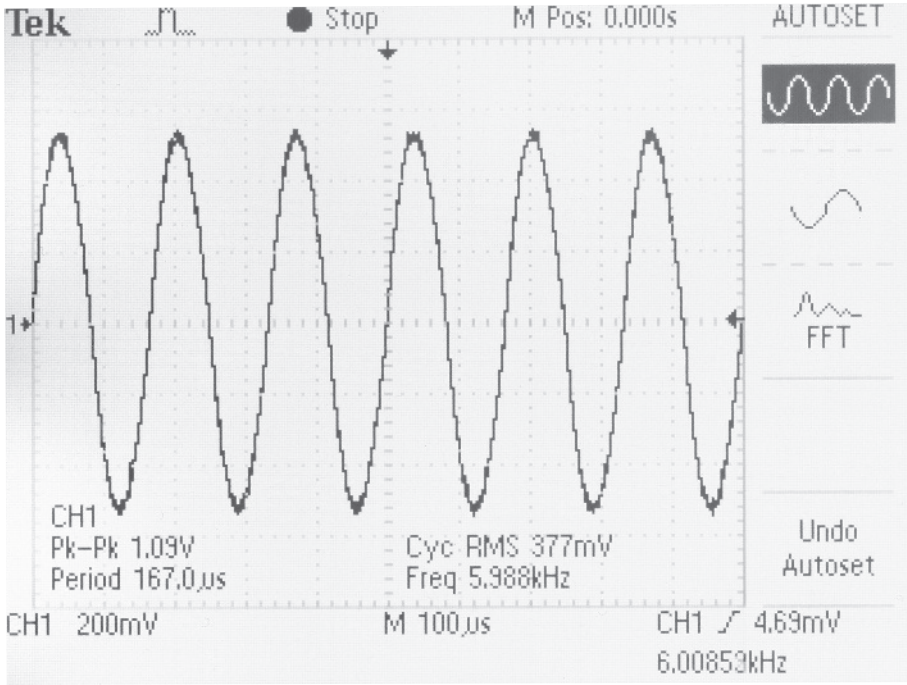
© Cengage Learning 2014

FIGURE 8-46 Wheatstone bridge.

Voltage Range Selection

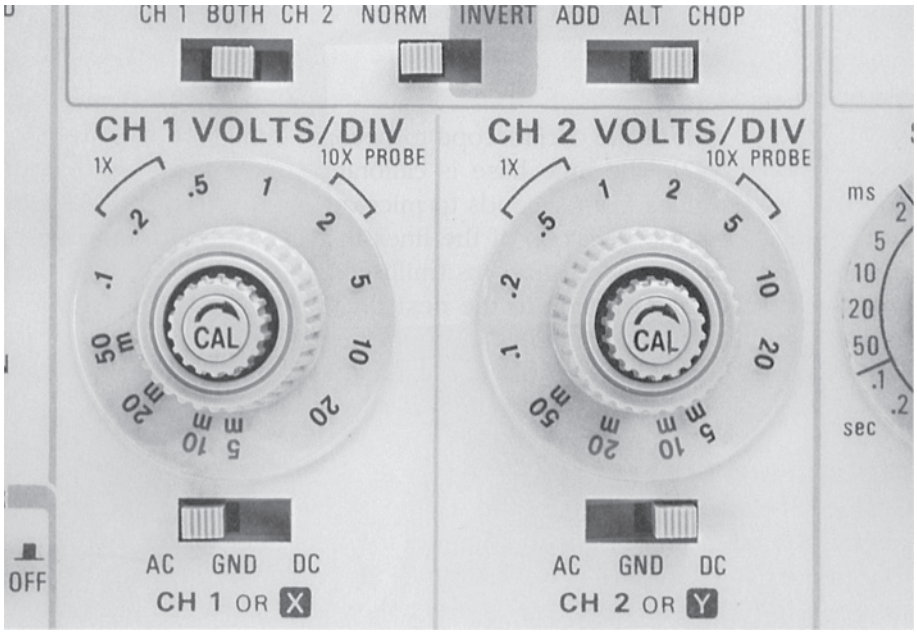
The oscilloscope is divided into two main sections. One section is the voltage section, and the other is the time base. The display of the oscilloscope is divided by vertical and horizontal lines, FIGURE 8-47. Voltage is measured on the vertical, or Y, axis of the display, and time is measured on the horizontal, or X, axis. When using a VOM, a range selection switch is used to determine the full-scale value of the meter. Ranges of 600 V, 300 V, 60 V, and 12 V are common. The ability to change ranges permits more-accurate measurements to be made. The oscilloscope has a voltage range selection switch also, FIGURE 8-48. The voltage range selection switch on an oscilloscope selects volts per division instead of volts full scale. Assume that the voltage range switch shown in Figure 8-48 is set for 10 mV at the 1X position. This means that each of the vertical lines on the Y axis of the display has a value of 10 mV. Assume the oscilloscope has been adjusted to permit 0 V to be shown on the center line of the display. If the oscilloscope probe were connected to a positive voltage of 30 mV, the trace would rise to the position shown in FIGURE 8-49A. If the probe were connected to a negative 30 mV, the trace would fall to the position shown in FIGURE 8-49B. Notice that the oscilloscope has the ability to display both a positive and a negative voltage. If the range switch were changed to 20 V per division, Figure 8-49A would be displaying 60 V positive.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



Courtesy of Tektronix Inc.

FIGURE 8-47 Oscilloscope display.



Courtesy of Tektronix Inc.

FIGURE 8-48 Voltage control.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

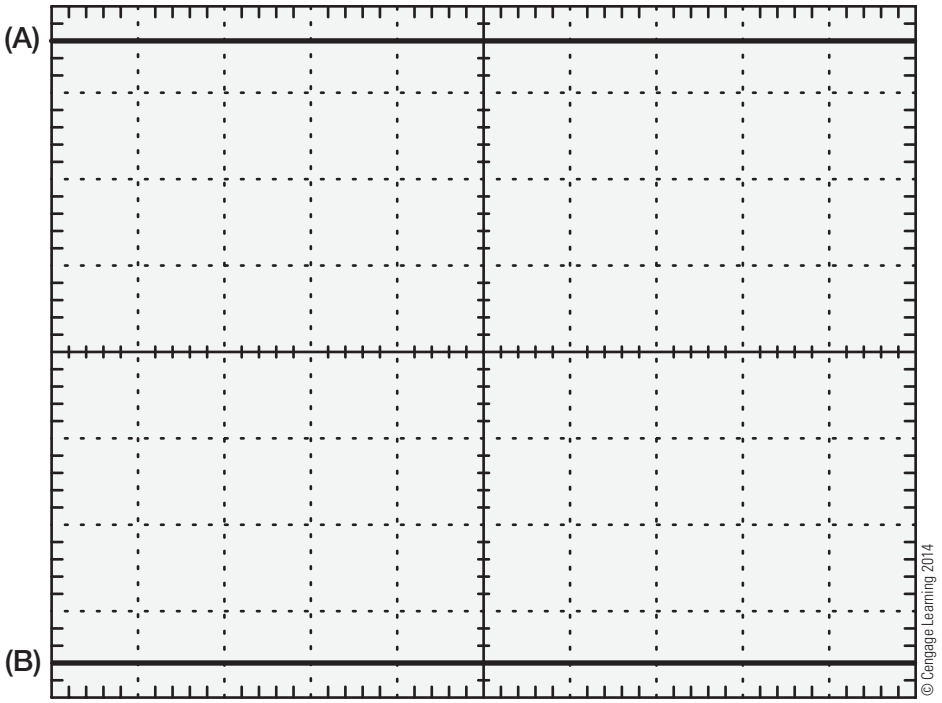


FIGURE 8-49 The oscilloscope displays both positive and negative voltages.

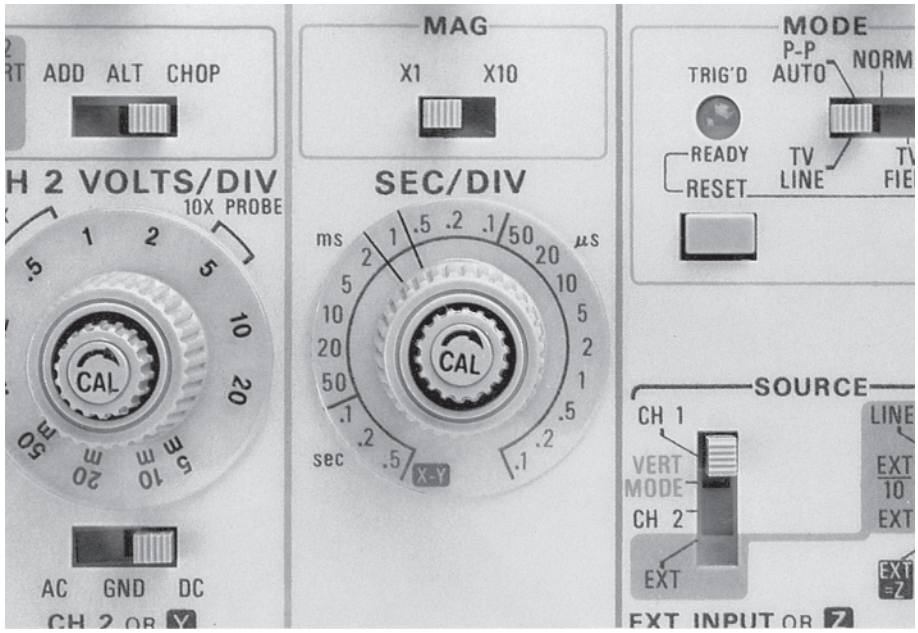
The Time Base

The next section of the oscilloscope to become familiar with is the time base, FIGURE 8-50. The time base is calibrated in seconds per division and has range values from seconds to microseconds. The time base controls the value of the divisions of the lines in the horizontal direction (X axis). If the time base is set for 5 ms (milliseconds) per division, the trace will sweep from one division to the next division in 5 ms. With the time base set in this position, it will take 50 ms to sweep from one side of the display screen to the other. If the time base is set for 2 μs (microseconds) per division, the trace will sweep the screen in 2 μs.

Measuring Frequency

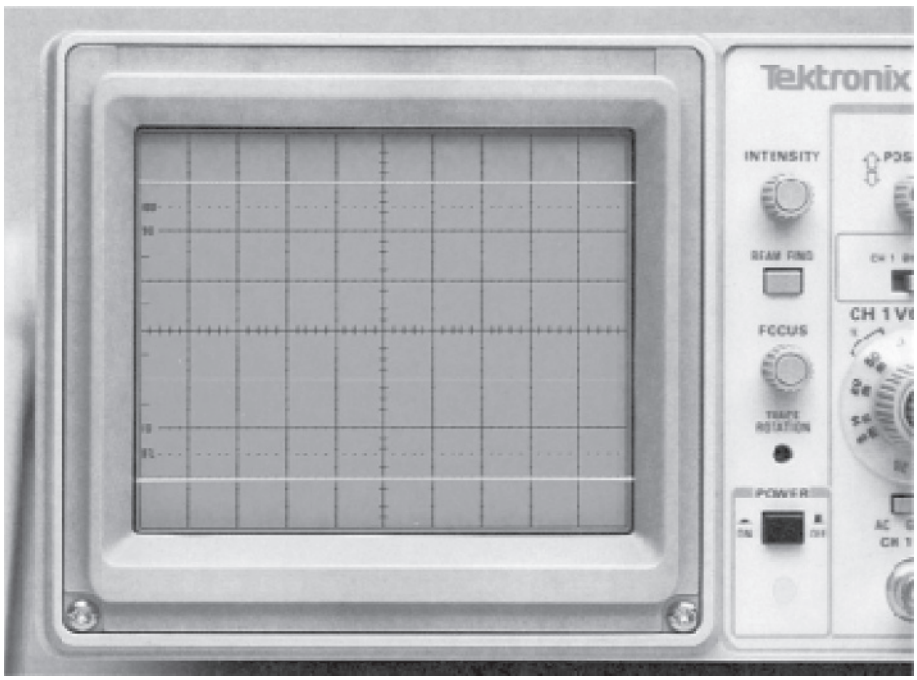
Since the oscilloscope has the ability to measure the voltage with respect to time, it is possible to compute the frequency of the waveform. The frequency (F) of an AC waveform can be found by dividing 1 by the time (T) it takes to complete one cycle ($F = 1/T$). For example, assume the time base is set for 0.5 ms per division, and the voltage range is set for 20 V per division. If the oscilloscope has been set so that the center line of the display is 0 V, the AC waveform shown in FIGURE 8-51 has a peak value of 55 V. The oscilloscope displays the peak or peak-to-peak value of voltage and not the root mean

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



Courtesy of Tektronix Inc.

FIGURE 8-50 Time base.



Courtesy of Tektronix Inc.

FIGURE 8-51 AC sine wave.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

square (RMS), or effective, value. These terms will be discussed in greater detail in later units.

To measure the frequency, count the time it takes to complete one full cycle. A cycle is one complete waveform. Begin counting when the waveform starts to rise in the positive direction and stop when it again starts to rise in the positive direction. Since the time base is set for a value of 0.5 ms per division, the waveform shown in Figure 8–51 takes 4 ms to complete one full cycle. The frequency therefore is 250 Hz (1/0.004 = 250).

Attenuated Probes

Most oscilloscopes use a probe that acts as an attenuator. An attenuator is a device that divides or makes smaller the input signal, FIGURE 8-52. An attenuated probe is used to permit higher voltage readings than are normally possible. For example, most attenuated probes are 10 to 1. This means that if the voltage range switch is set for 5 V per division, the display would actually indicate 50 V per division. If the voltage range switch is set for 2 V per division, each division on the display actually has a value of 20 V per division.



Courtesy of Tektronix Inc.

FIGURE 8-52 An oscilloscope probe and attenuator.

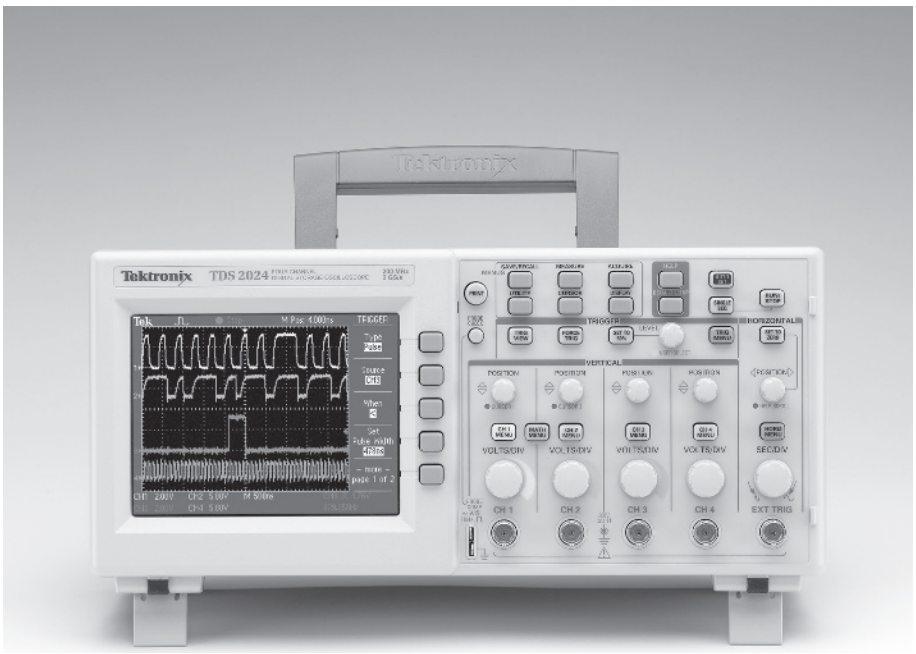
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Probe attenuators are made in different styles by different manufacturers. On some probes the attenuator is located in the probe head itself, while on others the attenuator is located at the scope input. Regardless of the type of attenuated probe used, it may have to be compensated or adjusted. In fact, probe compensation should be checked frequently. Different manufacturers use different methods for compensating their probes, so it is generally necessary to follow the procedures given in the operator's manual for the oscilloscope being used.

OSCILLOSCOPE CONTROLS

The following is a list of common controls found on the oscilloscope. Refer to the oscilloscope shown in FIGURE 8-53.

1. **Power.** The power switch is used to turn the oscilloscope on or off.
2. **Beam finder.** This control is used to locate the position of the trace if it is off the display. The beam finder button will indicate the approximate location of the trace. The position controls are then used to move the trace back on the display.
3. **Probe adjust** (sometimes called calibrate). This is a reference voltage point used to compensate the probe. Most probe adjust points produce a square wave signal of about 0.5 V.



Courtesy of Tektronix Inc.

FIGURE 8-53 An oscilloscope.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

4. **Intensity and focus.** The intensity control adjusts the brightness of the trace. A bright spot should never be left on the display because it will burn a spot on the face of the CRT (cathode ray tube). This burned spot results in permanent damage to the CRT. The focus control sharpens the image of the trace.
5. **Vertical position.** This is used to adjust the trace up or down on the display. If a dual-trace oscilloscope is being used, there will be two vertical position controls. (A dual-trace oscilloscope contains two separate traces that can be used separately or together.)
6. **CH 1-both-CH 2.** This control determines which channel of a dual-trace oscilloscope is to be used, or if they are both to be used at the same time.
7. **ADD-ALT.-CHOP.** This control is active only when both traces are being displayed at the same time. The ADD adds the two waves together. ALT. stands for alternate. This alternates the sweep between channel 1 and channel 2. The CHOP mode alternates several times during one sweep. This generally makes the display appear more stable. The chop mode is generally used when displaying two traces at the same time.
8. **AC-GRD-DC.** The AC is used to block any DC voltage when only the AC portion of the voltage is to be seen. For instance, assume an AC voltage of a few millivolts is riding on a DC voltage of several hundred volts. If the voltage range is set high enough so that 100 VDC can be seen on the display, the AC voltage cannot be seen. The AC section of this switch inserts a capacitor in series with the probe. The capacitor blocks the DC voltage and permits the AC voltage to pass. Since the 100 VDC has been blocked, the voltage range can be adjusted for millivolts per division, which will permit the AC signal to be seen.

   The GRD section of the switch stands for ground. This section grounds the input so the sweep can be adjusted for 0 V at any position on the display. The ground switch grounds at the scope and does not ground the probe. This permits the ground switch to be used when the probe is connected to a live circuit. The DC section permits the oscilloscope to display all of the voltage, both AC and DC, connected to the probe.
9. **Horizontal position.** This control adjusts the position of the trace from left to right.
10. **Auto-Normal.** This determines whether the time base will be triggered automatically or operated in a free-running mode. If this control is operated in the normal setting, the trigger signal is taken from the line

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

to which the probe is connected. The scope is generally operated with the trigger set in the automatic position.

11. **Level.** The level control determines the amplitude the signal must be before the scope triggers.
12. **Slope.** The slope permits selection as to whether the trace is triggered by a negative or positive waveform.
13. **Int.-Line-Ext.** The *Int.* stands for internal. The scope is generally operated in this mode. In this setting, the trigger signal is provided by the scope. In the line mode, the trigger signal is provided from a sample of the line. The *Ext.,* or external, mode permits the trigger pulse to be applied from an external source.

These are not all the controls shown on the oscilloscope in Figure 8-53, but they are the major controls. Most oscilloscopes contain these controls.

Interpreting Waveforms

The ability to interpret the waveforms on the display of the oscilloscope takes time and practice. When using the oscilloscope, one must keep in mind that the display shows the voltage with respect to time.

In FIGURE 8-54, it is assumed that the voltage range has been set for 0.5 V per division, and the time base is set for 2 ms per division. It is also assumed that 0 V has been set on the center line of the display. The waveform shown is a square wave. The display shows that the voltage rises in the positive direction to a value of 1.4 V and remains there for 2 ms. The voltage then drops to 1.4 V negative and remains there for 2 ms before going back to positive. Since the voltage changes between positive and negative, it is an AC voltage. The length of one cycle is 4 ms. The frequency is therefore 250 Hz (1/0.004 = 250).

In FIGURE 8-55, the oscilloscope has been set for 50 mV per division and 20 μs (microseconds) per division. The display shows a voltage that is negative to the probe's ground lead and has a peak value of 150 mV. The waveform lasts for 20 μs and produces a frequency of 50 kHz (1/0.000020 = 50,000). The voltage is DC since it never crosses the zero reference and goes in the positive direction. This type of voltage is called *pulsating* DC.

In FIGURE 8-56, assume the scope has been set for a value of 50 V per division and 5 ms per division. The waveform shown rises from 0 to about 40 V in a period of about 2 ms. The voltage gradually increases to about 50 V in the space of 1 ms and then rises to a value of about 100 V in the next 2 ms. The voltage then decreases to 0 in the next

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

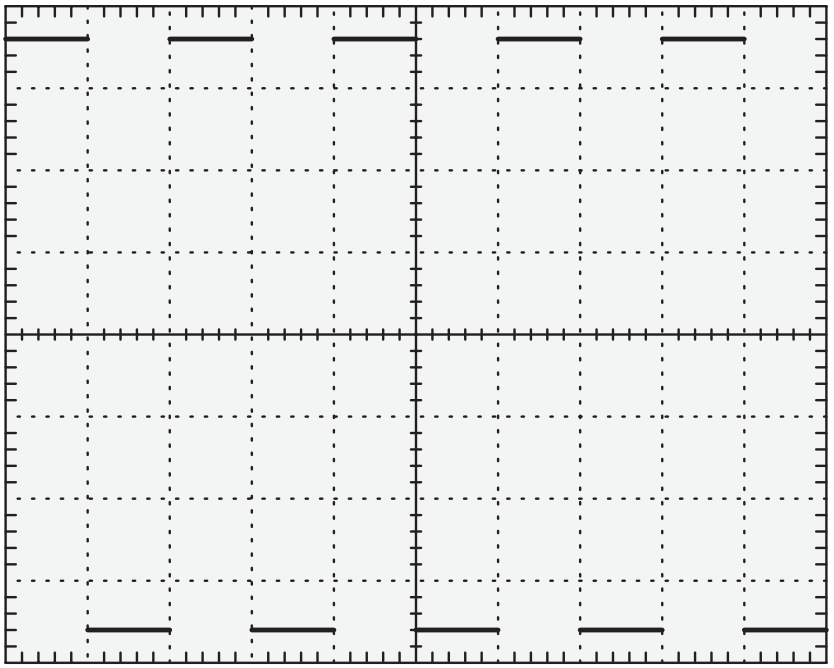


FIGURE 8-54 An AC square wave.

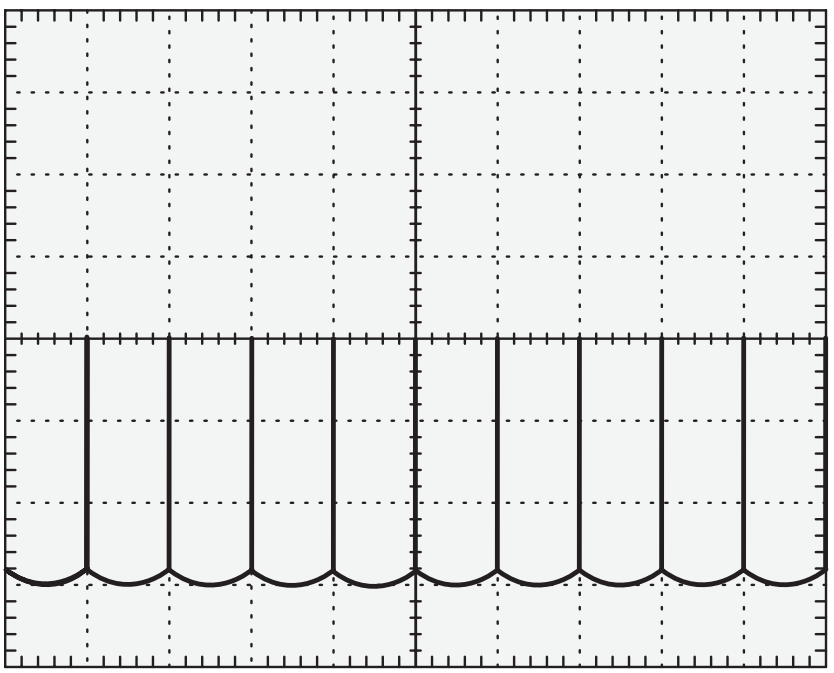


FIGURE 8-55 A DC waveform.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

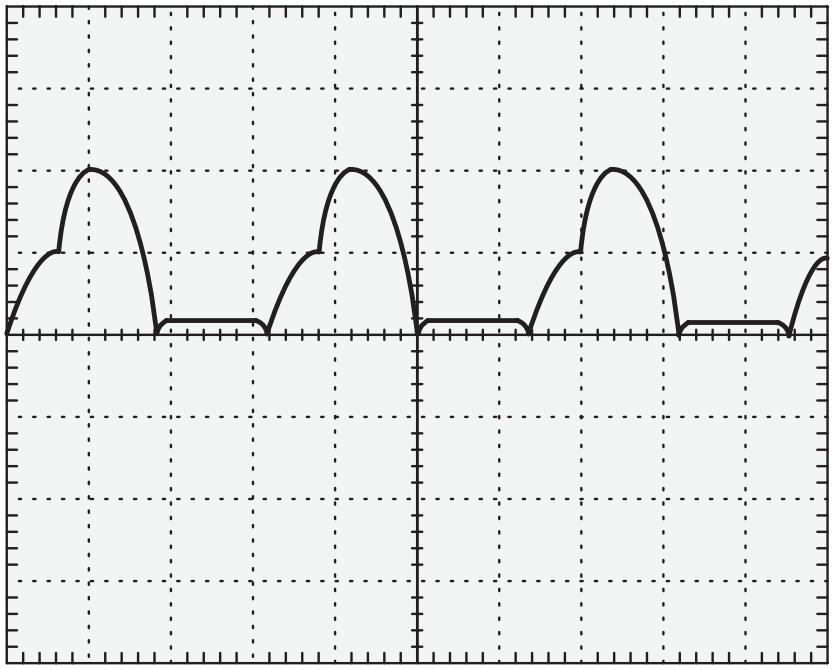

© Cengage Learning 2014

FIGURE 8-56 A chopped DC waveform.

4 ms. It then increases to a value of about 10 V in 0.5 ms and remains at that level for about 7 ms. This is one complete cycle for the waveform. The length of one cycle is about 16 ms, which is a frequency of 62.5 Hz (1/0.016 = 62.5). The voltage is DC because it remains positive and never drops below the 0 line.

Learning to interpret the waveforms seen on the display of an oscilloscope will take time and practice, but it is well worth the effort. The oscilloscope is the only means by which many of the waveforms and voltages found in electronic circuits can be understood. Consequently, the oscilloscope is the single most valuable piece of equipment a technician can use.

MEGOHMMETERS

meggers
common name for megohmmeters.

Megohmmeters, or "**meggers,**" are special ohmmeters intended to test extremely high resistances in the range of millions of ohms. They are generally used to test wire installations. After the conductors have been installed in conduits or raceways, it is accepted practice to test the installation for grounds and shorts. This test requires an ohmmeter, which cannot only measure resistance in millions of ohms, but also provide a high enough voltage to ensure the insulation will not break down when rated

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

line voltage is applied to the conductors. Most ohmmeters operate with a maximum voltage that ranges from 1.5 to about 9 V depending on the type of ohmmeter and the setting of the range scale. To test wire insulation, a special type of ohmmeter called a Megger® is used. The term Megger® is a registered trademark of Biddle Instruments. The Megger® is a megohmmeter that can produce voltages that range from about 250 to 5000 V depending on the model of the meter and the range setting. One model of a Megger® is shown in FIGURE 8-57. This instrument contains a hand crank that is connected to the rotor of a brushless AC generator. The advantage of this particular instrument is that it does not require the use of batteries. A range selector switch permits the meter to be used as a standard ohmmeter or as a megohmmeter. When it is used as a megohmmeter, the selector switch permits the test voltage to be selected. Test voltages of 100, 250, 500, and 1000 V can be obtained.

Megger®s can also be obtained in battery-operated models as shown in FIGURE 8-58. These models are small, lightweight, and particularly useful when it becomes necessary to test the **dielectric** of a capacitor.

dielectric
electrical insulator.

Wire installations are generally tested for two conditions, shorts and grounds. Shorts are current paths that exist between conductors. To test an installation for shorts, the Megger® is connected across two conductors at a time as shown in FIGURE 8-59. The circuit is tested at rated voltage or slightly higher. The Megger® indicates the resistance between the two conductors. Since both conductors are insulated, the resistance between them should be extremely high. Each conductor should be tested against every other conductor in the installation.



Courtesy of Megger®

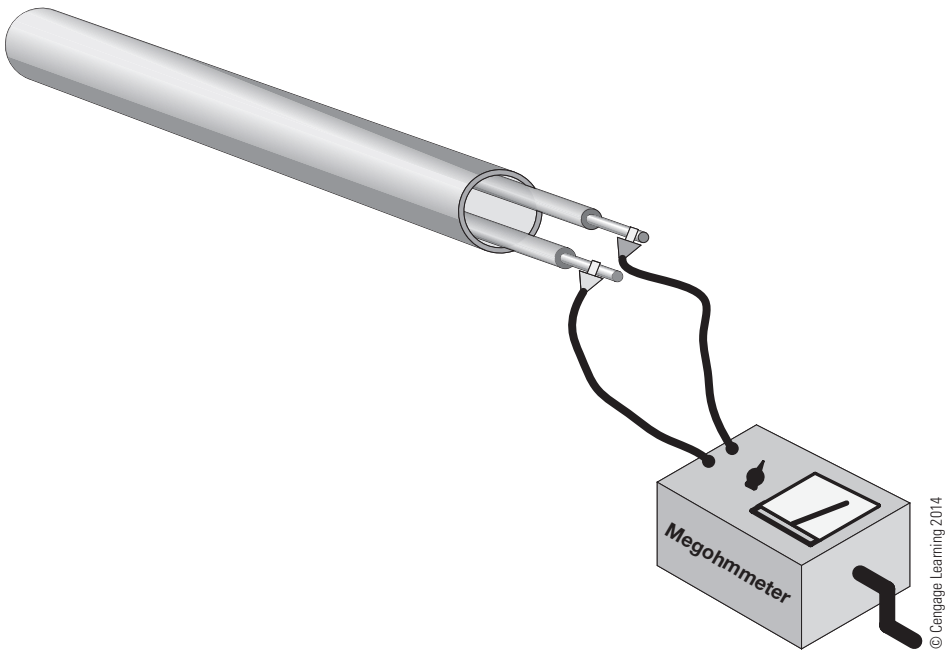
FIGURE 8-57 Hand crank Megger®.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



Courtesy of Megger®

FIGURE 8-58 Battery powered Megger®.



© Cengage Learning 2014

FIGURE 8-59 A Megger® is used to test a wire installation for shorts.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

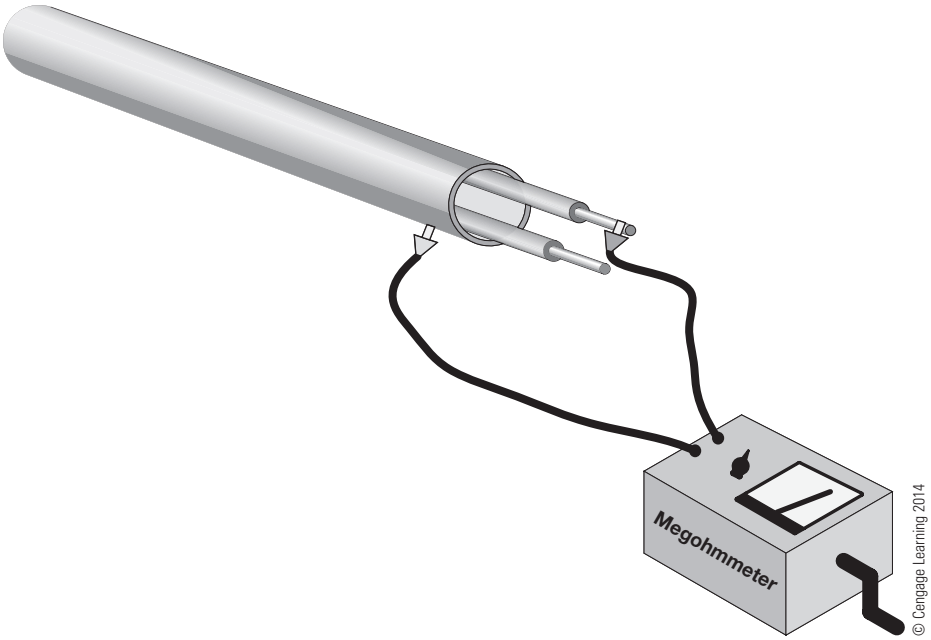


FIGURE 8-60 A Megger® is used to test a wire installation for grounds.

To test the installation for grounds, one lead of the Megger® is connected to the conduit or raceway as shown in FIGURE 8-60. The other meter lead is connected to one of the conductors. The conductor should be tested at rated voltage or slightly higher. Each conductor should be tested.

Summary

1. The d'Arsonval type of meter movement is based on the principle that like magnetic fields repel.
2. The d'Arsonval movement operates only on DC current.
3. Voltmeters have a high resistance and are designed to be connected directly across the power line.
4. The steps to reading a meter are as follows:
   A. Determine what quantity the meter is set to measure.
   B. Determine the full range value of the meter.
   C. Read the meter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. Ammeters have a low resistance and must be connected in series with a load to limit the flow of current.
6. Shunts are used to change the value of DC ammeters.
7. AC ammeters use a current transformer to change the range setting.
8. Clamp-on ammeters measure the flow of current by measuring the strength of the magnetic field around a conductor.
9. Ohmmeters are used to measure the resistance in a circuit.
10. Ohmmeters contain an internal power source, generally batteries.
11. Ohmmeters must never be connected to a circuit that has power applied to it.
12. Digital multimeters display their value in digits instead of using a meter movement.
13. Digital multimeters generally have an input impedance of 10 MΩ on all ranges.
14. The stationary coil of a wattmeter is connected in series with the load and the moving coil is connected to the line voltage.
15. The turning force of the wattmeter is proportional to the strength of the magnetic field of the stationary coil and the strength of the magnetic field of the moving coil.
16. Digital ohmmeters measure resistance by measuring the voltage drop across an unknown resistor when a known amount of current flows through it.
17. Low-impedance voltage testers are not susceptible to indicating a voltage caused by a high-impedance ground or a feedback.
18. A bridge circuit can be used to accurately measure values of resistance, inductance, and capacitance.
19. The oscilloscope measures the amplitude of voltage with respect to time.
20. The frequency of a waveform can be determined by dividing 1 by the time of one cycle ($F = 1/T$).
21. Megohmmeters are used to test insulation resistance.
22. Megohmmeters can be hand crank or battery powered.
23. Megohmmeters develop voltages that can range from 250 to 5,000 V.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Review Questions

1. To what is the turning force of a d'Arsonval meter movement proportional?
2. What type of voltage must be connected to a d'Arsonval meter movement?
3. A DC voltmeter has a resistance of 20,000 Ω per volt. What is the resistance of the meter if the range selection switch is set on the 250-V range?
4. What is the purpose of an ammeter shunt?
5. Name two methods used to make a DC multirange ammeter.
6. How is an ammeter connected into a circuit?
7. How is a voltmeter connected into a circuit?
8. An ammeter shunt has a voltage drop of 50 mV when 50 A of current flows through it. What is the resistance of the shunt?
9. What type of meter contains its own, separate power source?
10. What is the major difference between a wattmeter and a d'Arsonval meter?
11. What two factors determine the turning force of a wattmeter?
12. What electrical quantity is measured with an oscilloscope?
13. What is measured on the Y axis of an oscilloscope?
14. What is measured on the X axis of an oscilloscope?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 9

Alternating Current

OBJECTIVES: After studying this unit, you should be able to:

- Discuss differences between direct and alternating current.
- Compute instantaneous values of voltage and current for a sine wave.
- Compute peak, RMS, and average values of voltage and current.
- Discuss the phase relationship of voltage and current in a pure resistive circuit.

Most of the electrical power produced in the world is alternating current. It is used to operate everything from home appliances such as television sets, computers, microwave ovens, and electric toasters to the largest motors found in industry. Alternating current has several advantages over direct current that make it a better choice for the large-scale production of electrical power.

ADVANTAGES OF ALTERNATING CURRENT

Probably the single greatest advantage of alternating current is the fact that AC current can be transformed and DC current cannot. A transformer permits voltage to be stepped up or down. Voltage can be stepped up for the purpose of transmission and then stepped back down when it is to be used by some device. Transmission voltages of 69 kV, 138 kV, and 345 kV are common.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The advantage of high-voltage transmission is that less current is required to produce the same amount of power. The reduction of current permits smaller wires to be used, which results in a savings of material.

In the very early days of electric power generation, Thomas Edison, an American inventor, proposed powering the country with low-voltage direct current. He reasoned that low-voltage direct current was safer for people to use than the higher-voltage alternating current. A Serbian immigrant named Nikola Tesla, however, argued that direct current was impractical to use for large-scale applications. The disagreement was finally settled at the 1904 World's Fair held in St. Louis, Missouri. The 1904 World's Fair not only introduced the first ice cream cone and the first iced tea, it was also the first World's Fair to be lighted with "electric candles." At that time, the only two companies capable of providing electric lighting for the World's Fair were the Edison Company, headed by Thomas Edison, and the Westinghouse Company, headed by George Westinghouse, a close friend of Nikola Tesla. The Edison Company submitted a bid of over one dollar per lamp to light the fair with low-voltage direct current. The Westinghouse Company submitted a bid of less than 25 cents per lamp to light the fair using higher-voltage alternating current. This set the precedent for how electric power would be supplied throughout the world.

ALTERNATING CURRENT WAVEFORMS

SQUARE WAVES

Alternating current differs from direct current in that AC current reverses its direction of flow at periodic intervals, FIGURE 9-1. Alternating current waveforms can vary depending on how the current is produced. One waveform frequently encountered is the square wave, FIGURE 9-2. It is assumed that the oscilloscope, an instrument for measuring the polarity, amplitude, and duration of voltage in Figure 9-2, has been adjusted so that 0 V is represented by the center horizontal line. The waveform shows that the voltage is in the positive direction for some length of time and then

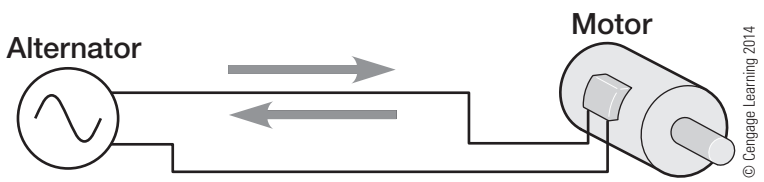


FIGURE 9-1 Alternating current flows first in one direction and then in the other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

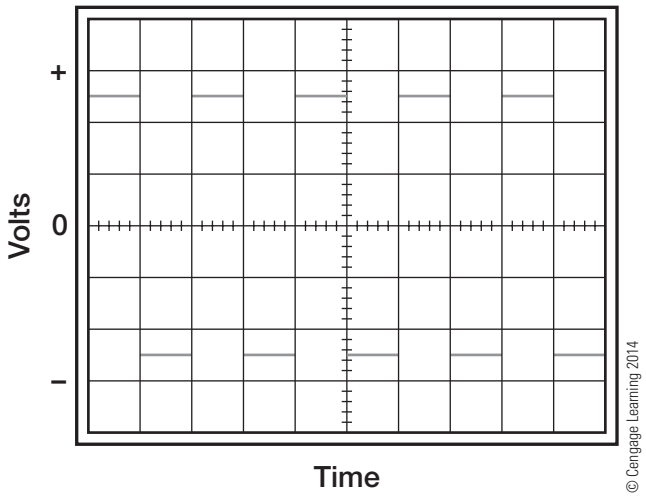


FIGURE 9-2 Square-wave alternating current.

changes polarity. The voltage remains negative for some length of time and then changes back to positive again. Each time the voltage reverses polarity, the current flow through the circuit changes direction. A square wave could be produced by a simple single-pole double-throw switch connected to two batteries, as shown in FIGURE 9-3. Each time the switch position is changed, current flows through the resistor in a different direction. Although this circuit will produce a square-wave alternating current, it is not practical. Square waves are generally produced by electronic

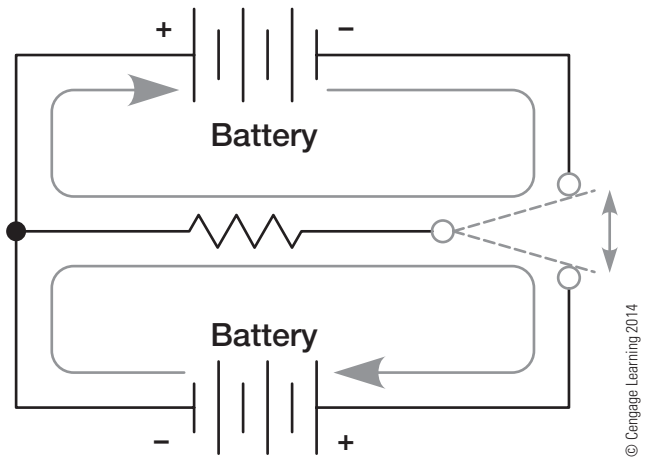


FIGURE 9-3 Square-wave alternating current produced with a switch and two batteries.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

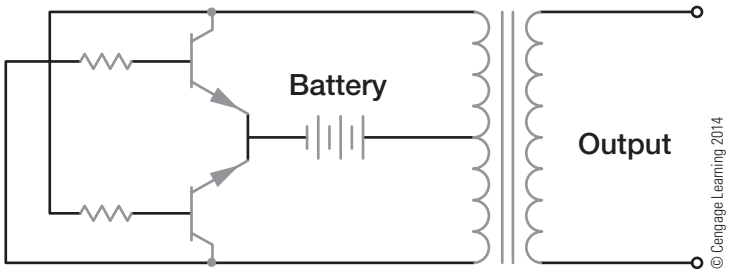


FIGURE 9-4 Square wave oscillator.

devices called **oscillators.** The schematic diagram of a simple square wave oscillator is shown in FIGURE 9-4. In this circuit, two bipolar transistors are used as switches to reverse the direction of current flow through the windings of the transformer. This type of oscillator is often used to change the 12-V DC of an automobile battery into 120-V AC to operate electric hand tools such as drills and saws. This oscillator should not be used to power electronic devices such as television sets.

oscillators
device used to change DC voltage into AC voltage.

TRIANGLE WAVES

Another common AC waveform is the **triangle wave** shown in FIGURE 9-5. The triangle wave is a linear wave. A **linear wave** is one in which the voltage rises at a constant rate with respect to time. Linear waves form straight lines when plotted on a graph. For example, assume the waveform shown in Figure 9-5 reaches a maximum positive value of 100 V after 2 ms. The voltage will be 25 V after 0.5 ms, 50 V after 1 ms, and 75 V after 1.5 ms.

triangle wave
a linear wave form.

linear wave
a waveform in which the voltage increases and decreases at a constant rate with respect to time.

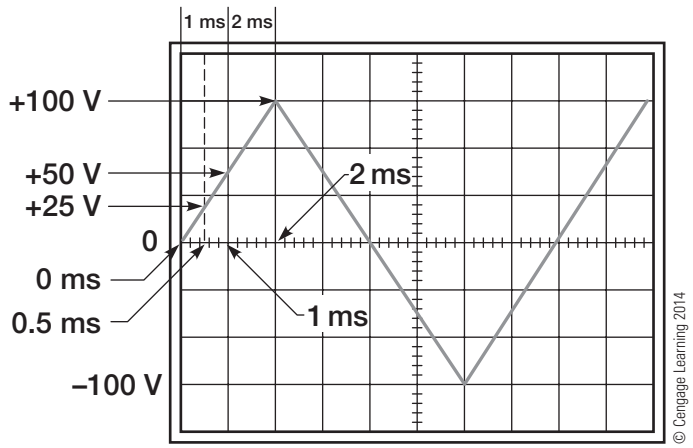


FIGURE 9-5 Triangle wave.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

sine wave
a waveform in which the voltage value increases and decreases in accord with the sine of the angel of rotation.

cycle
one complete AC waveform.

frequency
number of complete cycles of AC voltage that occur in 1 second.

hertz (Hz)
international unit of frequency.

KEY POINT

Sine waves are so named because the voltage at any point along the waveform is equal to the maximum, or peak, value times the sine of the angle of rotation.

SINE WAVES

The most common of all AC waveforms is the **sine wave,** FIGURE 9-6. They are produced by all rotating machines. The sine wave contains a total of 360 electrical degrees. It reaches its peak positive voltage at 90°, returns to a value of 0 V at 180°, increases to its maximum negative voltage at 270°, and returns to 0 V at 360°. Each complete waveform of 360° is called a **cycle.** The number of complete cycles that occur in one second is called the **frequency.** Frequency is measured in **hertz (Hz).** The most common frequency in the United States and Canada is 60 (Hz). This means that the voltage increases from zero to its maximum value in the positive direction, returns to zero, increases to its maximum value in the negative direction, and returns to zero 60 times each second.

Sine waves are so named because the voltage at any point along the waveform is equal to the maximum, or peak, value times the sine of the angle of rotation. FIGURE 9-7 illustrates one-half of a loop of wire cutting through lines of magnetic flux. The flux lines are shown with equal spacing between each line, and the arrow denotes the arc of the loop as it cuts through the lines of flux. Notice the number of flux lines that are cut by the loop during the first 30° of rotation. Now notice the number of flux lines that are cut during the second and third 30° of rotation. Because the loop is cutting the flux lines at an angle, it must travel a greater distance between flux lines during the first degrees of rotation. This means that fewer flux lines are cut per second, which results in a lower induced voltage. *One volt is induced in a conductor when it cuts lines of magnetic flux at a rate of 1 Wb/s.* One weber is equal to 100,000,000 lines of flux.

When the loop has rotated 90°, it is perpendicular to the flux lines and is cutting them at the maximum rate, which results in the highest, or peak,

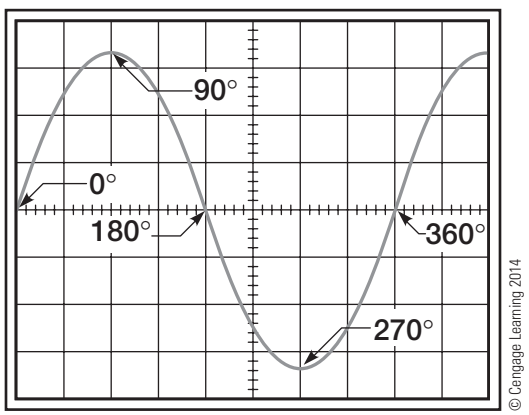


FIGURE 9-6 Sine wave.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

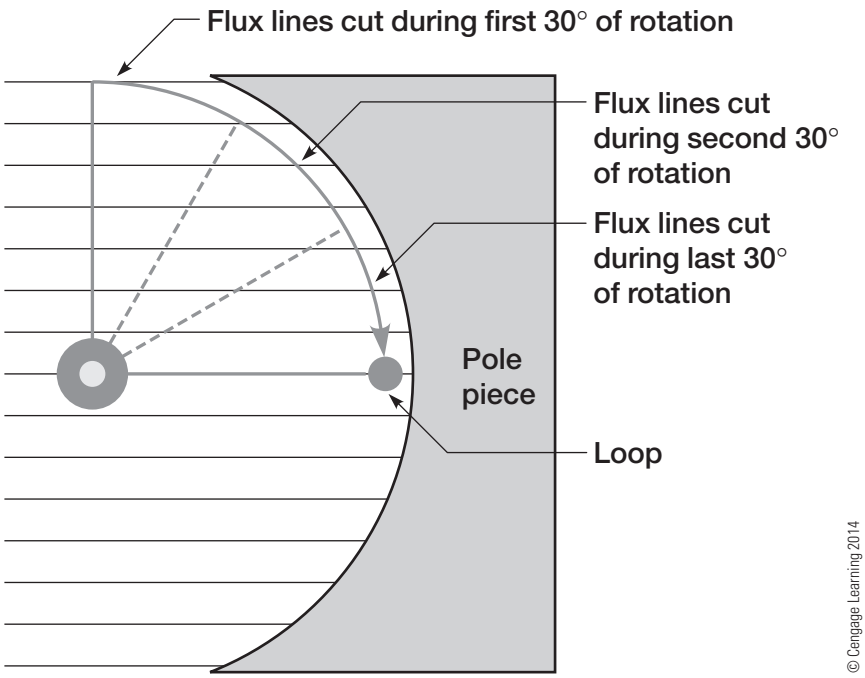


FIGURE 9-7 As the loop approaches 90° of rotation, the flux lines are cut at a faster rate.

voltage being induced in the loop. The voltage at any point during the rotation is equal to the maximum induced voltage times the sine of the angle of rotation. For example, if the induced voltage after 90° of rotation is 100 V, the voltage after 30° of rotation will be 50 V because the sine of a 30° angle is 0.5 (100 × 0.5 = 50 V). The induced voltage after 45° of rotation is 70.7 V because the sine of a 45° angle is 0.707 (100 × 0.707 = 70.7 V). A sine wave showing the instantaneous voltage values after different degrees of rotation is shown in FIGURE 9-8. The instantaneous voltage value is the value of voltage at any instant on the waveform.

The following formula can be used to determine the instantaneous value at any point along the sine wave:

$$E_{(INST)} = E_{(MAX)} \times \text{SIN} \angle$$

where

$E_{(INST)}$ = the voltage at any point on the waveform

$E_{(MAX)}$ = the maximum, or peak, voltage

SIN ∠ = the sine of the angle of rotation

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

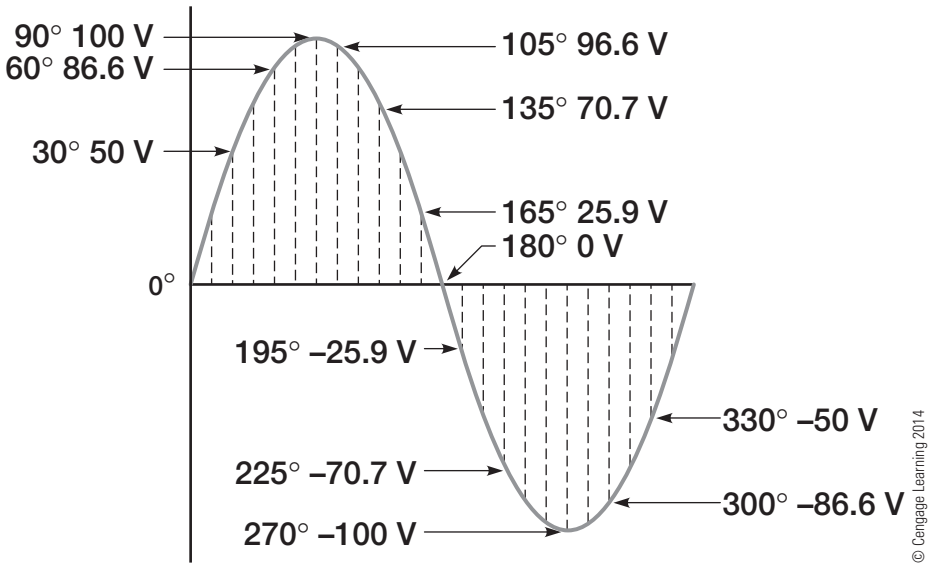


FIGURE 9-8 Instantaneous values of voltage along a sine wave.

EXAMPLE 1: A sine wave has a maximum voltage of 138 V. What is the voltage after 78° of rotation?

Solution:

$$E_{(INST)} = E_{(MAX)} \times \text{SIN} \angle$$

$$E_{(INST)} = 138 \times 0.978 \text{ (SIN of } 78°)$$

$$E_{(INST)} = 134.96 \text{ V}$$

The formula can be changed to find the maximum value if the instantaneous value and the angle of rotation are known or to find the angle if the maximum and instantaneous values are known.

$$E_{(MAX)} = \frac{E_{(INST)}}{\text{SIN} \angle}$$

$$\text{SIN} \angle = \frac{E_{(INST)}}{E_{(MAX)}}$$

EXAMPLE 2: A sine wave has an instantaneous voltage of 246 V after 53° of rotation. What is the maximum value the waveform will reach?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Solution:

$$E_{(MAX)} = \frac{E_{(INST)}}{SIN \angle}$$

$$E_{(MAX)} = \frac{246}{0.799}$$

$$E_{(MAX)} = 307.88 \text{ V}$$

EXAMPLE 3: A sine wave has a maximum voltage of 350 V. At what angle of rotation will the voltage reach 53 V?

Solution:

$$SIN \angle = \frac{E_{(INST)}}{E_{(MAX)}}$$

$$SIN \angle = \frac{53}{350}$$

$$SIN \angle = 0.151$$

Note: 0.151 is the *sine* of the angle, not the angle. To find the angle that corresponds to a sine of 0.151 use the trigonometric function of a scientific calculator.

$$\angle = 8.71°$$

Sine Wave Values

Several measurements of voltage and current are associated with sine waves. These measurements are peak-to-peak, peak, RMS, and average. A sine wave showing these different measurements is shown in FIGURE 9-9.

Peak-to-Peak and Peak Values

The peak-to-peak value is measured from the maximum value in the positive direction to the maximum value in the negative direction. The peak-to-peak value is often the simplest measurement to make when using an oscilloscope.

The **peak** value is measured from zero to the highest value obtained in either the positive or negative direction. The peak value is one-half of the peak-to-peak value.

peak
highest value obtained by the wave.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

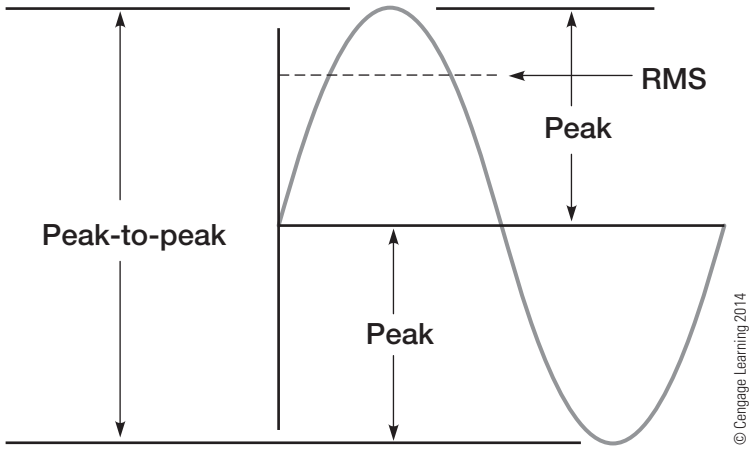


FIGURE 9-9 Sine wave values.

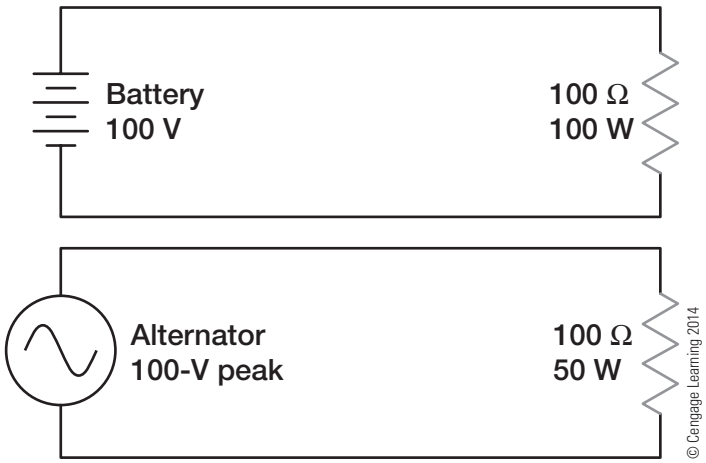


FIGURE 9-10 Direct current compared with a sine wave AC current.

RMS Values

In FIGURE 9-10, a 100-V battery is connected to a 100-Ω resistor. This connection will produce 1 A of current flow and the resistor will dissipate 100 W of power in the form of heat. An AC alternator that produces a peak voltage of 100 V is also shown connected to a 100-Ω resistor. A peak current of 1 A will flow in the circuit, but the resistor will dissipate only 50 W in the form of heat. The reason is that the voltage produced by a pure source of direct current, such as a battery, is one continuous value, FIGURE 9-11. The AC sine wave,

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

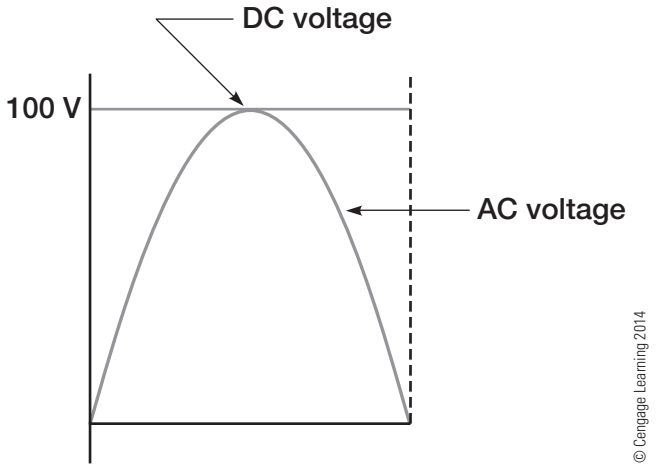


FIGURE 9-11 The DC voltage remains at a constant value during a half cycle of AC voltage.

however, begins at zero, increases to the maximum value, and decreases back to zero during the same period of time. Since the sine wave has a value of 100 V for only a short period of time and is less than 100 V during the rest of the half cycle, it cannot produce as much power as 100 V of DC.

The solution to this problem is to use a value of AC voltage that will produce the same amount of power as a similar value of DC voltage. This AC value is called the **RMS,** or **effective,** value and is the value indicated by almost all AC voltmeters and ammeters. **RMS stands for root-mean-square, which is an abbreviation for the square root of the mean of the square of the instantaneous currents.** The RMS value can be found by dividing the peak value by the square root of 1.414, or by multiplying the peak value by 0.707 (the reciprocal of 1.414). The formulas for determining the RMS or peak value are

$$\text{RMS} = \text{peak} \times 0.707$$

$$\text{peak} = \text{RMS} \times 1.414$$

RMS
value of AC voltage that will produce as much power when connected across a resistor as a like amount of DC voltage.

effective
value of AC voltage that will produce as much power when connected across a resistor as a like amount of DC voltage.

KEY POINT
RMS stands for root-mean-square, which is an abbreviation for the square root of the mean of the square of the instantaneous currents.

EXAMPLE 4: A sine wave has a peak value of 354 V. What is the RMS value?

Solution:

$$\text{RMS} = \text{peak} \times 0.707$$

$$\text{RMS} = 354 \times 0.707$$

$$\text{RMS} = 250.3 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 5: An AC voltage has a value of 120-V RMS. What is the peak value of voltage?

Solution:

$$\text{peak} = \text{RMS} \times 1.414$$

$$\text{peak} = 120 \times 1.414$$

$$\text{peak} = 169.7 \text{ V}$$

When the RMS value of voltage and current is used, it will produce the same amount of power as a similar value of DC voltage or current. If 100-V RMS is applied to a 100-Ω resistor, the resistor will produce 100 W of heat. AC voltmeters and ammeters indicate the RMS value, not the peak value. All values of AC voltage and current used in this text will be RMS values unless otherwise stated.

Average Values

average
the voltage produced by converting AC into DC.

Average values of voltage and current are actually direct current values. The average value must be found when a sine wave AC voltage is changed into DC with a rectifier, FIGURE 9-12. The rectifier shown is a bridge-type rectifier that produces full-wave rectification. This means that both the positive and negative half of the AC waveform is changed into DC. The average value is the amount of voltage that would be indicated by a DC voltmeter if it were connected across the load resistor. The average voltage is proportional to the peak, or maximum, value of the waveform and to the length of time it is on as

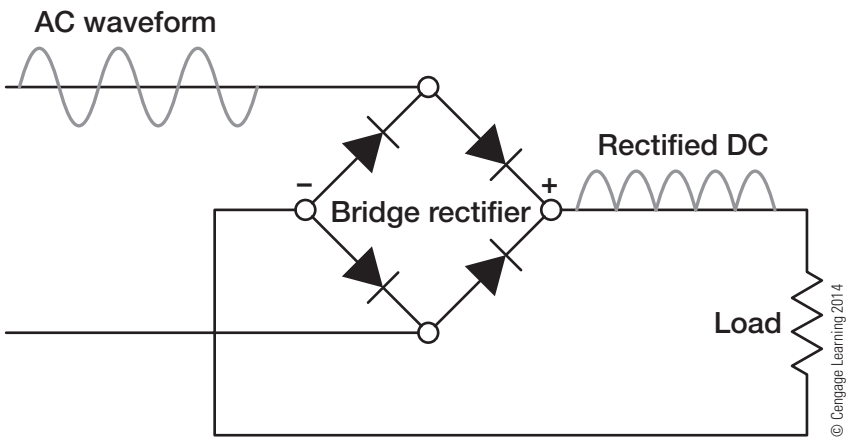


FIGURE 9-12 The bridge rectifier changes AC voltage into DC voltage.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

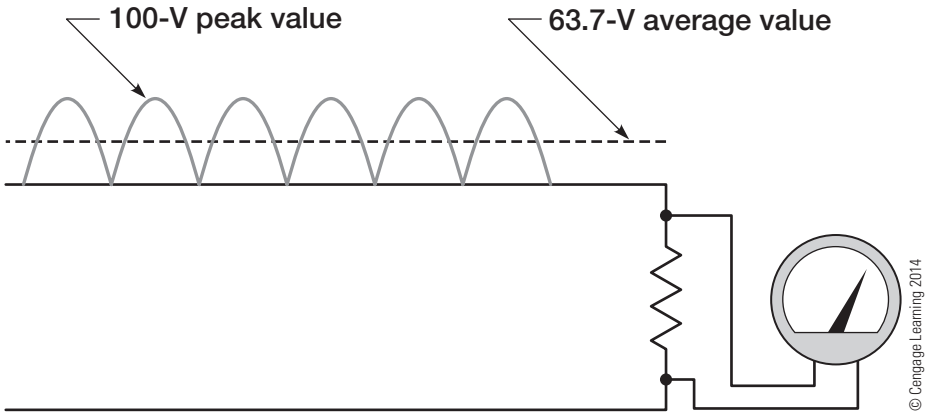


FIGURE 9-13 A DC voltmeter indicates the average value.

compared to the length of time it is off, FIGURE 9-13. Notice in Figure 9-13 that the voltage waveform turns on and off, but it never changes polarity. The current, therefore, never reverses direction. This is called pulsating direct current. The pulses are often referred to as **ripple.** The average value of voltage will produce the same amount of power as a nonpulsating source of voltage such as a battery, FIGURE 9-14. For a sine wave, the average value of voltage is found by multiplying the peak value by 0.637, or by multiplying the RMS value by 0.9.

ripple
pulses of direct current.

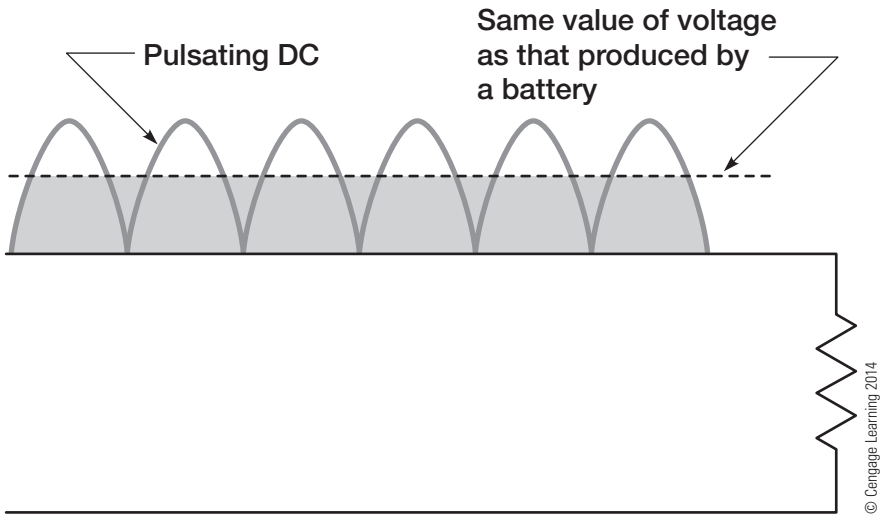


FIGURE 9-14 The average value produces the same amount of power as a nonpulsating source of voltage.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 6: An AC sine wave with an RMS value of 120 V is connected to a full-wave rectifier. What is the average DC voltage?

Solution:
The problem can actually be solved in two ways. The RMS value can be changed into peak and then the peak value can be changed to the average value.

$$\text{peak} = \text{RMS} \times 1.414$$
$$\text{peak} = 120 \times 1.414$$
$$\text{peak} = 169.7 \text{ V}$$
$$\text{average} = \text{peak} \times 0.637$$
$$\text{average} = 169.7 \times 0.637$$
$$\text{average} = 108 \text{ V}$$

EXAMPLE 7: The second method of determining the average value is to multiply the RMS value by 0.9.

$$\text{average} = \text{RMS} \times 0.9$$
$$\text{average} = 120 \times 0.9$$
$$\text{average} = 108 \text{ V}$$

The conversion factors given are for full-wave rectification. If a half-wave rectifier is used, FIGURE 9-15, only one-half of the AC waveform is converted into DC. To determine the average voltage for a half-wave rectifier, multiply the peak value by 0.637 or the RMS value by 0.9 and then divide the product by 2. Since only half of the AC waveform has been converted into direct current, the average voltage will be only half that of a full-wave rectifier, FIGURE 9-16.

A half-wave rectifier is connected to 277-V AC. What is the average DC voltage?

Solution:

$$\text{average} = \text{RMS} \times \frac{0.9}{2}$$
$$\text{average} = 277 \times \frac{0.9}{2}$$
$$\text{average} = 124.6 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

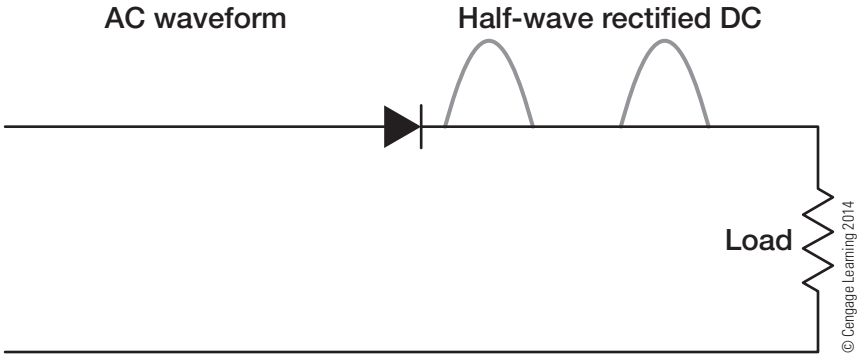


FIGURE 9-15 A half-wave rectifier converts only one-half of the AC waveform into DC.

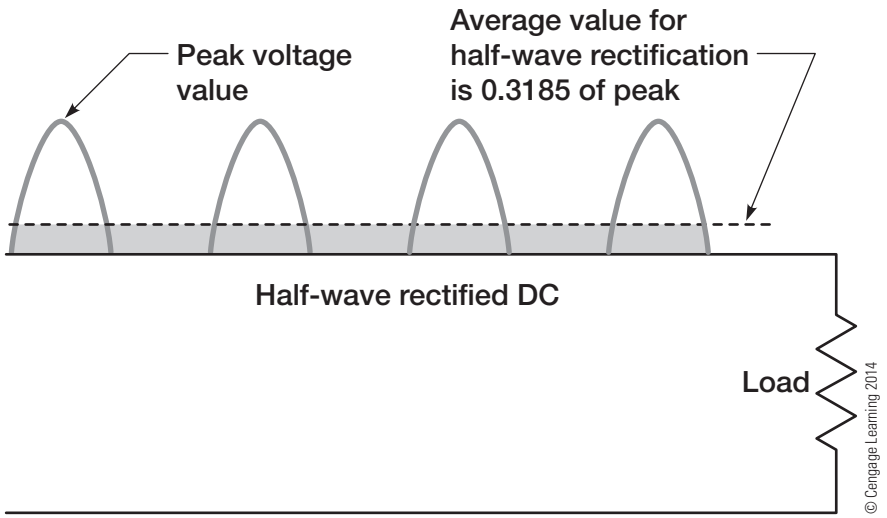


FIGURE 9-16 The average value for a half-wave rectifier is only half that of a full-wave rectifier.

Summary

1. Most of the electrical power generated in the world is alternating current.
2. Alternating current can be transformed and direct current cannot.
3. Alternating current reverses its direction of flow at periodic intervals.
4. The most common AC waveform is the sine wave.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. There are 360 degrees in one complete sine wave.
6. One complete waveform is called a cycle.
7. The number of complete cycles that occur in one second is called the frequency.
8. Sine waves are produced by rotating machines.
9. Frequency is measured in hertz (Hz).
10. The instantaneous voltage at any point on a sine wave is equal to the peak, or maximum, voltage times the sine of the angle of rotation.
11. The peak-to-peak voltage is the amount of voltage measured from the positive-most peak to the negative-most peak.
12. The peak value is the maximum amount of voltage attained by the waveform.
13. The RMS value of voltage will produce as much power as an equal amount of DC voltage.
14. The average value of voltage is used when an AC sine wave is changed into DC.

Review Questions

1. What is the most common type of AC waveform?
2. How many degrees are there in one complete sine wave?
3. At what angle does the voltage reach its maximum negative value on a sine wave?
4. What is frequency?
5. A sine wave has a maximum value of 230 V. What is the voltage after 38° of rotation?
6. A sine wave has a voltage of 63 V after 22° of rotation. What is the maximum voltage reached by this waveform?
7. A sine wave has a maximum value of 560 V. At what angle of rotation will the voltage reach a value of 123 V?
8. A sine wave has a peak value of 433 V. What is the RMS value?
9. A sine wave has a peak-to-peak value of 88 V. What is the average value?
10. A DC voltage has an average value of 68 V. What is the RMS value?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 10

Alternating Current Loads

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the relationships of voltage and current in a pure resistive load.
- Discuss the differences in true power, apparent power, and reactive power.
- Determine the phase angle of voltage and current in an AC circuit.
- Discuss the properties of inductance.
- Discuss the properties of capacitance.
- Compute values of inductive reactance.
- Compute values of capacitive reactance.
- Compute the value of impedance in an AC circuit.
- Discuss the differences between resistance and impedance.

In a DC circuit, there is one basic type of load, which is resistive. In a DC circuit volts times amperes always equals **watts** or **true power.** This is not true in an alternating current circuit. Alternating current

watts
measure of true power.

true power
the amount of electrical energy converted into some other form.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

circuits can have three different types of loads: resistive, inductive, and capacitive. Each of these loads produces a different circuit condition. In this unit it will be shown that volts times amperes may not always equal watts in an AC circuit.

RESISTIVE LOADS

resistive loads
loads that are comprised of resistive elements.

Resistive loads contain pure resistance; examples include electric heating equipment and incandescent lighting. Resistive loads are characterized by the fact that

1. they produce heat;
2. the current and voltage are in phase with each other; and
3. only the resistive part of an AC circuit can produce true power or watts.

Any time that a circuit contains resistance, heat will be produced.

in phase
state at which the voltage and current rise and fall at the same rate and in the same time.

When an AC voltage is applied to a resistor, the current flow through the resistor will be a copy of the voltage, FIGURE 10-1. The current will rise and fall at the same rate as the voltage and will reverse the direction of flow when the voltage reverses polarity. In this condition, the current is said to be **in phase** with the voltage.

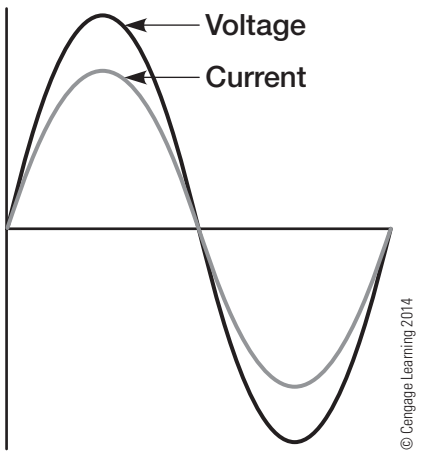


FIGURE 10-1 In a pure resistive circuit the voltage and current are in phase with each other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

POWER IN AN AC CIRCUIT

True power, or watts, can be produced only when both current and voltage are either positive or negative. When like signs are multiplied, the product is positive ($+ \times + = +$ or $- \times - = +$) and when unlike signs are multiplied the product is negative ($+ \times - = -$). Since current and voltage are either positive or negative at the same time, the product, watts, will always be positive, FIGURE 10-2.

KEY POINT

True power, or watts, can be produced only when both current and voltage are either positive or negative.

INDUCTANCE

Inductance (L) is one of the primary types of loads in alternating current circuits. Some amount of inductance is present in all alternating current circuits because of the continually changing magnetic field, FIGURE 10-3. The amount of inductance of a single conductor is extremely small, and in most instances it is not considered in circuit calculations. Circuits are generally considered to contain inductance when any type of load that contains a coil is used. Loads such as motors, transformers, lighting ballast, and chokes all contain coils of wire.

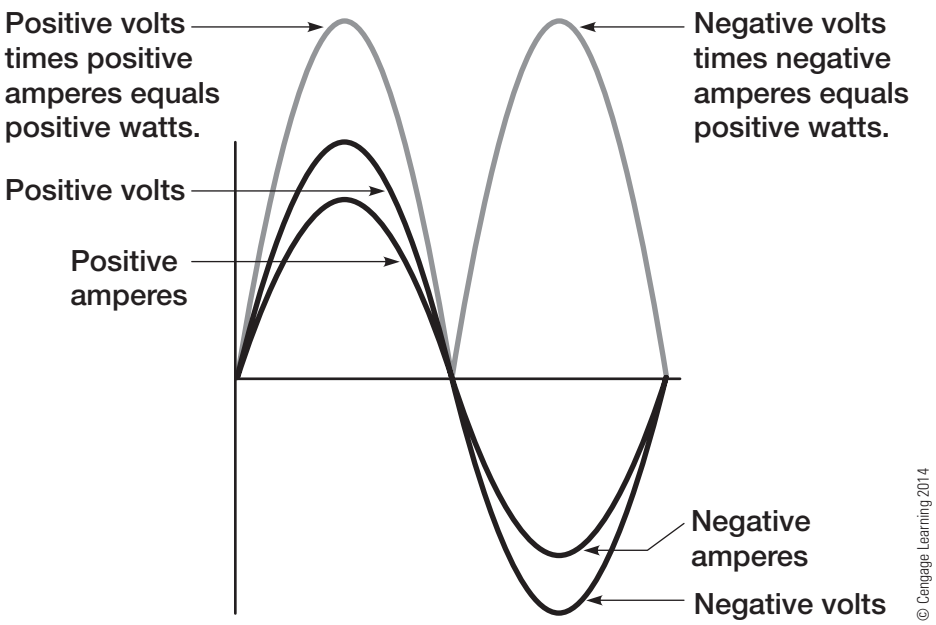


FIGURE 10-2 Power in a pure resistive AC circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

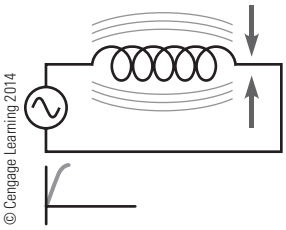

© Cengage Learning 2014

FIGURE 10-4 As current flows through a coil, a magnetic field is created around the coil.

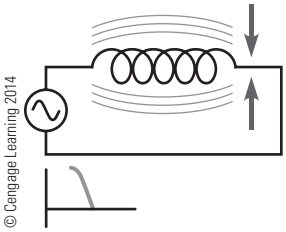

© Cengage Learning 2014

FIGURE 10-5 As current flow decreases, the magnetic field collapses.

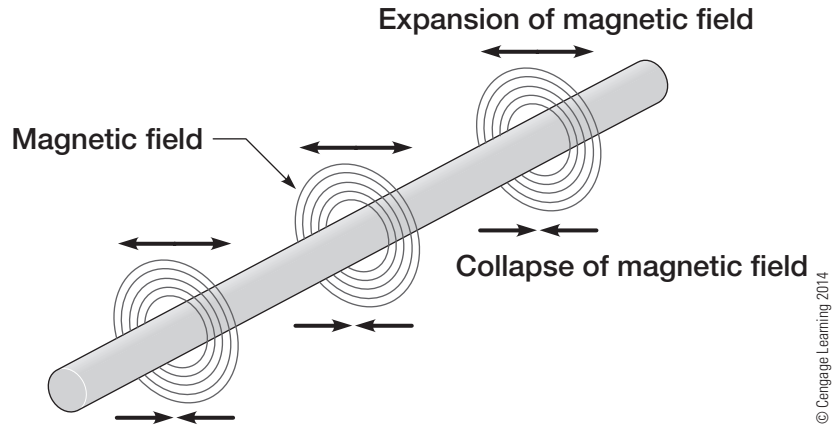


FIGURE 10-3 A continually changing magnetic field induces a voltage into any conductor.

In Unit 4, it was discussed that whenever current flows through a coil of wire, a magnetic field is created around the wire, FIGURE 10-4. If the amount of current decreases, the magnetic field will collapse, FIGURE 10-5. Several facts concerning inductance are as follows:

1. When magnetic lines of flux cut through a coil, a voltage is induced in the coil.
2. An induced voltage is always opposite in polarity to the applied voltage.
3. The amount of induced voltage is proportional to the rate of change of current.
4. An inductor opposes a change of current.

The inductors in FIGURE 10-4 and FIGURE 10-5 are connected to an alternating voltage. This causes the magnetic field to continually increase, decrease, and reverse polarity. Since the magnetic field continually changes magnitude and direction, a voltage is continually being induced in the coil. This **induced voltage** is 180° out of phase with the applied voltage and is always in opposition to the applied voltage, FIGURE 10-6. Since the induced voltage is always in opposition to the applied voltage, the applied voltage must overcome the induced voltage before current can flow through the circuit. For example, assume an inductor is connected to a 120-V AC line. Now assume that the inductor has an induced voltage of 116 V. Since an equal amount of applied voltage must be used to overcome the induced voltage, there will be only 4 V to push current through the wire resistance of the coil ($120 - 116 = 4$).

induced voltage
voltage that is induced.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

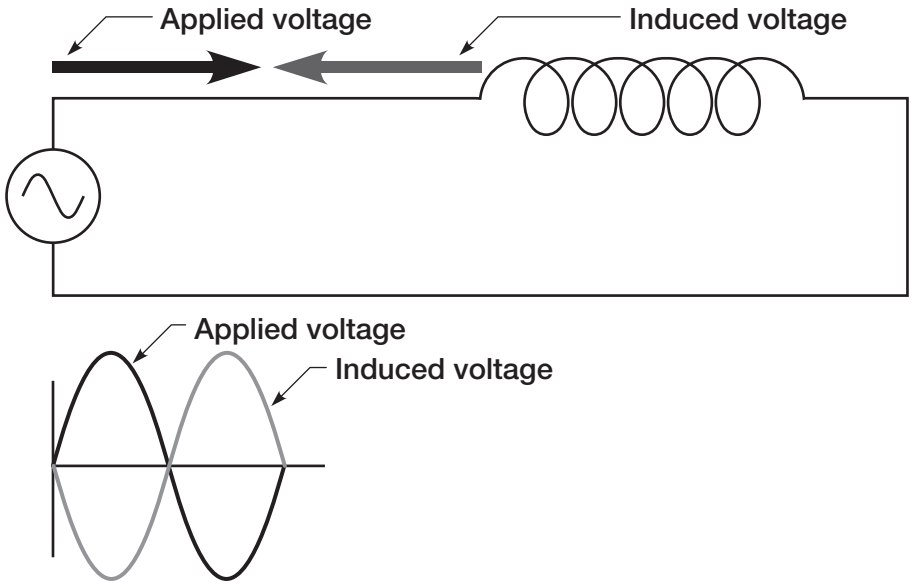


FIGURE 10-6 The applied voltage and induced voltage are 180° out of phase with each other.

COMPUTING THE INDUCED VOLTAGE

The amount of induced voltage in an inductor can be computed if the resistance of the wire in the coil and the amount of circuit current are known. For example, assume that an ohmmeter is used to measure the actual amount of resistance in a coil and the coil is found to contain 6 Ω of wire resistance, FIGURE 10-7. Now assume that the coil is connected to a 120-V AC circuit and an ammeter measures a current flow of 0.8 A,

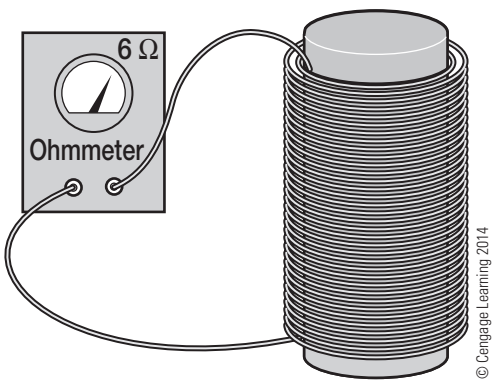


FIGURE 10-7 Measuring the resistance of a coil.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

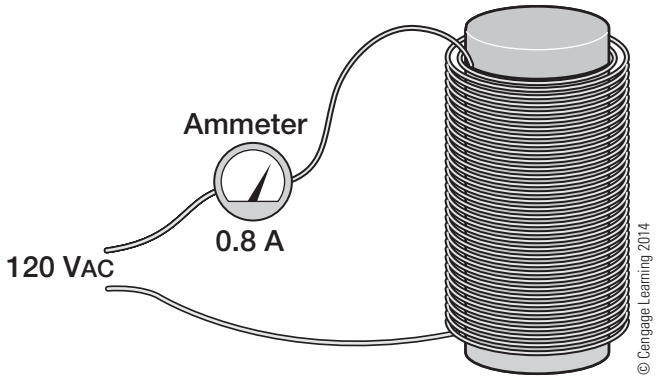


FIGURE 10-8 Measuring circuit current with an ammeter.

FIGURE 10-8. Ohm's Law can now be used to determine the amount of voltage necessary to push 0.8 A of current through 6 Ω of resistance.

$$E = I \times R$$

$$E = 0.8 \times 6$$

$$E = 4.8 \text{ V}$$

Since only 4.8 V is needed to push the current through the wire resistance of the inductor, the remainder of the 120 V is used to overcome the coil's induced voltage of 119.9 V ($\sqrt{120^2 - 4.8^2} = 119.9$).

INDUCTIVE REACTANCE

reactance
opposition to current flow in an AC circuit offered by pure inductance or pure capacitance.

inductive reactance (X_L)
current-limiting property of an inductor in an alternating-current circuit.

Notice that the induced voltage can limit the flow of current through the circuit in a manner similar to resistance. This induced voltage is *not* resistance, but it can limit the flow of current just as resistance does. This current-limiting property of the inductor is called **reactance** and is symbolized by the letter X. Since this reactance is caused by inductance, it is called **inductive reactance** and is symbolized by **X_L,** pronounced "X sub L." Inductive reactance is measured in ohms just as resistance is, and it can be computed when the values of inductance and frequency are known. The following formula can be used to find inductive reactance:

$$X_L = 2\pi FL$$

where

X_L = inductive reactance

2 = a constant

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$\pi = 3.1416$

F = frequency in hertz (Hz)

L = inductance in henrys (H)

Inductive reactance is an inducted voltage and is, therefore, proportional to the three factors that determine induced voltage:

1. The *number* of turns of wire
2. The *strength* of the magnetic field
3. The *speed* of the cutting action (relative motion between the inductor and the magnetic lines of flux)

The number of turns of wire and the strength of the magnetic field are determined by the physical construction of the inductor. Factors such as the size of wire used, the number of turns, how close the turns are to each other, and the type of core material determine the amount of inductance (measured in henrys) of the coil, FIGURE 10-9. The speed of the cutting action is proportional to the frequency (Hz). An increase in frequency will cause the magnetic lines of flux to cut the conductors at a faster rate. This will produce a higher induced voltage or more inductive reactance.

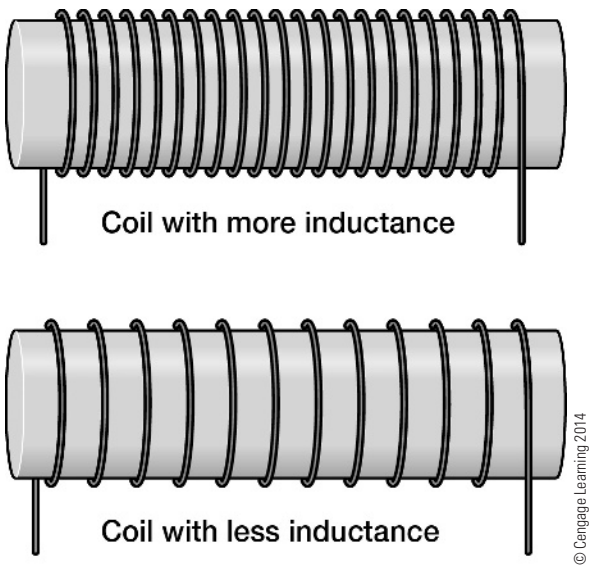


FIGURE 10-9 Coils with turns closer together produce more inductance than coils with turns far apart.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

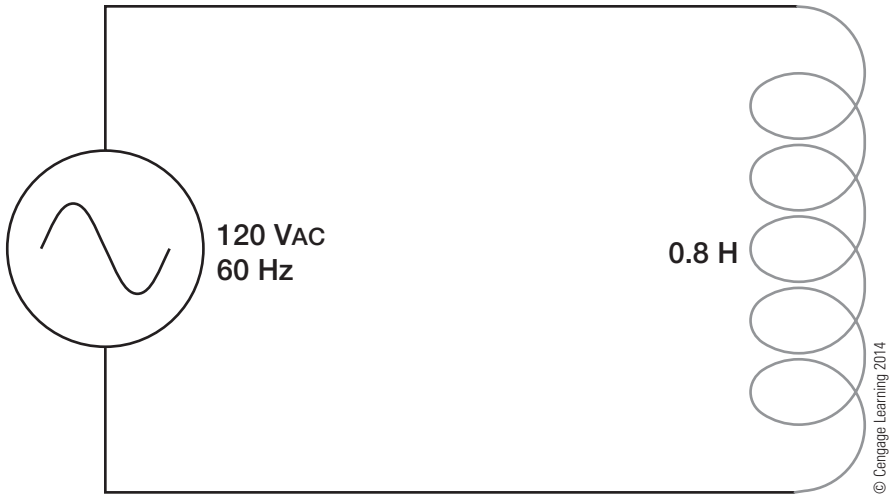


FIGURE 10-10 Circuit current is limited by inductive reactance.

EXAMPLE 1: The inductor shown in FIGURE 10-10 has an inductance of 0.8 H and is connected to a 120-V, 60-Hz line. How much current will flow in this circuit if the wire resistance of the inductor is negligible?

Solution:

The first step in solving this problem is to determine the amount of inductive reactance of the inductor.

$$X_L = 2\pi FL$$
$$X_L = 2 \times 3.1416 \times 60 \times 0.8$$
$$X_L = 301.6\ \Omega$$

Since inductive reactance is the current-limiting property of this circuit, it can be substituted for the value of R in an Ohm's Law formula.

$$I = \frac{E}{X_L}$$
$$I = \frac{120}{301.6}$$
$$I = 0.398\ A$$

If the amount of inductive reactance is known, the inductance of the coil can be determined using the formula

$$L = \frac{X_L}{2\pi F}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 2: Assume an inductor with a negligible resistance is connected to a 36-V, 400-Hz line. If the circuit has a current flow of 0.2 A, what is the inductance of the inductor?

Solution:
The first step is to determine the inductive reactance of the circuit.

$$X_L = \frac{E}{I}$$

$$X_L = \frac{36}{0.2}$$

$$X_L = 180\ \Omega$$

Now that the inductive reactance of the inductor is known, the inductance can be determined.

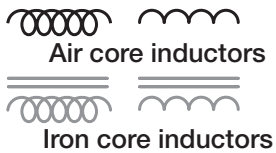
$$L = \frac{X_L}{2\pi F}$$

$$L = \frac{180}{2 \times 3.1416 \times 400}$$

$$L = 0.0716\ \text{H}$$

SCHEMATIC SYMBOLS

The schematic symbol used to represent an inductor depicts a coil of wire. Several symbols for inductors are shown in FIGURE 10-11. Although these symbols are different, they are similar. The symbols shown with the two parallel lines represent iron core inductors, and the symbols without the parallel lines represent air core inductors.



© Cengage Learning 2014

FIGURE 10-11
Schematic symbols for inductors.

VOLTAGE AND CURRENT RELATIONSHIPS IN AN INDUCTIVE CIRCUIT

When current flows through a pure resistive circuit, the current and voltage are in phase with each other. **In a pure inductive circuit the current lags the voltage by 90°.** At first this may seem to be an impossible condition until the relationship of applied voltage and induced voltage is considered. To understand how the current and applied voltage can become 90° out of phase with each other can best be explained by comparing the relationship of the current and induced voltage, FIGURE 10-12.

KEY POINT
In a pure inductive circuit the current lags the voltage by 90°.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

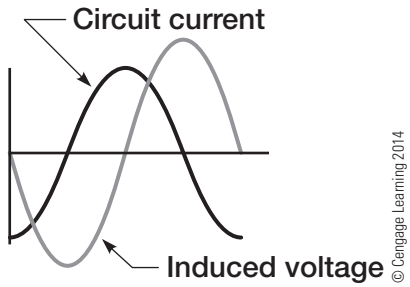


FIGURE 10-12 Induced voltage is proportional to the rate of change of current.

Recall that the induced voltage is proportional to the rate of change of the current (speed of cutting action). At the beginning of the waveform, the current is shown at its maximum value in the negative direction. At this point, the current is not changing, so induced voltage is zero. As the current begins to decrease in value, the magnetic field produced by the flow of current decreases or collapses and begins to induce a voltage into the coil as it cuts through the conductors, as shown in FIGURE 10-5.

The greatest rate of current change occurs when the current passes from negative through zero and begins to increase in the positive direction, FIGURE 10-13. Since the current is changing at the greatest rate, the induced

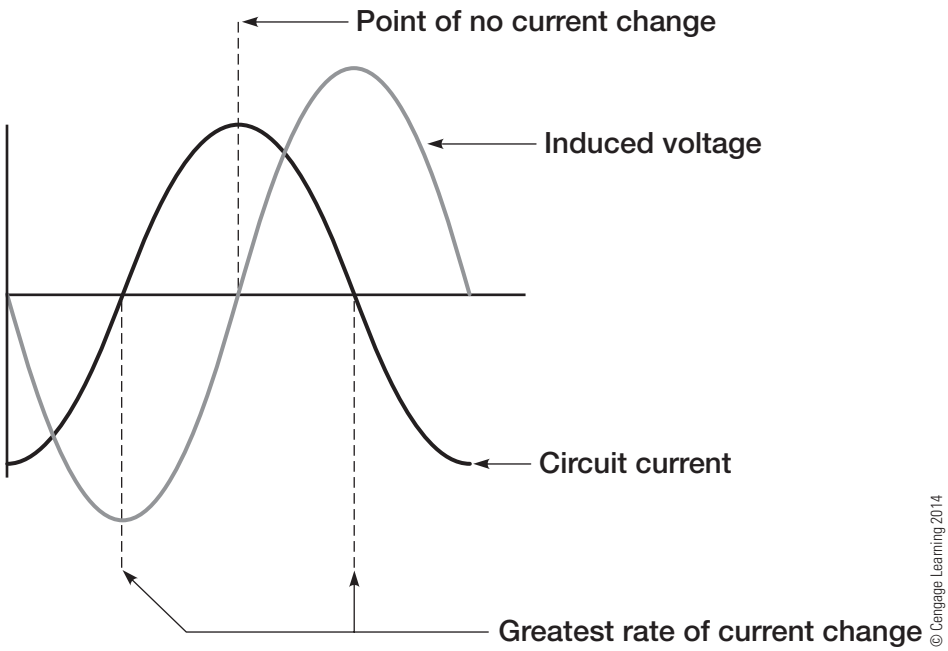


FIGURE 10-13 No voltage is induced when the current does not change.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

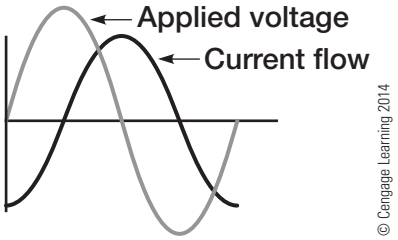


FIGURE 10-14 The current lags the applied voltage by 90°.

voltage is maximum. As current approaches its peak value in the positive direction, the rate of change decreases, causing a decrease in the induced voltage. The induced voltage will again be zero when the current reaches its peak value and the magnetic field stops expanding.

It can be seen that the current flowing through the inductor is leading the induced voltage by 90°. Since the induced voltage is 180° out of phase with the applied voltage, the current will lag the applied voltage by 90°, FIGURE 10-14.

POWER IN AN INDUCTIVE CIRCUIT

In a pure resistive circuit, the true power, or watts, is equal to the product of the voltage and current. In a pure inductive circuit, however, no true power or watts is produced. Recall that voltage and current must both be either positive or negative before true power can be produced. Since the voltage and current are 90° out of phase with each other in a pure inductive circuit, the current and voltage will be at different polarities 50% of the time and at the same polarity 50% of the time. During the period of time when the current and voltage have the same polarity, power is being given to the circuit in the form of creating a magnetic field. When the current and voltage are opposite in polarity, power is being given back to the circuit as the magnetic field collapses and induces a voltage back into the circuit. Since power is stored in the form of a magnetic field and then given back, no power is used by the inductor. Any power used in an inductor is caused by losses such as the resistance of the wire used to construct the inductor; these are generally referred to as I^2R losses, eddy current losses, and hysteresis losses.

The current and voltage waveform in FIGURE 10-15 has been divided into four sections: A, B, C, and D. During the first time period, indicated by A, the current is negative and the voltage is positive. During this period of time, energy is being given to the circuit as the magnetic field collapses. During the second time period, section B, both the voltage and

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

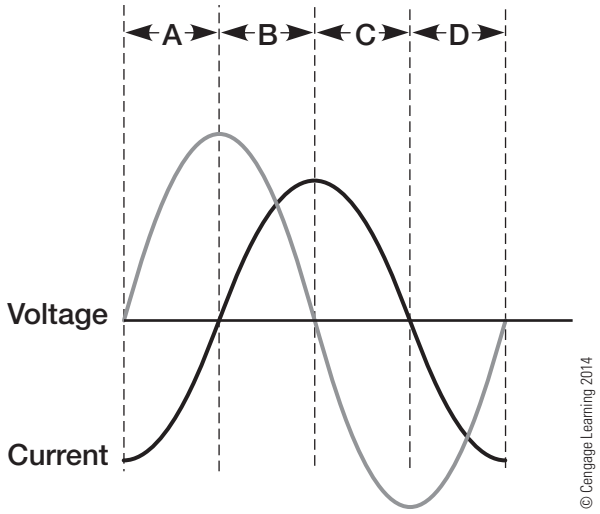


FIGURE 10-15 Voltage and current relationships during different parts of a cycle.

current are positive. Power is being used to produce the magnetic field. In the third time period, indicated by C, the current is positive and the voltage is negative. Power is again being given back to the circuit as the field collapses. During the fourth time period, indicated by D, both the voltage and current are negative. Power is again being used to produce the magnetic field. If the amount of power used to produce the magnetic field is subtracted from the power given back, the result is zero.

REACTIVE POWER

reactive power (VARs) the amount of power required to operate reactive components such as inductors and capacitors.

Although essentially no true power is used in a pure inductive circuit (except by previously mentioned losses), an electrical measurement called **VARs** is used to measure the **reactive power** in a pure inductive circuit. VARs is an abbreviation for volt-amps-reactive. VARs can be computed in the same way as watts, except that inductive values are substituted for resistive values in the formulas. VARs is equal to the amount of current flowing through an inductive circuit times the voltage applied to the inductive part of the circuit. Several formulas for computing VARs are

$$\text{VARs} = E_L \times I_L$$

$$\text{VARs} = \frac{E_L^2}{X_L}$$

$$\text{VARs} = I_L^2 \times X_L$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

where

E_L = voltage applied to an inductor

I_L = current flow through an inductor

X_L = inductive reactance

Summary

1. The three basic types of alternating current loads are resistive, inductive, and capacitive.
2. In a pure resistive load, the current and voltage are in phase with each other.
3. In a pure resistive load, V × A = W.
4. Watts is a measure of true power.
5. True power, or watts, can be produced only during the periods of time that both the voltage and current have the same polarity.
6. An electric circuit produces true power when electrical energy is converted into some other form.
7. Induced voltage is proportional to the rate of change of current.
8. Induced voltage is always opposite in polarity to the applied voltage.
9. Inductive reactance is a counter-voltage that limits the flow of current like resistance.
10. Inductive reactance is measured in ohms (Ω).
11. Inductive reactance is proportional to the inductance of the coil and the frequency of the line.
12. Inductive reactance is symbolized by X_L.
13. Inductance is measured in henrys and is symbolized by the letter L.
14. The current lags the applied voltage by 90° in a pure inductive circuit.
15. All inductors contain some amount of resistance.
16. Pure inductive circuits contain no true power, or watts.
17. Reactive power is measured in VARs.
18. VARs is an abbreviation for volt-amps-reactive.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Review Questions

1. How many degrees are the current and voltage out of phase with each other in a pure resistive circuit?
2. How many degrees are the current and voltage out of phase with each other in a pure inductive circuit?
3. To what is inductive reactance proportional?
4. An inductor is connected to a 240-V, 1000-Hz line. The circuit current is 0.6 A. What is the inductance of the inductor?
5. An inductor with an inductance of 3.6 H is connected to a 480-V, 60-Hz line. How much current will flow in this circuit?
6. If the frequency in question 5 is reduced to 50 Hz, how much current will flow in the circuit?
7. An inductor has an inductive reactance of 250 Ω when connected to a 60-Hz line. What will be the inductive reactance if the inductor is connected to a 400-Hz line?
8. An electric heating element has a current draw of 12 A when connected to a 240-V AC line. What is the true power of this circuit?
9. Reactive power is measured in what units?
10. A pure inductive load has an inductive reactance of 8.4 Ω and is connected to a 480-V AC line. What is the true power, or W, produced in this circuit? How many VARs are produced in this circuit?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Practice Problems

INDUCTIVE CIRCUITS

Fill in all missing values in the chart. Refer to the following formulas:

$$X_L = 2\pi FL$$

$$L = \frac{X_L}{2\pi F}$$

$$F = \frac{X_L}{2\pi L}$$

Inductance (H)	Frequency (Hz)	Inductive Reactance (Ω)
1.2	60	
0.085		213.628
	1000	4712.389
0.65	600	
3.6		678.584
	25	411.459
0.5	60	
0.85		6408.849
	20	201.062
0.45	400	
4.8		2412.743
	1000	40.841

© Cengage Learning 2014

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 11

Capacitive Loads

OBJECTIVES: After studying this unit, you should be able to:

- Discuss differences between capacitive and inductive loads.
- Describe the construction of a capacitor.
- List the three factors that determine the capacitance of a capacitor.
- Discuss electrostatic charges.
- Compute values of capacitive reactance.
- Discuss the charge and discharge rates of a capacitor.
- Describe differences between AC and electrolytic capacitors.

Capacitive loads are the third type of loads that can be encountered in an alternating current circuit. Capacitive loads are the exact opposite of inductive loads. Inductors oppose a change of current and capacitors oppose a change of voltage. In a pure inductive circuit the current lags the applied voltage by 90°, and in a pure capacitive circuit the current leads the applied voltage by 90°. Inductors store electrical energy in the form of an electromagnetic field and then return it to the circuit. Capacitors store electrical energy in the form of an electrostatic field and then return it to the circuit. To better understand how a capacitor works, it will first be necessary to discuss what a capacitor is.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CAPACITORS

Caution: It is the habit of some people to charge a capacitor to high voltage and then hand it to another person. While some people think this is comical, it is an extremely dangerous practice. Capacitors have the ability to supply an almost infinite amount of current. Under some conditions, a capacitor can have enough energy to cause a person's heart to go into fibrillation.

This statement is intended to make you realize the danger that capacitors can pose under certain conditions. Capacitors perform a variety of jobs, such as power factor correction, storing an electrical charge to produce a large current pulse, timing circuits, and electronic filters.

KEY POINT Capacitors are devices that oppose a change of voltage.

Capacitors are devices that oppose a change of voltage. The simplest type of capacitor is constructed by separating two metal **plates** with some type of insulating material called the **dielectric,** FIGURE 11-1. Three factors that determine the capacitance of a capacitor:

plates thin pieces of metal.

dielectric electrical insulator.

1. The area of the plates
2. The distance between the plates
3. The type of dielectric used

The greater the surface area of the plates, the more capacitance a capacitor will have. If a capacitor is charged by connecting it to a source of direct current, FIGURE 11-2, electrons are removed from the plate connected to the positive battery terminal and deposited on the plate connected to the negative terminal. This flow of current will continue until a voltage equal to the battery voltage is established across the plates of the capacitor, FIGURE 11-3. When these two voltages become equal, the flow of electrons will stop. The capacitor is now charged. If the battery is disconnected from the capacitor,

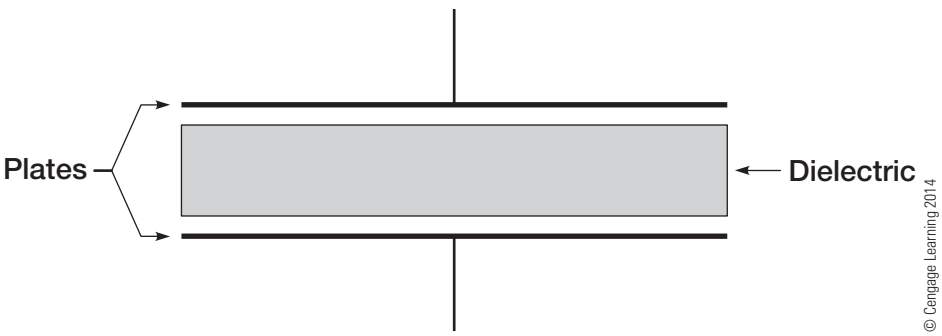


FIGURE 11-1 A capacitor is made by separating two metal plates with a dielectric.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

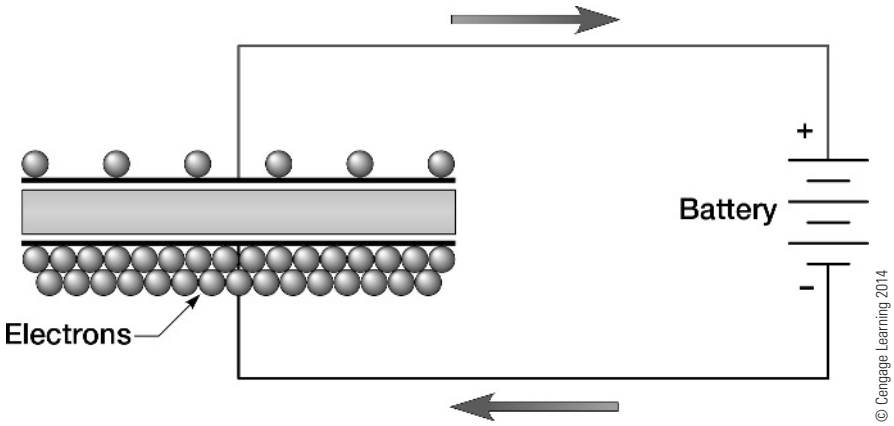


FIGURE 11-2 A capacitor can be charged by removing electrons from one plate and depositing electrons on the other plate.

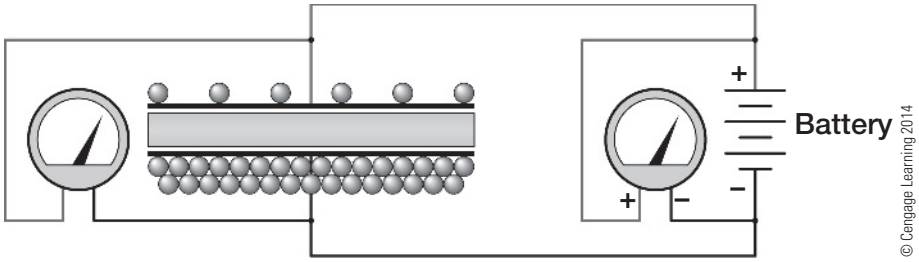


FIGURE 11-3 Current flows until the voltage across the capacitor is equal to the voltage of the battery.

KEY POINT

Current can flow only during the period of time that a capacitor is either charging or discharging.

the capacitor will remain charged as long as there is no path by which the electrons can move from one plate to the other, FIGURE 11-4. A good rule to remember concerning a capacitor and current flow is that **current can flow only during the period of time that a capacitor is either charging or discharging.**

In theory, it should be possible for a capacitor to remain in a charged condition forever. In actual practice, this is not the case. No dielectric is a perfect insulator, and electrons eventually move through the dielectric from the negative plate to the positive, causing the capacitor to discharge, FIGURE 11-5. This current flow through the dielectric is called **leakage current,** and is proportional to the resistance of the dielectric and the charge across the plates. If the dielectric of a capacitor becomes weak, it permits an excessive amount of leakage current to flow. A capacitor in this condition is often referred to as a leaky capacitor.

leakage current
the amount of current that passes through the dielectric.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

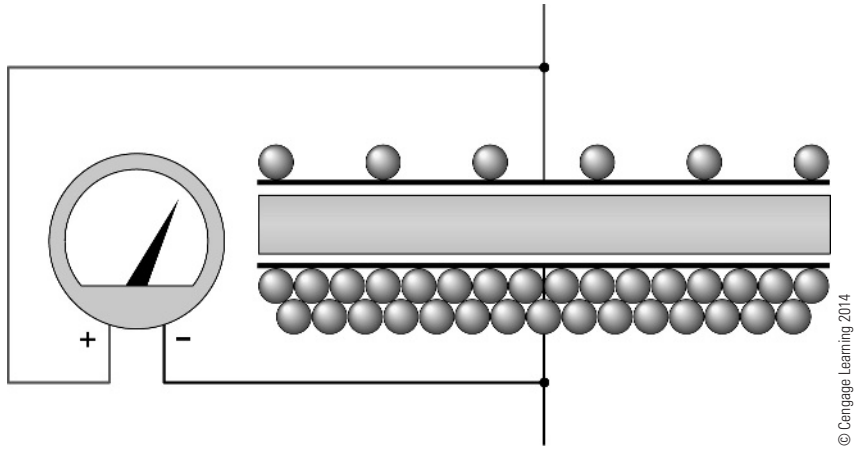


FIGURE 11-4 The capacitor remains charged after the battery is removed from the circuit.

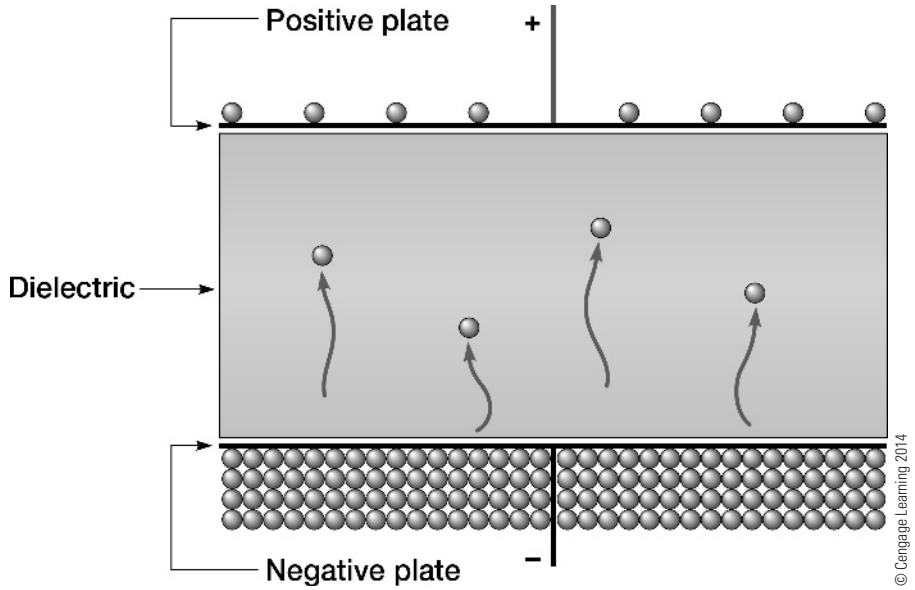


FIGURE 11-5 Electrons eventually leak through the dielectric. This flow of electrons is known as leakage current.

ELECTROSTATIC CHARGE

Two other factors that determine capacitance are the type of dielectric used and the distance between the plates. To understand these concepts, it is necessary to understand how a capacitor stores energy. In previous units it was

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

discussed that an inductor stores energy in the form of an electromagnetic field. A capacitor stores energy in an electrostatic field.

DIELECTRIC STRESS

When a capacitor is not charged, the atoms of the dielectric are uniform as shown in FIGURE 11-6. The valence electrons orbit the nucleus in a circular pattern. When the capacitor becomes charged, however, a potential exists between the plates of the capacitor. The plate with the lack of electrons has a positive charge, and the plate with the excess of electrons has a positive charge. Since electrons are negative particles, they are repelled away from the negative plate and attracted to the positive plate. This attraction causes the electron orbit to become stretched as shown in FIGURE 11-7. This stretching of the atoms of the dielectric is called **dielectric stress.** Placing the atoms of the dielectric under stress has the same effect as drawing back a bow string and arrow, and holding it, FIGURE 11-8.

dielectric stress
stress placed on the molecular structure of the dielectric.

The amount of dielectric stress is proportional to the voltage difference between the plates. The greater the voltage, the greater the dielectric stress. If the voltage becomes too great, the dielectric will break down and permit current to flow between the plates. At this point the capacitor becomes shorted. Capacitors have a voltage rating that should not be exceeded. The voltage rating indicates the maximum amount of voltage the dielectric is

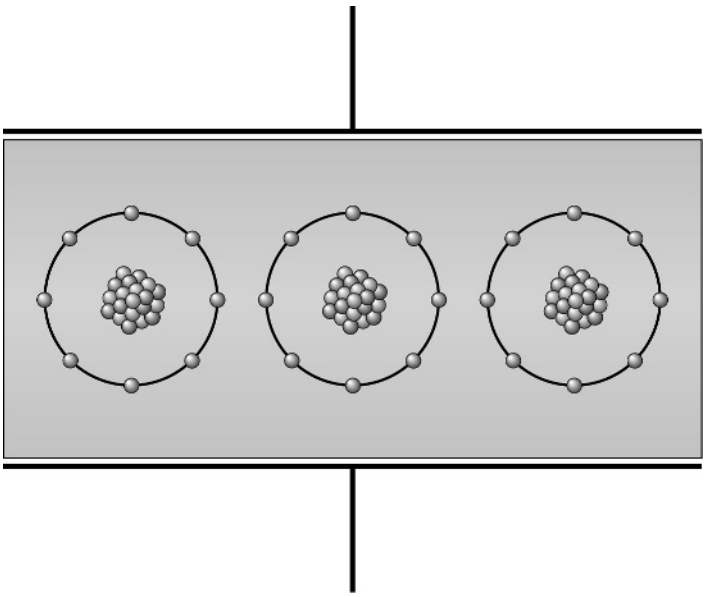

© Cengage Learning 2014

FIGURE 11-6 Atoms of the dielectric in an uncharged capacitor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

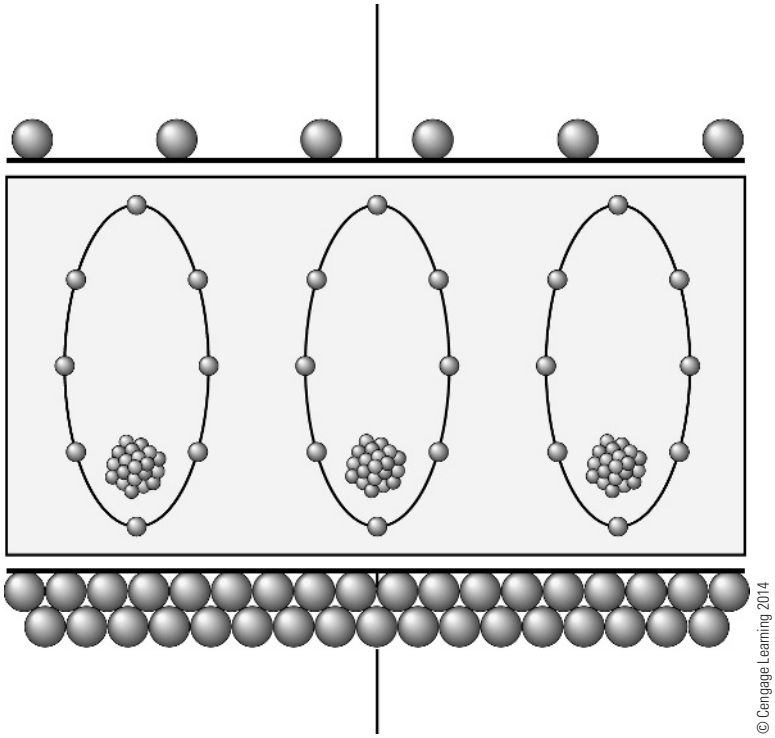


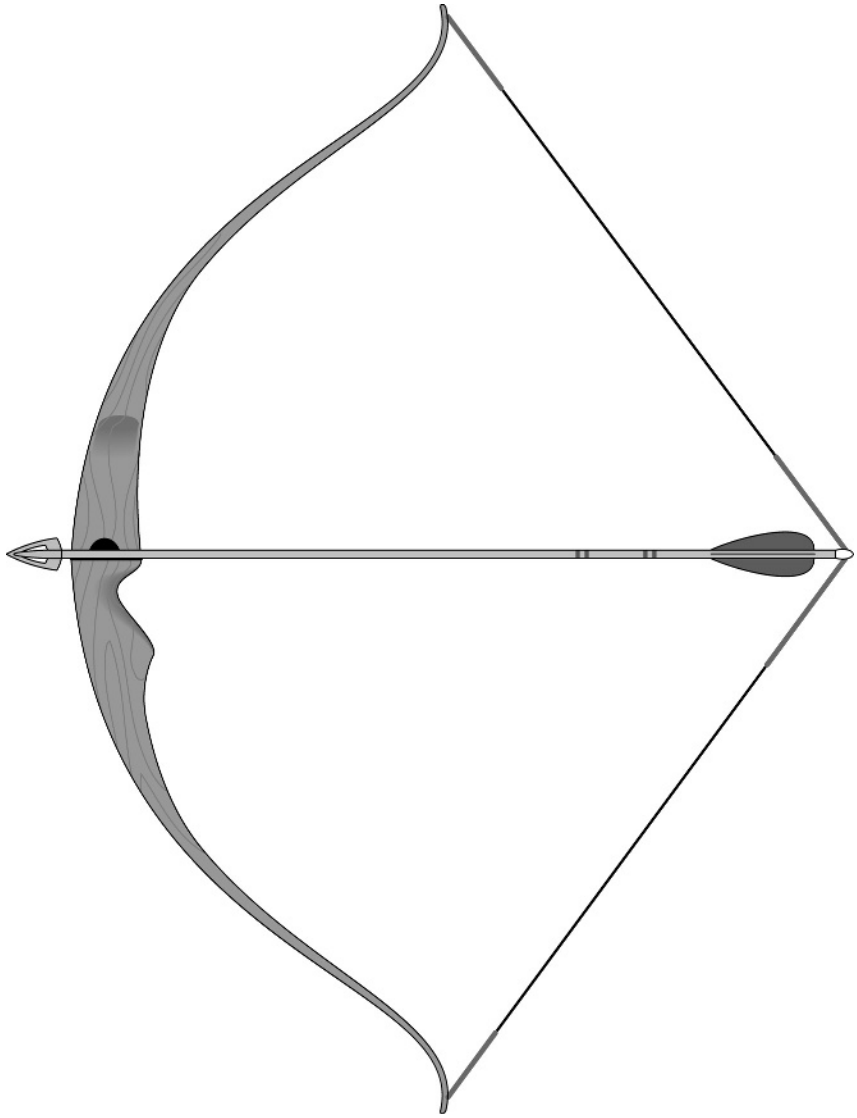
FIGURE 11-7 Atoms of the dielectric in a charged capacitor.

intended to withstand without breaking down. The amount of voltage applied to a capacitor is critical to its life span. Capacitors operated above their voltage rating will fail relatively quickly. Many years ago, the U.S. military made a study of the voltage rating of a capacitor as compared to its life span. The results showed that a capacitor operated at one-half its rated voltage will have a life span approximately eight times longer than a capacitor operated at the rated voltage.

The energy of the capacitor is stored in the dielectric in the form of an **electrostatic charge.** It is this electrostatic charge that permits the capacitor to produce extremely high currents under certain conditions. If the leads of a capacitor are shorted together, it has the effect of releasing the drawn-back bow string, FIGURE 11-8. When the bowstring is released, the arrow will be propelled forward at a high rate of speed. The same is true for the capacitor. When the leads are shorted, the atoms of the dielectric snap back to their normal position. Shorting causes the electrons on the negative plate to be literally blown off and attracted to the positive plate. Capacitors can produce currents of thousands of amperes for short periods of time.

electrostatic charge charge caused by the accumulation of electrons on one plate and the lack of electrons on the other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 11-8 Dielectric stress is similar to drawing back a bowstring with an arrow and holding it.

This principle is used to operate the electronic flash of many cameras. Electronic flash attachments contain a small glass tube filled with a gas called xenon. Xenon produces a very bright white light similar to sunlight when the gas is ionized. A large amount of power is required, however, to produce a bright flash. A battery capable of directly ionizing the xenon would

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

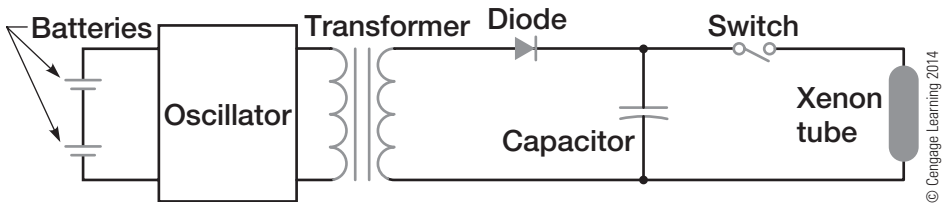


FIGURE 11-9 Energy is stored in a capacitor.

be very large, expensive, and have a potential of about 500 V. The simple circuit shown in FIGURE 11-9 can be used to overcome the problem. In this circuit, two small 1.5-V batteries are connected to an oscillator. The oscillator changes the direct current of the batteries into square wave alternating current. The alternating current is then connected to a transformer and the voltage is increased to about 500-V peak. A diode changes the AC voltage back into DC and charges a capacitor. The capacitor charges to the peak value of the voltage waveform. When the switch is closed, the capacitor suddenly discharges through the xenon tube and supplies the power needed to ionize the gas. It may take several seconds to store enough energy in the capacitor to ionize the gas in the tube, but the capacitor can release the stored energy in a fraction of a second.

To understand how the capacitor can supply the energy needed, consider the amount of gunpowder contained in a 0.357 cartridge. If the powder were to be removed from the cartridge and burned in the open air, it would be found that the actual amount of energy contained in the powder is very small. This amount of energy would not even be able to raise the temperature by a noticeable amount in a small enclosed room. If this same amount of energy is converted into heat in a fraction of a second, however, enough force is developed to propel a heavy projectile with great force. This same principle is at work when a capacitor is charged over some period of time and then discharged in a fraction of a second.

DIELECTRIC CONSTANTS

Since the energy of the capacitor is stored in the dielectric, the type of dielectric used is extremely important in determining the amount of capacitance a capacitor will have. Different materials are assigned a number called the **dielectric constant.** Air is assigned the number 1 and is used as a reference for comparison. For example, assume a capacitor uses air as the dielectric and its capacitance value is found to be 1 microfarad (μF). Now

dielectric constant a measurement of the characteristics of different types of dielectric material.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

MATERIAL	DIELECTRIC CONSTANT
Air	1
Bakelite	4.0–10.0
Castor Oil	4.3–4.7
Cellulose Acetate	7.0
Ceramic	1200
Dry Paper	3.5
Hard Rubber	2.8
Insulating Oils	2.2–4.6
Lucite	2.4–3.0
Mica	6.4–7.0
Mycalex	8.0
Paraffin	1.9–2.2
Porcelain	5.5
Pure Water	81
Pyrex Glass	4.1–4.9
Rubber Compounds	3.0–7.0
Teflon	2
Titanium Dioxide Compounds	90–170

© Cengage Learning 2014

FIGURE 11-10 Dielectric constant of different materials.

farad
basic unit of capacitance.

KEY POINT

A capacitor has a capacitance of one farad when a change of one volt across its plates results in a movement of one coulomb.

assume that some dielectric material is placed between the plates without changing the spacing and the capacitance value becomes 5 μF. This material has a dielectric constant of 5. A chart showing the dielectric constant of different materials is shown in FIGURE 11-10.

CAPACITOR RATINGS

The basic unit of capacitance is the **farad** and is symbolized by the letter F. It receives its name from a famous scientist named Michael Faraday. **A capacitor has a capacitance of one farad when a change of one volt across its plates results in a movement of one coulomb.**

$$Q = C \times V$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

where

Q = charge in coulombs
C = capacitance in farads
V = charging voltage

Although the farad is the basic unit of capacitance, it is seldom used because it is an extremely large amount of capacitance. The formula shown below can be used to determine the capacitance of a capacitor when the area of the plates, the dielectric constant, and the distance between the plates is known.

$$C = \frac{K \times A}{4.45\ D}$$

where

C = capacitance in pF (picofarads)
K = dielectric constant
A = area of one plate
D = distance between the plates

EXAMPLE 1: What would be the plate area of a 1-F capacitor if air is used as the dielectric and the plates are separated by a distance of 1 in?

Solution:
The first step is to convert the above formula to solve for area.

$$A = \frac{C \times 4.45 \times D}{K}$$

$$A = \frac{1{,}000{,}000{,}000{,}000 \times 4.45 \times 1}{1}$$

$$A = 4{,}450{,}000{,}000{,}000 \text{ square inches}$$

$$A = 1108.5 \text{ square miles}$$

Since the basic unit of capacitance is so large, other units such as the microfarad (μF), nanofarad (nF), and picofarad (pF) are generally used.

$$\mu F = \frac{1}{1{,}000{,}000}\ (1 \times 10^{-6}) \text{ of a farad}$$

$$nF = \frac{1}{1{,}000{,}000{,}000}\ (1 \times 10^{-9}) \text{ of a farad}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$\text{pF} = \frac{1}{1{,}000{,}000{,}000{,}000}(1 \times 10^{-12}) \text{ of a farad}$$

The picofarad is sometimes referred to as a micro-microfarad and is symbolized by $\mu\mu$F.

CAPACITORS CONNECTED IN PARALLEL

Connecting capacitors in parallel, FIGURE 11-11, has the same effect as increasing the plate area of one capacitor. In the example shown, three capacitors having a capacitance of 20 μF, 30 μF, and 60 μF are connected in parallel. The total capacitance of this connection is

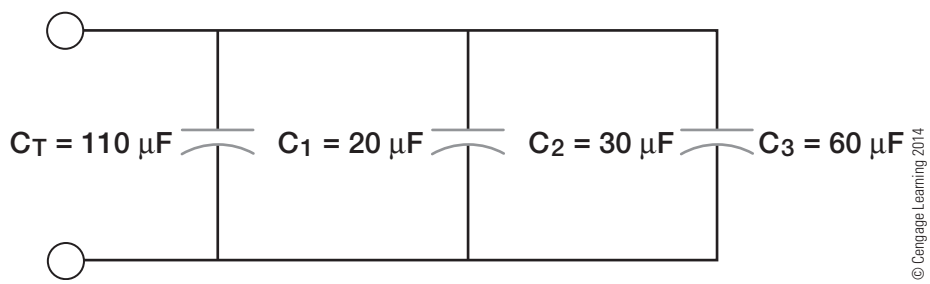
$$C_T = C_1 + C_2 + C_3$$
$$C_T = 20 + 30 + 60$$
$$C_T = 110\ \mu\text{F}$$

CAPACITIVE CHARGE AND DISCHARGE RATES

exponential
a natural curve.

Capacitors charge and discharge at an **exponential** rate. A charge curve for a capacitor is shown in FIGURE 11-12. The curve is divided into five time constants and each time constant is equal to 63.2% of the whole value. In Figure 11-12 it is assumed that a capacitor is to be charged to a total of 100 V. At the end of the first time constant the voltage has reached 63.2% of 100 or 63.2 V. At the end of the second time constant, the voltage reaches 63.2% of the remaining voltage, or 86.4 V. This continues until the capacitor has been charged to 100 V.

The capacitor discharges in the same manner, FIGURE 11-13. At the end of the first time constant the voltage will decrease to 63.2% of its charged value. In this example the voltage will decrease from 100 V to 36.8 V in the first time constant.



© Cengage Learning 2014

FIGURE 11-11 Capacitors connected in parallel.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

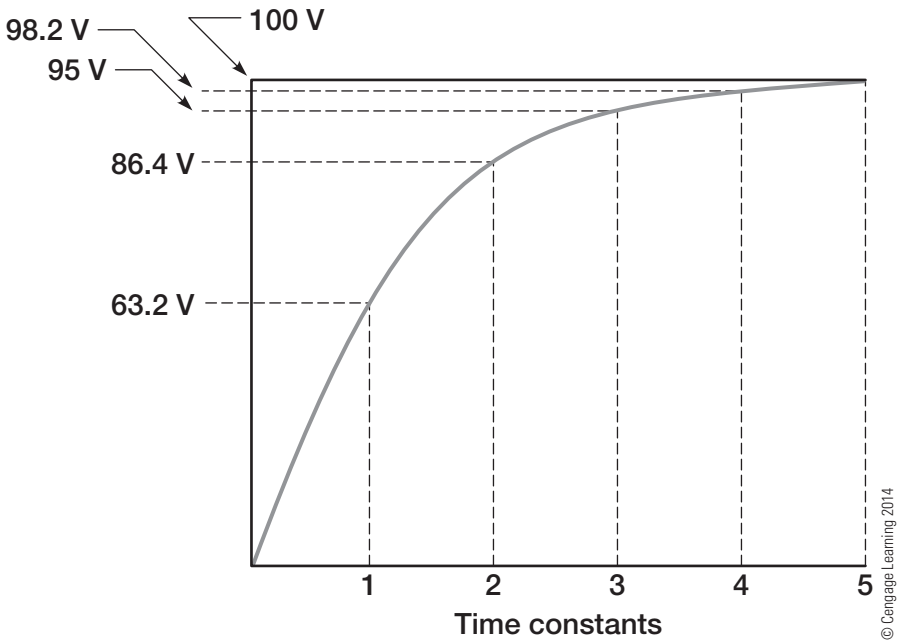


FIGURE 11-12 Capacitors charge at an exponential rate.

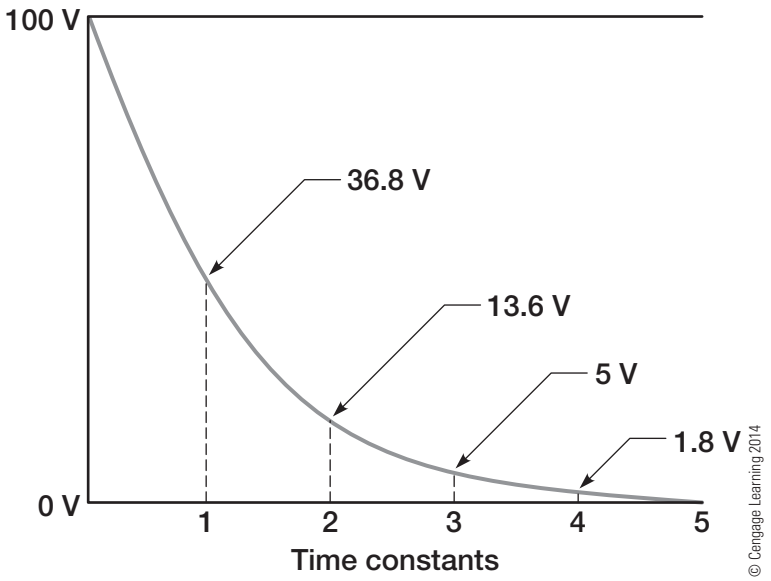


FIGURE 11-13 Capacitor discharge curve.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

At the end of the second time constant the voltage will drop to 13.6 V, and by the end of the third time constant the voltage has dropped to 5 V. The voltage will continue to drop at this rate until it reaches approximately 0 after five time constants.

APPLICATIONS FOR CAPACITORS

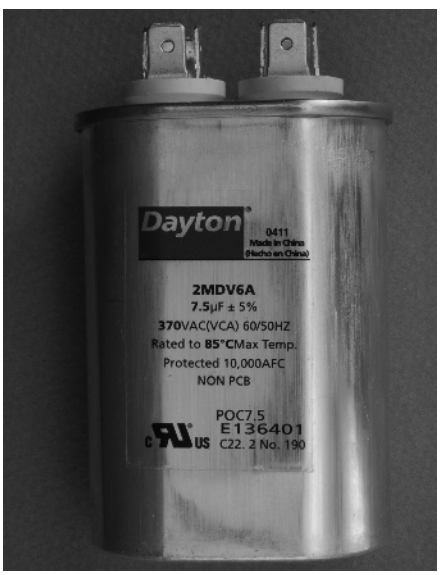
Capacitors are among the most used of electrical components. They are used for power factor correction in industrial applications, in the start windings of many single phase AC motors, to produce phase shifts for SCR and triac circuits, to filter pulsating DC, and in RC timing circuits. Capacitors are used extensively in electronic circuits for control of frequency and pulse generation. The type of capacitor used is dictated by the circuit application.

NONPOLARIZED CAPACITORS

Nonpolarized capacitors
capacitors that are not polarity sensitive.

Capacitors can be divided into two basic groups, nonpolarized and polarized. **Nonpolarized capacitors** are often referred to as AC capacitors because they are not sensitive to polarity connection. Nonpolarized capacitors can be connected to either DC or AC circuits without harm to the capacitor. Most nonpolarized capacitors are constructed by separating metal plates by some type of dielectric. These capacitors can be obtained in many different styles and case types.

A common type of AC capacitor, called the paper capacitor or oil-filled capacitor, is often used in motor circuits, FIGURE 11-14. This capacitor



© Cengage Learning 2014

FIGURE 11-14 Oil-filled paper capacitor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

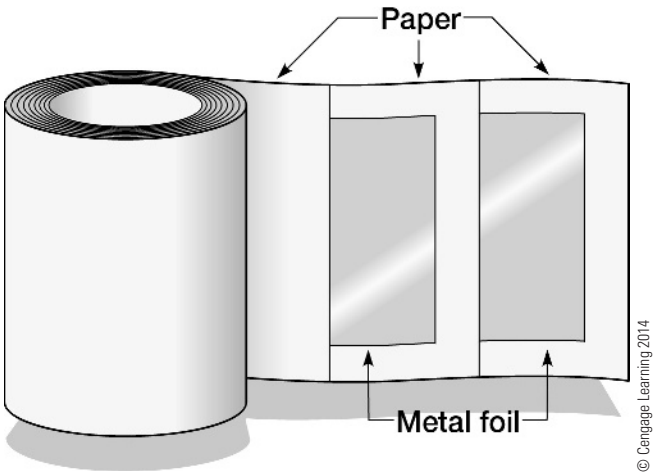


FIGURE 11-15 Oil-filled paper capacitor.

derives its name from the type of dielectric used. This capacitor is constructed by separating plates made of metal foil with thin sheets of paper soaked in a dielectric oil, FIGURE 11-15. These capacitors are often used as the run or starting capacitor for single-phase motors. Many manufacturers of oil-filled capacitors will identify one terminal with an arrow or painted dot or by stamping a dash in the capacitor can, FIGURE 11-16. This identified terminal

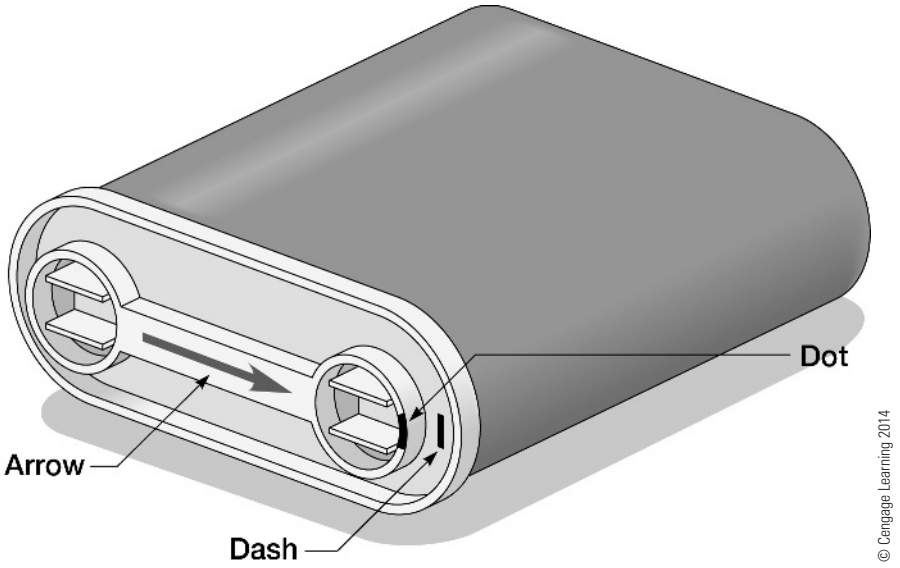


FIGURE 11-16 Marks indicate the plate nearest the capacitor case.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

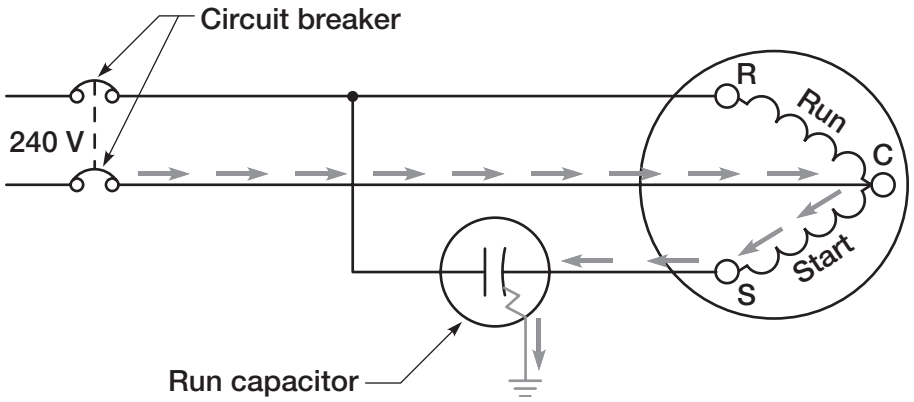


FIGURE 11-17 Identified capacitor terminal connected to motor start winding (incorrect connection).

marks the connection to the plate that is located nearer to the metal container or can. It has long been known that when a capacitor's dielectric breaks down and permits a short circuit to ground, it is most often the plate located nearer to the outside case that becomes grounded. For this reason, it is generally desirable to connect the identified capacitor terminal to the line side instead of to the motor start winding.

In FIGURE 11-17, the run capacitor has been connected in the circuit in such a manner that the identified terminal is connected to the start winding of a single-phase motor. If the capacitor should become shorted to ground, a current path will exist through the motor start winding. The start winding is an inductive-type load, and inductive reactance will limit the value of current flow to ground. Since the flow of current is limited, it will take the circuit breaker or fuse some time to open the circuit and disconnect the motor from the power line. This time delay can permit the start winding to overheat and become damaged.

In FIGURE 11-18, the run capacitor has been connected in the circuit in such a manner that the identified terminal is connected to the line side. If the capacitor should become shorted to ground, a current path exists directly to ground, bypassing the motor start winding. When the capacitor is connected in this manner, the start winding does not limit current flow and permits the fuse or circuit breaker to open the circuit almost immediately.

POLARIZED CAPACITORS

Polarized capacitors
capacitors that are polarity sensitive.

Polarized capacitors are generally referred to as **electrolytic** capacitors. These capacitors are sensitive to the polarity to which they are connected and will have one terminal identified as positive or negative, FIGURE 11-19.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

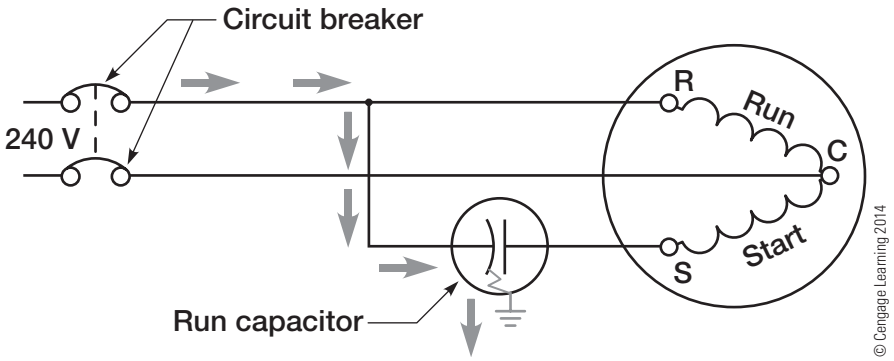


FIGURE 11-18 Identified terminal connected to the line (correct connections).



FIGURE 11-19 DC electrolytic capacitors.

Polarized capacitors can be used in DC circuits only. If their polarity connection is reversed, the capacitor can be damaged and will sometimes explode. The advantage of electrolytic capacitors is that they can have very high capacitance in a small case.

There are two basic types of electrolytic capacitors, the wet type and the dry type. The wet-type electrolytic capacitor, FIGURE 11-20, has a positive plate made of aluminum foil. The negative plate is actually an electrolyte made from a borax solution. A second piece of aluminum foil is placed in contact with the electrolyte and becomes the negative terminal. When a source of direct current is connected to the capacitor, the borax solution forms an insulating oxide film on the positive plate. This film is only a few molecules thick and acts as the insulator to separate the plates. The capacitance is very high because the distance between the plates is so small.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

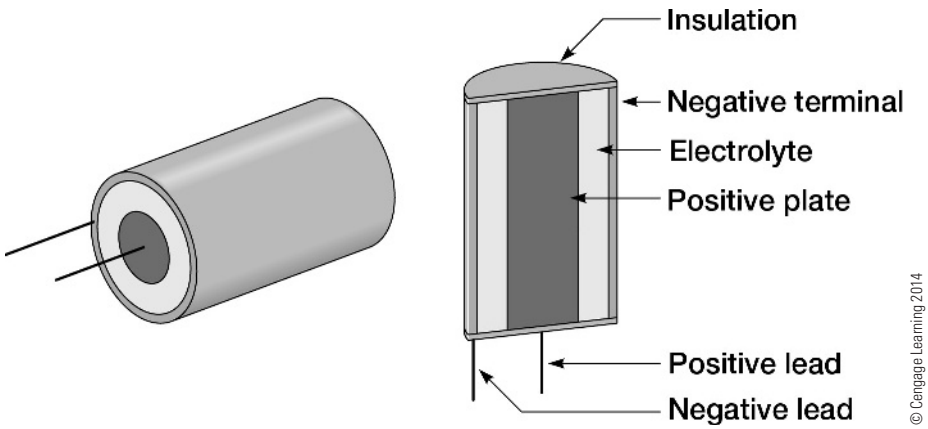


FIGURE 11-20 Wet-type electrolytic capacitor.

If the polarity of the wet-type electrolytic capacitor becomes reversed, the oxide insulating film will dissolve and the capacitor will become shorted. If the polarity connection is corrected, the film will reform and restore the capacitor.

AC ELECTROLYTIC CAPACITORS

This ability of the wet-type electrolytic capacitor to be shorted and then reformed is the basis for a special type of nonpolarized electrolytic capacitor called the AC electrolytic capacitor. This capacitor is used as the starting capacitor for many small single-phase motors, as the run capacitor in many ceiling fan motors, and for low-power electronic circuits when a nonpolarized capacitor with a high capacitance is required. The AC electrolytic capacitor is made by connecting two wet-type electrolytic capacitors inside the same case, FIGURE 11-21. In the example shown,

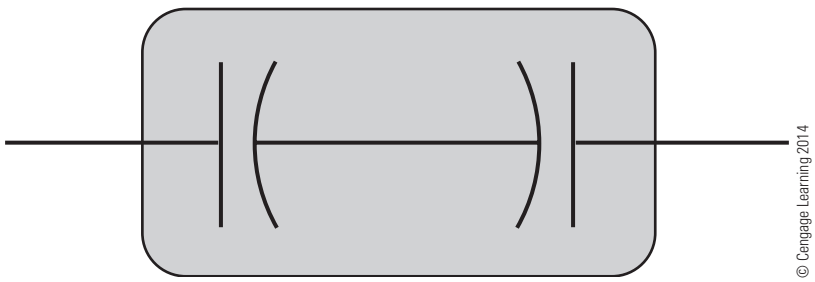


FIGURE 11-21 Two wet-type electrolytic capacitors connect to form an AC electrolytic capacitor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

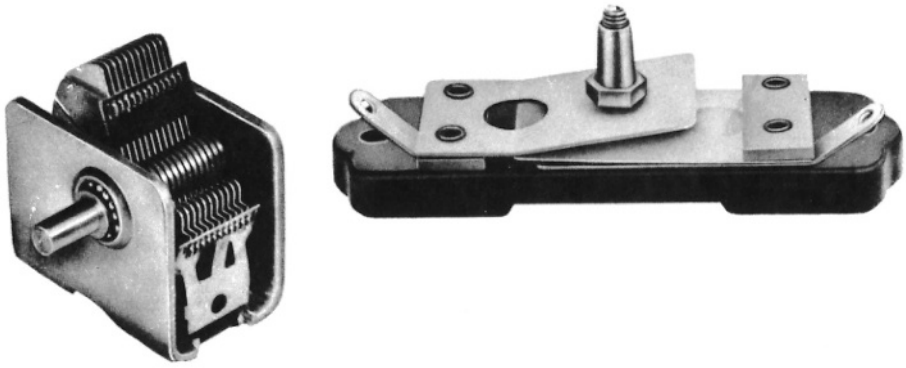
FIGURE 11-22 An AC electrolytic capacitor.

the two wet-type electrolytic capacitors have their negative terminals connected. When alternating current is applied to the leads, one capacitor will be connected to reverse polarity and become shorted. The other capacitor will be connected to the correct polarity and will form. During the next half cycle, the polarity changes: it forms the capacitor that was shorted and shorts the other capacitor. An AC electrolytic capacitor is shown in FIGURE 11-22.

DRY-TYPE ELECTROLYTIC CAPACITORS

The dry-type electrolytic capacitor is very similar to the wet-type except that gauze is used to hold the borax solution. This prevents the capacitor from leaking. Although the dry-type electrolytic has the advantage of being relatively leak proof, it does have one disadvantage. If the polarity connection should become reversed and the oxide film is broken down, it will not reform when connected to the proper polarity. Reversing the polarity of a dry-type electrolytic capacitor will permanently damage the capacitor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 11-23 Variable capacitors.

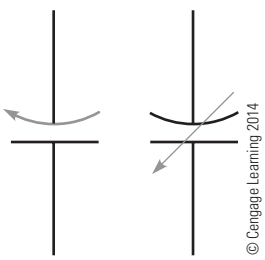
VARIABLE CAPACITORS

Variable capacitors are constructed so that their capacitance value can be changed over a certain range. They generally contain a set of movable plates, which are connected to a shaft, and a set of stationary plates, FIGURE 11-23. The movable plates can be interleaved with the stationary plates to increase or decrease the capacitance value. Since air is used as the dielectric and the plate area is relatively small, variable capacitors are generally rated in picofarads. Another type of small variable capacitor is called the trimmer capacitor, also shown in Figure 11-23. This capacitor has one movable plate and one stationary plate. The capacitance value is changed by turning an adjustment screw that moves the movable plate closer to or farther away from the stationary plate. FIGURE 11-24 shows schematic symbols used to represent variable capacitors.

TESTING CAPACITORS

Testing capacitors is difficult at best. Small electrolytic capacitors are generally tested for shorts with an ohmmeter. If the capacitor is not shorted, it should be tested for leakage using a variable DC power supply and a microammeter, FIGURE 11-25. When rated voltage is applied to the capacitor, the microammeter should indicate zero current flow.

Large AC oil-filled capacitors can be tested in a similar manner. To test the capacitor accurately, two measurements must be made. One is to measure the capacitance value of the capacitor to determine if it is the same or approximately the same as the rate value. The other is to test the strength of the dielectric.



© Cengage Learning 2014

FIGURE 11-24 Variable capacitor symbols.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

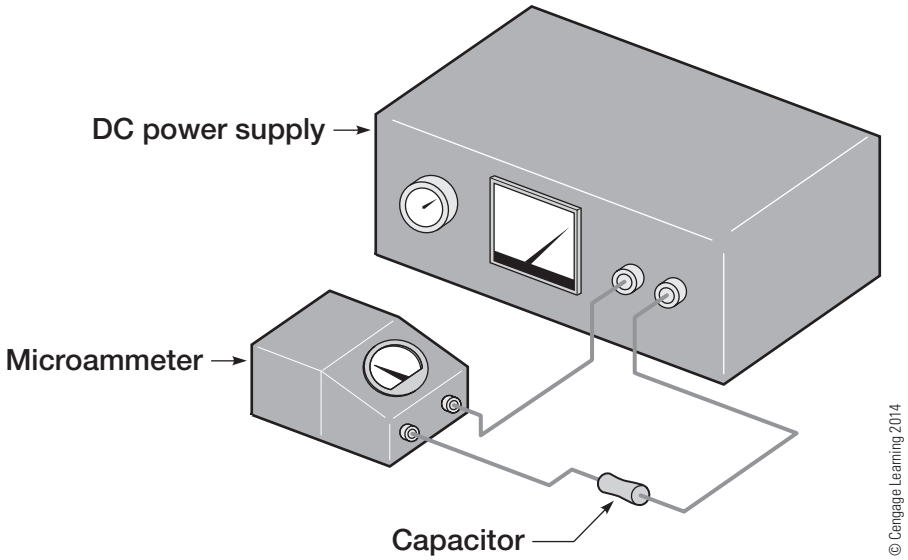


FIGURE 11-25 Testing a capacitor for leakage.

The first test should be made with an ohmmeter. With the power disconnected, connect the terminals of an ohmmeter directly across the capacitor terminals, FIGURE 11-26. This test determines if the dielectric is shorted. When the ohmmeter is connected, the needle should swing up scale and return to infinity. The amount of needle swing is determined by the capacitance of the capacitor. Then reverse the ohmmeter connection, and the needle should move twice as far up scale and then return to the infinity setting.

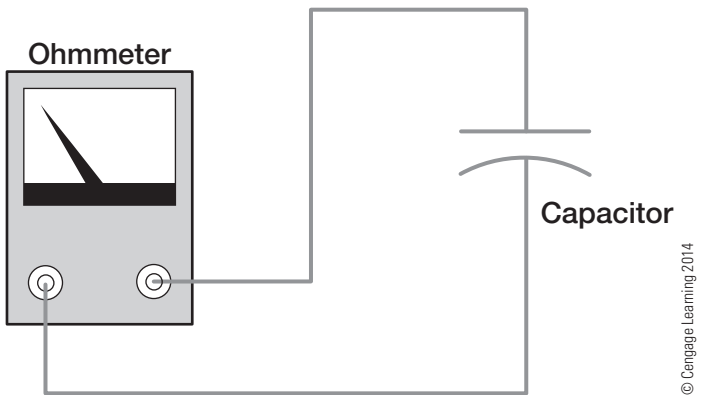


FIGURE 11-26 Testing the capacitor with an ohmmeter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

HIPOT
a device used to test the dielectric strength.

If the ohmmeter test is successful, the dielectric must be tested at its rated voltage. This is called a dielectric strength test. To make this test, a dielectric test set must be used. This device is often referred to as a **HIPOT** because of its ability to produce a high voltage or high potential. The dielectric test set contains a variable voltage control, a voltmeter, and a microammeter. To use the HIPOT, connect its terminal leads to the capacitor terminals. Increase the output voltage until the rated voltage is applied to the capacitor. The microammeter indicates any current flow between the plates of the dielectric. If the capacitor is good, the microammeter should indicate zero current flow.

The capacitance value must be measured to determine if there are any open plates in the capacitor. To measure the capacitance value of the capacitor, connect some value of AC voltage across the plates of the capacitor, FIGURE 11-27. This voltage must not be greater than the rated capacitor voltage. Then measure the amount of current flow in the circuit. Now that the voltage and current flow are known, the capacitive reactance of the capacitor can be computed using the formula

$$X_C = \frac{E}{I}$$

After the capacitive reactance has been determined, the capacitance can be computed using the formula

$$C = \frac{1}{2\pi F X_C}$$

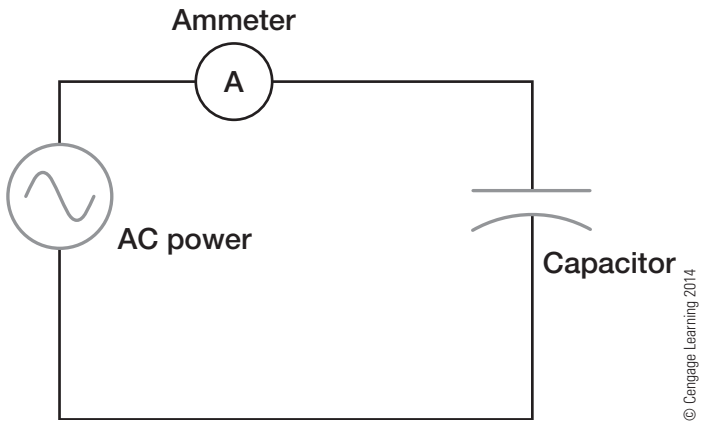


FIGURE 11-27 Determining the capacitance value.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CAPACITANCE IN ALTERNATING CURRENT CIRCUITS

When a capacitor is connected to an alternating current circuit, current will *appear to flow* through the capacitor. The reason is that in an AC circuit, the current is continually changing direction and polarity. To understand this concept, consider the hydraulic circuit shown in FIGURE 11-28. Two tanks are connected to a common pump. Assume tank A to be full and tank B to be empty. Now assume that the pump is used to pump water from tank A to tank B. When tank B becomes full, the pump reverses and pumps the water from tank B back into tank A. Each time a tank becomes filled, the pump reverses and pumps water back into the other tank. Notice that water is continually flowing in this circuit, but there is no direct connection between the two tanks.

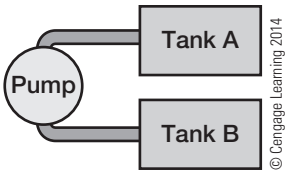


FIGURE 11-28 Water can flow continuously, but not between the two tanks.

A similar action takes place when a capacitor is connected to an alternating current circuit, FIGURE 11-29. In this circuit, the AC generator or alternator charges one plate of the capacitor positive and the other plate negative. During the next half cycle, the voltage will change polarity and the capacitor will discharge and recharge to the opposite polarity also. As long as the voltage continues to increase, decrease, and change polarity, current will flow from one plate of the capacitor to the other. If an ammeter were placed in the circuit, it would indicate a continuous flow of current, giving the appearance that current is flowing through the capacitor.

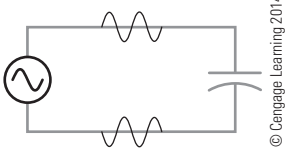


FIGURE 11-29 A capacitor connected to an AC circuit.

CAPACITIVE REACTANCE

As the capacitor is charged, an impressed voltage is developed across its plates as an electrostatic charge is built up, FIGURE 11-30. This impressed voltage opposes the applied voltage and limits the flow of current in the circuit. This counter-voltage is very similar to the counter-voltage produced by an inductor. The counter-voltage developed by the capacitor is called reactance also.

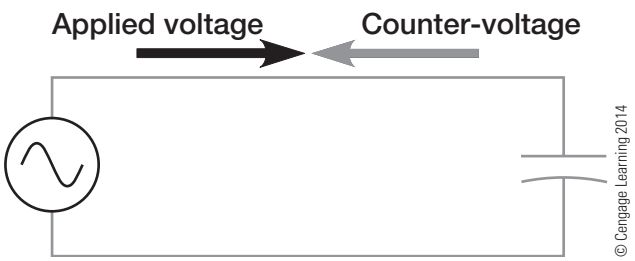


FIGURE 11-30 Counter-voltage limits the flow of current.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

capacitive reactance (X_C) reactance caused by capacitance.

Since this counter-voltage is caused by capacitance, it is called **capacitive reactance (X_C)** and is measured in ohms. The formula for finding capacitive reactance is

$$X_C = \frac{1}{2\pi FC}$$

where

X_C = capacitive reactance
π = 3.1416
F = frequency in hertz
C = capacitance in farads

EXAMPLE 2: A 35-μF capacitor is connected to a 120-V, 60-Hz line. How much current will flow in this circuit?

Solution:
The first step is to compute the capacitive reactance. Recall that the value of C in the formula is given in farads. This must be changed to the capacitive units being used; in this case it will be microfarads.

$$X_C = \frac{1}{2 \times 3.1416 \times 60 \times (35 \times 10^{-6})}$$

$$X_C = 75.79\ \Omega$$

Now that the value of capacitive reactance is known, it can be used like resistance in an Ohm's Law formula. Since capacitive reactance is the current-limiting factor, it will replace the value of R.

$$I = \frac{E}{X_C}$$

$$I = \frac{120}{75.79}$$

$$I = 1.58\ A$$

COMPUTING CAPACITANCE

If the value of capacitive reactance is known, the capacitance of the capacitor can be found using the formula

$$C = \frac{1}{2\pi FX_C}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 3: A capacitor is connected into a 480-V, 60-Hz circuit. An ammeter indicates a current flow of 2.6 A. What is the capacitance value of the capacitor?

Solution:

The first step is to compute the value of capacitive reactance. Since capacitive reactance, like resistance, limits current flow, it can be substituted for R in an Ohm's Law formula.

$$X_C = \frac{E}{I}$$

$$X_C = \frac{480}{2.6}$$

$$X_C = 184.61\ \Omega$$

Now that the capacitive reactance of the circuit is known, the value of capacitance can be found.

$$C = \frac{1}{2\pi F X_C}$$

$$C = \frac{1}{2 \times 3.1416 \times 60 \times 184.61}$$

$$C = \frac{1}{69{,}596.49}$$

$$C = 0.00001437\ \text{F} = 14.37\ \mu\text{F}$$

VOLTAGE AND CURRENT RELATIONSHIPS IN A PURE CAPACITIVE CIRCUIT

Earlier in this text it was shown that the current in a pure resistive circuit is in phase with the applied voltage, whereas current in a pure inductive circuit lags the applied voltage by 90°. In this unit it will be shown that in a pure capacitive circuit the current will *lead* the applied voltage by 90°.

When a capacitor is connected to an alternating current, the capacitor will charge and discharge at the same rate and time as the applied voltage. The charge in coulombs is equal to the capacitance of the capacitor times the applied voltage ($Q = C \times V$). When the applied voltage is zero, the charge in coulombs and impressed voltage will be zero also. When the applied voltage reaches its maximum value, positive or negative, the charge in coulombs and

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

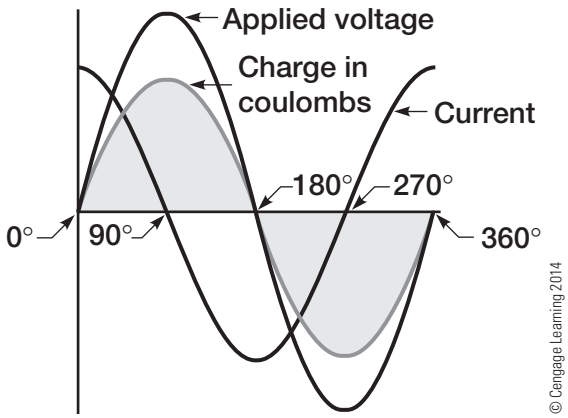


FIGURE 11-31 Capacitive current leads the applied voltage by 90°.

impressed voltage will reach maximum also, FIGURE 11-31. The impressed voltage will follow the same curve as the applied voltage.

In the waveform shown, voltage and charge are both shown to be zero at 0°. Since there is no charge on the capacitor, there is no opposition to current flow, which is shown to be maximum. As the applied voltage increases from zero toward its positive peak at 90°, the capacitor begins to charge at the same time. The charge produces an impressed voltage across the plates of the capacitor that opposes the flow of current. The impressed voltage is 180° **out of phase** with the applied voltage, FIGURE 11-32. When the applied voltage reaches 90° in the positive direction, the charge reaches maximum, the impressed voltage reaches peak in the negative direction, and the current flow is zero.

out of phase
condition in which two components do not reach their positive or negative peaks at the same time.

As the applied voltage begins to decrease, the capacitor begins to discharge, causing the current to flow in the opposite or negative direction. When the applied voltage and charge reach zero at 180°, the impressed voltage is zero also and the current flow is maximum in the negative direction. As the applied voltage and charge increase in the negative direction, the increase of the impressed voltage across the capacitor again causes the current to decrease. The applied voltage and charge reach maximum negative after 270° of rotation. The impressed voltage reaches maximum positive and the current has decreased to zero, FIGURE 11-33. As the applied voltage decreases from its maximum negative value, the capacitor again begins to discharge. This causes the current to flow in the positive direction. The current again reaches its maximum positive value when the applied voltage and charge reach zero after 360° of rotation.

POWER IN A PURE CAPACITIVE CIRCUIT

Since the current flow in a pure capacitive circuit is leading the applied voltage by 90°, the voltage and current will both have the same polarity for half the time during one cycle and have opposite polarities the other half of the time,

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

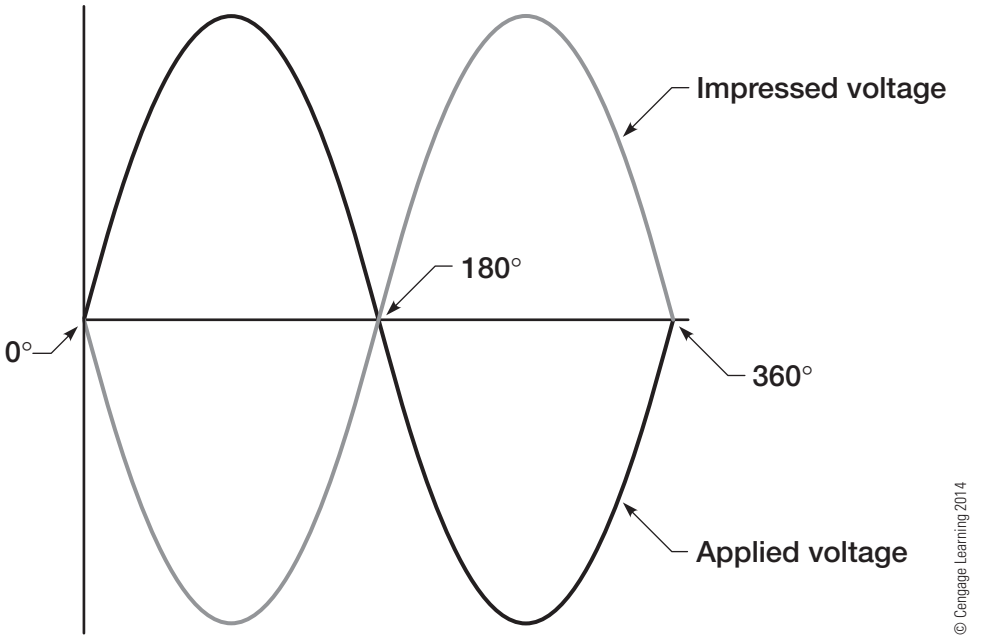


FIGURE 11-32 The impressed voltage is 180° out of phase with the applied voltage.

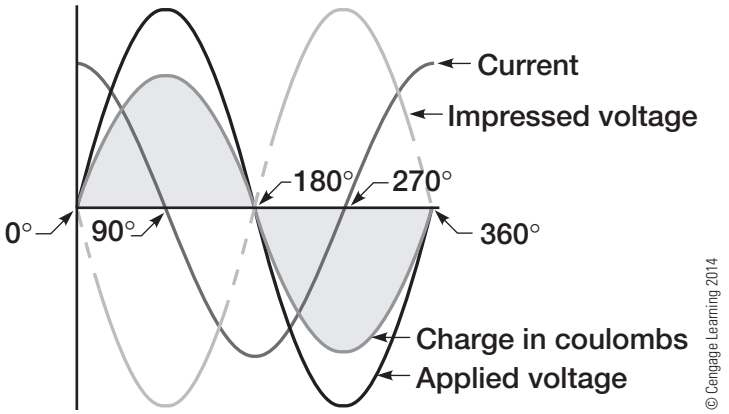


FIGURE 11-33 Voltage, current, and charge relationships for a capacitive circuit.

FIGURE 11-34. During the period of time when both the voltage and current have the same polarity, energy is being stored in the capacitor in the form of an electrostatic field. When the voltage and current have opposite polarities, the capacitor is discharging and the energy is returned to the circuit. When

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

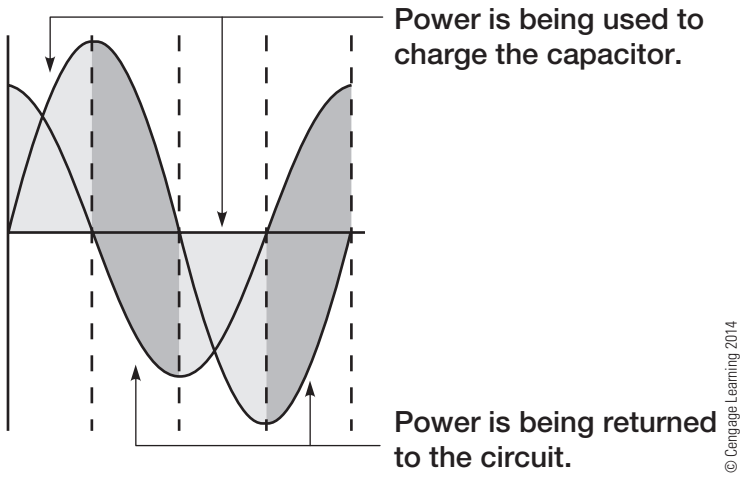


FIGURE 11-34 A pure capacitive circuit has no true power (watts). The power required to charge the capacitor is returned to the circuit when the capacitor discharges.

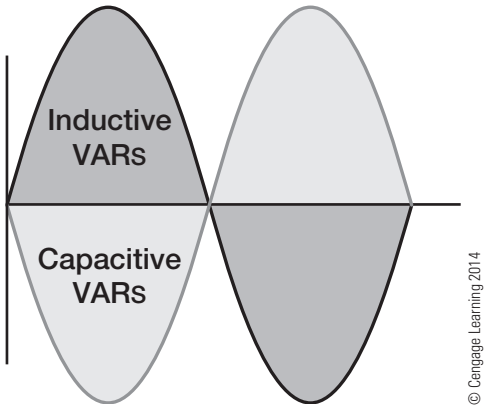


FIGURE 11-35 Inductive VARs and capacitive VARs are 180° out of phase with each other.

these values are added, the sum will equal zero just as it does with pure inductive circuits. Therefore, there is no true power, or watts, produced in a pure capacitive circuit.

The power value for a capacitor is reactive and is measured in VARs, just as it is for an inductor. Inductive VARs and capacitive VARs are 180° out of phase with each other, however, FIGURE 11-35.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Summary

1. Capacitors are devices that oppose a change of voltage.
2. Three factors that determine the capacitance of a capacitor are as follows:
   A. The surface area of the plates
   B. The distance between the plates
   C. The type of dielectric
3. A capacitor stores energy in an electrostatic field.
4. Current can flow only during the time a capacitor is charging or discharging.
5. Capacitors charge and discharge at an exponential rate.
6. The basic unit of capacitance is the farad.
7. Capacitors are generally rated in microfarads, nanofarads, or picofarads.
8. When capacitors are connected in parallel, their capacitance values are added together.
9. Five time constants are required to charge or discharge a capacitor.
10. Nonpolarized capacitors are often called AC capacitors.
11. Nonpolarized capacitors can be connected to direct or alternating current circuits.
12. Polarized capacitors are often referred to as electrolytic capacitors.
13. Polarized capacitors can be connected to direct current circuits only.
14. There are two basic types of electrolytic capacitors, the wet type and the dry type.
15. Wet-type electrolytic capacitors can be reformed if reconnected to the correct polarity.
16. Dry-type electrolytic capacitors will be permanently damaged if connected to the incorrect polarity.
17. To test a capacitor for leakage, a microammeter should be connected in series with the capacitor and rated voltage applied to the circuit.
18. When a capacitor is connected to an alternating current circuit, current will appear to flow through the capacitor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

19. Current appears to flow through a capacitor because of the continuous increase and decrease of voltage and also because of the continuous change of polarity in an AC circuit.
20. The current flow in a pure capacitive circuit is limited by capacitive reactance.
21. Capacitive reactance is proportional to the capacitance of the capacitor and the frequency of the AC line.
22. Capacitive reactance is measured in ohms.
23. In a pure capacitive circuit, the current leads the applied voltage by 90°.
24. There is no true power, or watts, in a pure capacitive circuit.
25. Capacitive power is reactive and is measured in VARs, as is inductance.
26. Capacitive and inductive VARs are 180° out of phase with each other.

Review Questions

1. What is the dielectric?
2. List three factors that determine the capacitance of a capacitor.
3. A capacitor uses air as a dielectric and has a capacitance of 3 μF. A dielectric material is inserted between the plates without changing the spacing and the capacitance becomes 15 μF. What is the dielectric constant of this material?
4. In what form is the energy of a capacitor stored?
5. Four capacitors having values of 20 μF, 50 μF, 40 μF, and 60 μF are connected in parallel. What is the total capacitance of this circuit?
6. Can a nonpolarized capacitor be connected to a direct current circuit?
7. Explain how an AC electrolytic capacitor is constructed.
8. What type of electrolytic capacitor will be permanently damaged if connected to the incorrect polarity?
9. Can current flow through a capacitor?
10. What two factors determine the capacitive reactance of a capacitor?
11. How many degrees are the current and voltage out of phase in a pure capacitive circuit?
12. Does the current in a pure capacitive circuit lead or lag the applied voltage?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

13. A 30 μF capacitor is connected into a 240-V, 60-Hz circuit. What is the current flow in this circuit?
14. A capacitor is connected into a 1,250-V, 1,000-Hz circuit. The current flow is 80 A. What is the capacitance of the capacitor?
15. On the average, how many times is the life expectancy of a capacitor increased if the capacitor is operated at half its voltage rating?
16. A capacitor is connected into a 277-V, 400-Hz circuit. The circuit current is 12 A. What is the capacitance of the capacitor?

Practice Problems

CAPACITIVE CIRCUITS

Fill in all missing values in the chart using the following formulas.

$$X_C = \frac{1}{2\pi FC}$$

$$C = \frac{1}{2\pi FX_C}$$

$$F = \frac{1}{2\pi CX_C}$$

Capacitance	X_C	Frequency
38 μF		60 Hz
	78.8 Ω	400 Hz
250 pF	4.5 k Ω	
234 μF		10 kHz
	240 Ω	50 Hz
10 μF	36.8 Ω	
560 nF		2 MHz
	15 kΩ	60 Hz
75 μF	560 Ω	
470 pF		200 kHz
	6.8 kΩ	400 Hz
34 μF	450 Ω	

© Cengage Learning 2014

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 12

Three-Phase Circuits

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the differences between three-phase and single-phase voltages.
- Discuss the characteristics of delta and wye connections.
- Compute voltage and current values for delta and wye circuits.
- Connect delta and wye circuits and make measurements with measuring instruments.

Most of the electrical power generated in the world today is three-phase. Three-phase power was first conceived by Nikola Tesla. In the early days of electric power generation, Tesla not only led the battle concerning whether the nation should be powered with low-voltage direct current or high-voltage alternating current, but he also proved that three-phase power was the most efficient way that electricity could be produced, transmitted, and consumed.

THREE-PHASE CIRCUITS

There are several reasons why three-phase power is superior to single-phase power.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

1. The horsepower rating of three-phase motors and the KVA (kilo-volt-amp) rating of three-phase transformers is about 150% greater than for single-phase motors or transformers with a similar frame size.
2. The power delivered by a single-phase system pulsates, FIGURE 12-1. The power falls to zero three times during each cycle. The power delivered by a three-phase circuit pulsates also, but it never falls to zero, FIGURE 12-2. In a three-phase system, the power delivered to the load is the same at any instant. This produces superior operating characteristics for three-phase motors.
3. In a balanced three-phase system, the conductors need be only about 75% the size of conductors for a single-phase two-wire system of the same KVA rating. This helps offset the cost of supplying the third conductor required by three-phase systems.

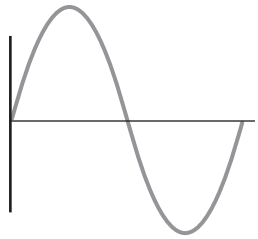

© Cengage Learning 2014

FIGURE 12-1 Single-phase power falls to zero three times each cycle.

A single-phase alternating voltage can be produced by rotating a magnetic field through the conductors of a stationary coil, as shown in FIGURE 12-3.

Since alternate polarities of the magnetic field cut through the conductors of the stationary coil, the induced voltage will change polarity at the

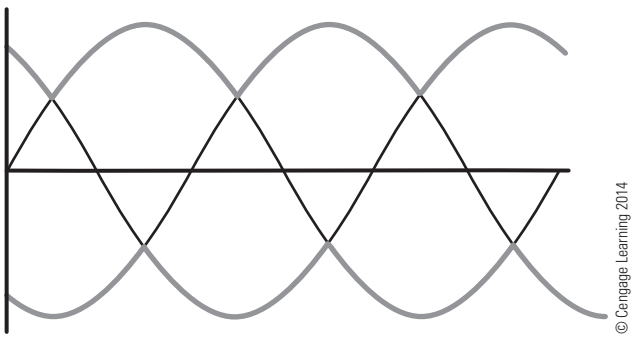

© Cengage Learning 2014

FIGURE 12-2 Three-phase power never falls to zero.



FIGURE 12-3 Producing a single-phase voltage.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

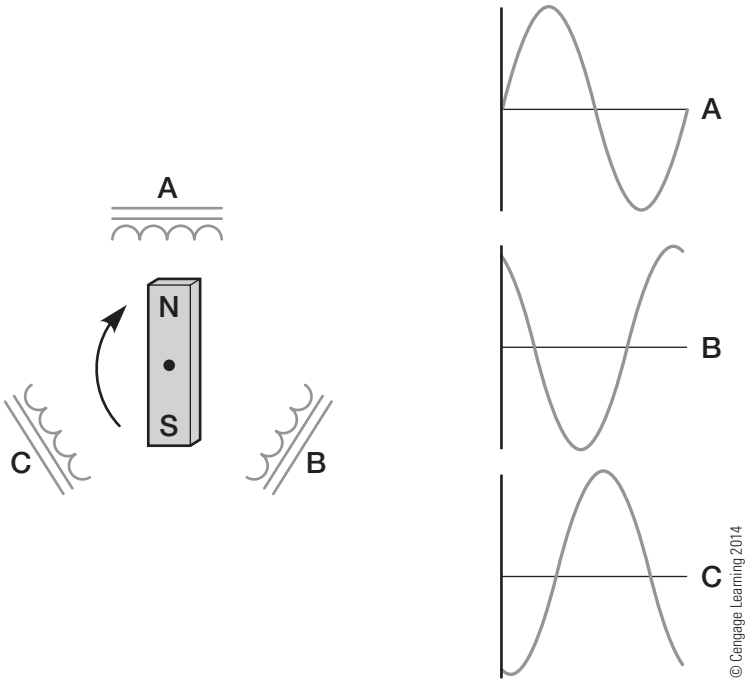


FIGURE 12-4 The voltages of a three-phase system are 120° out of phase with each other.

wye connection
connection of three components made in such a manner that one end of each component is connected. This connection is generally used to connect devices to a three-phase power system.

star connection
see wye connection

phase voltage
voltage measured across a single winding.

line voltage
voltage measured between the lines.

same speed as the rotation of the magnetic field. The alternator shown in Figure 12-3 is single-phase because it produces only one AC voltage.

If three separate coils are spaced 120° apart, as shown in FIGURE 12-4, three voltages 120° out of phase with each other will be produced when the magnetic field cuts through the coils. This is the manner in which a three-phase voltage is produced. There are two basic three-phase connections, the wye or star connection and the delta connection.

WYE CONNECTION

The **wye** or **star connection** is made by connecting one end of each of the three-phase windings together as shown in FIGURE 12-5. The voltage measured across a single winding or phase is known as the **phase voltage,** as shown in FIGURE 12-6. The voltage measured between the lines is known as the line-to-line voltage or simply as the **line voltage.**

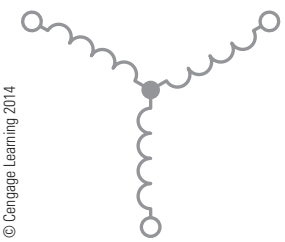


FIGURE 12-5 A wye connection is formed by joining one end of each of the windings together.

In FIGURE 12-7, ammeters have been placed in the phase winding of a wye-connected load and in the line supplying power to the load. Voltmeters have been connected across the input to the load and across the phase. A line

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

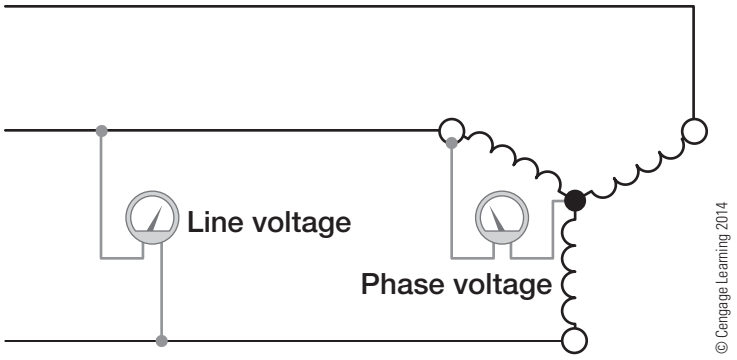


FIGURE 12-6 Line and phase voltages are different in a wye connection.

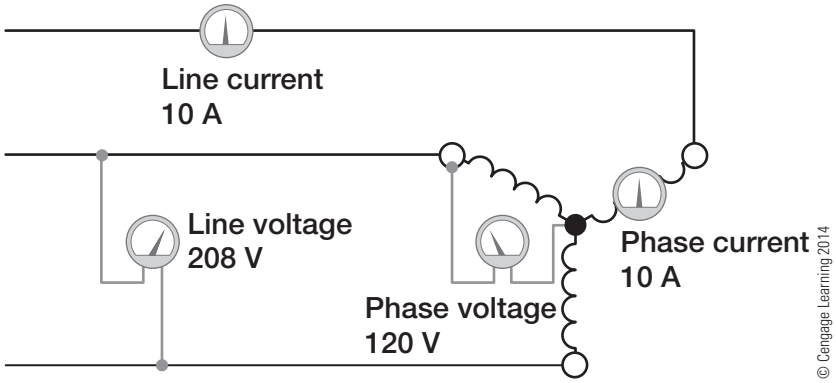


FIGURE 12-7 Line current and phase current are the same in a wye connection.

voltage of 208 V has been applied to the load. Notice that the voltmeter connected across the lines indicates a value of 208 V, but the voltmeter connected across the phase indicates a value of 120 V.

In a wye-connected system, the line voltage is higher than the phase voltage by a factor of the square root of 3 (1.732). Two formulas used to compute the voltage in a wye-connected system are

$$E_{Line} = E_{Phase} \times 1.732$$

and

$$E_{phase} = \frac{E_{Line}}{1.732}$$

KEY POINT

In a wye-connected system, the line voltage is higher than the phase voltage by a factor of the square root of 3 (1.732).

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

KEY POINT
In a wye-connected system, phase current and line current are the same.

Notice in Figure 12-7 that 10 A of current flow in both the phase and the line. **In a wye-connected system, phase current and line current are the same.**

$$I_{Line} = I_{Phase}$$

VOLTAGE RELATIONSHIPS IN A WYE CONNECTION

Many students of electricity have difficulty at first understanding why the line voltage of the wye connection used in this illustration is 208 V instead of 240 V. Since line voltage is measured across two phases that have a value of 120 V each, it would appear that the sum of the two voltages should be 240 V. One cause of this misconception is that many students are familiar with the 240/120-V connection supplied to most homes. If voltage is measured across the two incoming lines, a voltage of 240 V will be seen. If voltage is measured from either of the two lines to the neutral, a voltage of 120 V will be seen. The reason for this is that this is a single-phase connection derived from the center tap of a transformer, FIGURE 12-8. The center tap is common between two voltages that are in phase with each other, FIGURE 12-9. The vector sum of these two voltages is 240 V.

Three-phase voltages are 120° apart, not 180°. If the three voltages are drawn 120° apart, it will be seen that the vector sum of these voltages is 208 V, FIGURE 12-10. Another illustration of vector addition is shown in

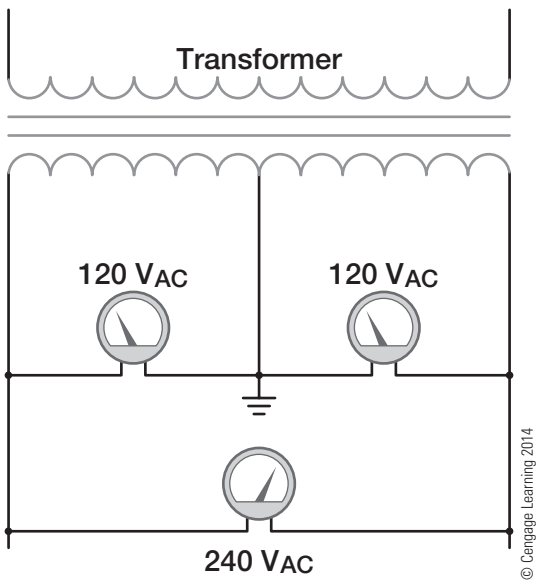


FIGURE 12-8 Single-phase transformer with grounded center tap.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

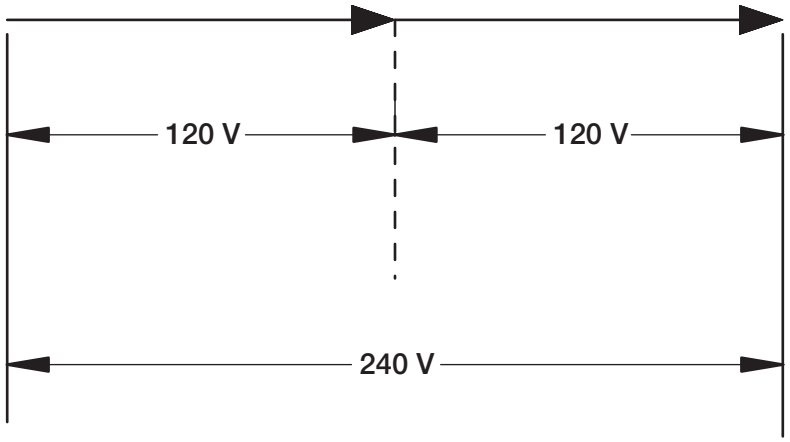


FIGURE 12-9 Two in-phase voltages of 120 V each produce a total voltage of 240 V.

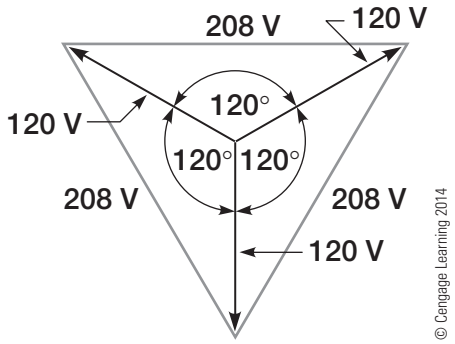


FIGURE 12-10 Vector sum of the voltages in a three-phase wye connection.

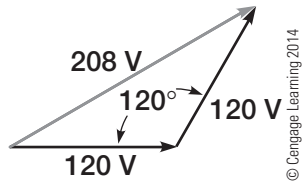


FIGURE 12-11 Adding voltage vectors of two-phase voltage values.

FIGURE 12-11. In this illustration two-phase voltage vectors are added and the resultant is drawn from the starting point of one vector to the end point of the other. The parallelogram method of vector addition for the voltages in a wye-connected three-phase system is shown in FIGURE 12-12.

DELTA CONNECTIONS

In FIGURE 12-13, three separate inductive loads have been connected to form a **delta connection.** This connection receives its name from the fact that a schematic diagram of this connection resembles the Greek letter delta (Δ). In FIGURE 12-14, voltmeters have been connected across the lines and across the phase. Ammeters have been connected in the line and in the phase. **In the delta connection, line voltage and phase voltage are the same.** Notice that both voltmeters indicate a value of 480 V.

$$E_{Line} = E_{Phase}$$

KEY POINT

In the delta connection, line voltage and phase voltage are the same.

delta connection
circuit formed by connecting three electrical devices in series to form a closed loop. It is used most often in three-phase connections.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

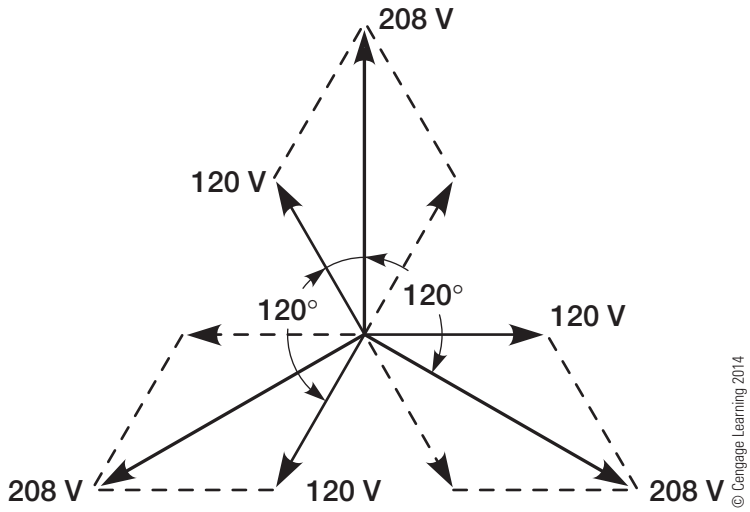


FIGURE 12-12 The parallelogram method of adding three-phase vectors.

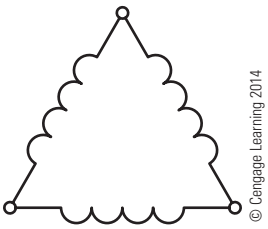


FIGURE 12-13 Three-phase delta connection.

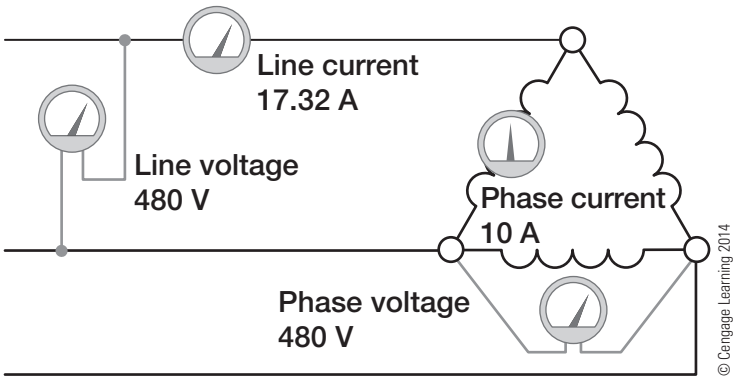


FIGURE 12-14 Voltage and current relationships in a delta connection.

KEY POINT

The line current of a delta connection is higher than the phase current by a factor of the square root of 3 (1.732).

Notice that the line current and phase current are different, however. **The line current of a delta connection is higher than the phase current by a factor of the square root of 3 (1.732).** In the example shown, it is assumed that each of the phase windings has a current flow of 10 A. The current in each of the lines, however, is 17.32 A. The reason for this difference in current is that current flows through different windings at different times in a three-phase circuit. During some periods of time, current will flow between two

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

lines only. At other times, current will flow from two lines to the third, FIGURE 12-15. The delta connection is similar to a parallel connection because there is always more than one path for current flow. Since these currents are 120° out of phase with each other, vector addition must be used when finding the sum of the currents, FIGURE 12-16. Formulas for determining the current in a delta connection are

$$I_{Line} = I_{Phase} \times 1.732$$

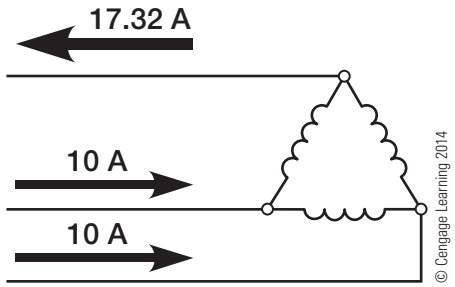


FIGURE 12-15 Division of currents in a delta connection.

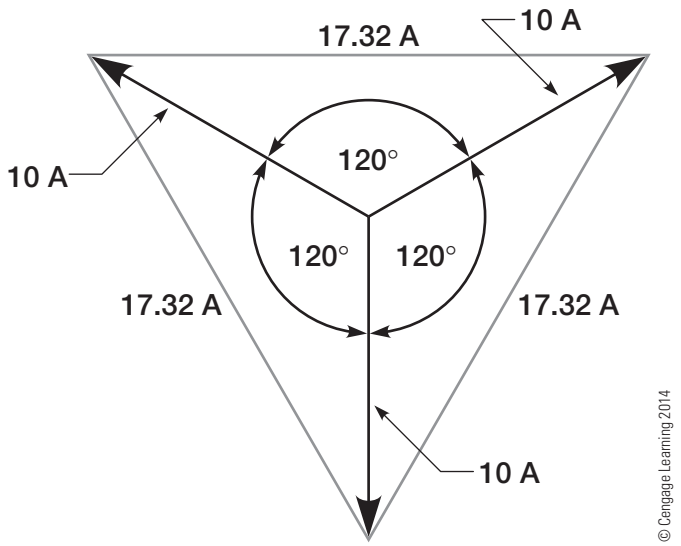


FIGURE 12-16 Vector addition is used to compute the sum of the currents in a delta connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

and

$$I_{phase} = \frac{I_{Line}}{1.732}$$

THREE-PHASE POWER

Students sometimes become confused when computing power in three-phase circuits. One reason for this confusion is that there are actually two formulas that can be used. If *line* values of voltage and current are known, the power (watts) of a pure resistive load can be computed using the formula

$$VA = \sqrt{3} \times E_{Line} \times I_{Line}$$

If the *phase* values of voltage and current are known, the apparent power can be computed using the formula

$$VA = 3 \times E_{Phase} \times I_{Phase}$$

Notice that in the first formula, the line values of voltage and current are multiplied by the square root of 3. In the second formula, the phase values of voltage and current are multiplied by 3. The first formula is used more often because it is generally more convenient to obtain line values of voltage and current, which can be measured with a voltmeter and clamp-on ammeter.

THREE-PHASE CIRCUIT CALCULATIONS

In the following examples, values of line and phase voltage, line and phase current, and power will be computed for different types of three-phase connections.

EXAMPLE 1: A wye-connected three-phase alternator supplies power to a delta-connected resistive load, FIGURE 12-17. The alternator has a line voltage of 480 V. Each resistor of the delta load has 8 Ω of resistance. Find the following values:

$E_{L(Load)}$ — line voltage of the load
$E_{P(Load)}$ — phase voltage of the load
$I_{P(Load)}$ — phase current of the load
$I_{L(Load)}$ — line current to the load
$I_{L(Alt)}$ — line current delivered by the alternator
$I_{P(Alt)}$ — phase current of the alternator
$E_{P(Alt)}$ — phase voltage of the alternator
P — true power

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

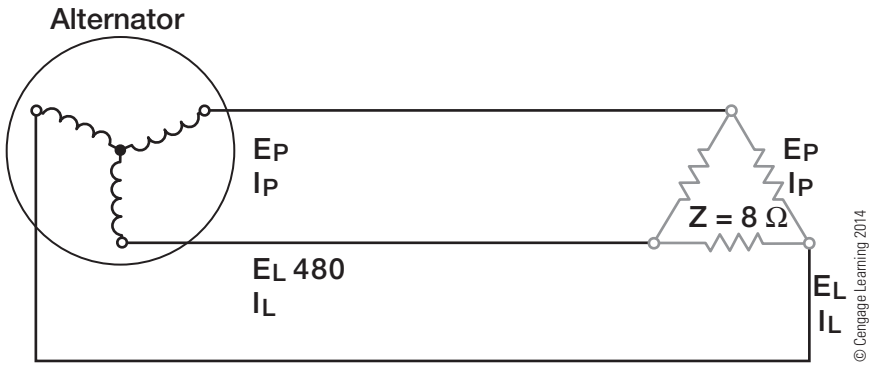


FIGURE 12-17 Computing three-phase values using a wye-connected power source and a delta-connected load (Example 1 circuit).

Solution:

The load is connected directly to the alternator. Therefore, the line voltage supplied by the alternator is the line voltage of the load.

$$E_{L(Load)} = 480 \text{ V}$$

The three resistors of the load are connected in a delta connection. In a delta connection, the phase voltage is the same as the line voltage.

$$E_{P(Load)} = E_{L(Load)}$$

$$E_{P(Load)} = 480 \text{ V}$$

Each of the three resistors in the load is one phase of the load. Now that the phase voltage is known (480 V), the amount of phase current can be computed using Ohm's Law.

$$I_{P(Load)} = \frac{E_{P(Load)}}{Z}$$

$$I_{P(Load)} = \frac{480}{8}$$

$$I_{P(Load)} = 60 \text{ A}$$

The three load resistors are connected as a delta with 60 A of current flow in each phase. The line current supplying a delta connection must be 1.732 times greater than the phase current.

$$I_{L(Load)} = I_{P(Load)} \times 1.732$$

$$I_{L(Load)} = 60 \times 1.732$$

$$I_{L(Load)} = 103.92 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The alternator must supply the line current to the load or loads to which it is connected. In this example, only one load is connected to the alternator. Therefore, the line current of the load will be the same as the line current of the alternator.

$$I_{L(Alt)} = 103.92 \text{ A}$$

The phase windings of the alternator are connected in a wye connection. In a wye connection, the phase current and line current are equal. The phase current of the alternator will, therefore, be the same as the alternator line current.

$$I_{P(Alt)} = 103.92 \text{ A}$$

The phase voltage of a wye connection is less than the line voltage by a factor of the square root of 3. The phase voltage of the alternator will be

$$E_{P(Alt)} = \frac{E_{L(Alt)}}{1.732}$$

$$E_{P(Alt)} = \frac{480}{1.732}$$

$$E_{P(Alt)} = 277.13 \text{ V}$$

In this circuit, the load is pure resistive. The voltage and current are in phase with each other, which produces a unity power factor of 1. The true power in this circuit will be computed using the formula

$$P = 1.732 \times E_{L(Alt)} \times I_{L(Alt)} \times PF$$

$$P = 1.732 \times 480 \times 103.92 \times 1$$

$$P = 86{,}394.93 \text{ W}$$

EXAMPLE 2: A delta-connected alternator is connected to a wye-connected resistive load, FIGURE 12-18. The alternator produces a line voltage of 240 V and the resistors have a value of 6 Ω each. The following values will be found:

$E_{L(Load)}$ — line voltage of the load
$E_{P(Load)}$ — phase voltage of the load
$I_{P(Load)}$ — phase current of the load
$I_{L(Load)}$ — line current to the load
$I_{L(Alt)}$ — line current delivered by the alternator

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

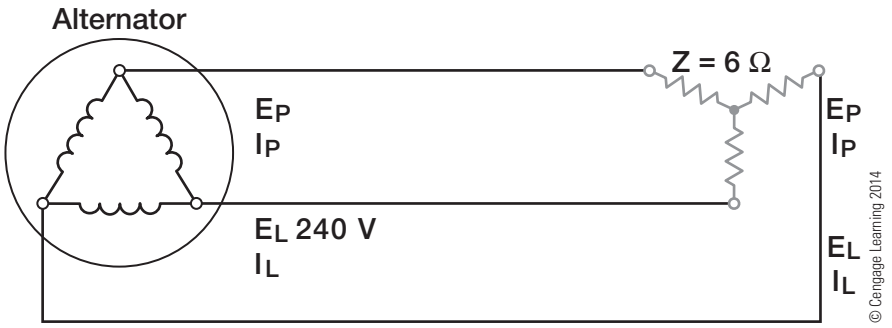


FIGURE 12-18 Computing three-phase values using a delta-connected source and a wye-connected load (Example 2 circuit).

$I_{P(Alt)}$ — phase current of the alternator
$E_{P(Alt)}$ — phase voltage of the alternator
P — true power

Solution:

As was the case in Example 1, the load is connected directly to the output of the alternator. The line voltage of the load must, therefore, be the same as the line voltage of the alternator.

$$E_{L(Load)} = 240 \text{ V}$$

The phase voltage of a wye connection is less than the line voltage by a factor of 1.732.

$$E_{P(Load)} = \frac{240}{1.732}$$

$$E_{P(Load)} = 138.57 \text{ V}$$

Each of the three 6-Ω resistors is one phase of the wye-connected load. Since the phase voltage is 138.57 V, this voltage is applied to each of the three resistors. The amount of phase current can now be determined using Ohm's Law.

$$I_{P(Load)} = \frac{E_{P(Load)}}{Z}$$

$$I_{P(Load)} = \frac{138.57}{6}$$

$$I_{P(Load)} = 23.1 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The amount of line current needed to supply a wye-connected load is the same as the phase current of the load.

$$I_{L(Load)} = 23.1 \text{ A}$$

Only one load is connected to the alternator. The line current supplied to the load is the same as the line current of the alternator.

$$I_{L(Alt)} = 23.1 \text{ A}$$

The phase windings of the alternator are connected in delta. In a delta connection the phase current is less than the line current by a factor of 1.732.

$$I_{P(Alt)} = \frac{I_{L(Alt)}}{1.732}$$

$$I_{P(Alt)} = \frac{23.1}{1.732}$$

$$I_{P(Alt)} = 13.34 \text{ A}$$

The phase voltage of a delta is the same as the line voltage.

$$E_{P(Alt)} = 240 \text{ V}$$

Since the load in this example is pure resistive, the power factor has a value of unity, or 1. Power will be computed by using the line values of voltage and current.

$$P = 1.732 \times E_L \times I_L \times PF$$

$$P = 1.732 \times 240 \times 23.1 \times 1$$

$$P = 9{,}602.21 \text{ W}$$

EXAMPLE 3: The phase windings of an alternator are connected in wye. The alternator produces a line voltage of 440 V, and supplies power to two resistive loads. One load contains resistors with a value of 4 Ω each, connected in wye. The second load contains resistors with a value of 6 Ω each, connected in delta, FIGURE 12-19. The following circuit values will be found.

$E_{L(Load\ 2)}$ — line voltage of load 2
$E_{P(Load\ 2)}$ — phase voltage of load 2`

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

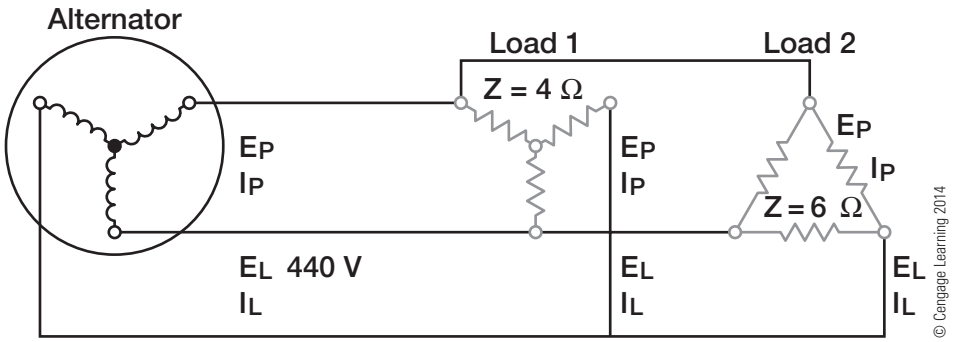


FIGURE 12-19 Computing three-phase values using a wye-connected source and two three-phase loads (Example 3 circuit).

$I_{P(Load\ 2)}$ — phase current of load 2
$I_{L(Load\ 2)}$ — line current to load 2
$E_{P(Load\ 1)}$ — phase voltage of load 1
$I_{P(Load\ 1)}$ — phase current of load 1
$I_{L(Load\ 1)}$ — line current to load 1
$I_{L(Alt)}$ — line current delivered by the alternator
$I_{P(Alt)}$ — phase current of the alternator
$E_{P(Alt)}$ — phase voltage of the alternator
P — true power

Solution:

Both loads are connected directly to the output of the alternator. The line voltage for both loads 1 and 2 will be the same as the line voltage of the alternator.

$$E_{L(Load\ 2)} = 440\ V$$

$$E_{L(Load\ 1)} = 440\ V$$

Load 2 is connected as a delta. The phase voltage will be the same as the line voltage.

$$E_{P(Load\ 2)} = 440\ V$$

Each of the resistors that constitutes a phase of load 2 has a value of 6 Ω. The amount of phase current can be found using Ohm's Law.

$$I_{P(Load\ 2)} = \frac{E_{P(Load\ 2)}}{Z}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$I_{P(Load\ 2)} = \frac{440}{6}$$

$$I_{P(Load\ 2)} = 73.33\ A$$

The line current supplying a delta-connected load is 1.732 times greater than the phase current. The amount of line current needed for load 2 can be computed by increasing the phase current value by 1.732.

$$I_{L(Load\ 2)} = I_{P(Load\ 2)} \times 1.732$$

$$I_{L(Load\ 2)} = 73.33 \times 1.732$$

$$I_{L(Load\ 2)} = 127.01\ A$$

The resistors of load 1 are connected to form a wye. The phase voltage of a wye connection is less than the line voltage by a factor of 1.732.

$$E_{P(Load\ 1)} = \frac{E_{L(Load\ 1)}}{1.732}$$

$$E_{P(Load\ 1)} = \frac{440}{1.732}$$

$$E_{P(Load\ 1)} = 254.04\ V$$

Now that the voltage applied to each of the 4-Ω resistors is known, the phase current can be computed using Ohm's Law.

$$I_{P(Load\ 1)} = \frac{E_{P(Load\ 1)}}{Z}$$

$$I_{P(Load\ 1)} = \frac{254.04}{4}$$

$$I_{P(Load\ 1)} = 63.51\ A$$

The line current supplying a wye-connected load is the same as the phase current. Therefore, the amount of line current needed to supply load 1 is

$$I_{L(Load\ 1)} = 63.51\ A$$

The alternator must supply the line current needed to operate both loads. In this example, both loads are resistive. The total line current supplied by the alternator will be the sum of the line currents of the two loads.

$$I_{L(Alt)} = I_{L(Load\ 1)} + I_{L(Load\ 2)}$$

$$I_{L(Alt)} = 63.51 + 127.01$$

$$I_{L(Alt)} = 190.52\ A$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Since the phase windings of the alternator in this example are connected in a wye, the phase current will be the same as the line current.

$$I_{P(Alt)} = 190.52 \text{ A}$$

The phase voltage of the alternator will be less than the line voltage by a factor of 1.732.

$$E_{P(Alt)} = \frac{440}{1.732}$$

$$E_{P(Alt)} = 254.04 \text{ V}$$

Both of the loads in this example are resistive and have a unity power factor of 1. The total power in this circuit can be found by using the line voltage and total line current supplied by the alternator.

$$P = 1.732 \times E_L \times I_L \times PF$$

$$P = 1.732 \times 440 \times 190.52 \times 1$$

$$P = 145{,}191.48 \text{ W}$$

PHASE ROTATION

An important concept when dealing with poly-phase power is phase rotation. Phase rotation can be a major concern in some situations. For example, assume that the three-phase transformer supplying power to an industrial location has to be replaced. If the phase rotation of the new connection is not the same as the old, all the motors in the plant will operate in reverse when power is restored. Phase rotation can best be illustrated with the stator winding of a three-phase motor. When power is applied to the stator, a magnetic field will rotate around the inside of the stator winding, FIGURE 12-20. Three factors that cause the field to rotate are the following:

1. The fact that the three voltages are 120° out of phase with each other.
2. The place of the windings around the stator core.
3. The fact that the voltages reverse polarity at regular intervals.

The direction of phase rotation can be reversed by changing the connection of any two of the three-phase power lines. A phase rotation meter, FIGURE 12-21, can be used to determine the phase rotation of a motor before power is applied to the circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

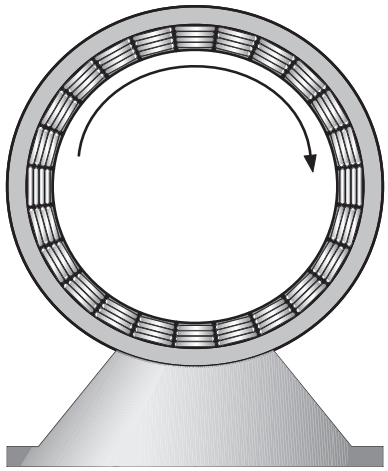

© Cengage Learning 2014

FIGURE 12-20 The stator of a three-phase motor will produce a rotating magnetic field when power is applied.


Courtesy of Megger®

FIGURE 12-21 Phase rotation meter.

Summary

1. The voltages of a three-phase system are 120° out of phase with each other.
2. The two types of three-phase connections are wye and delta.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

3. Wye connections are characterized by the fact that one terminal of each device is connected together.
4. In a wye connection, the phase voltage is less than the line voltage by a factor of 1.732. The phase current and line current are the same.
5. In a delta connection, the phase voltage is the same as the line voltage. The phase current is less than the line current by a factor of 1.732.

Review Questions

1. How many degrees out of phase with each other are the voltages of a three-phase system?
2. What are the two main types of three-phase connections?
3. A wye-connected load has a voltage of 480 V applied to it. What is the voltage drop across each phase?
4. A wye-connected load has a phase current of 25 A. How much current is flowing through the lines supplying the load?
5. A delta connection has a voltage of 560 V connected to it. How much voltage is dropped across each phase?
6. A delta connection has 30 A of current flowing through each phase winding. How much current is flowing through each of the lines supplying power to the load?
7. A three-phase resistive load has a phase voltage of 240 V and a phase current of 18 A. What is the power of this load?
8. If the load in question 7 is connected in a wye, what would be the line voltage and line current supplying the load?
9. An alternator with a line voltage of 2400 V supplies a delta-connected load. The line current supplied to the load is 40 A. Assuming the load is a balanced three-phase load, what is the impedance of each phase?
10. If the load is pure resistive, what is the power of the circuit in question 9?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Practice Problems

THREE-PHASE CIRCUITS

1. Refer to the circuit shown in FIGURE 12-17 to answer the following questions. It is assumed the alternator has a line voltage of 240 V and the load has an impedance of 12 Ω per phase. Find all missing values.

$E_{P(A)}$	_____	$E_{P(L)}$	_____
$I_{P(A)}$	_____	$I_{P(L)}$	_____
$E_{L(A)}$ 240	_____	$E_{L(L)}$	_____
$I_{L(A)}$	_____	$I_{L(L)}$	_____
P	_____	$Z_{(PHASE)}$ 12 Ω	

2. Refer to the circuit shown in FIGURE 12-18 to answer the following questions. Assume the alternator has a line voltage of 4,160 V and the load has an impedance of 60 Ω per phase. Find all missing values.

$E_{P(A)}$	_____	$E_{P(L)}$	_____
$I_{P(A)}$	_____	$I_{P(L)}$	_____
$E_{L(A)}$ 4160 V		$E_{L(L)}$	_____
$I_{L(A)}$	_____	$I_{L(L)}$	_____
P	_____	$Z_{(PHASE)}$ 60 Ω	

3. Refer to the circuit shown in FIGURE 12-19 to answer the following questions. It is assumed that the alternator has a line voltage of 560 V. Load 1 has an impedance of 5 Ω per phase and load 2 has an impedance of 8 Ω per phase. Find all missing values.

$E_{P(A)}$	_____	$E_{P(L1)}$	_____	$E_{P(L2)}$	_____
$I_{P(A)}$	_____	$I_{P(L1)}$	_____	$I_{P(L2)}$	_____
$E_{L(A)}$ 560 V		$E_{L(L1)}$	_____	$E_{L(L2)}$	_____
$I_{L(A)}$	_____	$I_{L(L1)}$	_____	$I_{L(L2)}$	_____
P	_____	$Z_{(PHASE)}$ 5 Ω		$Z_{(PHASE)}$ 8 Ω	

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 13

Transformers

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the different types of transformers.
- Calculate values of voltage, current, and turns for transformers using formulas.
- Calculate values of voltage, current, and turns for a transformer using the turns ratio.
- Connect a transformer and test the voltage output of different windings.

Transformers are one of the most common devices found in the electrical field. They range in size from less than one cubic inch to requiring rail cars to move them after they have been broken into sections. Their ratings can range from mVA (milli-volt-amps) to GVA (giga-volt-amps). It is imperative that anyone working in the electrical field have an understanding of transformer types and connections. This unit will present two main types of voltage transformers, isolation transformers, and auto transformers.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

SINGLE-PHASE TRANSFORMERS

transformer
electrical device that changes one value of AC voltage into another value of AC voltage.

A **transformer** is a magnetically operated machine that can change values of voltage, current, and impedance without a change of frequency. Transformers are the most efficient machines known. Their efficiencies commonly range from 90% to 99% at full load. Transformers can be divided into several classifications:

1. Isolation transformer
2. Auto transformer
3. Current transformer

KEY POINT
All values of a transformer are proportional to its turns ratio.

A basic law concerning transformers is that **all values of a transformer are proportional to its turns ratio**. This does not mean that the exact number of turns of wire on each winding must be known to determine different values of voltage and current for a transformer. What must be known is the *ratio* of turns. For example, assume a transformer has two windings. One winding, the primary, has 1,000 turns of wire and the other, the secondary, has 250 turns of wire, FIGURE 13-1. The **turns ratio** of this transformer is 4 to 1 or 4:1 (1000/250 = 4). This indicates there are four turns of wire on the primary for every one turn of wire on the secondary.

turns ratio
the ratio of the number of primary turns of wire as compared to the number of secondary turns.

TRANSFORMER FORMULAS

Different formulas can be used to find the values of voltage and current for a transformer. The following is a list of standard formulas:

where: N_P = number of turns in the primary

N_S = number of turns in the secondary

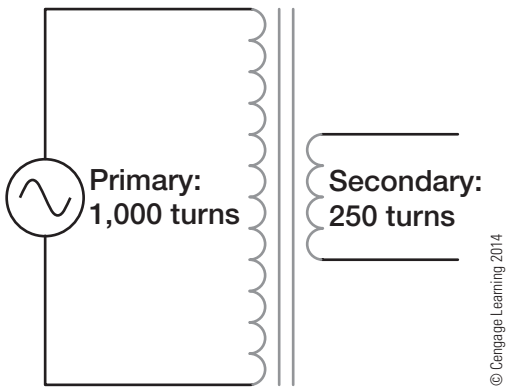


FIGURE 13-1 All values of a transformer are proportional to its turns ratio.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

E_P = voltage of the primary

E_S = voltage of the secondary

I_P = current in the primary

I_S = current in the secondary

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

or

$$E_P \times N_S = E_S \times N_P$$

$$E_P \times I_P = E_S \times I_S$$

$$N_P \times I_P = N_S \times I_S$$

The **primary winding** of a transformer is the power input winding. It is the winding that is connected to the incoming power supply. The **secondary winding** is the load winding or output winding. It is the side of the transformer that is connected to the driven load, FIGURE 13-2.

primary winding winding of a transformer to which power is applied.

secondary winding winding of a transformer to which the load is connected.

ISOLATION TRANSFORMERS

The transformers shown in Figure 13-1 and Figure 13-2 are **isolation transformers.** This means that the secondary winding is physically and electrically isolated from the primary winding. There is no electrical connection between the primary and secondary winding. This transformer is magnetically

isolation transformers transformer whose secondary winding is electrically isolated from its primary winding.



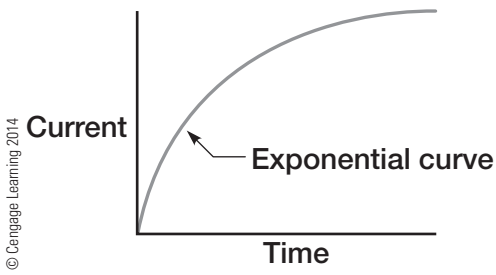
FIGURE 13-2 An isolation transformer has its primary and secondary winding electrically separated from each other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

coupled, not electrically coupled. This line isolation is often a very desirable characteristic. Since there is no electrical connection between the load and power supply, the transformer becomes a filter between the two. The isolation transformer will greatly reduce any voltage spikes that originate on the supply side before they are transferred to the load side. Some isolation transformers are built with a turns ratio of 1:1. A transformer of this type will have the same input and output voltage and is used for the purpose of isolation only.

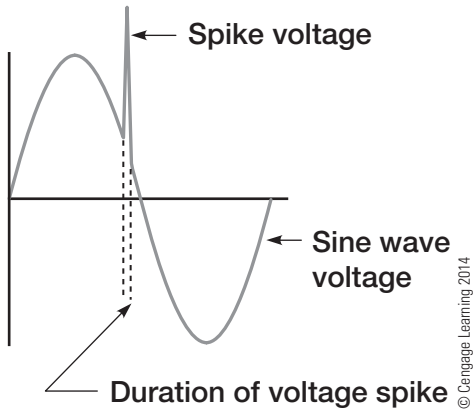
The reason that the transformer can greatly reduce any voltage spikes before they reach the secondary is because of the rise time of current through an inductor. Current in an inductor rises at an exponential rate, FIGURE 13-3. As the current increases in value, the expanding magnetic field cuts through the conductors of the coil and induces a voltage that is opposed to the applied voltage. The amount of induced voltage is proportional to the rate of change of current. This simply means that the faster current attempts to increase, the greater the opposition to that increase will be. Spike voltages and currents are generally of very short duration, which means that they increase in value very rapidly, FIGURE 13-4. This rapid change of value causes the opposition to the change to increase just as rapidly. By the time the spike has been transferred to the secondary winding of the transformer it has been eliminated or greatly reduced, FIGURE 13-5.

The basic construction of an isolation transformer is shown in FIGURE 13-6. A metal core is used to provide good magnetic coupling between the two windings. The core is generally made of laminations stacked together. Laminating the core helps reduce power losses due to eddy current induction.



© Cengage Learning 2014

FIGURE 13-3 The current through an inductor rises at an exponential rate.



© Cengage Learning 2014

FIGURE 13-4 Voltage spikes are generally of very short duration.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

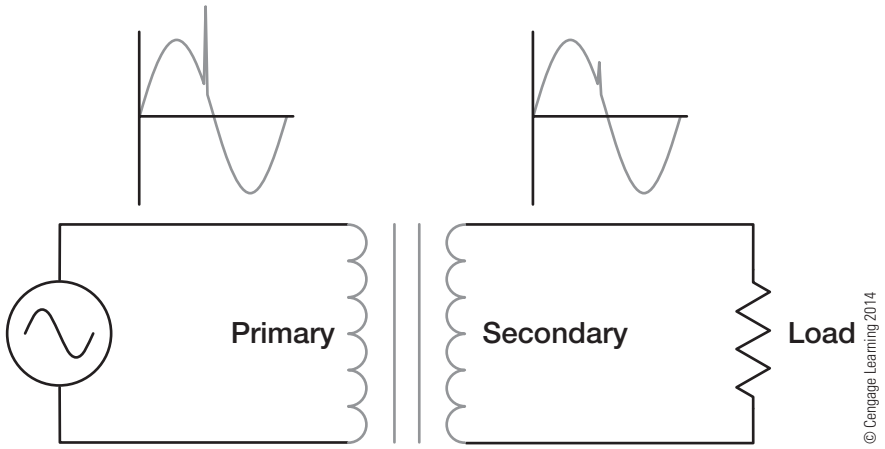


FIGURE 13-5 The isolation transformer greatly reduces the voltage spike.

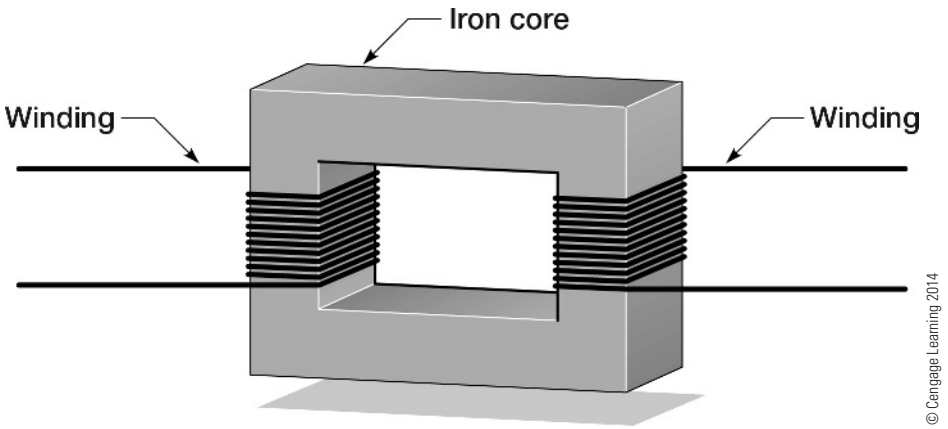


FIGURE 13-6 Basic construction of an isolation transformer.

BASIC OPERATING PRINCIPLES

In FIGURE 13-7, one winding of the transformer has been connected to an alternating current supply, and the other winding has been connected to a load. As current increases from zero to its peak positive point, a magnetic field expands outward around the coil. When the current decreases from its peak positive point toward zero, the magnetic field collapses. When the current increases toward its negative peak, the magnetic field again expands, but with an opposite polarity of that previously. The field again collapses when the current decreases from its negative peak toward zero. This continually expanding and collapsing magnetic field cuts the windings of the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

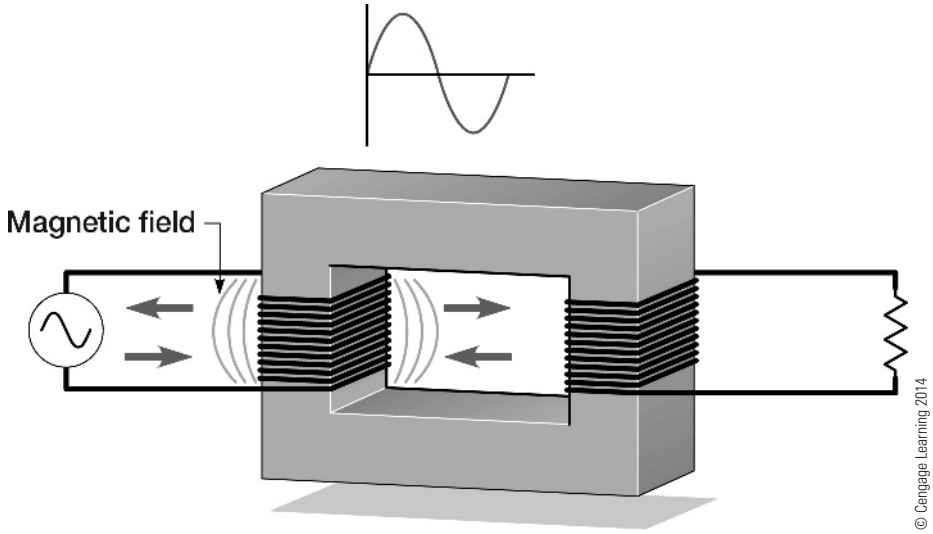


FIGURE 13-7 Magnetic field produced by alternating current.

primary and induces a voltage into it. This induced voltage opposes the applied voltage and limits the current flow of the primary. When a coil induces a voltage into itself, it is known as self-induction.

EXCITATION CURRENT

excitation current direct current used to produce electromagnetism in the fields of a DC motor or generator or in the rotor of an alternator or synchronous motor.

There will always be some amount of current flow in the primary of any voltage transformer regardless of type or size even if there is no load connected to the secondary. This is called the **excitation current** of the transformer. The excitation current is the amount of current required to magnetize the core of the transformer. The excitation current remains constant from no load to full load. As a general rule, the excitation current is such a small part of the full load current it is often omitted when making calculations.

MUTUAL INDUCTION

Since the secondary windings are wound on the same core as the primary, the magnetic field produced by the primary winding cuts the windings of the secondary also, FIGURE 13-8. This continually changing magnetic field induces a voltage into the secondary winding. The ability of one coil to induce a voltage into another coil is called *mutual induction*. The amount of voltage induced in the secondary is determined by the number of turns of wire in the secondary as compared to the primary. For example, assume the primary has 240 turns of wire and is connected to 120-V AC. This gives the transformer a **volts-per-turn ratio** of 0.5 (120 V/240

volts-per-turn ratio the ratio of the voltage to the number of turns of wire.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

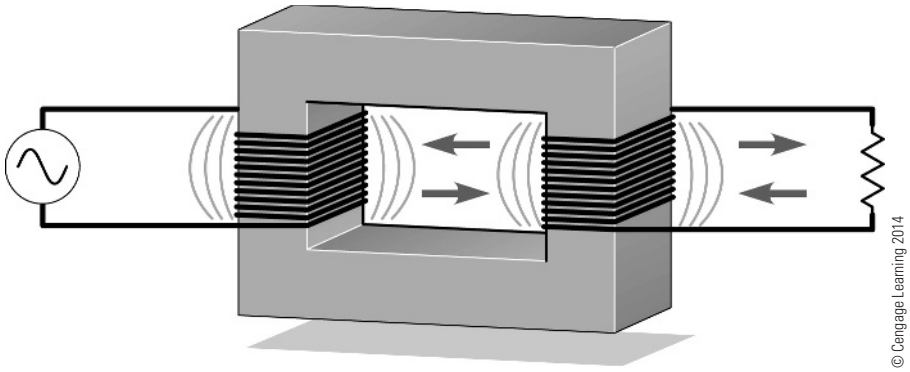

© Cengage Learning 2014

FIGURE 13-8 The magnetic field of the primary induces a voltage into the secondary.

turns = 0.5 V per turn). Now assume the secondary winding contains 100 turns of wire. Since the transformer has a volt-per-turn ratio of 0.5, the secondary voltage will be 50 V ($100 \times 0.5 = 50$).

TRANSFORMER CALCULATIONS

In the following examples, values of voltage, current, and turns for different transformers will be computed.

EXAMPLE 1: Assume the isolation transformer shown in Figure 13-2 has 240 turns of wire on the primary and 60 turns of wire on the secondary. This is a ratio of 4:1 (240/60 = 4). Now assume that 120 V is connected to the primary winding. What is the voltage of the secondary winding?

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{240}{60}$$

$$240\ E_S = 7200$$

$$E_S = 30\ V$$

Solution:

The transformer in this example is known as a **step-down transformer** because it has a lower secondary voltage than primary voltage.

step-down transformer transformer that produces a lower voltage at its secondary than is applied to its primary.

Now assume that the load connected to the secondary winding has an impedance of 5 Ω. The next problem is to calculate the current flow in the secondary and primary windings. The current flow of the secondary

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

can be computed using Ohm's Law since the voltage and impedance are known.

$$I = \frac{E}{Z}$$

$$I = \frac{30}{5}$$

$$I = 6 \text{ A}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{30} = \frac{6}{I_P}$$

$$120\ I_P = 180$$

$$I_P = 1.5 \text{ A}$$

KEY POINT

A good rule for any type of transformer is that power in must equal power out.

Notice that the primary voltage is higher than the secondary voltage, but the primary current is much less than the secondary current. **A good rule for any type of transformer is that power in must equal power out.** If the primary voltage and current are multiplied together, the product should equal the product of the voltage and current of the secondary.

Primary	Secondary
120 × 1.5 = 180 VA	30 × 6 = 180 VA

EXAMPLE 2: In the next example, assume that the primary winding contains 240 turns of wire and the secondary contains 1,200 turns of wire. This is a turns ratio of 1:5 (1200/240 = 5). Now assume that 120 V is connected to the primary winding. Compute the voltage output of the secondary winding.

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{240}{1200}$$

$$240\ E_S = 144{,}000$$

$$E_S = 600 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Notice that the secondary voltage of this transformer is higher than the primary voltage. This type of transformer is known as a **step-up transformer.**

step-up transformer transformer that produces a higher voltage at its secondary than is applied to its primary.

Now assume that the load connected to the secondary has an impedance of 2,400 Ω. Find the amount of current flow in the primary and secondary windings. The current flow in the secondary winding can be computed using Ohm's Law.

$$I = \frac{E}{Z}$$

$$I = \frac{600}{2{,}400}$$

$$I = 0.25 \text{ A}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{600} = \frac{0.25}{I_P}$$

$$120\, I_P = 150$$

$$I_P = 1.25 \text{ A}$$

Notice that the amount of power input equals the amount of power output.

Primary	Secondary
120 × 1.25 = 150 VA	600 × 0.25 = 150 VA

CALCULATING TRANSFORMER VALUES USING THE TURNS RATIO

As illustrated in the previous examples, transformer values of voltage, current, and turns can be computed using formulas. It is also possible to compute these same values using the turns ratio. To make calculations using the turns ratio, a ratio is established that compares some number to 1 or 1 to some number. For example, assume a transformer has a primary rated at 240 V and a secondary rated at 96 V, FIGURE 13-9. The turns ratio can be computed by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{240}{96}$$

$$\text{Ratio} = 2.5{:}1$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

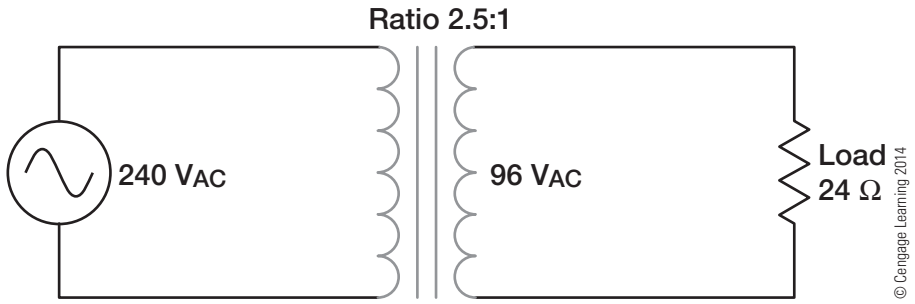


FIGURE 13-9 Computing transformer values using the turns ratio.

This ratio indicates that there are 2.5 turns of wire in the primary winding for every 1 turn of wire in the secondary. The side of the transformer with the lowest voltage will always have the lowest number (1) of the ratio.

Now assume that a resistance of 24 Ω is connected to the secondary winding. The amount of secondary current can be found using Ohm's Law.

$$I_S = \frac{96}{24}$$

$$I_S = 4 \text{ A}$$

The primary current can be found using the turns ratio. Recall that the volt-amps of the primary must equal the volt-amps of the secondary. Since the primary voltage is greater, the primary current will have to be less than the secondary current.

$$I_P = \frac{I_S}{\text{turns ratio}}$$

$$I_P = \frac{4}{2.5}$$

$$I = 1.6 \text{ A}$$

To check the answer, find the volt-amps of the primary and secondary.

Primary	Secondary
240 × 1.6 = 384 VA	96 × 4 = 384 VA

Now assume that the secondary winding contains 150 turns of wire. The primary turns can be found by using the turns ratio also. Since the primary voltage is higher than the secondary voltage, the primary must have more turns of wire.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

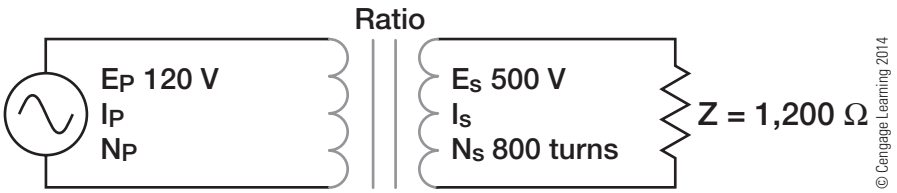


FIGURE 13-10 Calculating transformer values.

$$N_P = N_S \times \text{turns ratio}$$

$$N_P = 150 \times 2.5$$

$$N_P = 375 \text{ turns}$$

In the next example, assume an isolation transformer has a primary voltage of 120 V and a secondary voltage of 500 V. The secondary has a load impedance of 1200 Ω. The secondary contains 800 turns of wire, FIGURE 13-10. The turns ratio can be found by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{500}{120}$$

$$\text{Ratio} = 1{:}4.17$$

The secondary current can be found using Ohm's Law.

$$I_S = \frac{500}{1200}$$

$$I_S = 0.417 \text{ A}$$

In this example, the primary voltage is lower than the secondary voltage. Therefore, the primary current must be higher.

$$I_P = I_S \times \text{turns ratio}$$

$$I_P = 0.417 \times 4.17$$

$$I_P = 1.74 \text{ A}$$

To check this answer, compute the volt-amps of both windings.

Primary	Secondary
$120 \times 1.74 = 208.8$ VA	$500 \times 0.417 = 208.5$ VA

The slight difference in answers is caused by rounding off values.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

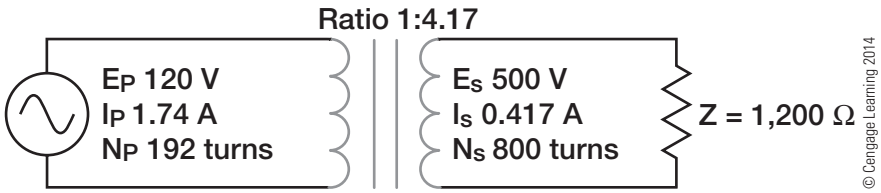


FIGURE 13-11 Transformer with completed values.

Since the primary voltage is less than the secondary voltage, the turns of wire in the primary will be less also.

$$N_P = \frac{N_S}{\text{turns ratio}}$$

$$N_P = \frac{800}{4.17}$$

$$N_P = 192 \text{ turns}$$

FIGURE 13-11 shows the transformer with all completed values.

MULTIPLE-TAPPED WINDINGS

It is not uncommon for transformers to be designed with windings that have more than one set of lead wires connected to the primary or secondary. The transformer shown in FIGURE 13-12 contains a secondary winding rated at 24 V. The primary winding contains several taps, however. One of the primary lead wires is labeled C and is the common for the other leads. The other leads are labeled 120, 208, and 240. This transformer is designed in such a manner that it can be connected to different primary voltages without changing the value of the secondary voltage. In this example, it is assumed that the secondary winding has a total of 120 turns of wire. To maintain the proper turns ratio, the primary would have 600 turns of wire between C and 120, 1,040 turns between C and 208, and 1,200 turns between C and 240.

A transformer with multiple primary taps is shown in FIGURE 13-13. This transformer has a 48-V center-tapped secondary winding. The primary winding is rated at 117 V and is marked as follows:

2–4	NOM	
1–4	−6%	OUTPUT
2–3	+12%	
1–3	+6%	

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

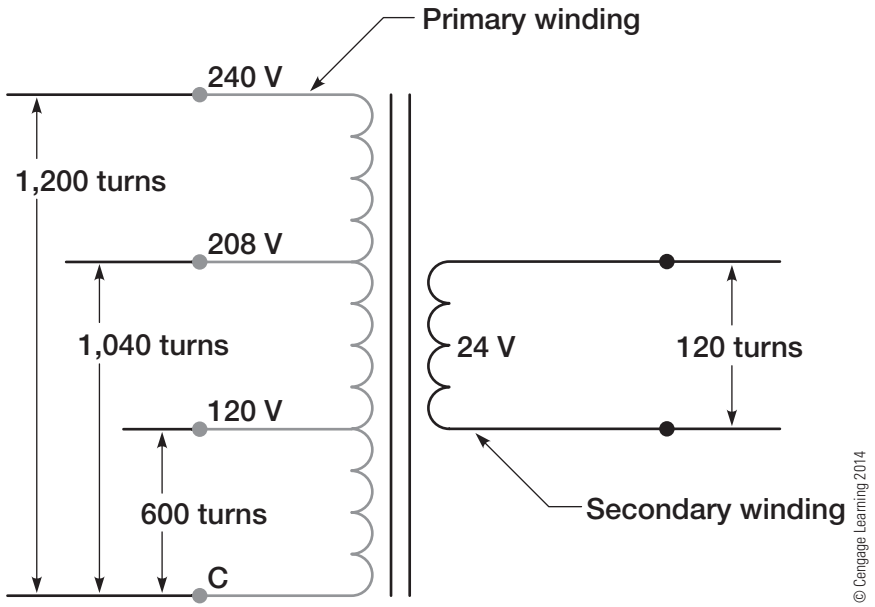


FIGURE 13-12 Transformer with multiple-tapped primary winding.

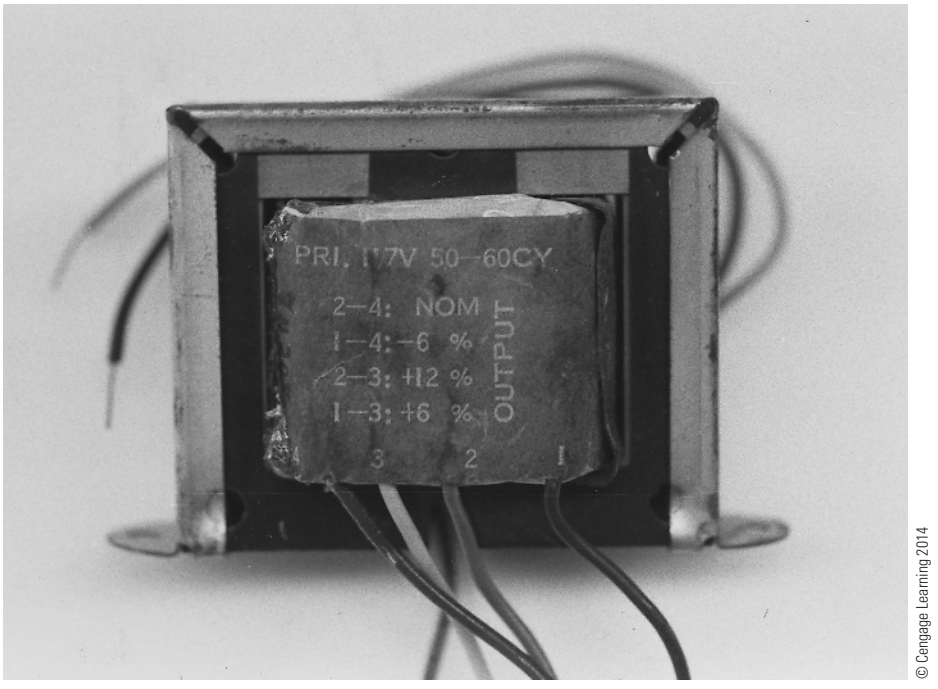


FIGURE 13-13 Transformer with multiple primary taps.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

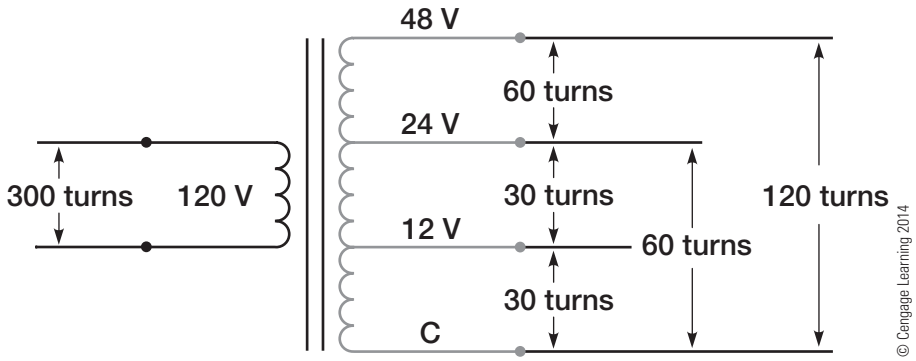


FIGURE 13-14 Transformer secondary with multiple taps.

These markings indicate that if 117 V is connected to terminals 2 and 4, the secondary voltage will be the normal 48 V. If 117 V is connected to terminals 1 and 4, the output voltage will be 6% less than the rate voltage or 45.12 V. If 117 V is connected to terminals 2 and 3, the output voltage will be 12% higher than the rated voltage or 53.76 V. Transformers of this type are designed to permit some adjustment of the output voltage.

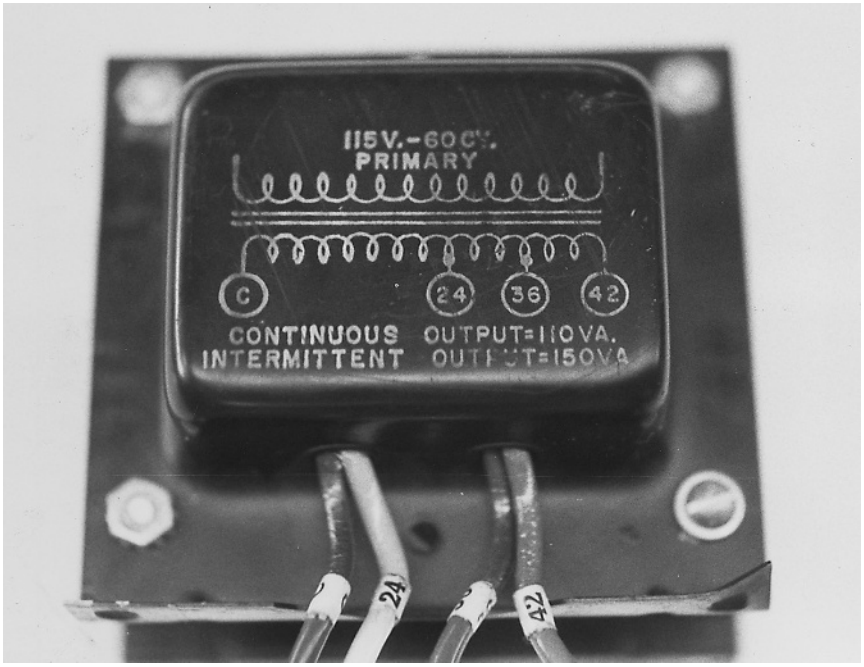
The transformer shown in FIGURE 13-14 contains a single primary winding. The secondary winding, however, has been tapped at several points. One of the secondary lead wires is labeled C and is common to the other lead wires. When rated voltage is applied to the primary, voltages of 12, 24, and 48 can be obtained at the secondary. It should also be noted that this arrangement of taps permits the transformer to be used as a center-tapped transformer for two of the voltages. If a load is placed across the lead wires labeled C and 24, the lead wire labeled 12 becomes a center tap. If a load is placed across the C and 48 lead wires, the 24 lead wire becomes a center tap.

In this example, it is assumed the primary winding has 300 turns of wire. In order to produce the proper turns ratio, it would require 30 turns of wire between C and 12, 60 turns of wire between C and 24, and 120 turns of wire between C and 48.

A transformer similar to the one just discussed is shown in FIGURE 13-15. This transformer, however, has taps labeled C, 24, 36, and 42.

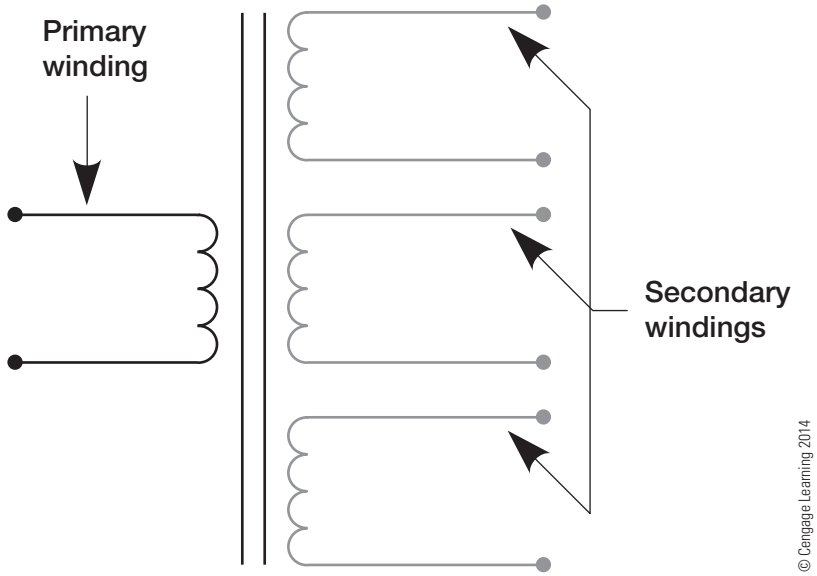
The transformer shown in FIGURE 13-16 is similar to the transformer in Figure 13-14. The transformer in Figure 13-16, however, has multiple secondary windings instead of a single secondary winding with multiple taps. The advantage of the transformer in Figure 13-16 is that the secondary windings are electrically isolated from each other. These secondary windings can be either step-up or step-down depending on the application of the transformer.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 13-15 Transformer with a multiple-tapped secondary winding.



© Cengage Learning 2014

FIGURE 13-16 Transformer with multiple secondary windings.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

COMPUTING VALUES FOR TRANSFORMERS WITH MULTIPLE SECONDARIES

When computing the values of a transformer with multiple secondary windings, each secondary must be treated as a different transformer. For example, the transformer in FIGURE 13-17 contains one primary winding and three secondary windings. The primary is connected to 120-V AC and contains 300 turns of wire. One secondary has an output voltage of 560 V and a load impedance of 1,000 Ω. The second secondary has an output voltage of 208 V and a load impedance of 400 Ω, and the third secondary has an output voltage of 24 V and a load impedance of 6 Ω. The current, turns of wire, and ratio for each secondary and the current of the primary will be found.

The first step will be to compute the turns ratio of the first secondary. The turns ratio can be found by dividing the smaller voltage into the larger.

$$\text{Ratio} = \frac{E_{S1}}{E_P}$$

$$\text{Ratio} = \frac{560}{120}$$

$$\text{Ratio} = 1{:}4.67$$

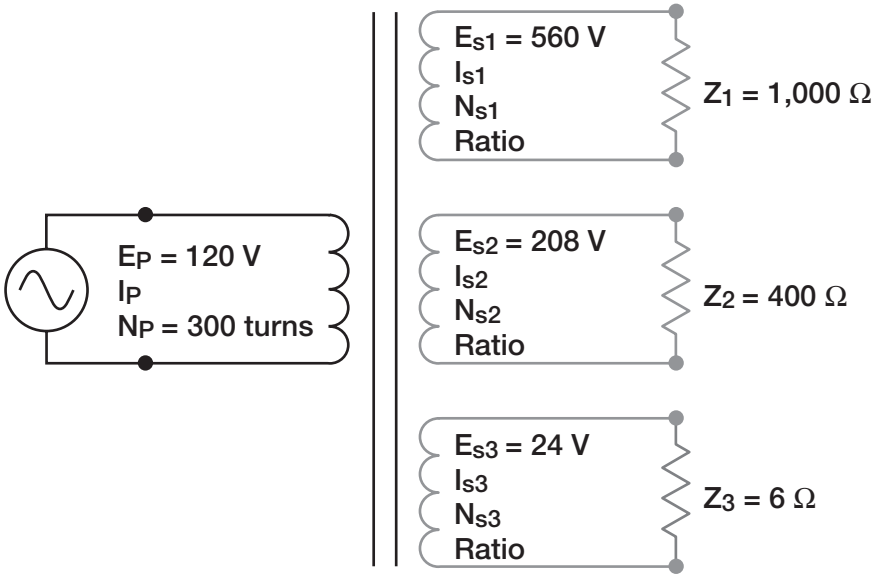


FIGURE 13-17 Computing values for a transformer with multiple secondary windings.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The current flow in the first secondary can be computed using Ohm's Law.

$$I_{S1} = \frac{560}{1{,}000}$$

$$I_{S1} = 0.56 \text{ A}$$

The number of turns of wire in the first secondary winding will be found using the turns ratio. Since this secondary has a higher voltage than the primary, it must have more turns of wire.

$$N_{S1} = N_P \times \text{turns ratio}$$

$$N_{S1} = 300 \times 4.67$$

$$N_{S1} = 1{,}401 \text{ turns}$$

The amount of primary current needed to supply this secondary winding can be found using the turns ratio also. Since the primary has less voltage, it will require more current.

$$I_{P(\text{FIRST SECONDARY})} = I_{S1} \times \text{turns ratio}$$

$$I_{P(\text{FIRST SECONDARY})} = 0.56 \times 4.67$$

$$I_{P(\text{FIRST SECONDARY})} = 2.61 \text{ A}$$

The turns ratio of the second secondary winding will be found by dividing the higher voltage by the lower.

$$\text{Ratio} = \frac{208}{120}$$

$$\text{Ratio} = 1{:}1.73$$

The amount of current flow in this secondary can be determined using Ohm's Law.

$$I_{S2} = \frac{208}{400}$$

$$I_{S2} = 0.52 \text{ A}$$

Since the voltage of this secondary is greater than the primary, it will have more turns of wire than the primary. The turns of this secondary will be found using the turns ratio.

$$N_{S2} = N_P \times \text{turns ratio}$$

$$N_{S2} = 300 \times 1.73$$

$$N_{S2} = 519 \text{ turns}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The voltage of the primary is less than this secondary. The primary will, therefore, require a greater amount of current. The amount of current required to operate this secondary will be computed using the turns ratio.

$$I_{P(SECOND\ SECONDARY)} = I_{S2} \times \text{turns ratio}$$

$$I_{P(SECOND\ SECONDARY)} = 0.52 \times 1.732$$

$$I_{P(SECOND\ SECONDARY)} = 0.9\ A$$

The turns ratio of the third secondary winding will be computed in the same way as the other two. The larger voltage will be divided by the smaller.

$$\text{Ratio} = \frac{120}{24}$$

$$\text{Ratio} = 5{:}1$$

The primary current will be found using Ohm's Law.

$$I_{S3} = \frac{24}{6}$$

$$I_{S3} = 4\ A$$

The output voltage of the third secondary is less than the primary. The number of turns of wire will, therefore, be less than the primary turns.

$$N_{S3} = \frac{N_P}{\text{turns ratio}}$$

$$N_{S3} = \frac{300}{5}$$

$$N_{S3} = 60\ \text{turns}$$

The primary has a higher voltage than this secondary. The primary current will, therefore, be less by the amount of the turns ratio.

$$I_{P(THIRD\ SECONDARY)} = \frac{I_{S3}}{\text{turns ratio}}$$

$$I_{P(THIRD\ SECONDARY)} = \frac{4}{5}$$

$$I_{P(THIRD\ SECONDARY)} = 0.8\ A$$

The primary must supply current to each of the three secondary windings. Therefore, the total amount of primary current will be the sum of the currents required to supply each secondary.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

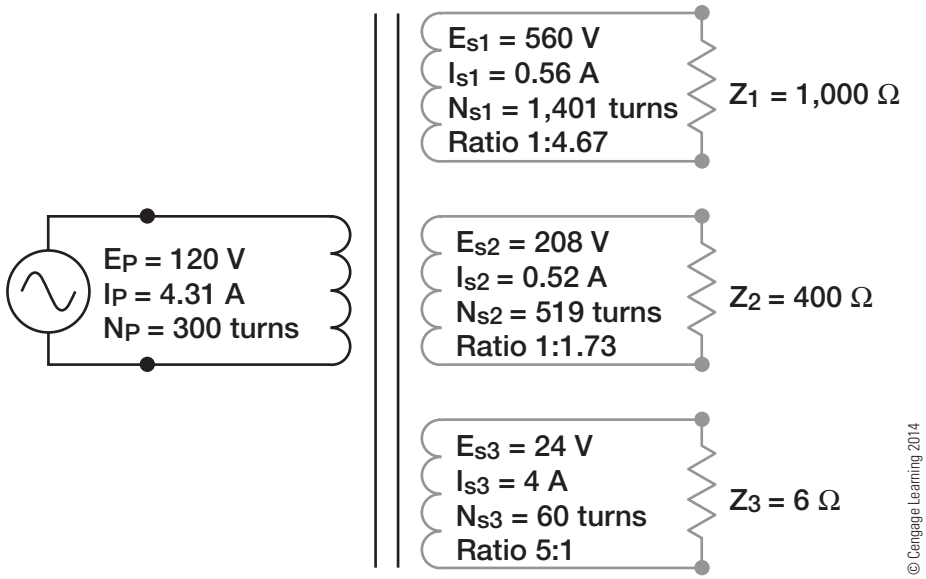


FIGURE 13-18 The transformer with all computed values.

$$I_{P(TOTAL)} = I_{P1} + I_{P2} + I_{P3}$$
$$I_{P(TOTAL)} = 2.61 + 0.9 + 0.8$$
$$I_{P(TOTAL)} = 4.31 \text{ A}$$

The transformer with all computed values is shown in FIGURE 13-18.

DISTRIBUTION TRANSFORMERS

A very common type of isolation transformer is the **distribution transformer,** FIGURE 13-19. This transformer changes the high voltage of power company distribution lines to the common 240/120 V used to supply power to most homes and many businesses. In this example, it is assumed that the primary is connected to a 7,200-V line. The secondary is 240 V with a center tap. The center tap is grounded and becomes the **neutral conductor.** If voltage is measured across the entire secondary, a voltage of 240 V will be seen. If voltage is measured from either line to the center tap, half of the secondary voltage, or 120 V, will be seen, FIGURE 13-20. The reason for this is that the voltages between the two secondary lines are in phase with each other. If a vector diagram is drawn to illustrate this condition, it will be seen that the grounded neutral conductor is connected to the axis point of the

distribution transformer transformer used to provide power to businesses or homes.

neutral conductor grounded conductor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

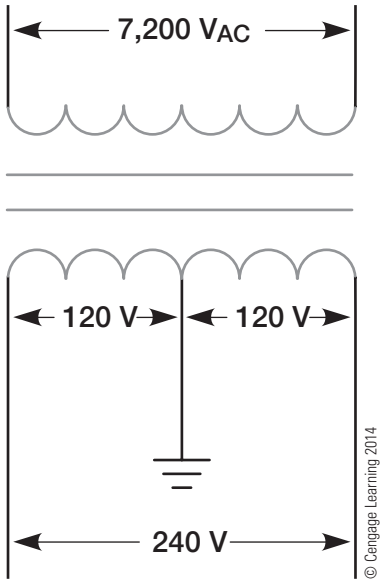


FIGURE 13-19 Distribution transformer.

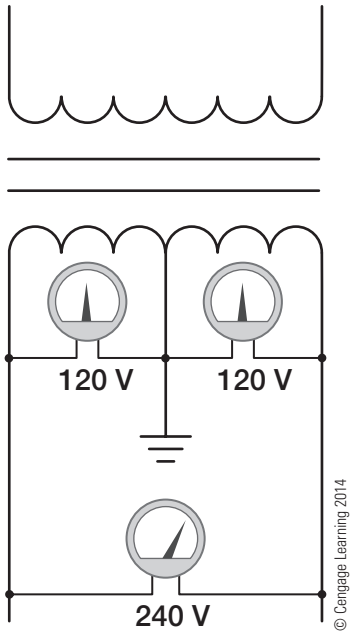


FIGURE 13-20 The voltage from either line to neutral is 120 V. The voltage across the entire secondary winding is 240 V.

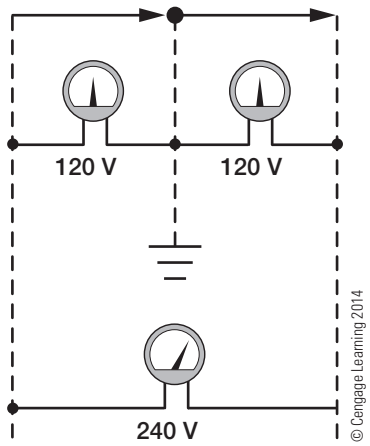


FIGURE 13-21 The voltages across the secondary are in phase with each other.

two voltage vectors, FIGURE 13-21. Loads that are intended to operate on 240 V, such as water heaters, electric resistance heating units, and central air conditioners, are connected directly across the lines of the secondary, FIGURE 13-22.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

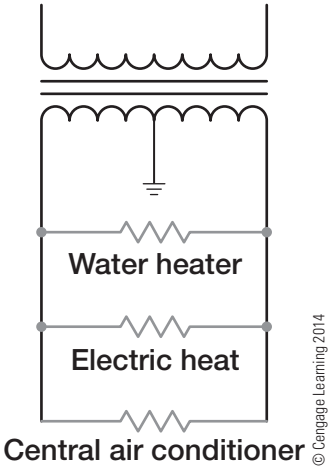


FIGURE 13-22 240-V loads connect directly across the secondary winding.

Loads that are intended to operate on 120 V connect from the center tap or neutral to one of the secondary lines. The function of the neutral is to carry the difference in current between the two secondary lines and maintain a balanced voltage. In the example shown, it is assumed that one of the secondary lines has a current flow of 30 A and the other has current flow of 24 A. The neutral will conduct the sum of the unbalanced load. In this example, the neutral current will be 6 A (30 − 24 = 6), FIGURE 13-23.

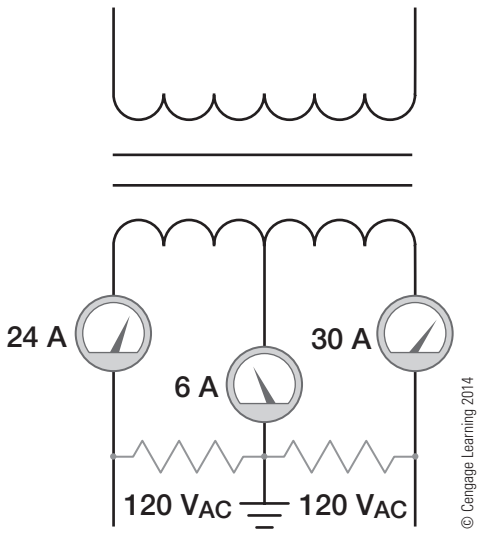


FIGURE 13-23 The neutral carries the sum of the unbalanced load.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

AUTOTRANSFORMERS

autotransformers
transformer that uses only one winding for both primary and secondary.

Autotransformers are one-winding transformers. They use the same winding for both the primary and secondary, FIGURE 13-24. The primary winding is between points B and N, and has a voltage of 120 V applied to it. If the turns of wire are counted between points B and N, it can be seen there are 120 turns of wire. Now assume that the selector switch is set to point D. The load is now connected between points D and N. The secondary of this transformer contains 40 turns of wire. If the amount of voltage applied to the load is to be computed, the following formula can be used:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{120}{40}$$

$$120\ E_S = 4800$$

$$E_S = 40\ V$$

Assume that the load connected to the secondary has an impedance of 10 Ω. The amount of current flow in the secondary circuit can be computed using the formula

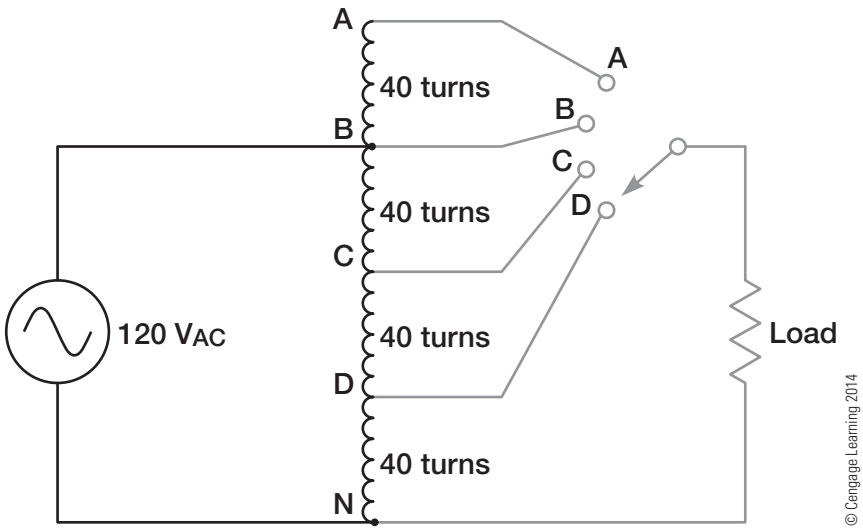


FIGURE 13-24 An autotransformer has only one winding for use by both the primary and secondary.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

$$I = \frac{E}{Z}$$

$$I = \frac{40}{10}$$

$$I = 4 \text{ A}$$

The primary current can be computed by using the same formula that was used to compute primary current for an isolation type of transformer.

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{40} = \frac{4}{I_P}$$

$$120\ I_P = 160$$

$$I_P = 1.333 \text{ A}$$

The amount of power input and output for the autotransformer must be the same, just as they are in an isolation transformer.

Primary	Secondary
$120 \times 1.333 = 160$ VA	$40 \times 4 = 160$ VA

Now assume that the rotary switch is connected to point A. The load is now connected to 160 turns of wire. The voltage applied to the load can be computed by

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{120}{160}$$

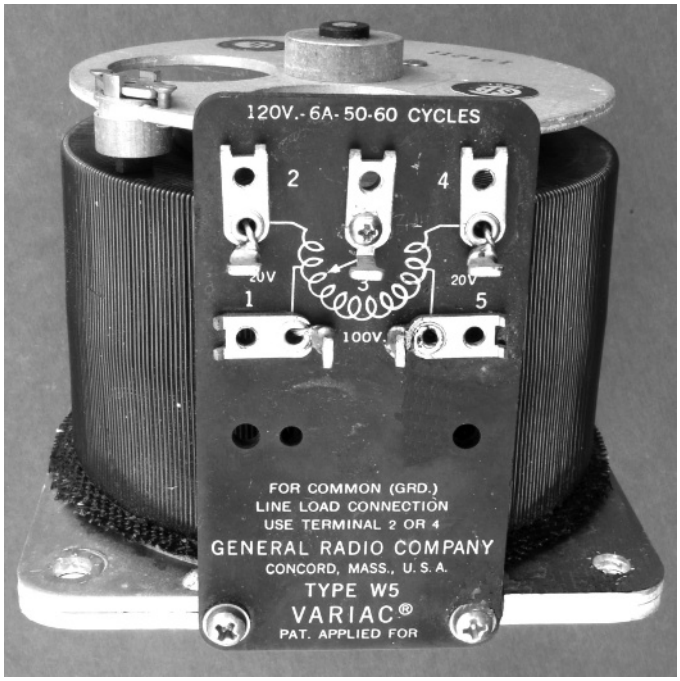
$$120\ E_S = 19{,}200$$

$$E_S = 160 \text{ V}$$

Notice that the autotransformer, like the isolation transformer, can be either a step-up or step-down transformer.

If the rotary switch shown in Figure 13-24 were to be removed and replaced with a sliding tap that made contact directly to the transformer winding, the turns ratio could be adjusted continuously. This type of transformer is commonly referred to as a Variac or Powerstat, depending on the manufacturer. A transformer of this type is shown in FIGURE 13-25.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 13-25 Autotransformer with sliding tap.

The autotransformer does have one disadvantage. Since the load is connected to one side of the power line, there is no line isolation between the incoming power and the load. This can cause problems with certain types of equipment and must be a consideration when designing a power system.

TESTING THE TRANSFORMER

Several tests can be made to determine the condition of the transformer. A simple test for grounds, shorts, or opens can be made with an ohmmeter, FIGURE 13-26. Ohmmeter A is connected to one lead of the primary and one lead of the secondary. This test checks for shorted windings between the primary and secondary. The ohmmeter should indicate infinity. If there is more than one primary or secondary winding, all isolated windings should be tested for shorts. Ohmmeter B illustrates testing the windings for grounds. One lead of the ohmmeter is connected to the case of the transformer and the other is connected to the winding. All windings should be tested for grounds and the ohmmeter should indicate infinity for each winding. Ohmmeter C

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

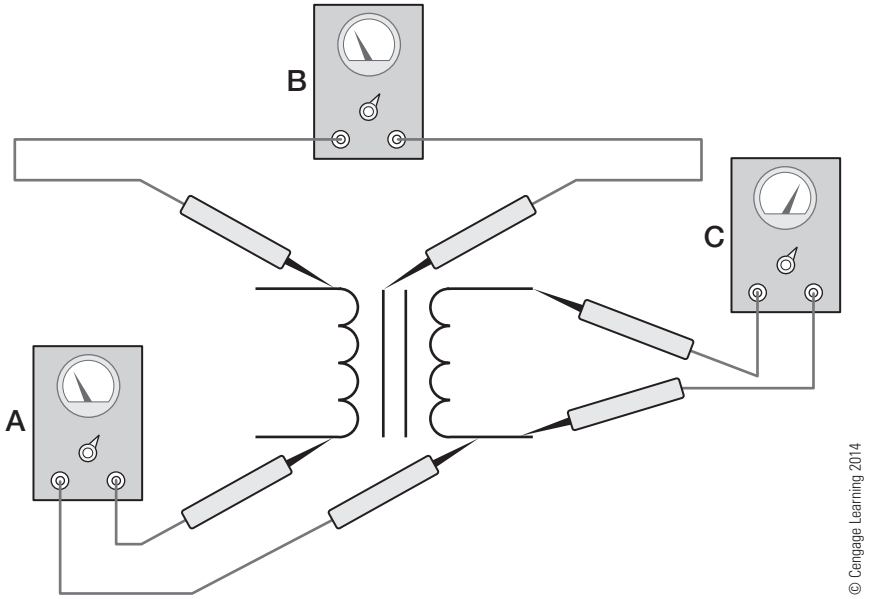


FIGURE 13-26 Testing a transformer with an ohmmeter.

illustrates testing the windings for continuity. The wire resistance of the winding should be indicated by the ohmmeter.

If the transformer appears to be in good condition after the ohmmeter test, it should then be tested for shorts and grounds with a megohmmeter (Megger®). A megger will reveal problems of insulation breakdown that an ohmmeter will not. Large oil-filled transformers should have the condition of the dielectric oil tested at periodic intervals. This involves taking a sample of the oil and performing certain tests for dielectric strength and contamination.

TRANSFORMER RATINGS

Most transformers contain a nameplate that lists information concerning the transformer. The information listed is generally determined by the size, type, and manufacturer. Almost all nameplates will list the primary voltage, secondary voltage, and kVA (kilo-volt-amps) rating. Transformers are rated in kilo-volt-amps and not kilowatts because the true power is determined by the power factor of the load. Other information that may be listed is frequency, temperature rise in C°, impedance, type of insulating oil, gallons of insulating oil, serial number, type number, model number, and whether the transformer is single phase or three phase.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

DETERMINING MAXIMUM CURRENT

Notice that the nameplate does not list the current rating of the windings. Since power input must equal power output, the current rating for a winding can be determined by dividing the kVA rating by the winding voltage. For example, assume a transformer has a kVA rating of 0.5 kVA, a primary voltage of 480 V and a secondary voltage of 120 V. To determine the maximum current that can be supplied by the secondary, divide the kVA rating by the secondary voltage.

$$I_S = \frac{kVA}{E_S}$$

$$I_S = \frac{500}{120}$$

$$I_S = 4.16 \text{ A}$$

The primary current can be computed in the same way.

$$I_P = \frac{kVA}{E_P}$$

$$I_P = \frac{500}{480}$$

$$I_P = 1.04 \text{ A}$$

Transformers with multiple secondary windings will generally have the current rating listed with the voltage rating.

Summary

1. All values of voltage, current, and impedance in a transformer are proportional to the turns ratio.
2. Transformers can change values of voltage, current, and impedance, but cannot change the frequency.
3. The primary winding of a transformer is connected to the power line.
4. The secondary winding is connected to the load.
5. A transformer that has a lower secondary voltage than primary voltage is a step-down transformer.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

6. A transformer that has a higher secondary voltage than primary voltage is a step-up transformer.
7. An isolation transformer has its primary and secondary windings electrically and mechanically separated from each other.
8. When a coil induces a voltage into itself, it is known as self-induction.
9. When a coil induces a voltage into another coil it is known as mutual induction.
10. Autotransformers have only one winding, which is used as both the primary and secondary.
11. Autotransformers have a disadvantage in that they have no line isolation between the primary and secondary winding.
12. Isolation transformers help filter voltage and current spikes between the primary and secondary side.
13. The ampere rating of a primary or secondary winding can be determined by dividing the kVA rating by the rated voltage of the winding.

Review Questions

1. What is a transformer?
2. What are common efficiencies for transformers?
3. What is an isolation transformer?
4. All values of a transformer are proportional to its _____ _____.
5. What is an autotransformer?
6. What is a disadvantage of an autotransformer?
7. Explain the difference between a step-up and a step-down transformer.
8. A transformer has a primary voltage of 240 V and a secondary voltage of 48 V. What is the turns ratio of this transformer?
9. A transformer has an output of 750 VA. The primary voltage is 120 V. What is the primary current?
10. A transformer has a turns ratio of 1:6. The primary current is 18 A. What is the secondary current?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Practice Problems

TRANSFORMERS

Refer to FIGURE 13-27 to answer the following questions. Find all the missing values.

1.

E_P 120	E_S 24
I_P _____	I_S _____
N_P 300	N_S _____
Ratio _____	Z = 3 Ω

2.

E_P 240	E_S 320
I_P _____	I_S _____
N_P _____	N_S 280
Ratio _____	Z = 500 Ω

3.

E_P_____	E_S 160
I_P _____	I_S _____
N_P _____	N_S 80
Ratio 1:2.5	Z = 12 Ω

4.

E_P 48	E_S 240
I_P _____	I_S _____
N_P 220	N_S _____
Ratio _____	Z = 360 Ω

5.

E_P _____	E_S _____
I_P 16.5	I_S 3.25
N_P _____	N_S 450
Ratio _____	Z = 56 Ω

6.

E_P 480	E_S _____
I_P _____	I_S _____
N_P 275	N_S 525
Ratio _____	Z = 1.2 kΩ

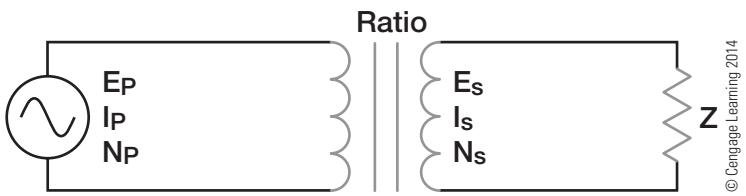


FIGURE 13-27 Isolation transformer, Practice Problems 1–6.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Refer to FIGURE 13-28 to answer the following questions. Find all the missing values.

7.

E_P 208	E_{S1} 320	E_{S2} 120	E_{S3} 24
I_P _____	I_{S1}_____	I_{S2}_____	I_{S3} _____
N_P 800	N_{S1}_____	N_{S2}_____	N_{S3} _____
	Ratio 1:	Ratio 2:	Ratio 3:
	R_1 12 kΩ	R_2 6 Ω	R_3 8 Ω

8.

E_P 277	E_{S1} 480	E_{S2} 208	E_{S3} 120
I_P _____	I_{S1}_____	I_{S2}_____	I_{S3} _____
N_P 350	N_{S1}_____	N_{S2}_____	N_{S3} _____
	Ratio 1:	Ratio 2:	Ratio 3:
	R_1 200 Ω	R_2 60 Ω	R_3 24 Ω

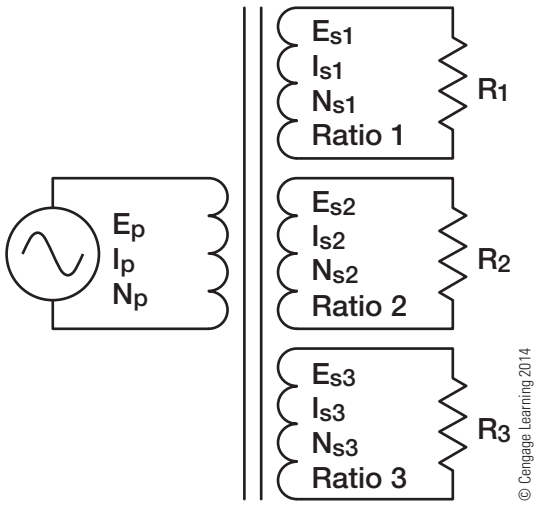


FIGURE 13-28 Single-phase transformer with multi-secondaries, Practice Problems 7 and 8.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 14

Three-Phase Transformers

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the difference between a true three-phase transformer and a three-phase transformer bank.
- Recognize delta and wye-connected transformer windings.
- Calculate three-phase transformer values.
- Make a three-phase connection using three single-phase transformers.

three-phase transformer three separate transformers wound on a common core.

magnetic coupling the amount of magnetic flux produced by one object that influences another.

A true **three-phase transformer** contains three separate transformers wound on a single core, FIGURE 14-1. The advantage of this arrangement is that the single core permits better **magnetic coupling** among the separate windings creating a higher efficiency than that possible with a transformer bank. The disadvantage is that if a single transformer should fail the entire transformer must be repaired or replaced. A pad mounted three-phase transformer is shown in FIGURE 14-2.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

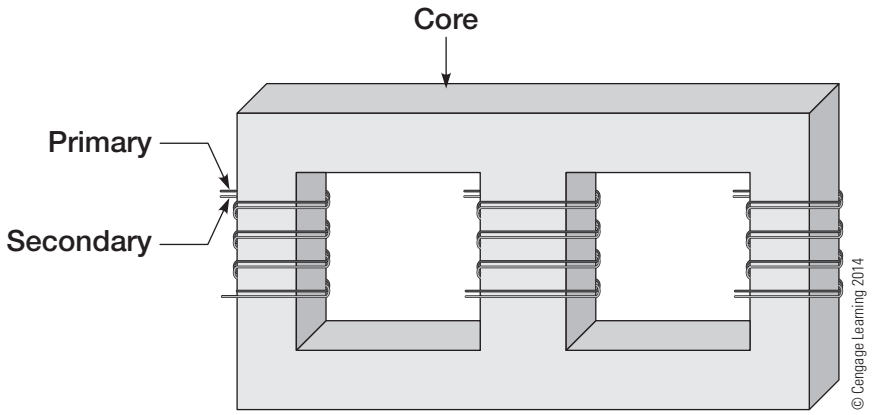


FIGURE 14-1 Three-phase transformers contain three separate transformers wound on a single core.



FIGURE 14-2 A pad-mounted three-phase transformer.

TRANSFORMER BANKS

transformer bank single-phase transformers connected in a three-phase configuration.

A three-phase **transformer bank** is made by connecting the windings of individual single-phase transformers in a three-phase connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

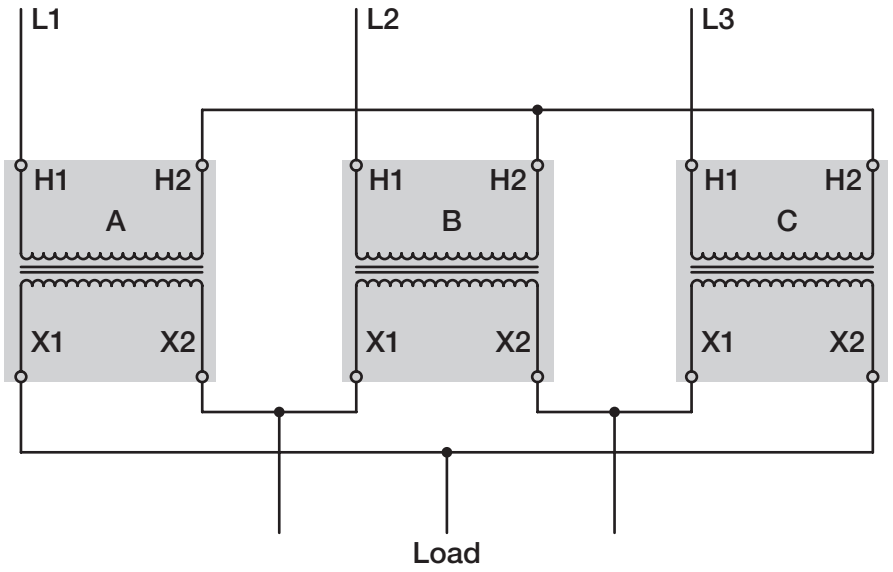


FIGURE 14-3 Three single-phase transformers connected to form a wye-delta three-phase bank.

wye
a three-phase connection formed by connecting one end of each phase together to form a center point.

delta
a three-phase connection formed by connecting the start end of a phase winding to the finish end of another.

unbalanced
a three-phase load that has unequal current flow through the phases.

The windings can be connected in either **wye** or **delta**. An illustration of a wye-delta connection is shown in FIGURE 14-3. In this example, the three primary windings are connected to form a wye connection by connecting all of the H2 leads together to form a common point. Power is connected to the H1 leads. The secondary windings are connected in delta by connecting X2 of transformer A to X1 of transformer B. X2 of transformer B is connected to X1 of transformer C, and X2 of transformer C is connected to X1 of transformer A. A schematic diagram of this connection is shown in FIGURE 14-4. Three-phase transformer banks can be connected wye-delta, delta-wye, delta-delta, or wye-wye. The first term describes how the primary windings are connected and the second describes how the secondary windings are connected. As a general rule, three-phase transformers will have one side connected as a delta. In a delta connection, the line voltage and phase voltage are the same. This characteristic greatly stabilizes the voltages in the event of an **unbalanced** load. Unbalanced loads occur when three-phase transformers are used to supply power to single-phase loads. Wye-wye connections will employ a grounded neutral conductor connected to the center point of the primary windings to help stabilize the voltages (FIGURE 14-5). The output voltages of a wye-wye connection without the grounded neutral can become extremely

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

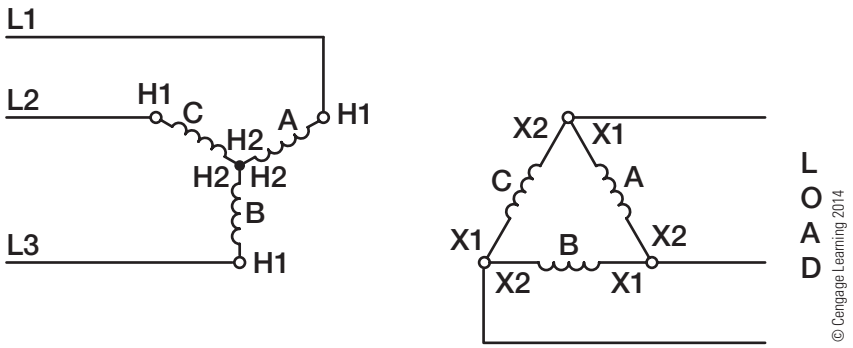


FIGURE 14-4 Schematic diagram of a wye-delta connection.

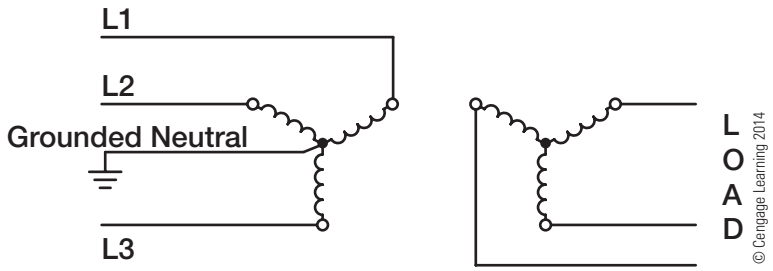


FIGURE 14-5 A grounded neutral conductor connected to the primary helps to stabilize the output voltages.

unbalanced if the load becomes unbalanced. A pole-mounted three-phase transformer bank is shown in FIGURE 14-6.

ONE LINE DIAGRAMS

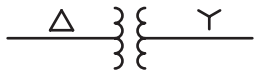
Three-phase transformer connections are often shown in schematic form as seen in Figures 14-3, 14-4, and 14-5. One line diagrams, however, are often used to show the power distribution system of a large industrial plant. A one line diagram would illustrate a delta-wye-connected three-phase transformer as shown in FIGURE 14-7. The one line diagram in FIGURE 14-8 illustrates the power distribution of an entire plant. The main incoming power is divided into different substation. The primary and secondary connections are indicated and the output voltage of each is shown on the diagram.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



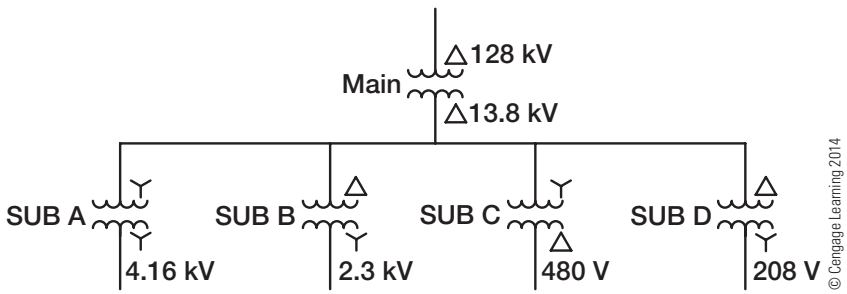
© Cengage Learning 2014

FIGURE 14-6 Pole-mounted three-phase transformer bank.



© Cengage Learning 2014

FIGURE 14-7 One line diagram of a delta-wye connected transformer.



© Cengage Learning 2014

FIGURE 14-8 One line diagram of a plant distribution system.

CLOSING A DELTA

phasing
checking a delta connection for proper connection.

Delta connections should be checked for proper polarity before making the final connection and applying power. If the phase winding of one transformer is reversed, an extremely high current will flow when power is applied. Proper **phasing** can be checked with a voltmeter as shown in FIGURE 14-9. If power is applied to the transformer bank before the delta connection is closed, the voltmeter should indicate 0 V. If one-phase winding has been reversed, however, the voltmeter will indicate double the amount of voltage. For example, assume the output voltage of a delta secondary is 240 V. If the voltage is checked before the delta is

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

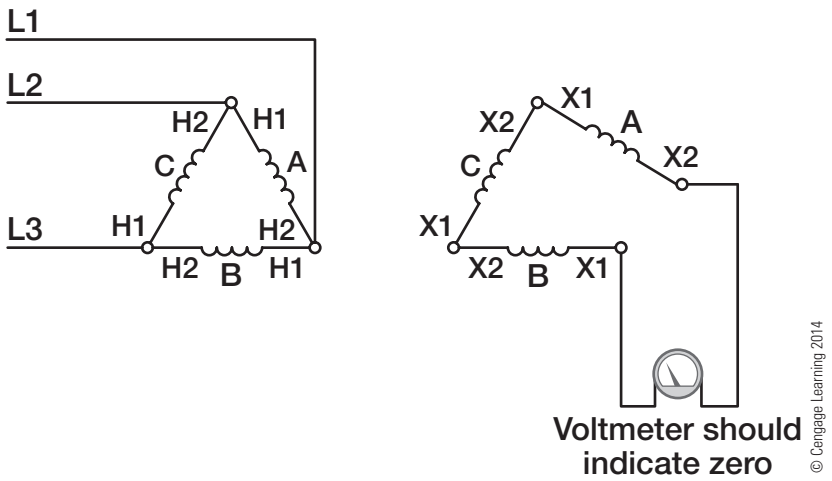


FIGURE 14-9 Checking the polarity before closing a delta connection.

closed, the voltmeter should indicate a voltage of 0 V if all windings have been phased properly. If one winding has been reversed, however, the voltmeter will indicate a voltage of 480 V (240 + 240). This test will confirm whether a phase winding has been reversed, but it will not indicate if the reversed winding is located in the primary or secondary. If either primary or secondary windings have been reversed, the voltmeter would have indicated double the output voltage.

It should be noted, however, that a voltmeter is a high-impedance device. It is not unusual for a voltmeter to indicate some amount of voltage before the delta is closed, especially if the primary has been connected as a wye and the secondary as a delta. When this is the case, however, the voltmeter will generally indicate close to the normal output voltage if the connection is correct and double the output voltage if the connection is incorrect.

THREE-PHASE TRANSFORMER CALCULATIONS

When computing the values of voltage and current for three-phase transformers, the formulas used for making transformer calculations and three-phase calculations must be followed. Another very important rule that must be understood is that **ONLY PHASE VALUES OF VOLTAGE AND CURRENT CAN BE USED WHEN COMPUTING TRANSFORMER VALUES**. Refer to transformer A in FIGURE 14-3. All transformation of voltage and current takes place between the primary and secondary windings. Since these windings form the phase values of the three-phase connection, only phase and not line values can be used when calculating transformed voltages and currents.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 1: A three-phase transformer connection is shown in FIGURE 14-10. Three single-phase transformers have been connected to form a wye-delta bank. The primary is connected to a three-phase line of 13,800 volts, and the secondary voltage is 480. A three-phase wye connected resistive load with an impedance of 2.77 Ω per phase is connected to the secondary of the transformer. The following values will be computed for this circuit:

$E_{P(Primary)}$ — phase voltage of the primary
$E_{P(Secondary)}$ — phase voltage of the secondary
Ratio — turns ratio of the transformer
$E_{P(Load)}$ — phase voltage of the load bank
$I_{P(Load)}$ — phase current of the load bank
$I_{L(Secondary)}$ — secondary line current
$I_{P(Secondary)}$ — phase current of the secondary
$I_{P(Primary)}$ — phase current of the primary
$I_{L(Primary)}$ — line current of the primary

The primary windings of the three single-phase transformers have been connected to form a wye connection. In a wye connection, the phase voltage is less than the line voltage by a factor of 1.732 ($\sqrt{3}$). Therefore, the phase value of voltage can be computed using the formula:

$$E_P = \frac{E_L}{1.732} \qquad E_P = \frac{13{,}800\ V}{1.723} \qquad E_P = 7967.7V$$

The secondary windings are connected as a delta. In a delta connection, the phase voltage and line voltage are the same.

$$E_P = E_L$$
$$E_P = 480\ V$$

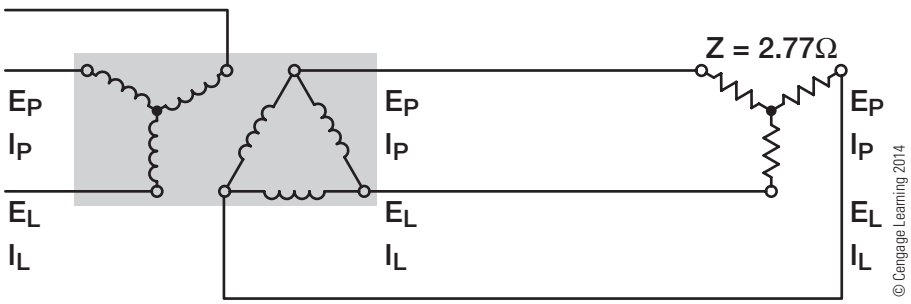


FIGURE 14-10 Example 1: Three-phase transformer calculation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The turns ratio can be computed by comparing the phase voltage of the primary to the phase voltage of the secondary.

$$\text{Ratio} = \frac{\text{primary phase voltage}}{\text{secondary phase voltage}} \qquad \text{Ratio} = \frac{7967.7}{480}$$

Turns ratio = 16.6:1

The load bank is connected in a wye connection. The voltage across the phase of the load bank will be less than the line voltage by a factor of 1.732.

$$E_{P_{(load)}} = \frac{E_L}{1.732} \qquad E_{P_{(load)}} = \frac{480}{1.732} \qquad E_{P_{(load)}} = 277 \text{ V}$$

Now that the voltage across each of the load resistors is known, the current flow through the phase of the load can be computed using Ohm's Law.

$$I_{P_{(load)}} = \frac{E_P}{Z} \qquad I_{P_{(load)}} = \frac{277}{2.77} \qquad I_{P_{(load)}} = 100 \text{ A}$$

Since the load is connected as a wye connection, the line current will be the same as the phase current.

$$I_L = 100 \text{ A}$$

Because there is only one load connected to the transformer, the line current of the load is the line current of the transformer secondary. The secondary of the transformer bank is connected as a delta. The phase current of the delta is less than the line current by a factor of 1.732.

$$I_{P_{(Secondary)}} = \frac{I_L}{1.732} \qquad I_{L_{(Secondary)}} = \frac{100}{1.732} \qquad I_{L_{(Secondary)}} = 57.7 \text{ A}$$

The amount of current flow through the phase windings of the primary can be computed using the turns ratio. Because the primary has a higher voltage, it will have a lower current (Volts × Amps input must equal Volts × Amps output):

$$\text{Primary phase current} = \frac{\text{secondary phase current}}{\text{turns ratio}}$$

$$\text{Primary phase current} = \frac{57.7}{16.6}$$

$$\text{Primary phase current} = 3.48 \text{ A}$$

In a wye connection, the phase current is the same as the line current.

$$I_L = 3.48 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

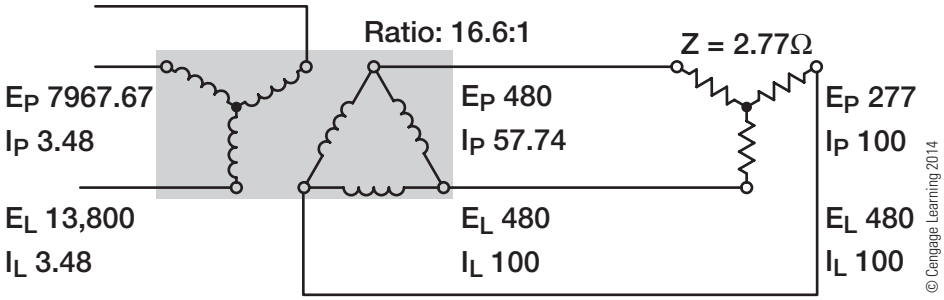


FIGURE 14-11 Example 1 with all calculated values.

The transformer connection with all computed values is shown in FIGURE 14-11.

EXAMPLE 2: In this example, a three-phase transformer is connected in a delta -delta configuration (FIGURE 14-12). The load is connected as a wye and each phase has an impedance of 7 Ω. The primary is connected to a line voltage 4160 V and the secondary line voltage is 440 V. The following values will be found:

$E_{P(Primary)}$ — phase voltage of the primary
$E_{P(Secondary)}$ — phase voltage of the secondary
Ratio — turns ratio of the transformer
$E_{P(Load)}$ — phase voltage of the load bank
$I_{P(Load)}$ — phase current of the load bank
$I_{L(Secondary)}$ — secondary line current
$I_{P(Secondary)}$ — phase current of the secondary
$I_{P(Primary)}$ — phase current of the primary
$I_{L(Primary)}$ — line current of the primary

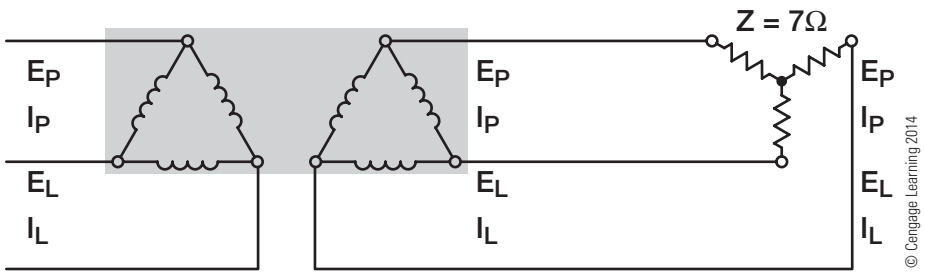


FIGURE 14-12 Example 2: Three-phase transformer calculation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The primary is connected as a delta. The phase voltage will be the same as the applied line voltage.

$$E_{P_{(Primary)}} = E_{L_{(Primary)}}$$

$$E_{P_{(Primary)}} = 4160 \text{ V}$$

The secondary of the transformer is connected as a delta also. Therefore, the phase voltage of the secondary will be the same as the line voltage of the secondary.

$$E_{P_{(Secondary)}} = 440 \text{ V}$$

All transformer values must be computed using phase values of voltage and current. The turns ratio can be found by dividing the phase voltage of the primary by the phase voltage of the secondary.

$$\text{Turns ratio} = \frac{E_{P_{(Primary)}}}{E_{P_{(Secondary)}}} \quad \text{Turns ratio} = \frac{4160}{440} \quad \text{Turns ratio} = 9.45{:}1$$

The load is connected directly to the output of the secondary. The line voltage applied to the load must, therefore, be the same as the line voltage of the secondary.

$$E_{L_{(Load)}} = 440 \text{ V}$$

The load is connected in a wye. The voltage applied across each phase will be less than the line voltage by a factor of 1.732.

$$E_{P_{(Load)}} = \frac{E_{L_{(Load)}}}{1.732} \qquad E_{P_{(Load)}} = \frac{440}{1.732} \qquad E_{P_{(Load)}} = 254 \text{ V}$$

The phase current of the load can be computed using Ohm's Law.

$$I_{P_{(Load)}} = \frac{E_{P_{(Load)}}}{Z} \qquad I_{P_{(Load)}} = \frac{254}{7} \qquad I_{P_{(Load)}} = 36.29 \text{ A}$$

The amount of line current supplying a wye-connected load will be the same as the phase current of the load.

$$I_{L_{(Load)}} = 36.29 \text{ A}$$

Since the secondary of the transformer is supplying current to only one load, the line current of the secondary will be the same as the line current of the load.

$$I_{L_{(Secondary)}} = 36.29 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

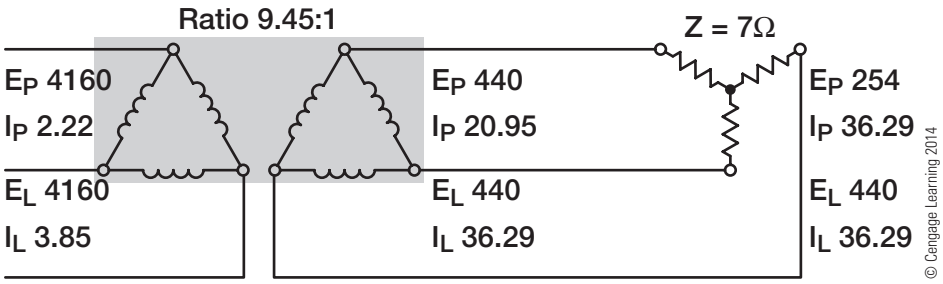


FIGURE 14-13 Example 2 with all calculated values.

The phase current in a delta connection is less than the line current by a factor of 1.732.

$$I_{P_{(Secondary)}} = \frac{I_{L_{(Secondary)}}}{1.732} \qquad I_{P_{(Secondary)}} = \frac{36.29}{1.732} \qquad I_{P_{(Secondary)}} = 20.95 \text{ A}$$

The phase current of the transformer primary can now be computed using the phase current of the secondary and the turns ratio.

$$I_{P_{(Primary)}} = \frac{I_{P_{(Secondary)}}}{\text{turns ratio}} \qquad I_{P_{(Primary)}} = \frac{20.95}{9.45} \qquad I_{P_{(Primary)}} = 2.22 \text{ A}$$

In this example, the primary of the transformer is connected as a delta. The line current supplying the transformer will be higher than the phase current by a factor of 1.732.

$$I_{L_{(Primary)}} = I_{P_{(Primary)}} \times 1.732$$

$$I_{L_{(Primary)}} = 2.22 \times 1.732$$

$$I_{L_{(Primary)}} = 3.85 \text{ A}$$

The circuit with all computed values is shown in FIGURE 14-13.

OPEN DELTA CONNECTION

open delta
a three-phase transformer connection requiring only two transformers.

The **open delta** transformer connection can be made with only two transformers instead of three (FIGURE 14-14). This connection is often used when the amount of three-phase power needed is not excessive, such as in a small business. It should be noted that the output power of an open delta connection is only 86.6% of the rated power of the two transformers. For example, assume two transformers, each having a capacity of 25 kVA (kilo-volt-amperes),

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

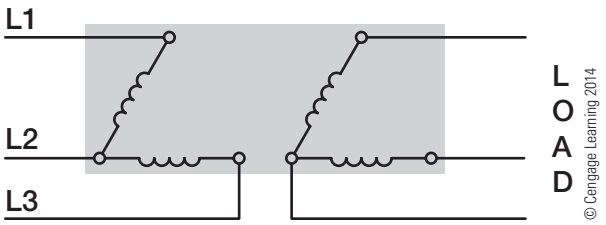


FIGURE 14-14 Open delta connection

are connected in an open delta connection. The total output power of this connection is 43.3 kVA ($50 \times 0.866 = 43.3$).

Another figure given for this calculation is 57.7%. This percentage assumes a closed delta bank containing three transformers. If three 25 kVA transformers were connected to form a closed delta connection, the total output power would be 75 kVA ($3 \times 25 = 75$). If one of these transformers were removed, and the transformer bank operated as an open delta connection, the output power would be reduced to 57.7% of its original capacity of 75 kVA. The output capacity of the open delta bank is 43.3 kVA ($75 \times 0.577 = 43.3$).

The voltage and current values of an open delta connection are computed in the same manner as a standard delta-delta connection when three transformers are employed. The voltage and current rules for a delta connection must be used when determining line and phase values of voltage and current. A pole-mounted open delta transformer bank is shown in FIGURE 14-15.

SINGLE-PHASE LOADS

When true three-phase loads are connected to a three-phase transformer bank, there are no problems in balancing the currents and voltages of the individual phases. This is the ideal condition and is certainly desired for all three-phase transformer loads. Although this is the ideal situation, it is not always possible to obtain a balanced load. Three-phase transformer connections are often used to supply single-phase loads which tend to unbalance the system.

OPEN DELTA CONNECTION SUPPLYING A SINGLE-PHASE LOAD

The type of three-phase transformer connection used is generally determined by the amount of power needed. When a transformer bank must supply both three-phase and single-phase loads, the utility company will often provide an open delta connection with one transformer center tapped as shown in

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 14-15 Pole-mounted open delta transformer bank.

FIGURE 14-16. In this connection, it is assumed that the amount of three-phase power needed is 20 kVA and the amount of single-phase power needed is 30 kVA. Notice that the transformer that has been center tapped must supply power its share of the three-phase load and all of the single-phase load. Since this is an open delta connection, the transformer bank can be loaded to only 86.6% of its full capacity when supplying a three-phase load. The rating of the three-phase transformer bank must therefore be 23 kVA ($20 \div 0.866 = 23$). Because the rating of the two transformers can be added to obtain a total output power rating, one transformer is rated at only half the total amount of power needed, or 12 kVA ($23 \div 2 = 11.5$). The transformer which is used to supply power to the three-phase load only will be rated at 12 kVA. The transformer that has been center tapped must supply power to both the single-phase and three-phase load. Its capacity will, therefore, be 12 kVA + 30 kVA = 42 kVA. A 45 kVA transformer will be used.

VOLTAGE VALUES

The connection shown in FIGURE 14-16 has a line to line voltage of 240 V. The three voltmeters V_1, V_2, and V_3 have all been connected across the three

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

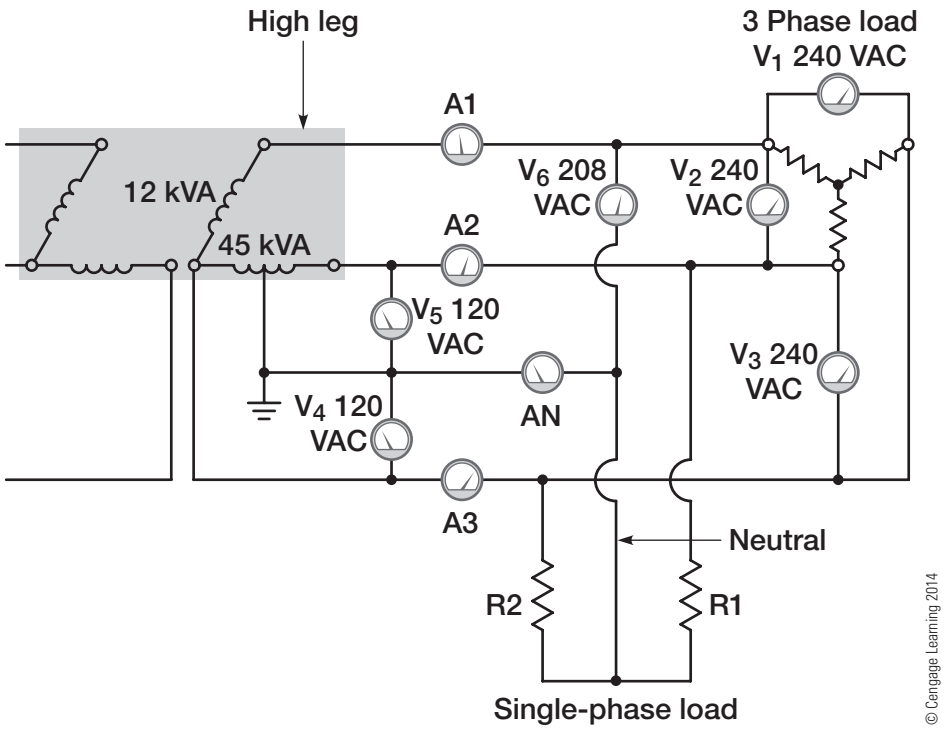


FIGURE 14-16 An open delta transformer with center tap supplying both three-phase and single-phase loads.

phase lines and should indicate 240 V each. Voltmeters V_4 and V_5 have been connected between the two lines of the larger transformer and its center tap. These two voltmeters will indicate a voltage of 120 V each. Notice that it is these two lines and the center tap that are used to supply the single-phase power needed. The center tap of the larger transformer is used as a neutral conductor for the single-phase loads. Voltmeter V_6 has been connected between the **center tap** of the larger transformer and the line of the smaller transformer. This line is known as a **high leg,** because the voltage between this line and the neutral conductor will be higher than the voltage between the neutral and either of the other two conductors. The high-leg voltage can be computed by increasing the single-phase center-tapped voltage value by 1.732. In this case, the high-leg voltage will be 208 V ($120 \times 1.732 = 208$). When this type of connection is employed, the *National Electrical Code*® requires that the high leg be identified by connecting it to an orange-colored wire or by tagging it at any point that it enters an enclosure with the neutral conductor.

center tap
a connection in the center of a transformer winding that will provide one half of the rated voltage of the winding.

high leg
one leg of a transformer that has a higher voltage to ground than the other two.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

LOAD CONDITIONS

In the first load condition, it will be assumed that only the three-phase load is in operation and none of the single-phase load is operating. If the three-phase load is operating at maximum capacity, ammeters A_1, A_2, and A_3 will indicate a current flow of 48.1 A each (20 kVA ÷ 240 V × 1.732 = 48.1 A). Notice that when only the three-phase load is in operation, the current on each line is balanced.

Now assume that none of the three-phase load is in operation and only the single-phase load is operating. If all the single-phase load is operating at maximum capacity, ammeters A_2 and A_3 will each indicate a value of 125 A (30 kVA ÷ 240 V = 125 A). Ammeter A_1 will indicate a current flow of 0 A because all of the load is connected between the other two lines of the transformer connection. Ammeter A_N will also indicate a value of 0 A. Ammeter A_N is connected in the neutral conductor, and the neutral conductor carries the sum of the unbalanced load between the two-phase conductors. Another way of stating this is to say that the neutral conductor carries the difference between the two line currents. Since both of these conductors are now carrying the same amount of current, the difference between them is 0 A.

Now assume that one side of the single-phase load, resistor R_2, has been opened and no current flows through it. If the other line maintains a current flow of 125 A, the neutral conductor will have a current flow of 125 A also (125 − 0 = 125).

Now assume that resistor R_2 has a value that will permit a current flow of 50 A on that phase. The neutral current will now be 75 A (125 − 50 = 75). Since the neutral conductor carries the sum of the unbalanced load, the size of the neutral conductor never needs to be larger than the largest line conductor.

It will now be assumed that both three-phase and single-phase loads are operating at the same time. If the three-phase load is operating at maximum capacity, and the single-phase load is operating in such a manner that 125 A flows through resistor R_1 and 50 A flows through resistor R_2, the ammeters will indicate the following values:

$A_1 = 48.1$ A

$A_2 = 98.1$ A (48.1 + 125 = 173.1)

$A_3 = 173.1$ A (48.1 + 50 = 98.1)

$A_N = 75$ A (125 − 50 = 75)

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

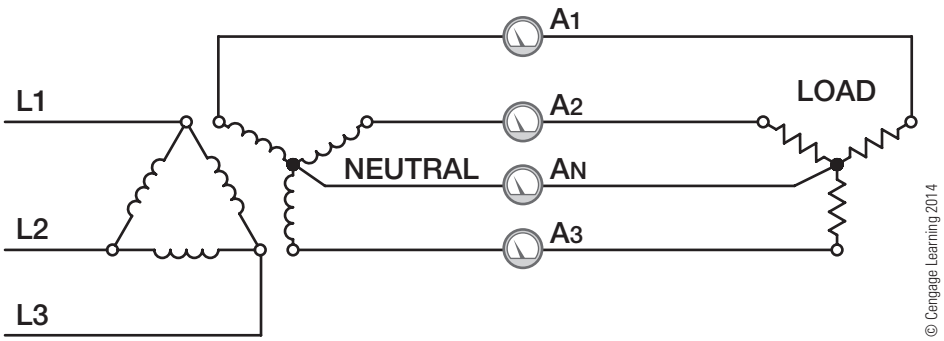


FIGURE 14-17 A wye-delta connection.

Notice that the smaller of the two transformers is supplying current to only the three-phase load, but the larger transformer must supply current for both the single-phase and three-phase loads.

DELTA-WYE CONNECTION WITH NEUTRAL

The circuit shown in FIGURE 14-17 is a three-phase transformer connection with a delta-connected primary and wye-connected secondary. The secondary has been center tapped to form a neutral conductor. This is one of the most common connections used to provide power for single-phase loads. Typical voltages for this type of connection are 208/120 and 480/277. The neutral conductor will carry the vector sum of the unbalanced current. It should be noted, however, that in this circuit the sum of the unbalanced current is not the difference between two phases. In the delta connection where one transformer was center tapped to form a neutral conductor, the two lines were 180° out of phase when compared to the center tap. In the wye connection, the lines will be 120° out of phase. When all three lines are carrying the same amount of amperage, the neutral current will be zero.

Summary

1. True three-phase transformers are constructed by winding three separate transformers on the same core material.
2. Single-phase transformers can be used as a three-phase transformer bank by connecting their primary and secondary windings as either wyes or deltas.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

3. When computing three-phase transformer values, the rules for three-phase circuits must be followed as well as the rules for transformers.
4. Phase values of voltage and current must be used when computing the values associated with the transformer.
5. The total power output of a three-phase transformer bank will be the sum of the rating of the three transformers.
6. An open delta connection can be made with the use of only two transformers.
7. When an open delta connection is used, the total output power is 86.6% of the sum of the power rating of both transformers.
8. It is common practice to center tap one of the transformers in a delta connection to provide power for single-phase loads. When this is done, the remaining phase connection becomes a high leg.
9. The *National Electrical Code*® requires that a high leg be identified by an orange wire or by tagging.
10. The center connection of a wye is often tapped to provide a neutral conductor for three-phase loads. This produces a three-phase four-wire system. Common voltages produced by this type of connection are 208/120 and 480/277.

Review Questions

1. How many transformers are needed to make an open delta connection?
2. Two transformers rated at 100 kVA each are connected in an open delta connection. What is the total output power that can be supplied by this bank?
3. How does the *National Electrical Code*® specify that the high leg of a four-wire delta connection be marked?
4. An open delta three-phase transformer system has one transformer center tapped to provide a neutral for single phase voltages. If the voltage from line to center tap is 277 V, what is the high-leg voltage?
5. If a single-phase load is connected across the two line conductors and neutral of the above transformer, and one line has a current of

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

80 A and the other line has a current of 68 A, how much current is flowing in the neutral conductor?

6. A three-phase transformer connection has a delta-connected secondary and one of the transformers has been center tapped to form a neutral conductor. The phase to neutral value of the center-tapped secondary winding is 120 V. If the high leg should become connected to a single-phase load, how much voltage will be applied to that load?
7. A three-phase transformer connection has a delta-connected primary and a wye-connected secondary. The center tap of the wye is used as a neutral conductor. If the line to line voltage is 480 V, what is the voltage between any one phase conductor and the neutral conductor?
8. A three-phase transformer bank has the secondary connected in a wye configuration. The center tap is used as a neutral conductor. If the voltage across any phase conductor and neutral is 120 V, how much voltage would be applied to a three-phase load connected to the secondary of this transformer bank?

Practice Problems

Refer to the transformer shown in Figure 14-10 to fill in the following unknown values.

1.

Primary	**Secondary**	**Load**
E_P _____	E_P _____	E_P _____
I_P _____	I_P _____	I_P _____
E_L 4160	E_L 440	E_L _____
I_L _____	I_L _____	I_L _____
	RATIO:	$Z = 3.5\ \Omega$

2.

Primary	**Secondary**	**Load**
E_P _____	E_P _____	E_P _____
I_P _____	I_P _____	I_P _____
E_L 7200	E_L 240	E_L _____
I_L _____	I_L _____	I_L _____
	RATIO:	$Z = 4\ \Omega$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Answers to Practice Problems

THREE-PHASE TRANSFORMERS

	Primary	Secondary	Load
1.	E_P 7205.1	E_P 440	E_P 254
	I_P 2.6	I_P 41.9	I_P 72.6
	E_L **4160**	E_L **440**	E_L 440
	I_L 2.6	I_L 72.6	I_L 72.6
		RATIO: 16.4:1	Z = **3.5** Ω

	Primary	Secondary	Load
2.	E_P 41.57	E_P 20	E_P 138.6
	I_P 1.15	I_P 240	I_P 34.65
	E_L 7200	E_L 240	E_L 240
	I_L 1.15	I_L 34.65	I_L 34.65
		RATIO: 17.32:1	Z = 4 Ω

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 15

Electrical Services

OBJECTIVES: After studying this unit, you should be able to:

- Describe the differences between three-phase and single-phase panels.
- Connect a three-phase branch circuit to a three-phase panel.
- Connect a 240-V single-phase circuit to a circuit breaker panel.
- Connect a 120-V single-phase circuit to a circuit breaker panel.
- Describe differences between ungrounded and neutral conductors.
- Select the proper conductor size for a particular circuit.

The heart of any electrical system is the service, or panel. All branch circuits originate from a fuse or circuit breaker panel. Industrial and large commercial services are generally three-phase and require the installation of a three-phase wattmeter and a three-phase panel. Residential and light commercial services are generally single phase.

THREE-PHASE SERVICES

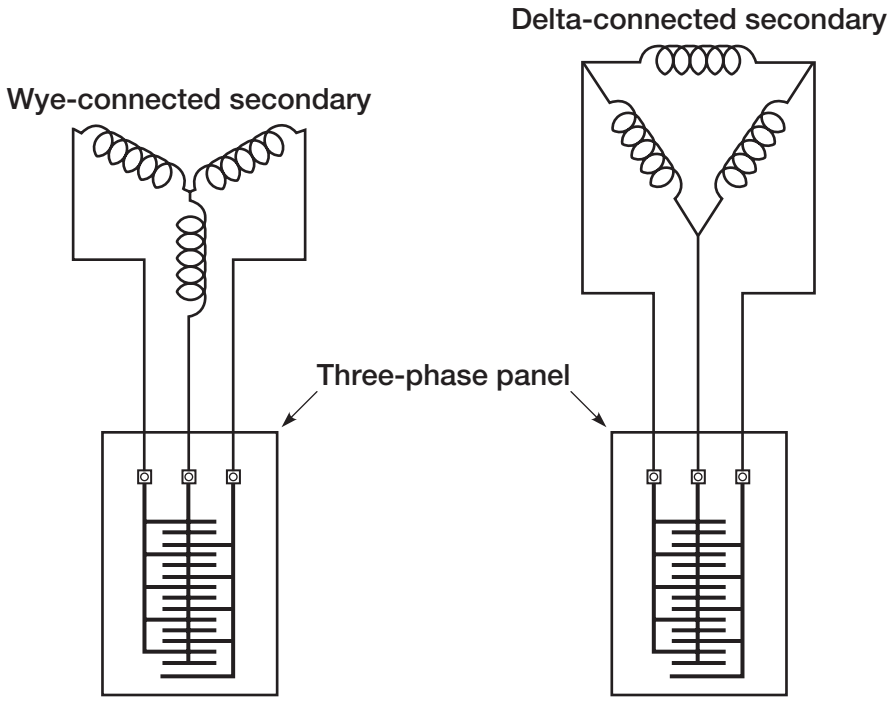
Three-phase services generally fall into one of three categories:

1. Three-phase three-wire system
2. Three-phase four-wire system with a grounded neutral conductor
3. Three-phase four-wire system with a grounded neutral and a high leg

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The type of three-phase service is determined by the type of secondary transformer connection supplied by the power company. The three-phase three-wire system is made by connecting the secondary windings of a three-phase transformer bank in either wye or delta and connecting the three lines to a three-phase panel, FIGURE 15-1. This system does not contain a neutral or grounded conductor. The lines are generally designated as L1, L2, and L3 or A, B, and C. Typical voltages for this type system are 240, 440, 480, and 560.

A three-phase four-wire system is produced by connecting the secondary of a three-phase transformer bank in wye and connecting a fourth wire to the center tap of the wye, FIGURE 15-2. The fourth wire is grounded and becomes the neutral conductor. Phase voltage values can be obtained by connecting between any line and the neutral conductor. Line-to-line voltage values can be obtained by connecting between the lines. Typical voltages for this type of connection are 208/120 and 480/277. The 480/277-V connection is very popular for large commercial and office buildings because the 480-V three-phase capability is used to operate



© Cengage Learning 2014

FIGURE 15-1 Three-phase three-wire system.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

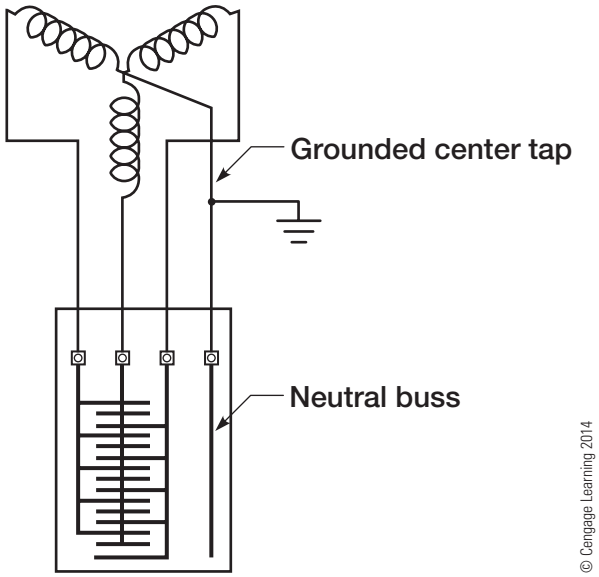


FIGURE 15-2 Three-phase four-wire system with grounded neutral conductor.

large air conditioning and heating loads, and the 277-V capability is used to operate fluorescent lighting.

The three-phase four-wire high-leg connection is made by connecting the secondary windings of a three-phase transformer bank in delta or open delta and center tapping one of the transformer secondaries to provide a neutral conductor, FIGURE 15-3. The open delta connection is often used for light commercial and small industrial locations because it permits three-phase power to be provided with the use of only two transformers. The high-leg connection is generally made when a major portion of the power needed is single phase, but there is some need for three-phase power. In this installation the transformer used to supply the single-phase power will be larger than the other transformer or transformers in the bank. The typical voltage for this system is 240 V between any of the three-phase lines. Since one of the transformers is center-tapped, single-phase voltages of 240/120 can be obtained by connecting between the two line conductors of the center-tapped transformer for 240 V, or between any of the line conductors and the center tap for 120 V, FIGURE 15-4. The high-leg voltage is obtained by connecting between the grounded center tap and the third leg of the three-phase system. The high-leg voltage for this system is 208 V. A vector

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

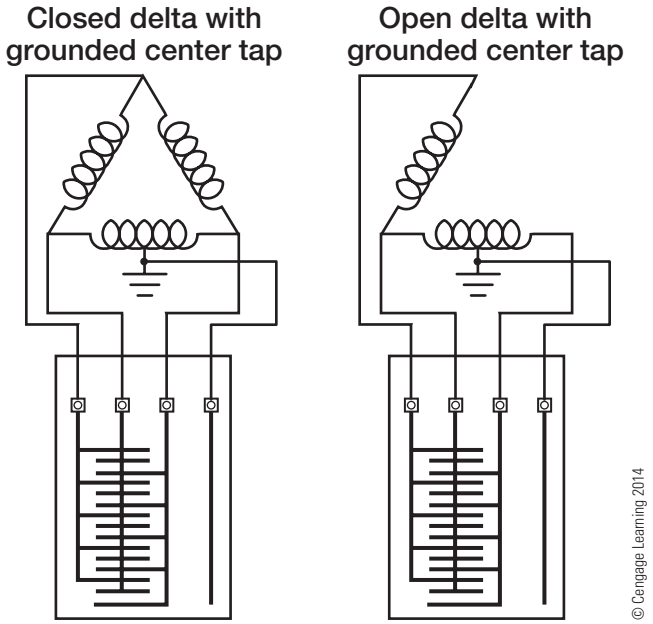


FIGURE 15-3 Three-phase four-wire system with high leg.

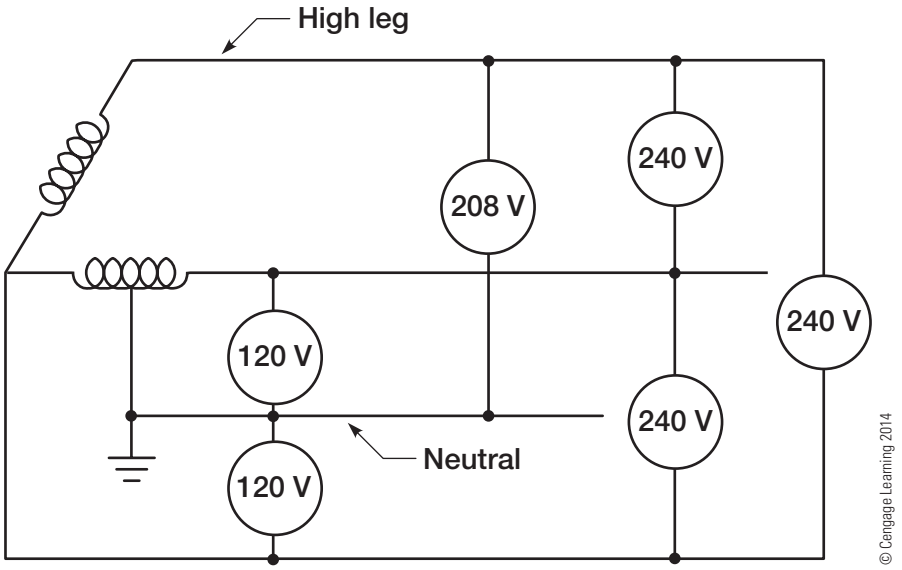


FIGURE 15-4 Voltages of a three-phase high-leg system.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

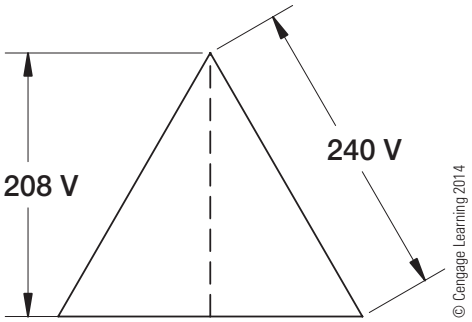


FIGURE 15-5 Vector diagram of a high-leg delta connection.

diagram illustrating how the high-leg voltage of a delta system is obtained is shown in FIGURE 15-5.

SINGLE-PHASE SERVICES

Single-phase services are derived from a single transformer with a center-tapped secondary winding, FIGURE 15-6. The center tap is grounded and becomes the neutral conductor. In this connection 240 V is available across the

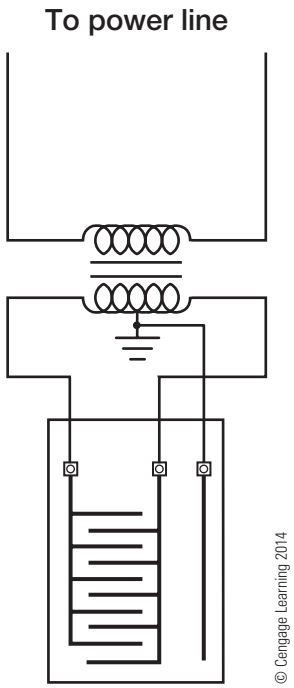


FIGURE 15-6 Single-phase service.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

secondary winding of the transformer, and 120 V is available from the center tap to either end of the secondary winding.

FUSES AND CIRCUIT BREAKERS

As a general rule, service technicians are not required to install an electrical service, but are sometimes required to make connection to an existing panel. These branch circuits are actually connected to a fuse or circuit breaker that protects the circuit against short circuits and excessive amounts of current. Fuses are devices that contain fusible links, which are metal alloy strips that are designed to melt at a predetermined amount of current flow. Fuses are connected in series with the load, FIGURE 15-7. If an excessive amount of current should flow, the link will melt and open the circuit. Single-phase circuits contain one fuse connected in series with the load as shown in Figure 15-7. Three-phase circuits will contain a fuse in each of the three lines, FIGURE 15-8.

Fuses are rated by amperage and voltage. The more current and voltage a fuse must interrupt, the larger it will be. Two fuses are shown in FIGURE 15-9. The smaller fuse has a rating of 250 V and the larger a rating of 600 V. Higher voltages require a greater distance between points to interrupt an arc.

time-delay fuses
fuses that provide some amount of time delay before opening.

Fuses are also rated other than by voltage and current. Some fuses are designed to delay for a period of time before they open. These fuses are often referred to as **time-delay fuses** or **slow-blow fuses.** They are generally used in motor circuits because they can give the motor an opportunity to start

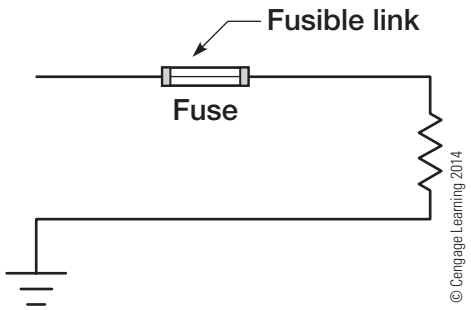


FIGURE 15-7 A single-phase circuit requires only one fuse in the ungrounded conductor.

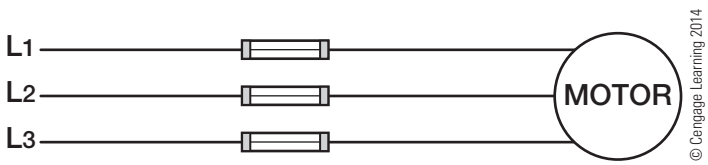


FIGURE 15-8 Three-phase circuits require a fuse in each of the three lines.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 15-9 Fuse size is determined by voltage and current rating.

before opening the circuit. Other types of fuses are designed to open immediately upon an overload. Some fuses have the ability to open so rapidly that they are referred to as **current limiters.** Current limiters actually open so fast that they limit the amount of current that can flow during a short circuit.

current limiters fuses that permit the current to rise to only a certain level before opening.

CIRCUIT BREAKERS

Another device used to limit the amount of current flow in a circuit is the circuit breaker. Circuit breakers are popular because they can be reset after tripping. There are two methods by which circuit breakers sense the amount of current flow, heat, and magnetism. Circuit breakers that operate by heat are known as **thermal circuit breakers.** They contain a small heating element that is connected in series with the load. As current flows through the load, the heating element begins to heat. The heating element is located near a bimetal strip, FIGURE 15-10. If the current becomes high enough the bimetal strip will warp enough to open the contacts and disconnect the load from the line, FIGURE 15-11. Thermal circuit breakers require a certain amount of time to operate because the bimetal strip must heat to a certain temperature before it will open the contacts. Therefore, thermal circuit breakers are often referred to as time-delay circuit breakers. The amount of time delay is proportional to the amount of overload. A large overload, such as a short circuit, will cause the circuit breaker to react very rapidly, while a small overload will permit the breaker to continue supplying current for a longer period of time. The schematic symbol for a thermal circuit breaker is shown in FIGURE 15-12.

thermal circuit breakers circuit breakers that are sensitive to heat.

Magnetic circuit breakers sense current by connecting a coil of large wire in series with the load, FIGURE 15-13. When current flows through the circuit, a magnetic field is developed around the wire. If the magnetic field becomes strong enough, it will pull in a solenoid and open the contacts

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

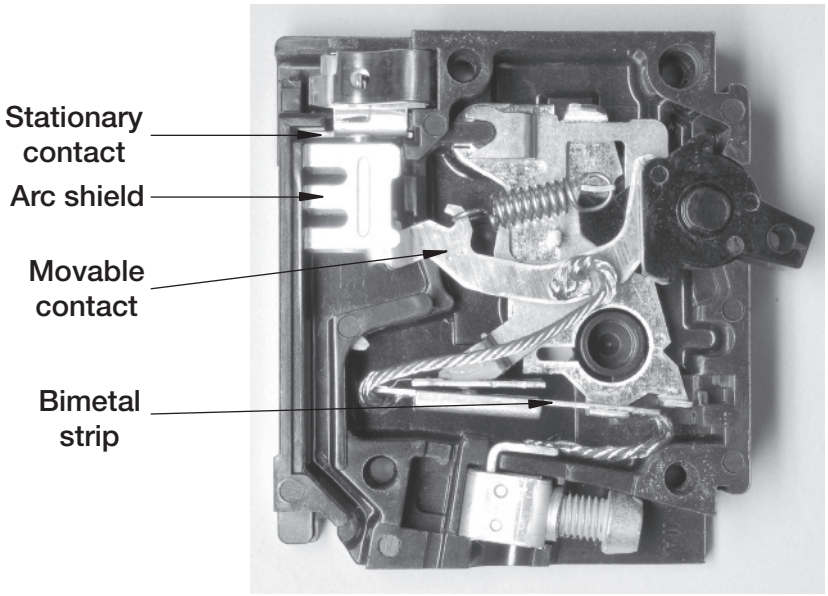


FIGURE 15-10 Single-pole thermal circuit breaker.

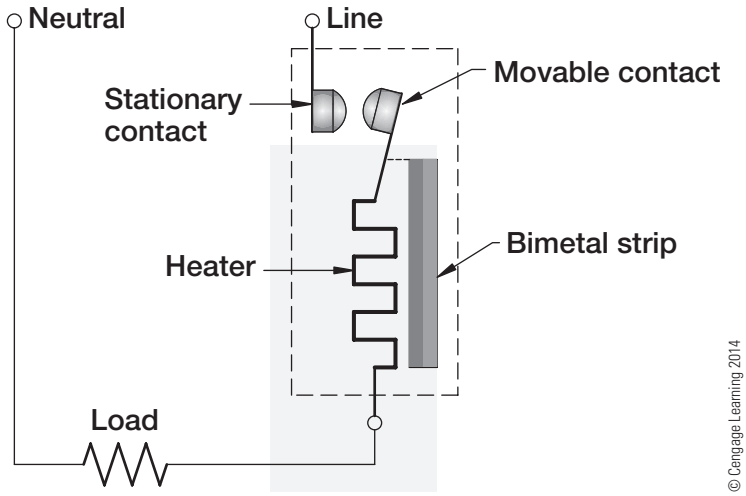


FIGURE 15-11 The thermal circuit breaker senses circuit current by inserting a heating element in series with the load.



FIGURE 15-12 Schematic symbol used to represent a single-pole thermal circuit breaker.

connected in series with the load, FIGURE 15-14. Magnetic circuit breakers are often referred to as instantaneous circuit breakers because there is almost no time delay upon opening when an overcurrent condition exists. The schematic symbol generally used to represent a magnetic circuit breaker is shown in FIGURE 15-15.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

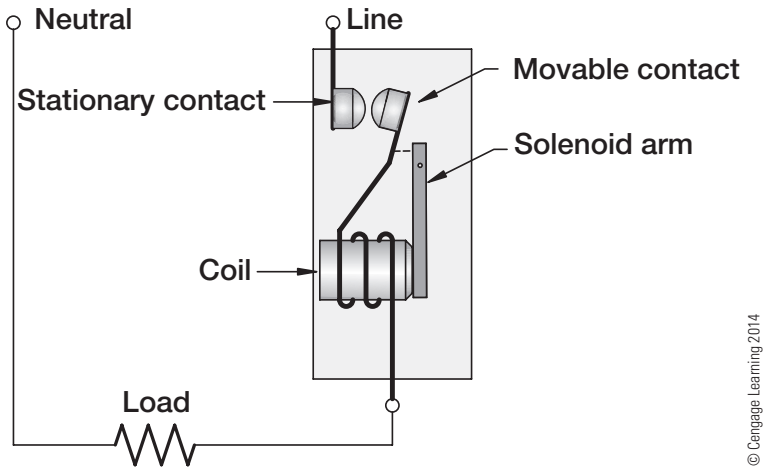


FIGURE 15-13 The magnetic circuit breaker senses circuit current by inserting a coil in series with the load.

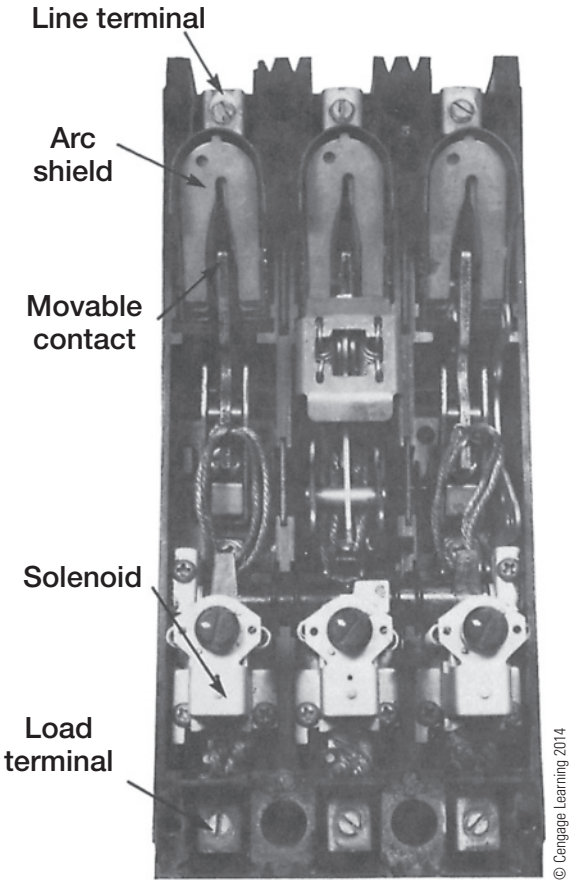


FIGURE 15-14 Internal construction of a three-pole magnetic circuit breaker.



FIGURE 15-15 Schematic symbol generally used to represent a magnetic circuit breaker.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

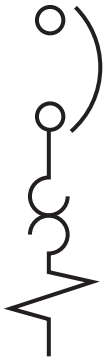

© Cengage Learning 2014

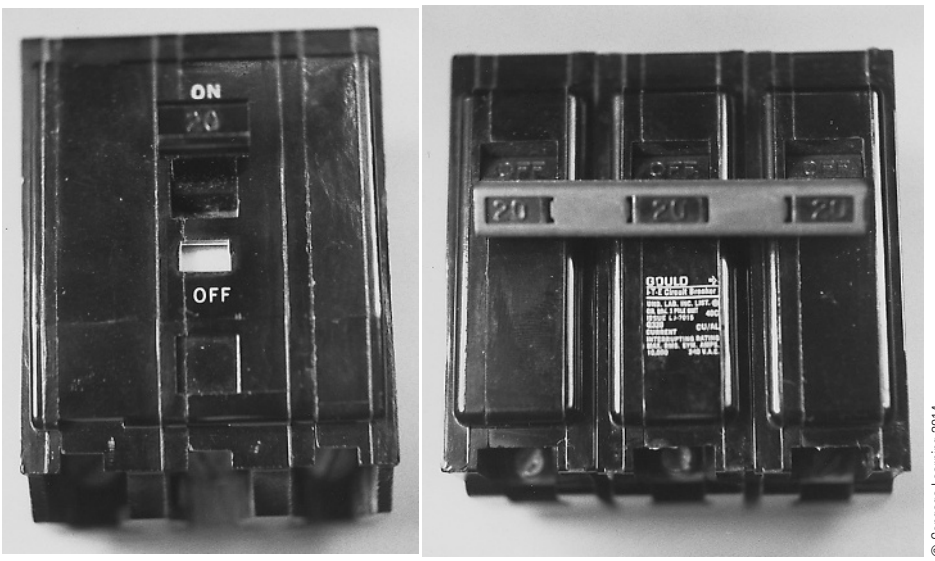
FIGURE 15-16
Schematic symbol generally used to represent a thermo-magnetic circuit breaker.

It should be noted that some circuit breakers are both thermal and magnetic. These circuit breakers contain both a heater element and bimetal strip, as well as a current-activated solenoid. The schematic symbol for this type of circuit breaker is shown in FIGURE 15-16.

CONNECTING BRANCH CIRCUITS TO THE PANEL

To connect a branch circuit to an electric panel several decisions must be made, such as the rating and type of circuit breaker to be installed and the size and type of wire to be used. The brand of circuit breaker to be purchased is generally determined by the type of panel that has been installed. Circuit breakers are not generic. Certain brands of circuit breakers are required to fit certain brands of panels.

The next decision is whether to purchase a three-pole circuit breaker, FIGURE 15-17, a double-pole circuit breaker, FIGURE 15-18, or a single-pole circuit breaker, FIGURE 15-19. Three-pole circuit breakers are used to connect three-phase circuits. When installing a three-phase three-wire branch circuit, one line of each phase is connected to a pole of the circuit breaker, FIGURE 15-20. If a three-phase four-wire branch circuit is to be installed, the three line conductors are connected to the poles of the circuit breaker and the fourth wire is connected to the neutral bus, FIGURE 15-21.



© Cengage Learning 2014

(A) **(B)**

FIGURE 15-17 Three-pole circuit breakers used to connect three-phase circuits.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

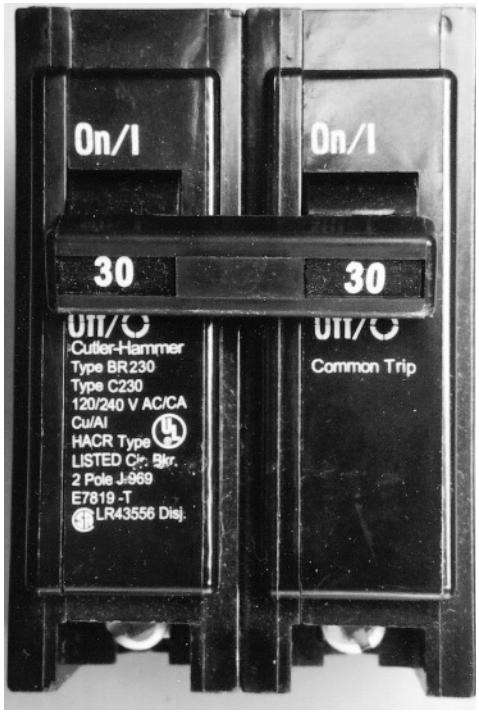


FIGURE 15-18 Double-pole circuit breaker used to connect 240-V single-phase circuits.



FIGURE 15-19 Single-phase circuit breaker used to connect 120-V single-phase circuits.

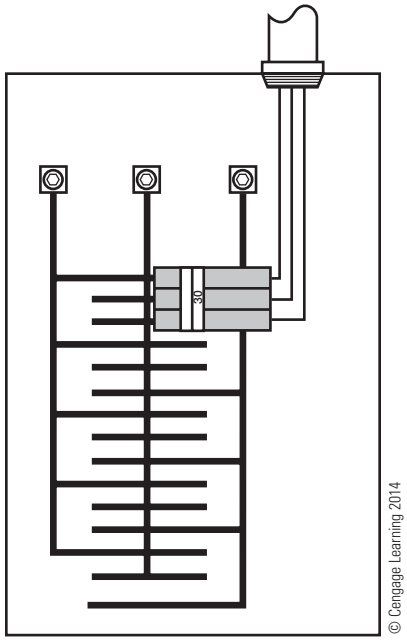


FIGURE 15-20 Three-phase three-wire connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

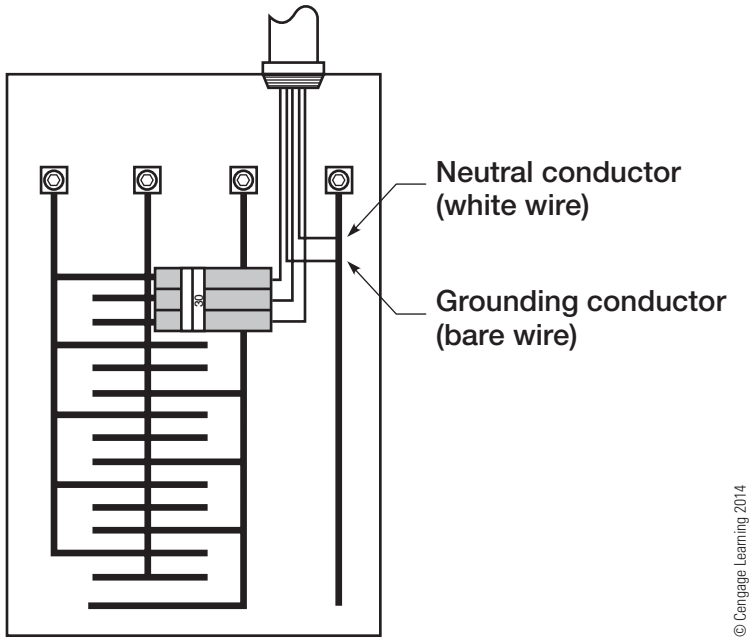


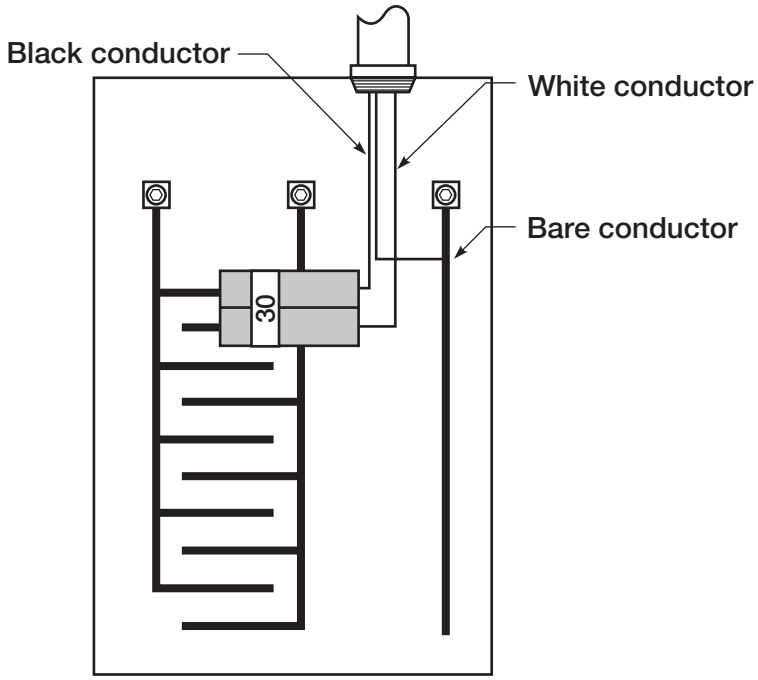
FIGURE 15-21 Three-phase four-wire connection.

A 240-V single-phase connection can be made in two ways. If the circuit does not contain a neutral conductor, as in the installation of a water heater or central heating or central air conditioning, the insulated wires of a two-conductor cable are connected to the poles of the circuit breaker, and the bare conductor is connected to the neutral bus, FIGURE 15-22 and FIGURE 15-23. When this connection is made, the white conductor must be re-identified by marking it with a piece of colored tape to indicate that it is no longer a neutral wire. The tape should be a color other than white, green, or gray, and the conductor should be marked at both the panel and at the point where it attaches to the equipment.

A 240-V single-phase connection with neutral is made using a three-conductor cable with ground. The black and red conductors are connected to the poles of the circuit breaker, and the white and bare conductors are connected to the neutral bus, FIGURE 15-24 and FIGURE 15-25. This type of branch circuit is used to operate equipment that operates on 240 V but also requires the use of a neutral conductor, as in clothes dryers and electric ranges.

A 120-V single-phase branch circuit is made by connecting the black wire of a two-conductor cable to a single-pole circuit breaker, and connecting the white and bare wires to the neutral bus, FIGURE 15-26 and FIGURE 15-27.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

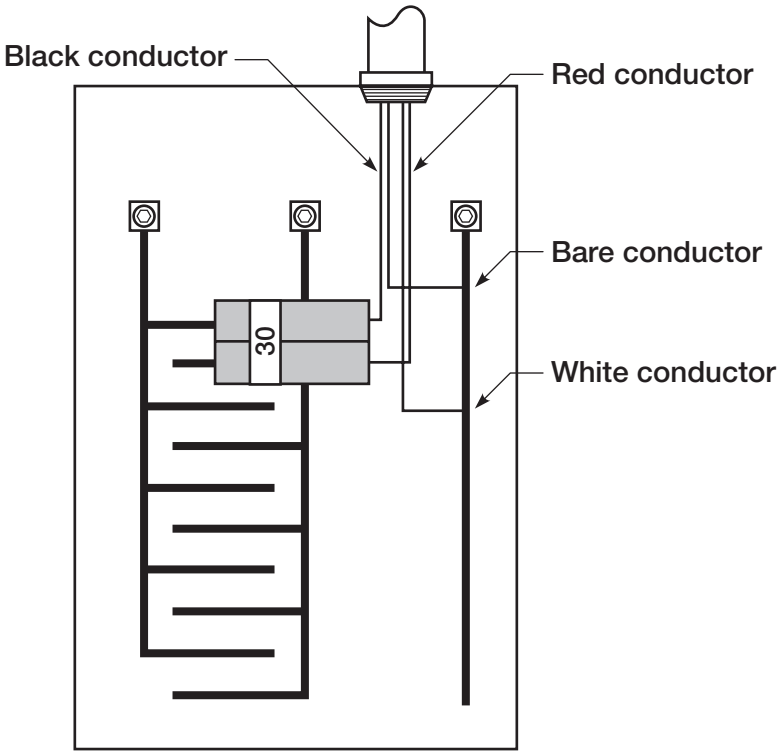
FIGURE 15-22 240-V single-phase circuit without neutral.



© Cengage Learning 2014

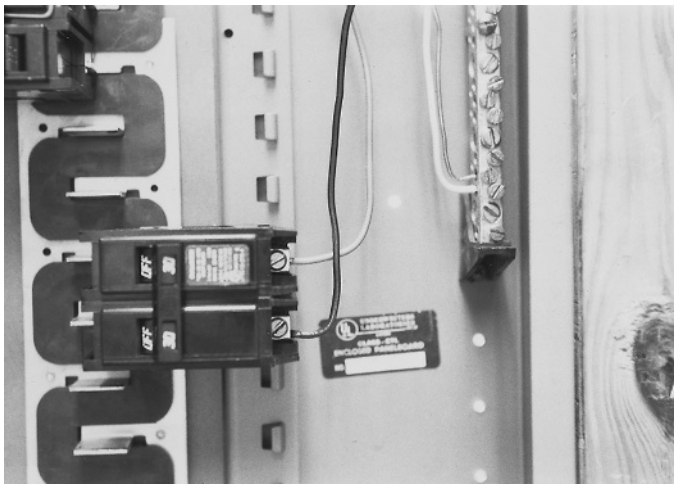
FIGURE 15-23 240-V single-phase connection with no neutral.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

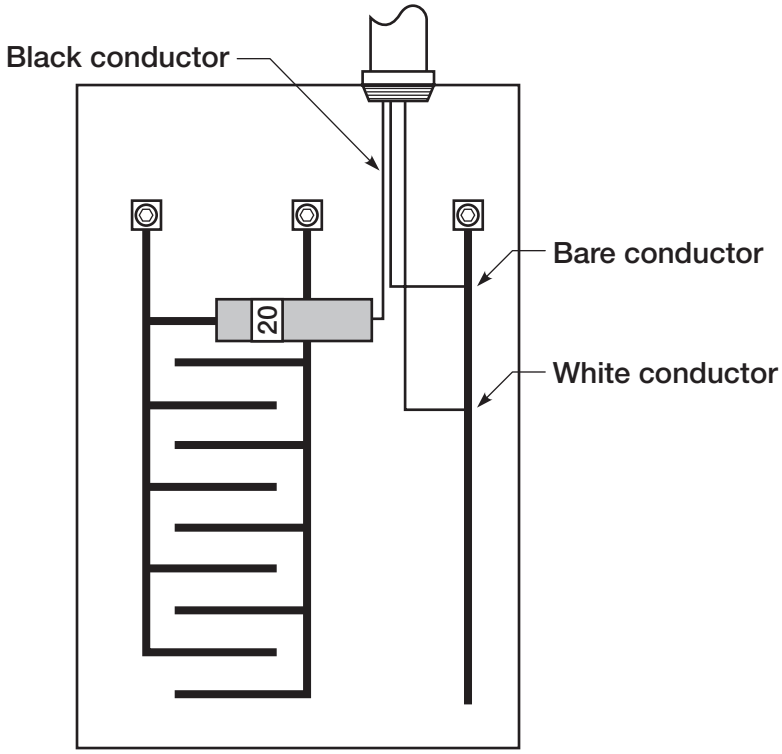
FIGURE 15-24 240-V single-phase circuit with neutral.



© Cengage Learning 2014

FIGURE 15-25 240-V single-phase connection with neutral.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 15-26 120-V single-phase circuit.



© Cengage Learning 2014

FIGURE 15-27 120-V single-phase connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

DUPLEX AND HALF-SIZE CIRCUIT BREAKERS

The circuit breakers illustrated so far in this unit are called full size or standard size. They are approximately one inch in width. Many circuit breaker panels are designed to employ half-size circuit breakers, FIGURE 15-28. Half-size circuit breakers are the same length as a standard-size breaker but approximately half the width. Half-size breakers permit the panel box to be smaller but contain the same number of circuit breakers as a panel that uses standard-size breakers. Double-pole, half-size breakers are available and are approximately the same size as a standard single-pole breaker, FIGURE 15-29. Duplex circuit breakers are also available from some manufacturers. Duplex breakers are basically two half-size breakers in one case, FIGURE 15-30. The only difference between a duplex circuit breaker and a double-pole breaker is that the duplex breaker does not have a connection bar between the switch levers of the two circuit breakers. This permits them to be turned on, off, or tripped individually.



© Cengage Learning 2014

FIGURE 15-28 Half-size circuit breaker.



© Cengage Learning 2014

FIGURE 15-29
Double-pole half-size circuit breaker.



© Cengage Learning 2014

FIGURE 15-30
Duplex circuit breaker.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Circuit breaker panels that employ half-size and duplex circuit breakers are constructed with a different type of bus. Half-size and duplex breakers are so constructed that they will not plug into a standard breaker box. Using duplex breakers in a standard circuit breaker box could cause the panel to become overloaded. Some panels designed to use duplex circuit breakers will permit the use of full-size breakers also. The buses in panels designed to permit the use of duplex breakers are generally shaped differently than panels with a straight bus, FIGURE 15-31. A panel intended for use with half-size circuit breakers is shown in FIGURE 15-32.

The material used to make the bus in a panel box can vary from one manufacturer to another or one model to another. Some contain a copper bus and

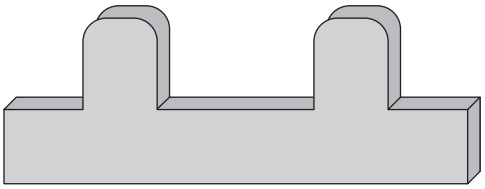

© Cengage Learning 2014

FIGURE 15-31 Panel bus intended to accept duplex circuit breaker.

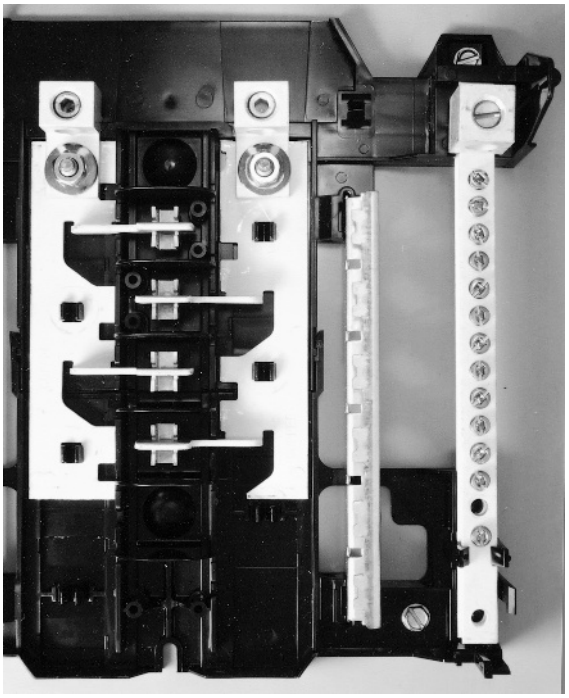

© Cengage Learning 2014

FIGURE 15-32 Panel bus designed for half-size circuit breakers.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

others may contain a bus made of cadmium-plated copper. A cadmium-plated copper bus looks very similar to an aluminum bus, but it is more corrosion resistant. Some circuit breaker panels do contain an aluminum bus. When aluminum is used for the bus material, an antioxidant compound, FIGURE 15-33, should be used to prevent corrosion.

In the 1960s, the *National Electrical Code*® permitted the use of solid aluminum conductors for 15- and 20-A circuits in residential construction. The *National Electrical Code*® was later modified to prevent the practice. The reason for the modification was the number of electrical fires that resulted from the use of aluminum conductors in #12 and #10 AWG sizes. The fires were not caused by the fact that aluminum is not as good of a conductor as copper, but because the aluminum conductor would cold flow away from a pressure connection. If an aluminum wire was placed under a screw connection, the pressure of the screw would cause the aluminum to cold flow and produce a poor connection. A round conductor would eventually appear to be flattened out as shown in FIGURE 15-34. The *National Electrical Code*® now permits aluminum conductors in sizes #8, #10, and #12 AWG to be used, provided they are made of type AA-8000 series electrical-grade aluminum alloy. The alloy is not as malleable as the older, pure aluminum conductors.



© Cengage Learning 2014

FIGURE 15-33 Anti-oxidant compound should be used on aluminum bus.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

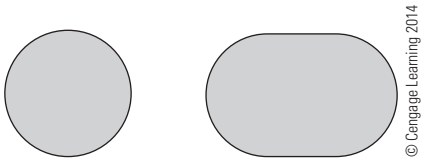


FIGURE 15-34 Round conductors eventually flatten out due to pressure.

CONDUCTOR SIZE

When installing a branch circuit consider the size and type of wire to be used. The wire size is determined by the ampere rating of the circuit. The copper wire size generally used for most common branch circuits is shown in TABLE 15-1.

Although the wire sizes listed in Table 15-1 are generally used for residential and commercial branch circuits, it may be necessary to select conductors for branch circuits that have a larger ampere rating. This is especially true when working in an industrial environment. The ampere ratings and wire sizes listed in TABLE 15-2 are a composite of values listed in the *National Electrical Code*® for not more than three-conductors in a raceway or cable or for direct burial. Although some of the insulation types listed at the top of columns A and B permit the conductors to be operated at a higher temperature, and therefore carry more current, termination temperature limitations listed in the *National Electrical Code*® hold the ampere ratings to those listed in Table 15-2.

The table lists ampere ratings for both copper and aluminum wire. The table is divided into columns A and B. Insulation types are listed at the top of each column. Column A, for example, lists only types TW and UF. Conductor sizes should be chosen using the ampere ratings listed in column A for circuits that are rated less than 100 A, and from column B for circuits rated at 100 A or more. The only exception to this rule is if the insulation type is TW or UF, in which case column A will be used for all ampere values.

BRANCH CIRCUIT (AMPERES)	AMERICAN WIRE GAUGE SIZE
15	#14 AWG
20	#12 AWG
30	#10 AWG
40	#8 AWG
50	#6 AWG
60	#4 AWG

© Cengage Learning 2014

TABLE 15-1 Copper wire sizes for common ampere rating.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

AWG or Kcmil	Copper Wire Amperes TW, UF (A)	Copper Wire Amperes FEPW, RH, RHW, THHW, THW, THWN, XHHW, USE, ZW, V, TA, TBS, SA, SIS, FEP, FEPB, RHH, THHN, THHW, XHHW (B)	Aluminum Wire Amperes TW, UF (A)	Aluminum Wire Amperes FEPW, RH, RHW, THHW, THW, THWN, XHHW, USE, ZW, V, TA, TBS, SA, SIS, FEP, FEPB, RHH, THHN, THHW, XHHW (B)
14 AWG	20	20	—	—
12 AWG	25	25	20	20
10 AWG	30	35	25	30
8 AWG	40	50	30	40
6 AWG	55	65	40	50
4 AWG	70	85	55	65
3 AWG	85	100	65	75
2 AWG	95	115	75	90
1 AWG	110	130	85	100
1/0 AWG	125	150	100	120
2/0 AWG	145	175	115	135
3/0 AWG	165	200	130	155
4/0 AWG	195	230	150	180
250 kcmil	215	255	170	205
300 kcmil	240	285	190	230
350 kcmil	260	310	210	250
400 kcmil	280	335	225	270
500 kcmil	320	380	260	310
600 kcmil	355	420	285	340
700 kcmil	385	460	310	375
750 kcmil	400	475	320	385
800 kcmil	410	490	330	395
900 kcmil	435	520	355	425
1,000 kcmil	455	545	375	445
1,250 kcmil	495	590	405	485
1,500 kcmil	520	625	435	520
1,750 kcmil	545	650	455	545
2,000 kcmil	560	665	470	560

© Cengage Learning 2014

TABLE 15-2 Ampere ratings for not more than three-conductors in a raceway or cable or for direct burial (Column A to be used for values less than 100 A and column B to be used for current values of 100 A or greater).

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 1: Assume a branch circuit rated at 90 A is to be installed using copper wire with type THW insulation. What size conductor should be used for this installation?

Solution:
Since the ampere rating is less than 100 A, column A will be used. The nearest current value listed without going under 90 A is 95. A #2 AWG copper conductor will be used for this installation.

EXAMPLE 2: A branch circuit rated at 150 A is to be installed using aluminum wire with type THHW insulation. What size conductor should be used for this installation?

Solution:
Column B of aluminum wire amperes will be used because the circuit rating is greater than 100 A. The nearest current value listed without going under 150 A is 155. This corresponds to a #3/0 AWG conductor.

EXAMPLE 3: A 200-A branch circuit is to be run underground using copper wire with type UF insulation. What size conductor should be used?

Solution:
Although the ampere rating is greater than 100 A, the insulation type is UF. Therefore, column A will be used to make the selection. The closest ampere rating without going under 200 is 215. A 250-Kcmil conductor will be used.

GROUNDING

transient
currents from other power sources.

In any service installation one of the most important considerations is the system ground. Proper grounding helps protect against **transient** currents, electrical noise, and lightning strikes. Several methods can be used to test the electrical grounding system. The effectiveness of the grounding system greatly depends on the resistivity of the earth at the location of the system ground. The resistivity of the earth varies greatly throughout the world and even within small areas. Many factors affect the earth's resistivity such as soil type (clay, shell, sand, etc.), moisture content, electrolyte content (acids, salts, etc.), and temperature.

In theory, the system ground is considered to have a resistance of zero because it is connected to system grounds everywhere, via the neutral conductor,

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

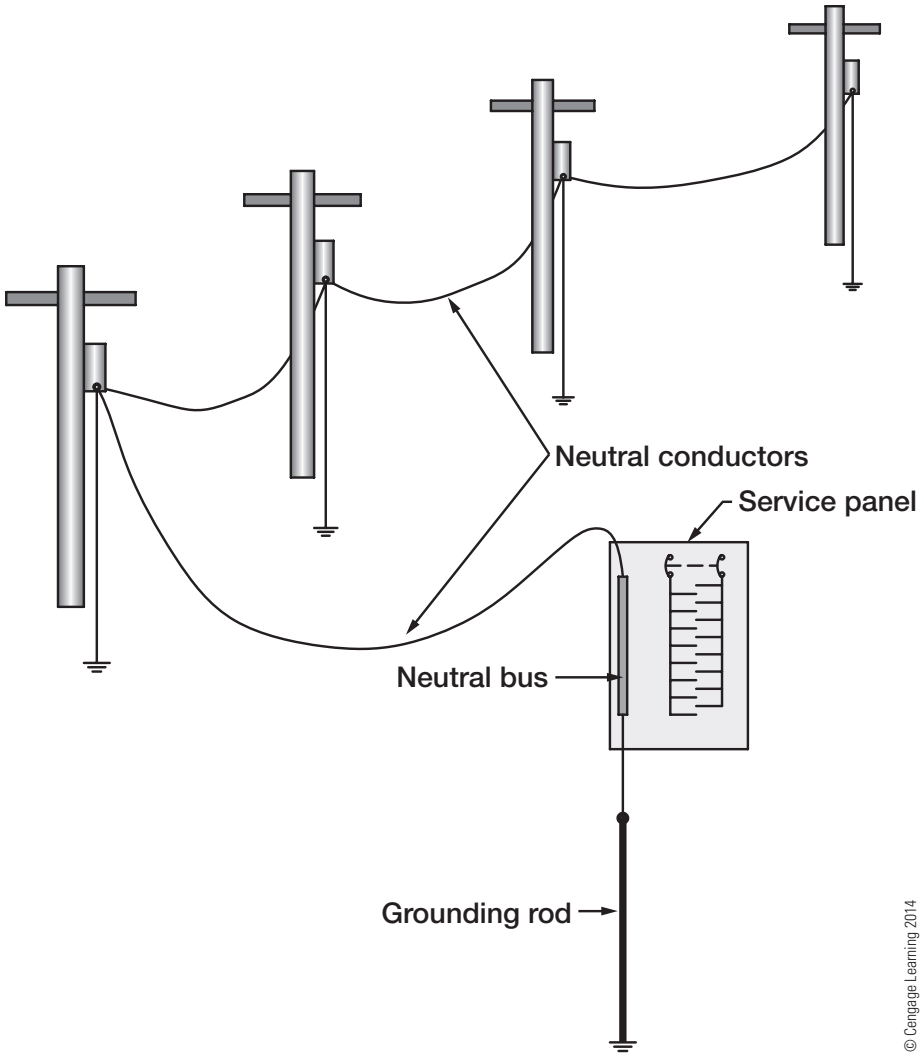


FIGURE 15-35 All neutral conductors are bonded together forming a continuous grounding system.

FIGURE 15-35. In actual practice, however, the current carrying capacity of the grounding system can vary greatly from one area to another.

TESTING

There are different methods for determining the resistivity of the grounding system. An old method used by electricians for many years is to connect a 100 W lamp between the ungrounded (hot) conductor and the grounding conductor, FIGURE 15-36. To perform this test, the grounding conductor must

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

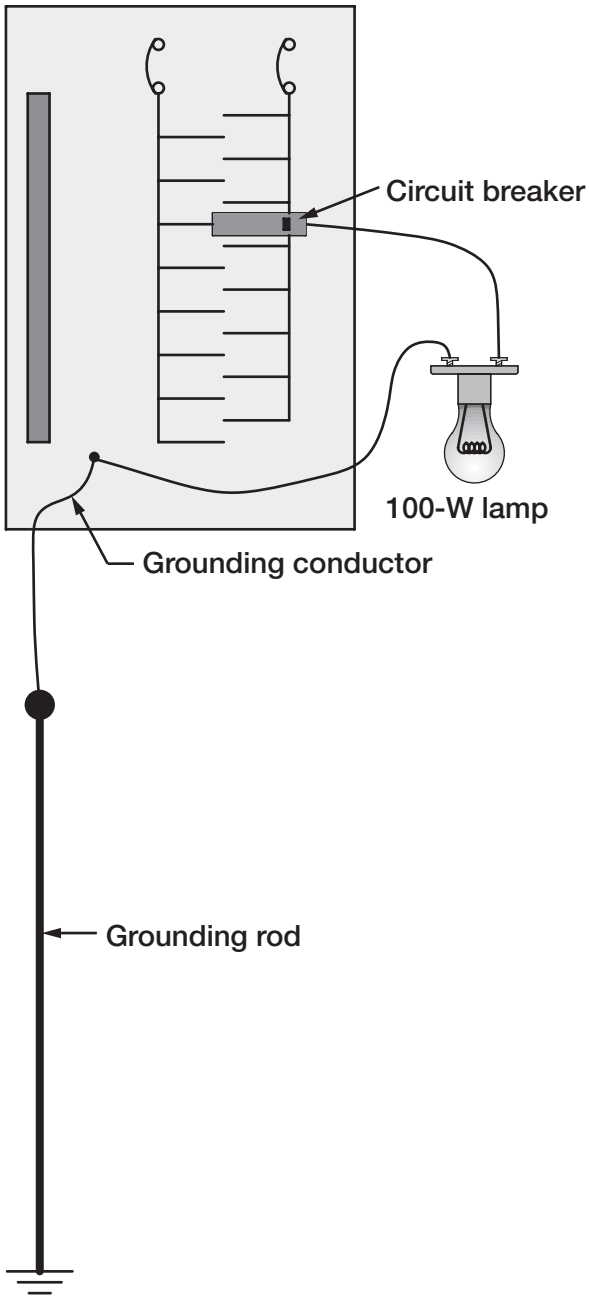


FIGURE 15-36 A 100 W lamp is used to test the grounding system.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

be disconnected from the neutral bus in the panel. The brightness of the lamp gives an indication of the effectiveness of the grounding system. Although this test gives an indication that the grounding system either works or not, it does not give any indication of the actual resistance of the system. To measure the actual resistance of the grounding system requires the use of special equipment such as a ground resistance tester, FIGURE 15-37. There are three main tests used to measure ground resistance, the **Wenner four-point test, The three-point fall-of-potential test,** and **the clamp-on ground resistance test.**

KEY POINT
Wenner four-point test, three-point fall-of-potential test, and clamp-on ground resistance test

THE WENNER FOUR-POINT METHOD

The Wenner four-point test is generally performed before building construction begins. This method measures the ground resistance over a wide



Courtesy AEMC® Instruments

FIGURE 15-37 Ground resistance tester.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

area. The results are used in designing the grounding system to ensure that it performs properly. This test requires the use of a four-pole ground resistance meter, four metal rods, and conductors. The four rods are driven into the ground in a straight line, with equal space between each rod, FIGURE 15-38. To perform this test, the ground resistance tester produces a known amount of current between rods C1 and C2, producing a voltage drop across rods P1 and P2. The amount of voltage drop is proportional to the amount of current and ground resistance. Readings are generally taken with probes C1 and C2 spaced 5, 10, 15, 20, 30, 40, 60, 80, and 100 feet apart. If possible, it is recommended that the test be performed with the probes spaces 150 feet apart.

The calculated soil resistance is the average of the soil resistance from the surface to a depth equal to the space between the probes. If the probes are set 30 feet apart, for example, each probe will provide an average resistance measurement from the surface to a depth of 30 feet. The tests should be made

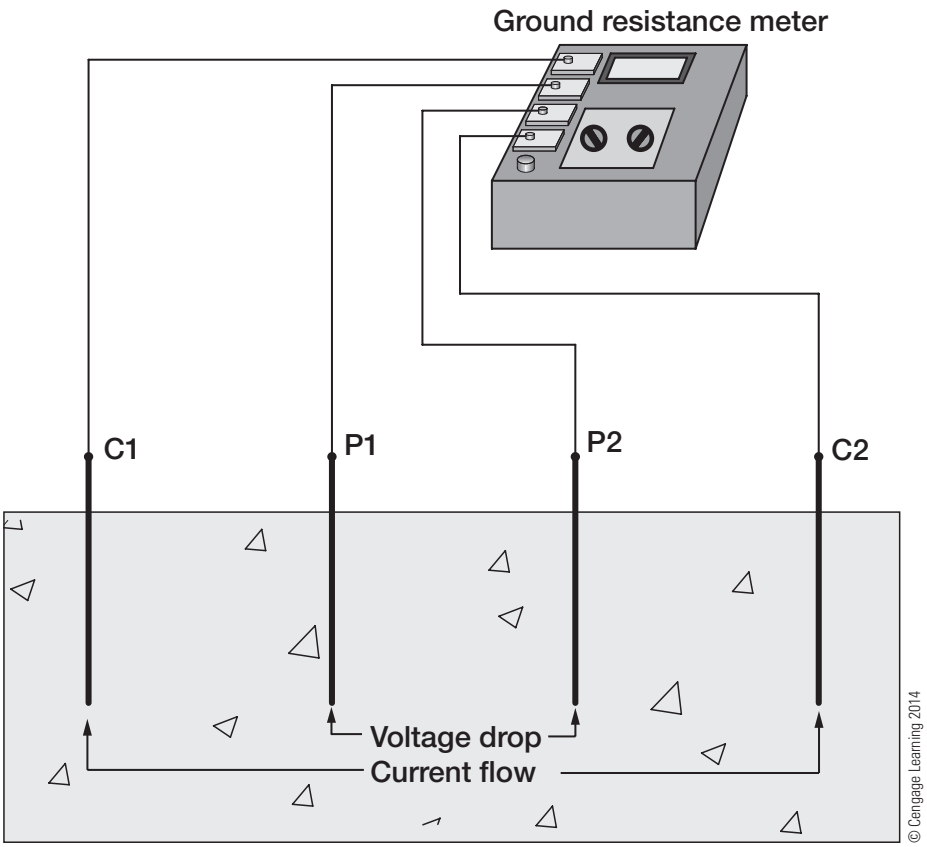


FIGURE 15-38 The Wenner four-point method for testing ground resistance.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

not only with the probes spaced different distances apart, but also with the probes in different directions from a central point. If the site is large enough, it is generally recommended that the test be performed along at least two sides, generally from one corner to the other. It should be noted that underground structures such as metal water pipes can influence the readings. The best results will be obtained by gathering as much data as possible.

THREE-POINT FALL-OF-POTENTIAL TEST

The fall-of-potential test requires the use of a ground resistance meter. It is performed after the installation of the grounding system and should be done annually to assure the quality of the grounding system. Annual testing provides protection against the degradation of the system before damage to equipment and performance problems occur.

In the three-point fall-of-potential test the three points of ground contact are as follows:

1. The system ground (grounding rod) (point A)
2. A current probe placed some distance from the grounding rod (point B)
3. A voltage probe that is inserted at various distances between the grounding rod and the current probe (point C). The voltage probe is placed in a straight line between the grounding rod and the current probe

Ideally, the current probe (B) should be placed at a distance that is at least 10 times the length of the grounding rod (A), FIGURE 15-39. If the grounding rod is 8 feet in length, the current probe should be placed at least 80 feet from the grounding rod.

To perform this test, the grounding rod must be disconnected (electrically isolated) from the neutral bus in the service panel. Failure to do so will completely invalidate the test. The meter provides a known amount of current that flows from the current probe and back to the meter through the system grounding rod. The resistance of the earth causes a voltage drop that is measured between the current probe and the voltage probe. The amount of voltage drop is proportional to the amount of current flow and the ground resistance. Resistance readings should be taken at several locations by moving the voltage probe a distance of that equal to 10% of the distance between the system grounding rod and the current probe. If performed properly, the three-point ground resistance test is the most accurate method of determining ground resistance.

THE CLAMP-ON GROUND RESISTANCE TEST

The clamp-on ground resistance test requires the use of a special clamp-on ground resistance meter. This test has several advantages over the three-point fall-of-potential test.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

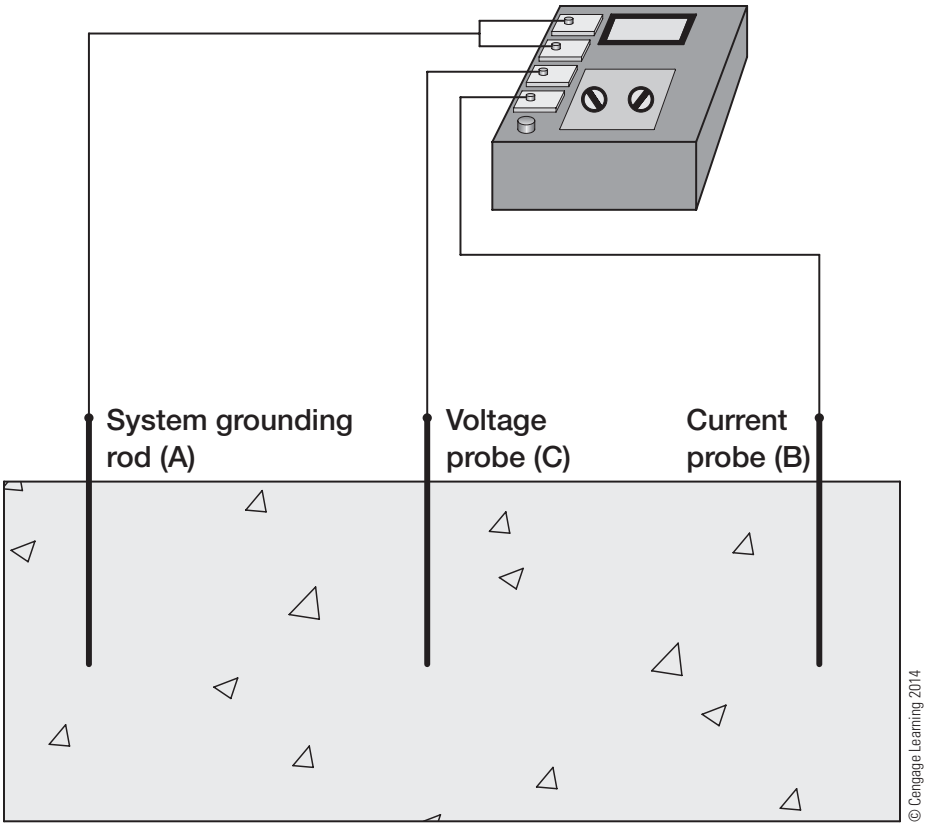


FIGURE 15-39 The three-point fall-of-potential test.

1. The service grounding system does not have to be disconnected and isolated from the neutral bus.
2. There are no probes that have to be driven into the ground or long connecting conductors.
3. The neutral conductor supplied by the utility company ties innumerable grounds together in parallel. The clamp-on ground tester measures the effective resistance of the entire grounding system.
4. Since this test is performed by a clamp-on meter, there are no connections that have to be broken or reconnected, resulting in a safer procedure, FIGURE 15-40.

The clamp-on ground resistance tester, FIGURE 15-41, contains two transformers. One transformer induces a small fixed voltage at

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

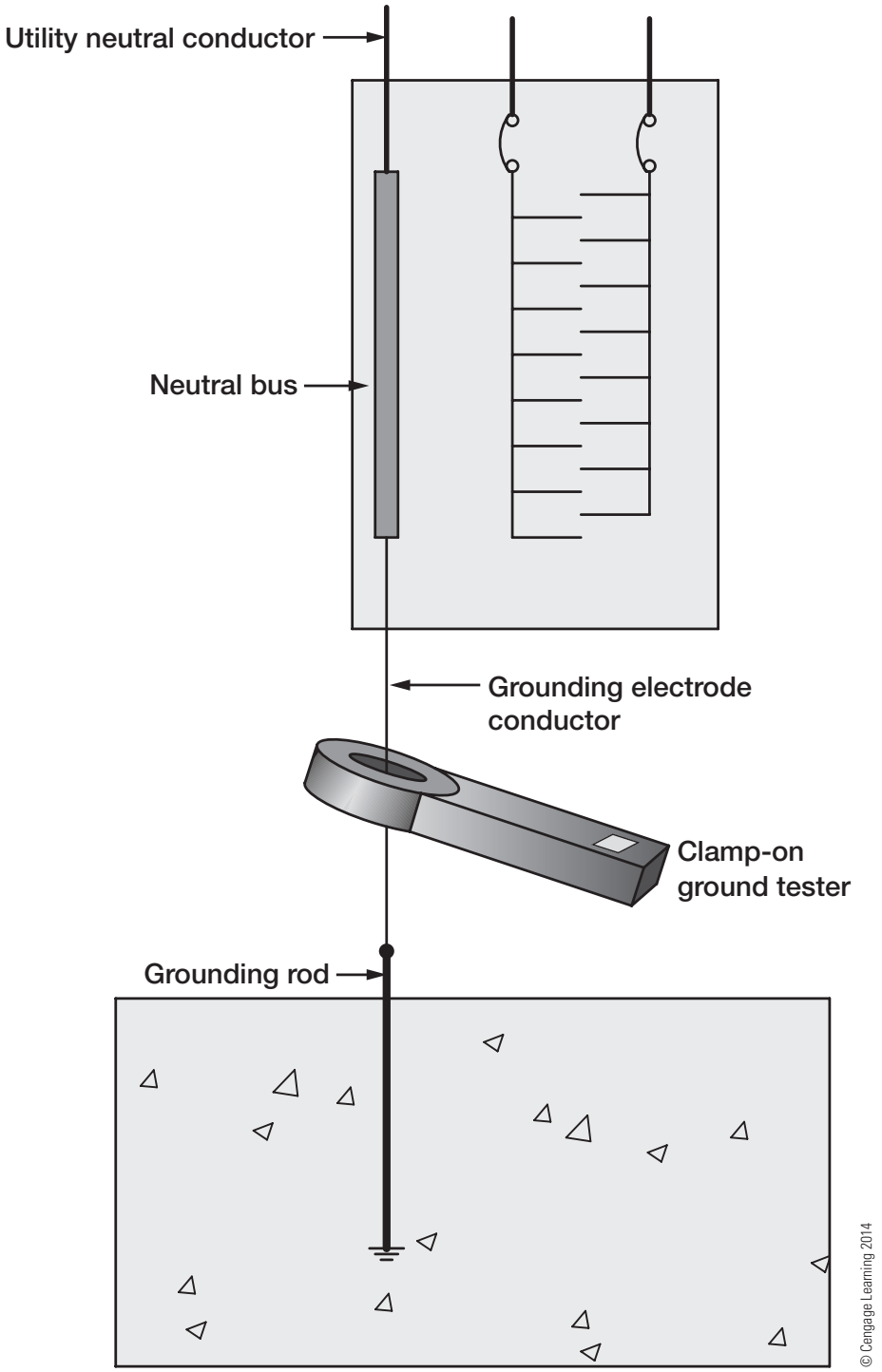


FIGURE 15-40 The clamp-on ground tester clamps around the grounding electrode conductor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

approximately 2 kHz on the grounding conductor. If a path exists, the voltage will result in a current flow. The path is provided by the grounding system under test, the utility neutral, and the utility grounding system. The second transformer inside the meter senses the amount of current at the unique frequency provided by the first transformer. The amount of current is proportional to the induced voltage and the resistance of the grounding system. The meter uses the two known electrical quantities to calculate the resistance of the grounding system.



Courtesy AEMC® Instruments

FIGURE 15-41 Clamp-on ground resistance tester.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Summary

1. The heart of any electrical system is the service or panel.
2. Large commercial and industrial locations are generally supplied with three-phase power.
3. Light commercial and residential locations are generally supplied with single-phase power.
4. Three basic types of three-phase service are:

   A. three-phase three-wire;
   B. three-phase four-wire with grounded neutral (no high leg); and
   C. three-phase four-wire with neutral and a high leg.
5. Common voltage values for a three-phase three-wire system are 240, 440, 480, and 560.
6. Common voltage values for a three-phase four-wire wye connected system with a grounded neutral are 480/277 and 208/120.
7. The open delta connection is often used because it requires the use of only two transformers to supply three-phase power.
8. The three-phase four-wire high-leg system generally provides 240 V between line conductors and 120 V between two of the line conductors and neutral.
9. Fuses and circuit breakers are used to protect the circuit against short circuits and excessive amounts of current.
10. Fuses protect the circuit by melting a metal alloy link and opening the circuit.
11. Fuses and circuit breakers are connected in series with the load.
12. The size of a fuse is determined by the ampere and voltage rating.
13. Two basic types of circuit breakers are thermal and magnetic.
14. Thermal circuit breakers sense circuit current by inserting a heating element in series with the load.
15. Magnetic circuit breakers sense circuit current by inserting a current-operated solenoid in series with the load.
16. Magnetic circuit breakers operate much faster than thermal circuit breakers.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

17. The wire size used to supply power to a branch circuit is determined by the ampere rating of the circuit.
18. The grounding system helps to guard against electrical noise, transient currents, and lightning strikes.
19. The three most common methods of determining ground resistance are the Wenner four-point test, the three-point fall-of-potential test, and the clamp-on ground resistance test.

Review Questions

1. An electrical service in a small commercial location is a three-phase four-wire system with a high leg. The voltage between the neutral conductor and two of the lines is 120 V. What will be the voltage between the neutral conductor and the high leg?
2. How does a fuse protect a circuit against short circuits?
3. What is used to sense current flow in a thermal circuit breaker?
4. What is used to sense current flow in a magnetic circuit breaker?
5. What is a current limiter?
6. In a thermal-type circuit breaker, what is used to actually cause the contacts to open and disconnect the load from the circuit?
7. When making a 240-V two-wire connection to a circuit breaker panel, what should be done to the white conductor?
8. Name two 240-V single-phase household appliances that require a neutral conductor.
9. What size copper conductor is generally used to supply power for a 240-V, 30-A circuit?
10. What size copper conductor is generally used to supply power for a 120-V, 30-A circuit?
11. An electric range is to be connected to a 50-A circuit breaker. What size copper conductor should be used to make this connection?
12. A 150-A branch circuit is to be connected to a service panel. The branch circuit conductor is aluminum with type-THHW insulation. What size conductors should be used?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

13. Assume that the circuit described in question 12 is to be connected with a copper conductor instead of aluminum. What size conductor should be used?
14. A 200-A branch circuit is to be connected to an electrical panel. The conductors are copper with type-TW insulation. What size conductors should be used?
15. A service technician has a roll of #8 AWG UF cable. Can this cable be used to supply a 240-V, 30-A branch circuit?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 16

General Wiring Practices Part 1—Receptacle and Switch Connections

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the types of cable used in most residential installations.
- Connect duplex receptacles.
- Connect single-pole switch circuits.
- List rules for connecting three-way switches.
- Make three-way switch connections.
- Make four-way switch connections.

This unit will present general wiring practices. Many times a service or maintenance technician needs to make general switch connections or connect a piece of equipment or an appliance to an electric service. It will be assumed that the connection is made with nonmetallic (NM) cable because nonmetallic cable is commonly used in residential applications. The same connection procedures would apply, however, if the conductors were run in conduit.

CABLES

In a residential occupancy, most circuits are connected with two- or three-conductor cable. A two-conductor cable actually contains three wires, a black, a white, and a bare, FIGURE 16-1. This cable is actually referred to as

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

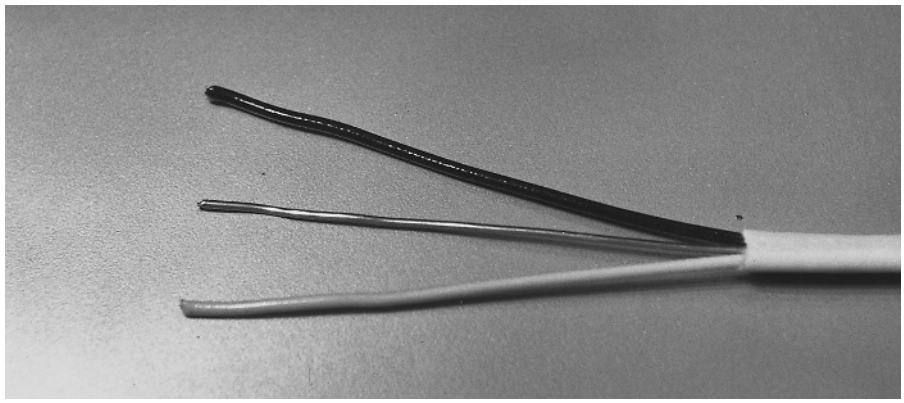

© Cengage Learning 2014

FIGURE 16-1 Two-conductor cable.

two-conductor with ground. It is called *two-conductor* because the only two wires used as part of the circuit are the black and the white. The third wire is a grounding wire and is never intended to be used as part of the actual circuit. The bare wire is connected to the green screw of a receptacle or the case of an appliance at one end, and to the neutral bus in the main service panel at the other. Grounding conductors are intended to provide a low path to ground in the event that the case of an appliance or device should come in contact with the ungrounded or hot conductor. Grounding conductors are there for safety reasons and not intended to be used as part of the circuit.

The three-conductor cable contains four wires, a black, a white, a red, and a bare, FIGURE 16-2. This cable is referred to as *three-conductor with ground.* As with two-conductor cable, only three of the wires are to be used as circuit

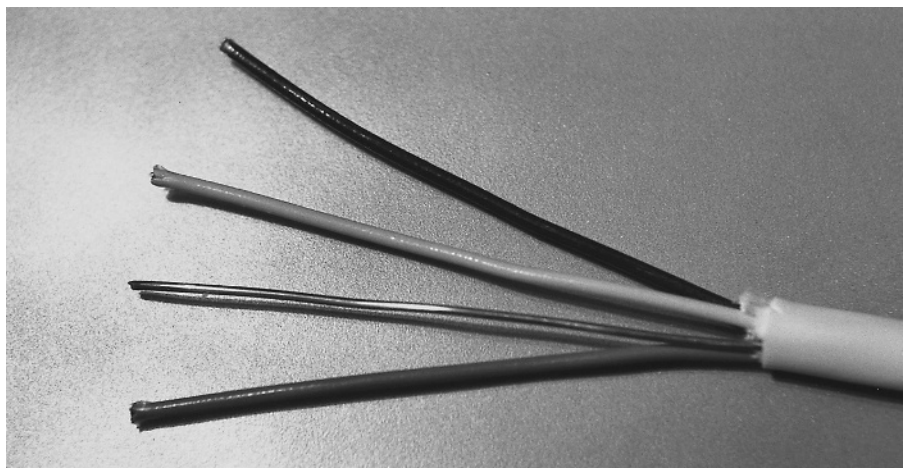

© Cengage Learning 2014

FIGURE 16-2 Three-conductor cable.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

conductors: the black, the white, and the red. The bare wire is the grounding conductor.

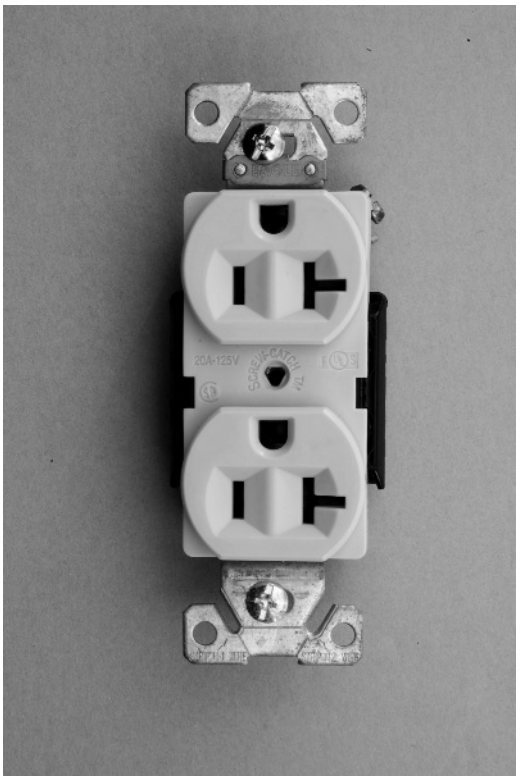
Although most circuits are connected using two- or three-conductor cable, there may be instances where a four-conductor cable may be necessary. The 2011 *National Electrical Code*® requires that a neutral or grounded conductor be present at any switch location, (*NEC* 404.2(C)). The reason is to provided a grounded conductor to operate electronic switching devices such as motion detectors or occupant sensors. The conductor colors for four conductor cable are generally black, white, red, and blue circuit conductors plus a bare grounding conductor.

RECEPTACLES

Receptacles, or outlets, are used throughout a building for the connection of 120-V AC appliances. Most of these receptacles are **duplex receptacles,** which means that they contain two outlets on the same strap, FIGURE 16-3. Notice that each of the two outlets contains three openings to permit the

receptacles
outlets for electrical power.

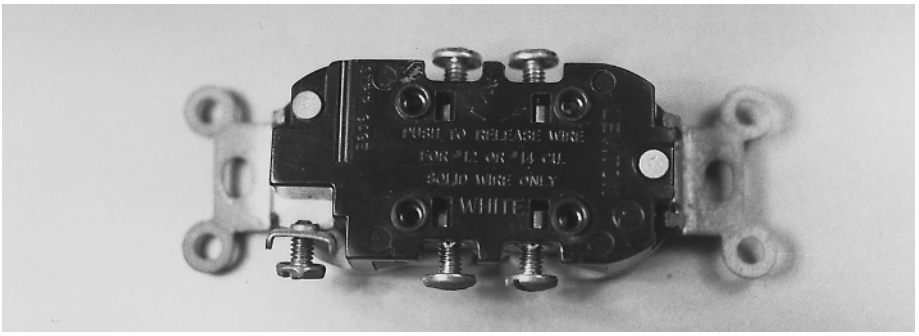
duplex receptacles
two outlets on the same strap.



© Cengage Learning 2014

FIGURE 16-3 Duplex receptacle.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 16-4 Stab-locks or quick-connects are located on the back of some receptacles.

attachment of a male plug. Two of the openings are rectangular in shape and the third is similar to a semicircle. The smaller of the two rectangular openings is connected to the hot, or ungrounded, conductor. In a two-conductor circuit this opening will be connected to the black conductor via the gold screws located on the side of the outlet.

The larger rectangular opening is connected to the neutral, or grounded, conductor. In a two-conductor circuit, this opening is connected to the white conductor via the silver screws. The semicircular opening is connected to the grounding, or bare, conductor via the green screw.

Many duplex receptacles contain a second method of making connection to the circuit conductors, FIGURE 16-4. Small, round holes located on the back of some receptacles can be used to make a connection to circuit conductors by removing about 3/4 inch of insulation from the conductor and inserting the bare wire into the hole. These connectors are generally referred to as **stab-locks** or **quick-connects,** and the advantage to using them is speed. Connection to the receptacle can be made by simply stripping about 3/4 inch of wire and inserting it into the proper hole. The disadvantage is contact resistance. Stab-locks make connection to the conductor with a piece of spring copper when the conductor is inserted into the hole. The spring copper is designed to bite into the copper wire and prevent it from slipping out, FIGURE 16-5. The only contact made with the conductor is the surface area of the spring copper holding the conductor against a small metal plate. Although the stab-lock connector provides the fastest method of making connection to the circuit conductors, it does not provide as good an electrical connection as bending a loop in the wire and tightening it under a screw. It should be noted that the primary cause of electrical fires is a poor connection.

stab-locks
a type of connection to outlets and switches.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

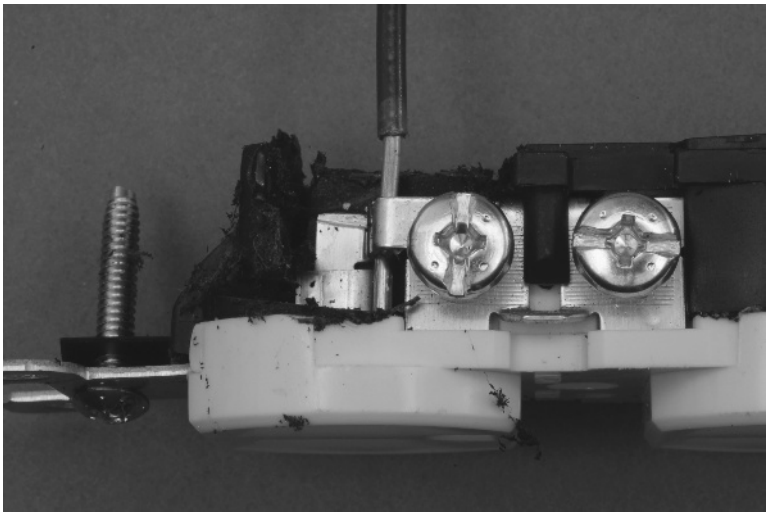

© Cengage Learning 2014

FIGURE 16-5 Stab-lock connectors make a relatively poor connection.

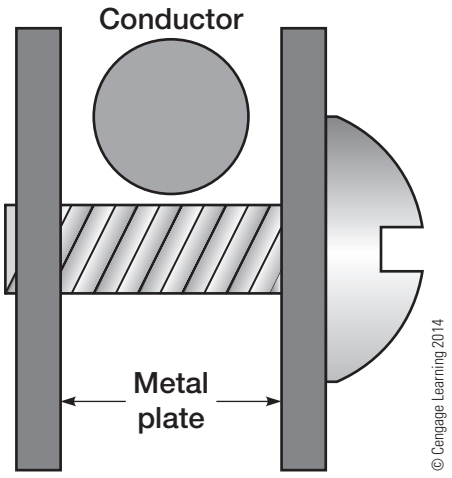


FIGURE 16-6 The conductor is sandwiched between two metal plates.

Another type connection that looks similar to a quick-connect or stab-lock employs a screw to tighten the conductor between two metal plates, FIGURE 16-6. Sandwiching the conductor between the two metal plates provides an excellent connection.

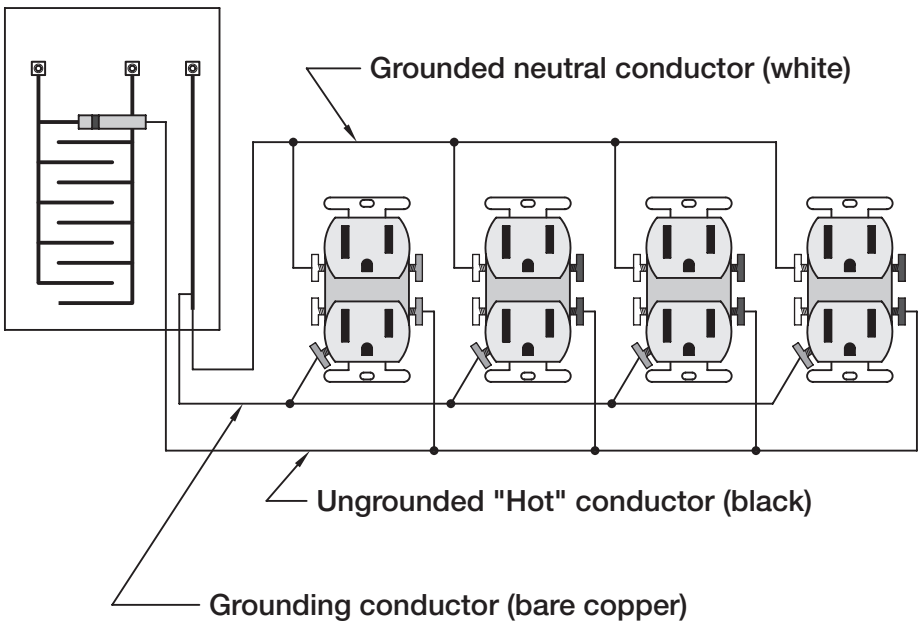
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CONNECTING RECEPTACLES

Receptacles or outlets are generally connected to a 15- or 20-A branch circuit. If a 15-A branch circuit is employed #14 AWG copper wire should be used. However, if a 20-A branch circuit is employed #12 AWG copper wire should be used. As a general rule, receptacle circuits are connected to a 20-A branch circuit and lighting circuits are connected to a 15-A branch circuit.

Receptacles are connected in parallel so that each is supplied with the same voltage, FIGURE 16-7. The ungrounded, or hot, conductor is connected to the gold screw; the grounded, or neutral, conductor is connected to the silver screw; and the grounding, or bare copper, conductor is connected to the green screw.

When outlets are installed, two-conductor cable is used to make connection from one outlet to another, FIGURE 16-8. The black wires are connected to the two gold screws, the white wires are connected to the silver screws, and the bare conductors are connected to the green screw(s). If the outlet contains only one green screw, grounding conductors must be connected together because it is not permissible to place more than one wire under a screw. When this is the case, it is common practice to connect all the grounding conductors together and cut off all but one, which is left long, FIGURE 16-9. The long conductor is often referred too as a **pig tail.** The pig tail is then connected to the green screw.



© Cengage Learning 2014

FIGURE 16-7 Electrical outlets are connected in parallel.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

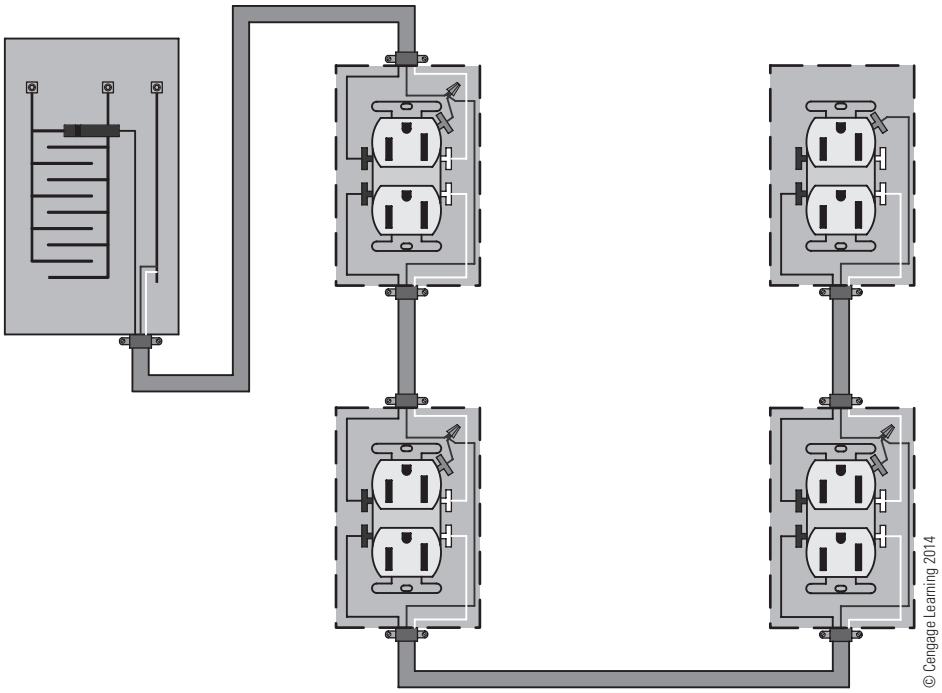

© Cengage Learning 2014

FIGURE 16-8 Receptacles are connected with two-conductor cable.

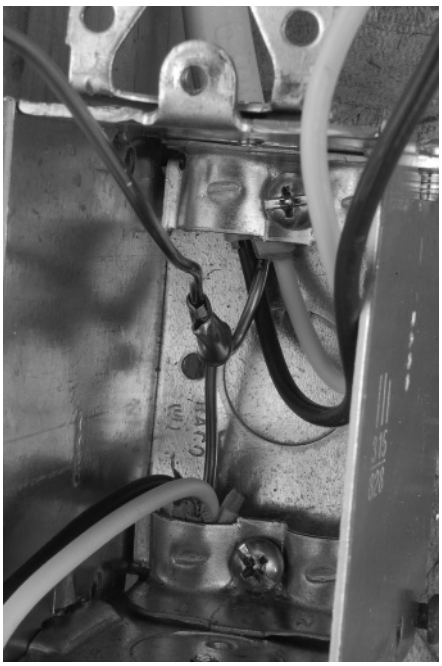

© Cengage Learning 2014

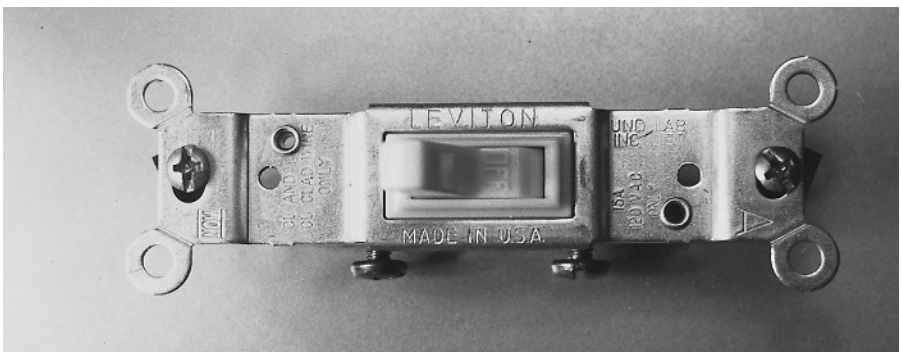
FIGURE 16-9 The pig tail is connected to the green grounding screw.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

SWITCH CONNECTIONS

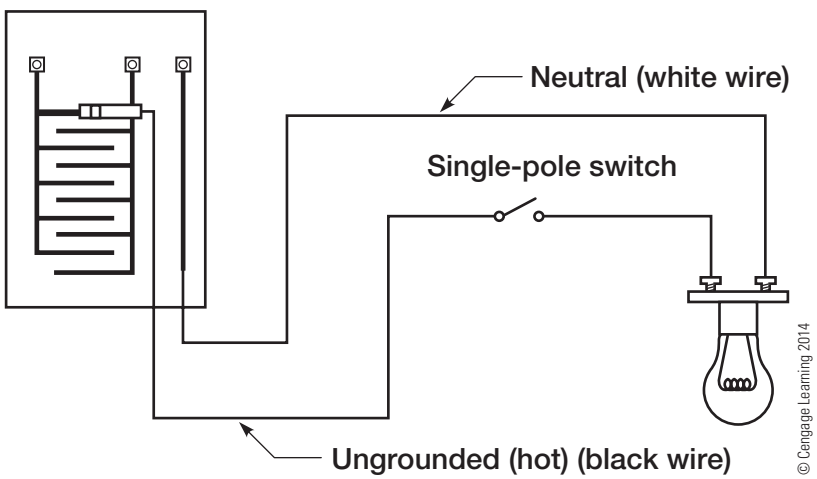
Three basic types of switches are used in general wiring, the single-pole, the three-way, and the four-way. Each of these switches is used for a particular application. Single-pole switches are employed when it is necessary to control a light or other electrical device from one location. Single-pole switches can be identified because they have only two connection screws, although some switches may have a third, grounding screw, which will be green. Single-pole switches also have ON and OFF printed on the switch lever, FIGURE 16-10.

Switch connections are made in the ungrounded, or hot, conductor only, FIGURE 16-11. The neutral, or grounded, conductor is not to be broken. The only time the *National Electrical Code*® permits the neutral conductor to be broken is when both the ungrounded and grounded conductors are broken simultaneously.



© Cengage Learning 2014

FIGURE 16-10 Single-pole switch.



© Cengage Learning 2014

FIGURE 16-11 The switch connects in series with the ungrounded conductor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

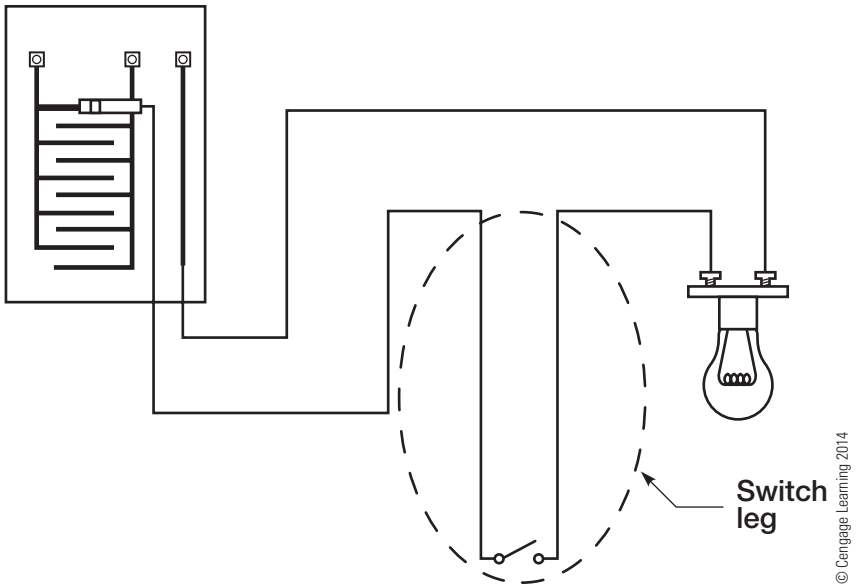


FIGURE 16-12 A switch leg is an extension of the ungrounded conductor.

Although the switch connection shown in Figure 16-11 is electrically correct, it is generally not possible to insert a switch directly in front of a light. The light is usually placed in the center of the ceiling, and the switch is placed beside a doorway. To accommodate the placement of the switch, a switch leg is used. A switch leg is actually an extension of the hot, or ungrounded, conductor, FIGURE 16-12.

As stated previously, all connections are made using two, three-, or four-conductor cable, and all connections must be made inside a box.

SINGLE-POLE SWITCH CONNECTIONS

Because of *NEC* 404.2(C), which requires a grounded or neutral conductor at any switch location, it becomes very important to plan the point at which power enters a circuit and the type of cables will be needed to complete the connection. There are several general rules that should be followed when making any type of switch connection. One rule is that the grounded or neutral conductor is never broken by a switch. The only time the *National Electrical Code*® permits the neutral conductor to be broken by a switch is if both the ungrounded and neutral conductors are broken simultaneously. Another rule is that when conductors are connected to a device, such as a lamp, they must be identifiable. This means that it must be possible to identify which conductor is grounded and which is ungrounded. There cannot be two white conductors or two black conductors connected to a lamp. Another rule states that if a

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

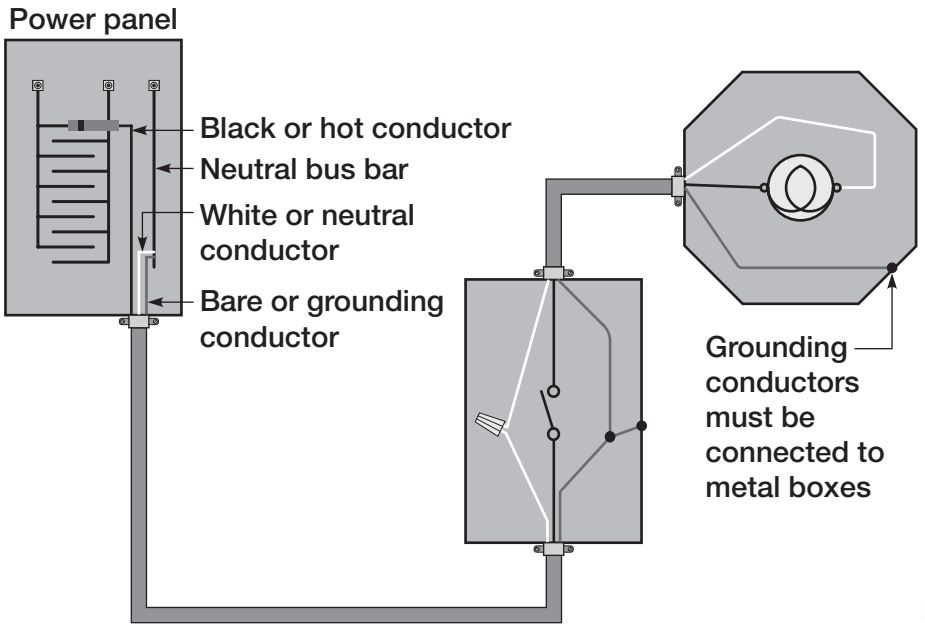


FIGURE 16-13 Power enters at the switch box.

white conductor is employed as part of the switch leg it must be re-identified by marking it with a different color. Re-identifying it with color tape or paint is common. Another method is to use colored heat shrink tubing. The tube is slid over the white conductor. When heated, the tubing will shrink and form a tight bond with the conductor.

There are two basic methods of connecting a single-pole switch with NM (nonmetallic) cable. The first method involves bringing the power supply into the switch box and then running a two-conductor cable from the switch to the lamp, FIGURE 16-13. In this example, the ungrounded or hot conductor is connected directly to the switch and the neutral conductor is connected to the white wire of the two-conductor cable that supplies power to the lamp. The black wire of the two-conductor supply is connected to the other side of the switch. Because the grounded or neutral conductor passes through the switch box, the requirements of *NEC* 404.2(C) have been met.

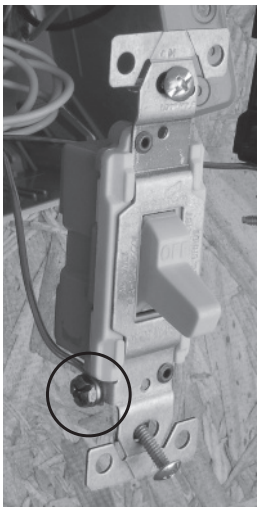


FIGURE 16-14 The grounding conductor is connected to the green grounding screw.

GROUNDING CONDUCTORS

The bare or grounding conductor must form a complete circuit throughout the entire electrical system. In this example, if the switch box is nonmetallic, the box itself does not require connection to the grounding conductor, but the grounding conductor should be connected to the green grounding screw on the switch, FIGURE 16-14. The green grounding screw grounds the metal yoke of the switch.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

If the box is metallic, it must be grounded. There are a couple of ways to accomplish this. Some metal enclosures provide a tapped hole to accept a green ground screw. The grounding conductor can be placed under the grounding screw. Another method is to employ the use of a grounding clamp, FIGURE 16-15. The grounding clamp attaches the grounding conductor to the surface of the metal box.


© Cengage Learning 2014

FIGURE 16-15 A metallic box must be grounded.

THE SECOND WIRING METHOD FOR A SINGLE-POLE SWITCH

The second method of connecting a single-pole switch is to connect the power supply cable to the ceiling box and connect a switch leg from the ceiling box to the switch box, FIGURE 16-16. In this example, the grounding or bare conductors have been omitted because of limited space. The same rules discussed in the previous example concerning grounding apply in this circuit also. Because of *NEC* 404.2(C), the switch leg is a three-conductor cable instead of a two-conductor cable. The white wire of the three-conductor cable permits a neutral conductor to be present at the switch. The white conductor or neutral of the power cable enters the ceiling box. This cable must be connected to the white wire of the switch leg and also to one side of the lamp. Because only one wire can be connected to a screw terminal, a pig tail is made

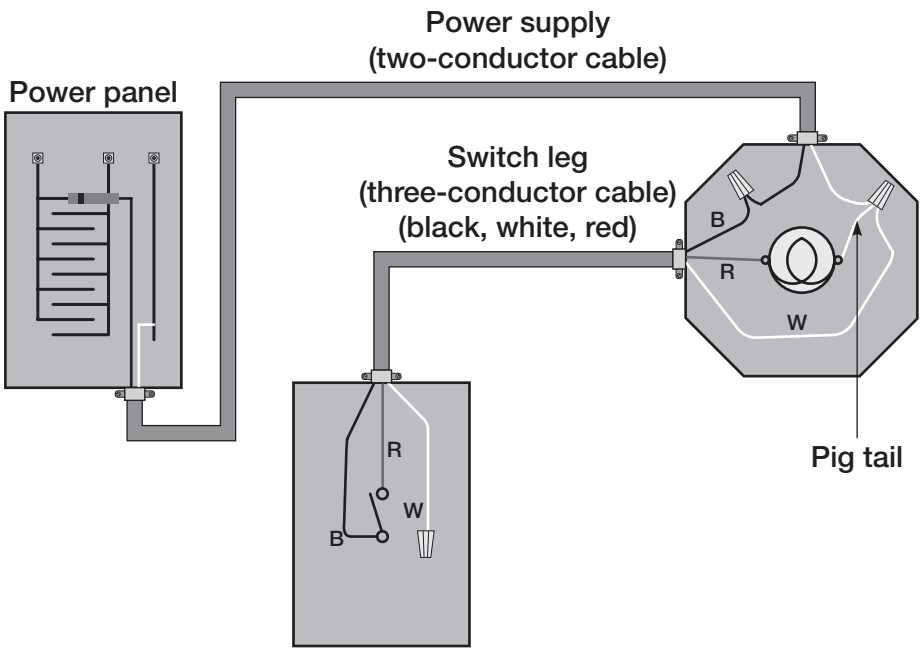


FIGURE 16-16 The power supply cable is connected to the ceiling box.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

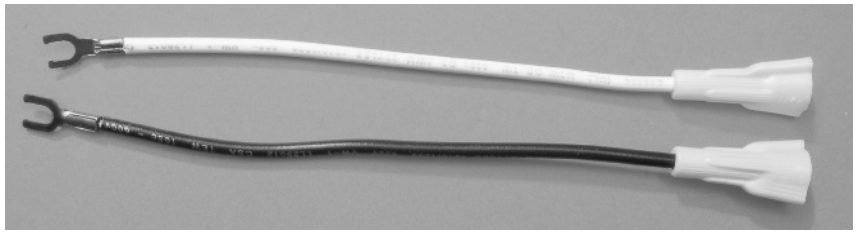

© Cengage Learning 2014

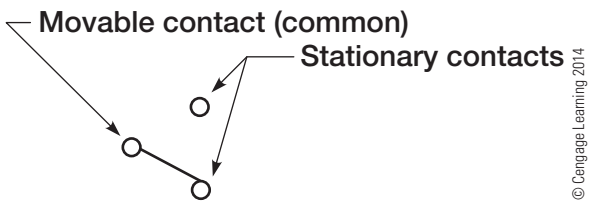
FIGURE 16-17 Wire nuts can be obtained that provide a pig tail connection.

by connecting a short piece of white wire with the white conductor of the power supply and the white conductor of the switch leg. It is also possible to obtain wire nuts that provide a pig tail connection, FIGURE 16-17. The black conductor of the switch leg is connected to the ungrounded conductor of the power supply and to one side of the switch. The red conductor provides the return path from the switch to the lamp.

THREE-WAY SWITCH CONNECTIONS

Three-way switches are used when it is desirable to control a light from two locations. The three-way switch is actually a single-pole double-throw (SPDT) switch, FIGURE 16-18. The switch contains two stationary contacts and one movable contact. The movable contact is referred to as the *pole* of the switch, and it is generally called the switch *common* because it can make connection between either of the two stationary contacts. The term *double-throw* means that it will make connection with a stationary contact when moved or thrown in either of two directions. The switch shown in Figure 16-18 makes connection between the movable, or *common*, contact and the bottom stationary contact. If the switch lever is flipped, or thrown, it will make connection between the common terminal and the top stationary contact, FIGURE 16-19.

As shown in the schematic diagrams in Figure 16-18 and Figure 16-19, the three-way switch contains three terminals. One way of identifying a three-way switch is that it has three terminal connection screws, FIGURE 16-20. The common screw must be identified because it is necessary to know which is



© Cengage Learning 2014

FIGURE 16-18 Schematic diagram of a three-way switch.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

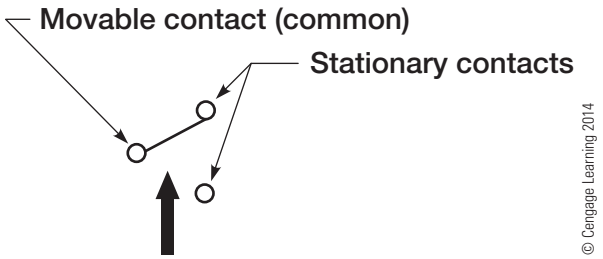


FIGURE 16-19 When the movable contact is changed, connection is made between the common terminal and the upper stationary contact.

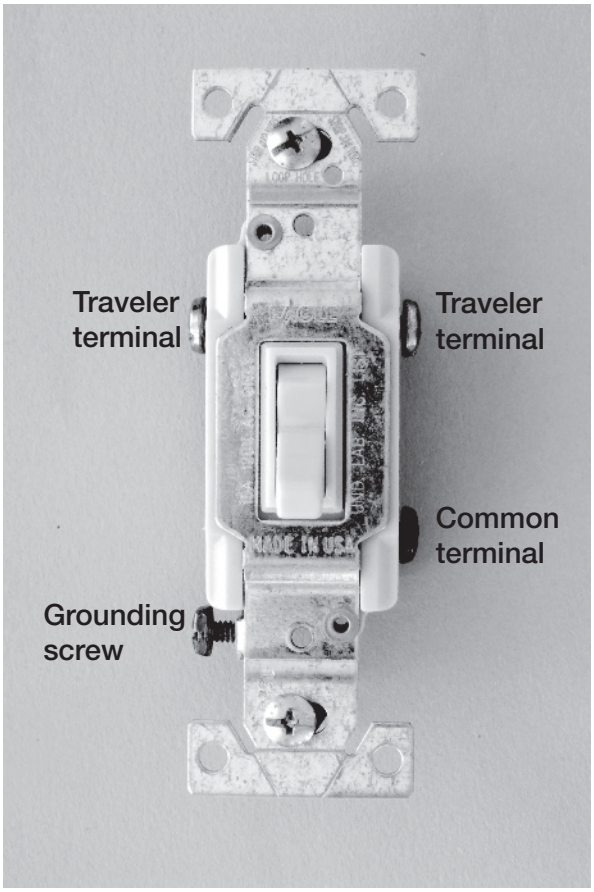
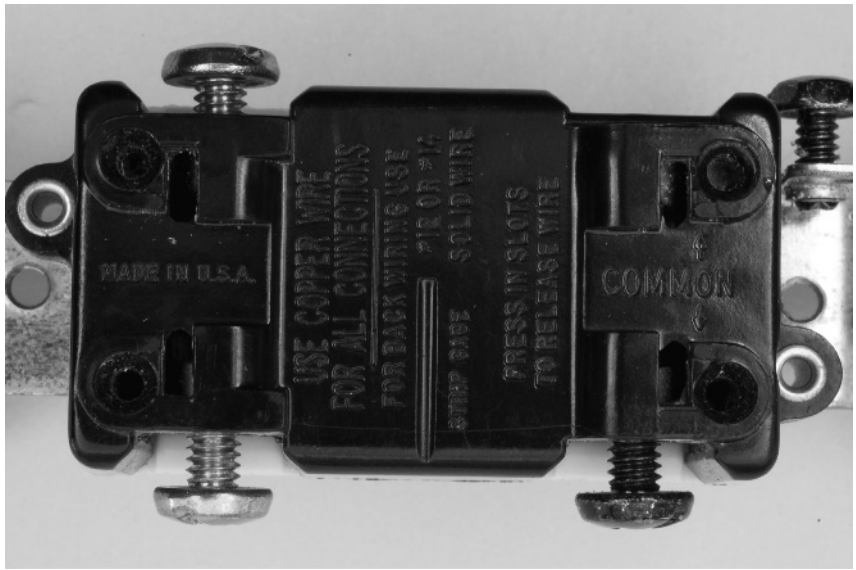


FIGURE 16-20 Three-way switch.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 16-21 Identifying the common terminal.

the common terminal when making a three-way switch connection. Some manufacturers identify the common terminal by making one screw a different color; other manufacturers mark the common terminal on the back side of the switch; and some manufacturers do both, FIGURE 16-21.

MAKING A THREE-WAY SWITCH CONNECTION

When making the connections for a three-way switch circuit, four rules can be used to simplify the procedure. Each of these rules will be presented with a schematic illustration.

The first rule is to connect the neutral to the light, FIGURE 16-22. The neutral conductor should never be broken and is, therefore, connected directly to the lighting fixture.

The second rule is to connect the hot conductor to the common terminal of one three-way switch, FIGURE 16-23. It makes no difference to which of the two switches the hot conductor is connected, but it must be connected to the common terminal of the switch.

The third rule is to connect the other side of the light to the common terminal of the second three-way switch, FIGURE 16-24. Notice that one side of the light has already been connected to the neutral conductor. The remaining side of the light is connected to the common terminal of the three-way switch that was not connected to the hot conductor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

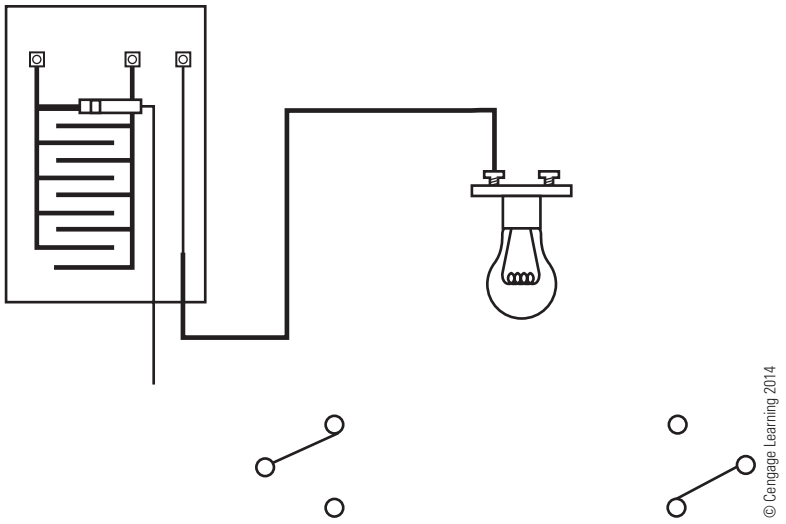


FIGURE 16-22 Rule 1: Connect the neutral to the light.

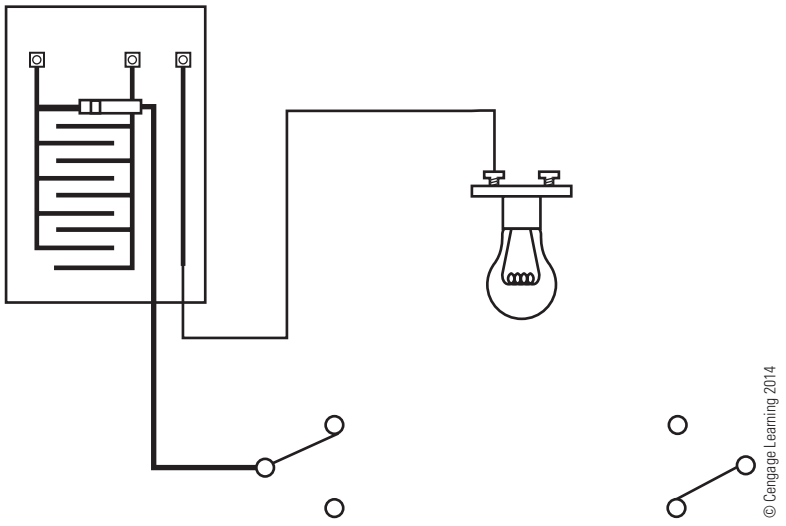


FIGURE 16-23 Rule 2: Connect the hot conductor to the common terminal of one three-way switch.

The fourth rule is to connect the travelers, FIGURE 16-25. The traveler conductors run between the stationary contact terminals of the two three-way switches.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

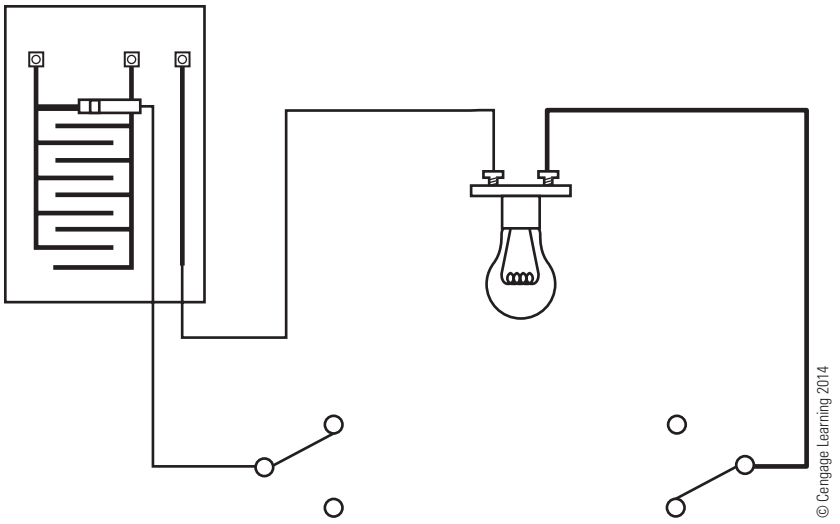


FIGURE 16-24 Rule 3: Connect the other side of the light to the common terminal of the second three-way switch.

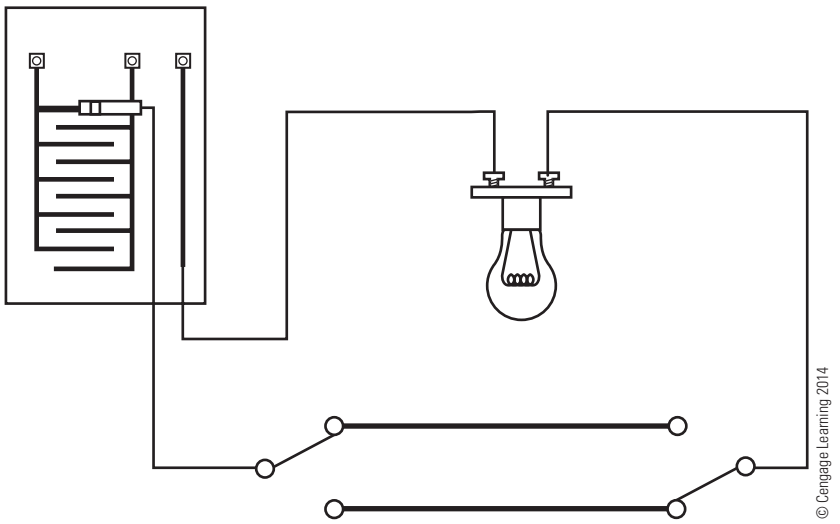


FIGURE 16-25 Rule 4: Connect the travelers.

TRACING A THREE-WAY SWITCH CIRCUIT

To understand how a three-way switch circuit operates, trace the current path starting at the circuit breaker. It will be assumed that current will flow from the circuit breaker and return to the neutral bus. In FIGURE 16-26, it can be seen

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

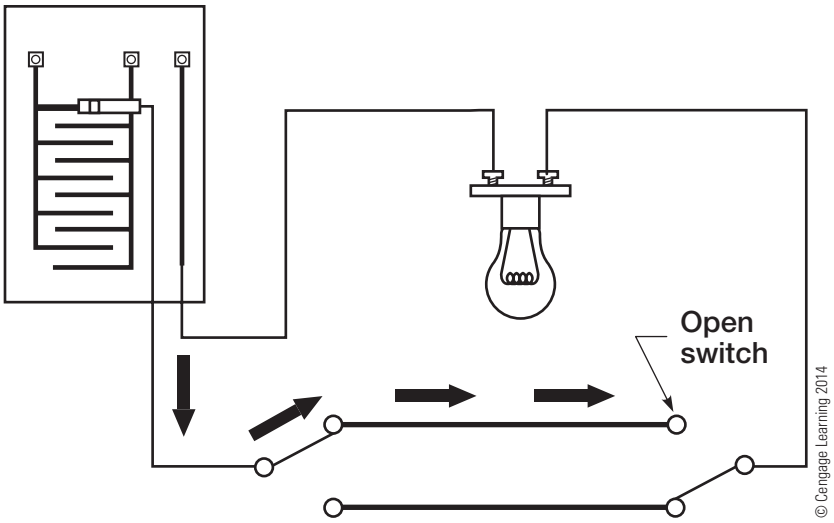


FIGURE 16-26 The circuit is open, and no current flows to the light.

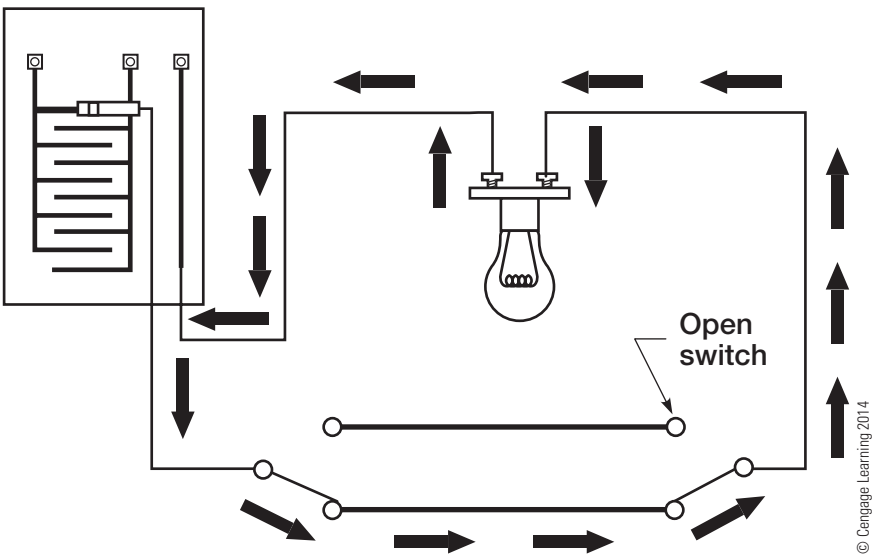


FIGURE 16-27 The circuit is closed, and current flows through the light.

that current cannot flow through this circuit because of the open switch. In this condition, the light is turned off.

If the movable contact of either switch should be changed, the circuit will toggle and a complete path will exist. In this example, it is assumed that the left switch position is changed, FIGURE 16-27. There is now a complete path

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

through the circuit, and the light is turned on. The circuit will toggle between on and off regardless of which switch is changed. The light can now be controlled from either switch position.

MAKING THREE-WAY SWITCH CONNECTIONS WITH CABLE

The examples of switch connection and operation were done with electrical schematic diagrams to aid in understanding how the circuit is connected and how it works. In actual practice, however, all connections are made with two-, three-, and sometimes four-conductor cable. A good rule to remember when installing the wiring for a three-way switch connection is that a three-conductor cable must be run between the switches. It is sometimes necessary to connect a four-conductor cable between the two three-way switches depending on the point that power is supplied to the circuit. In the following examples of connecting three-way switches using cable, the grounding conductors have been omitted due to space limitations and to aid in clarity. When making these connections in the field, the grounding conductors are connected in the same manner as shown for single-pole switch connections. All grounding conductors must be connected to provide continuity throughout the entire system. If a metal box is used, a grounding conductor must be connected to the box.

When making three-way switch connections using two-, three-, or four-conductor cables, it is permissible to connect any of the conductors to the hot conductor, because it is a switch leg. A good rule to observe, however, is to always connect a black conductor to the common terminal of a three-way switch. The reason for this is that a black conductor can always be used to connect to the common terminal, but it is not always possible to use a white, red, or blue conductor. If this is done there is no doubt as to which wire should be connected to the common terminal of the switch when the switches are physically connected in the circuit. When a residential location is roughed-in, it is common practice to pull the necessary cables to mounted switch boxes. The cables are identified by marking them with a permanent marker, FIGURE 16-28. The reason for this is that final connection of devices does not occur until the walls have been covered with some type of covering such as sheet rock or paneling. It is then not possible to see where the cables run.

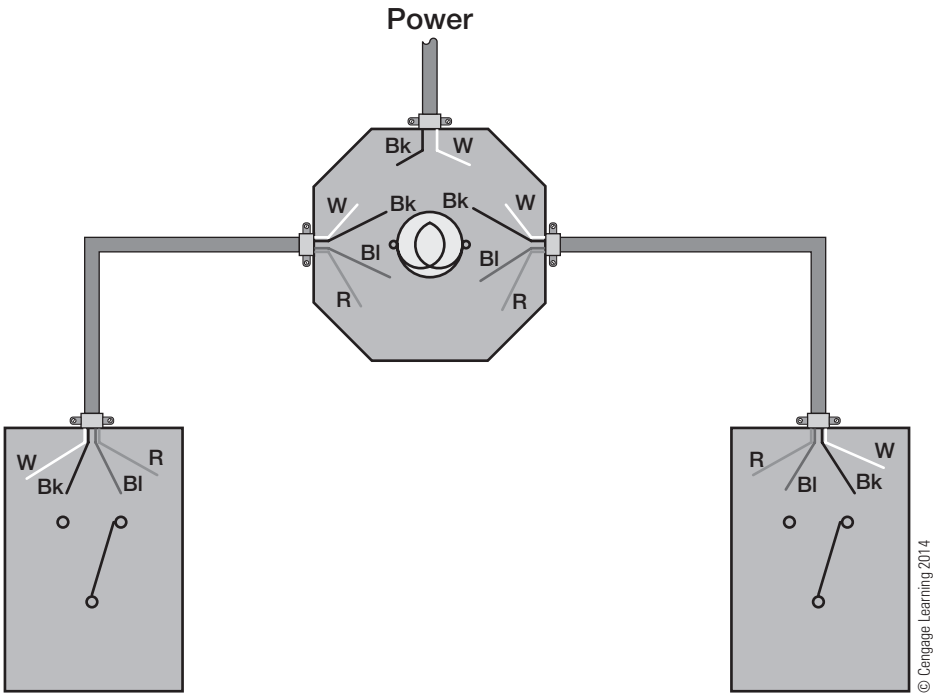
In the first example, a two-conductor power cable is supplied from the panel to the lighting fixture box and two four-conductor cables are run from the lighting outlet box to each switch box, FIGURE 16-29. The circuit will be connected using the four rules previously stated. The first step is to connect the neutral conductor to the light, FIGURE 16-30. The neutral conductor is the white wire of the power cable.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 16-28 Cables are marked during rough-in.



© Cengage Learning 2014

FIGURE 16-29 Four-conductor cables are connected between the ceiling box and the switch boxes.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

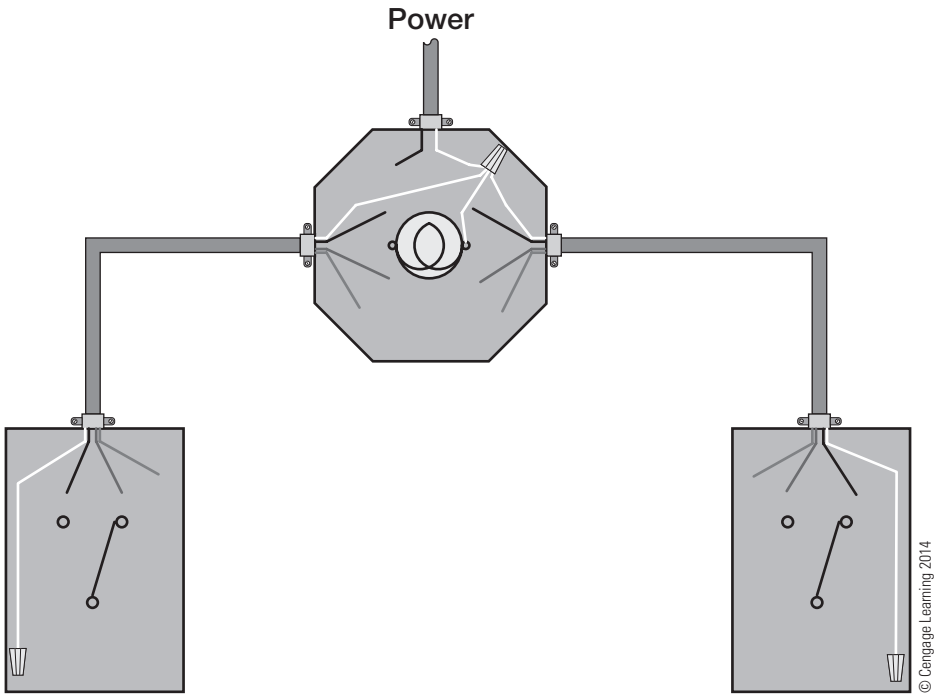


FIGURE 16-30 The neutral conductor is connected directly to the light.

It will be assumed that the colors contained in the four-conductor cable are black, white, red, and blue. There is also a bare grounding conductor that is not shown. To aid in understanding the connection, the wires will be labeled Bk for black, W for white, Bl for blue, and R for red. The first step in connecting the circuit is to connect the neutral to the lamp. The neutral is the white wire in the incoming power. In order to meet the requirement of *NEC* 404.2(C), a neutral conductor must also be provided at each switch location. All white conductors will be connected together and a pig tail connection will supply the neutral connection to the lamp, Figure 16-30.

The next step is to connect the ungrounded or hot conductor to the common terminal of one three-way switch. It does not matter which switch is used. In this example, the switch on the right will be used, FIGURE 16-31. Step three is to connect the other side of the lamp to the common terminal of the second three-way switch. The black conductor of the four-conductor cable will be used for this connection, FIGURE 16-32. Rule four is to connect the travelers. The red and blue wires will be used to connect the traveler terminals of the two switches together, FIGURE 16-33.

In the second example of making a three-way switch connection using cable, the power cable enters the lighting fixture outlet box. A three-conductor

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

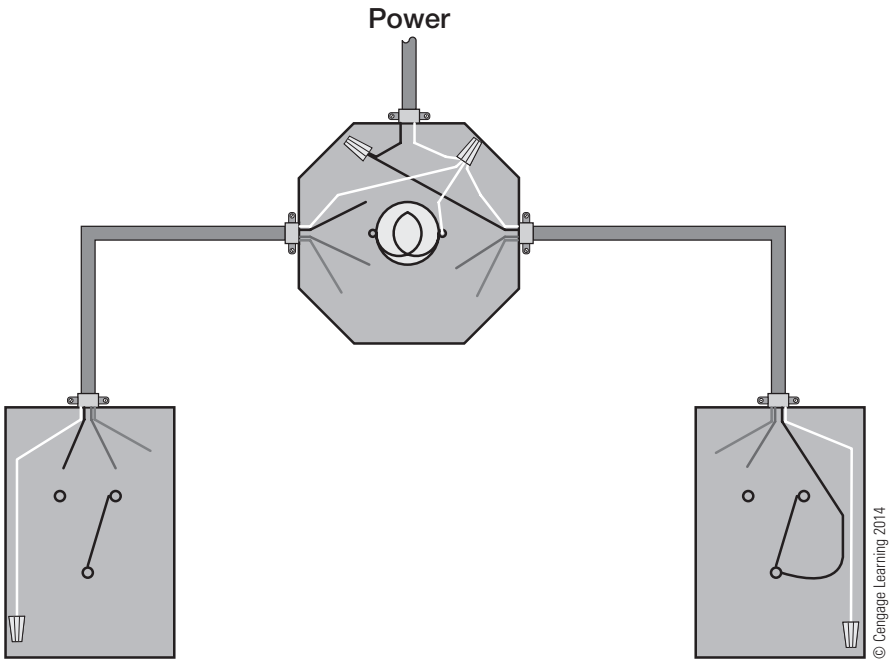


FIGURE 16-31 The ungrounded, or hot, conductor is connected to the common terminal of one three-way switch.

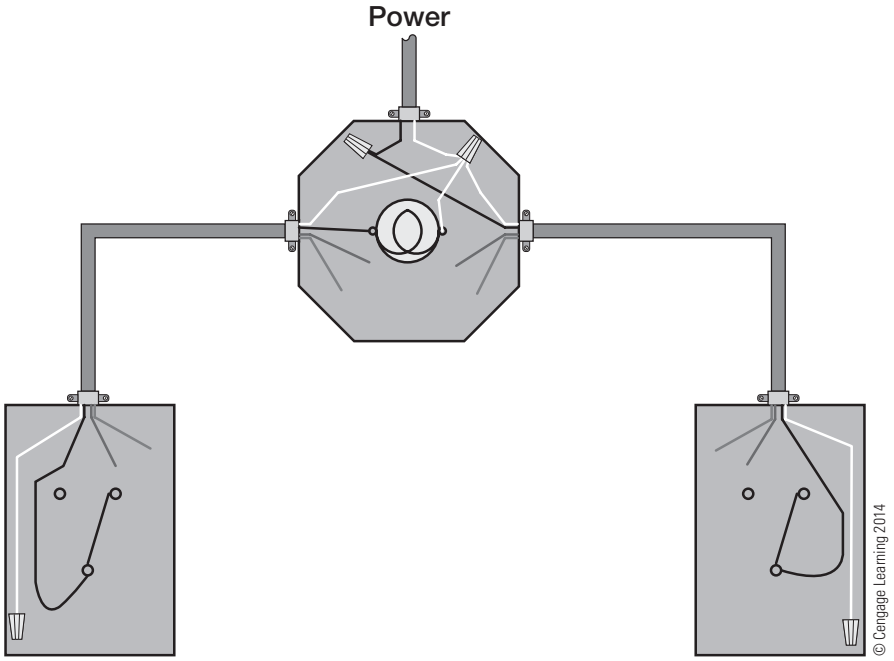


FIGURE 16-32 Connect the other side of the light to the common of the second three-way switch.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

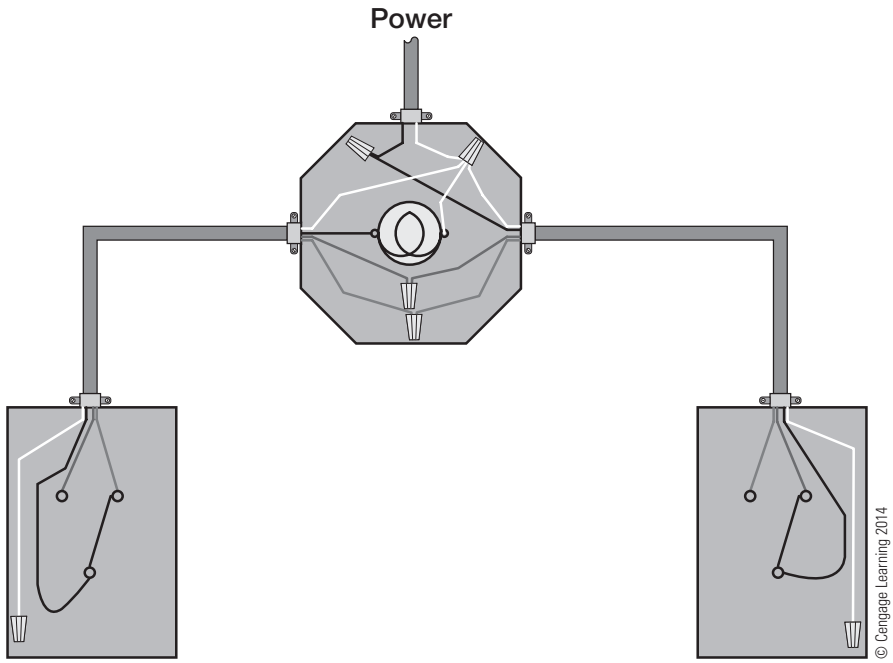


FIGURE 16-33 Connect the travelers.

cable is run between the lighting outlet box and one of the switch boxes, and a four-conductor cable is run between the two switch boxes, FIGURE 16-34. As in the previous example, the four rules will be followed to make this connection. The first step is to connect the grounded, or neutral, conductor to the light, FIGURE 16-35.

Because *NEC* 404.2(C) requires a neutral conductor at any switch location, the white wire of the power cable will be connected to the white wire of the three-conductor cable connected between the ceiling box and the switch, and to the white conductor of the four-conductor cable that is connected between the two switches. A pig tail connection will be used to connect the neutral to the lamp, Figure 16-35. Rule two is to connect the ungrounded or hot conductor to the common of one three-way switch. Because it is desirable to connect a black conductor to the common of a switch, the hot conductor of the power cable will be connected to the red wire of the three-conductor cable, supplying power to the switch box. The red conductor will then be connected to the black wire of the four-conductor cable to supply power to the common terminal of the first three-way switch, FIGURE 16-36.

Rule three is to connect the other side of the lamp to the common terminal of the second three-way switch. The black wire of the three-conductor cable will make this connection, FIGURE 16-37. The fourth rule is to connect the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

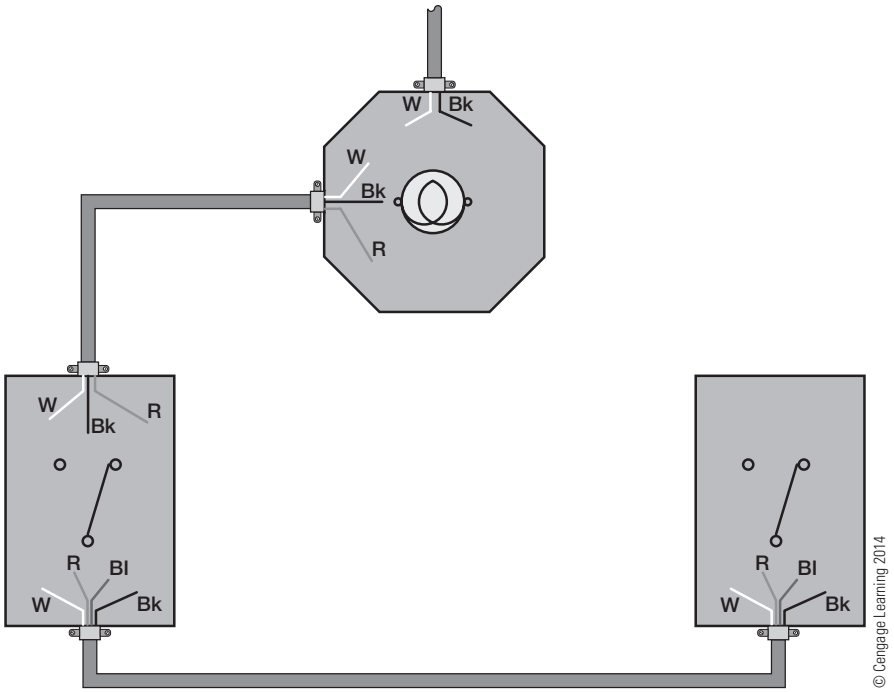


FIGURE 16-34 Example 2 for connecting three-way switches.

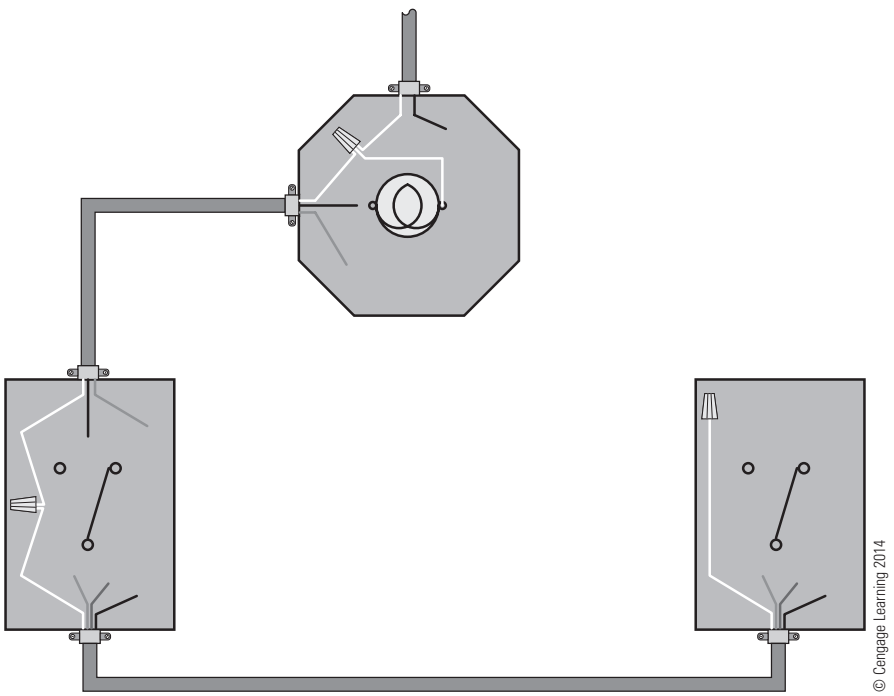


FIGURE 16-35 The neutral conductor is connected to the light.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

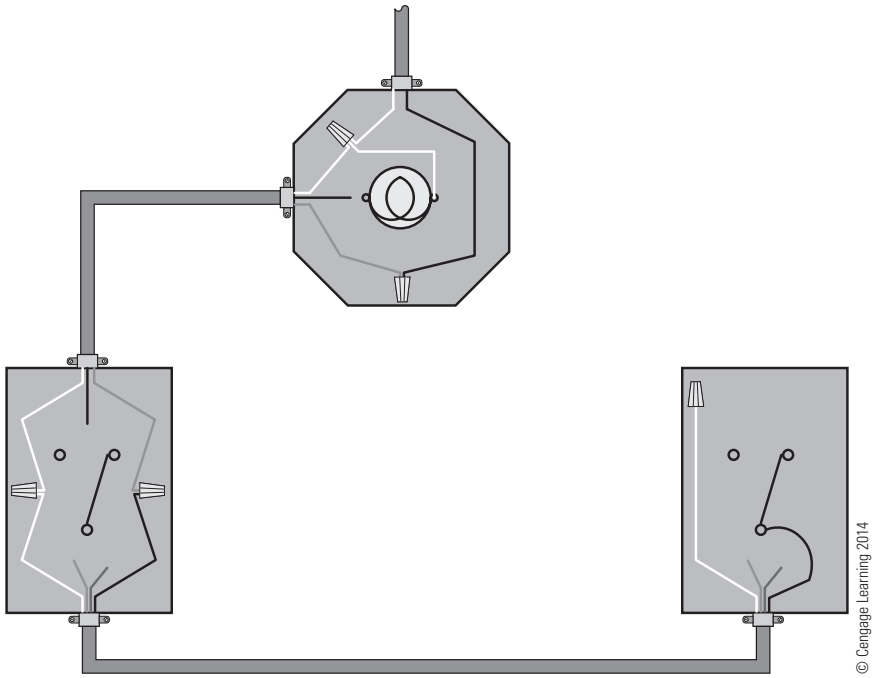


FIGURE 16-36 Connect the ungrounded conductor to the common terminal of one three-way switch.

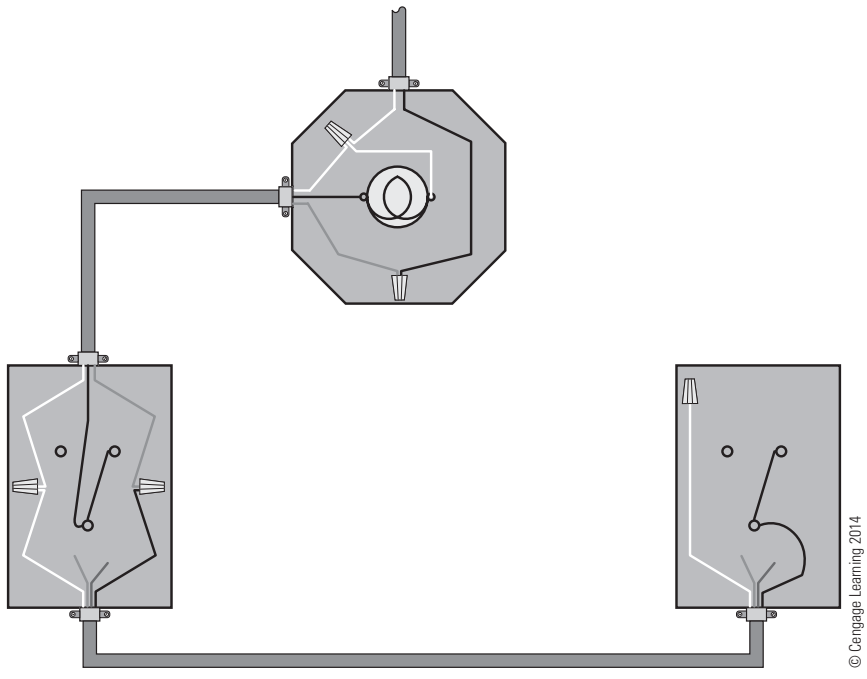


FIGURE 16-37 The other side of the light is connected to the common terminal of the second three-way switch.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

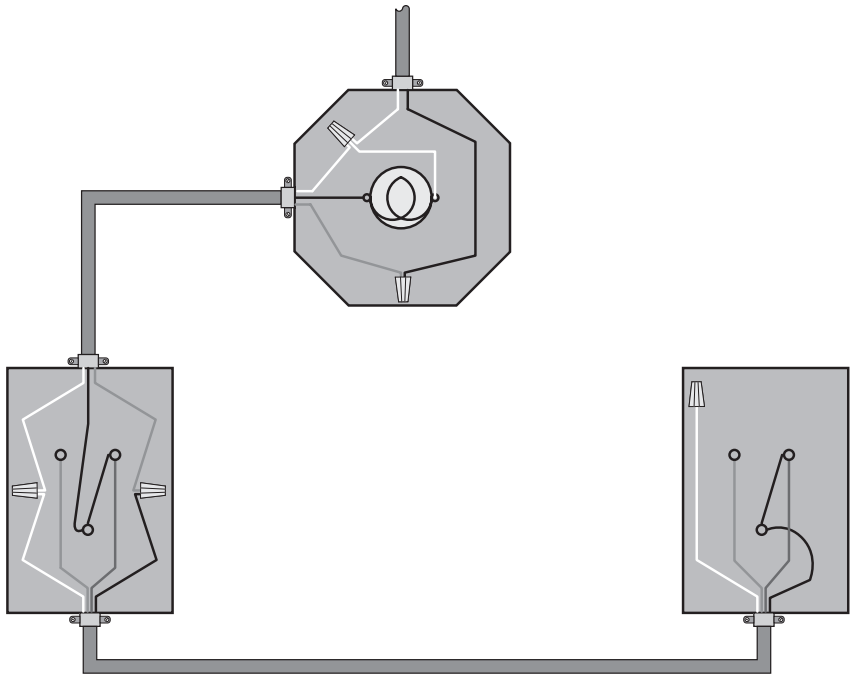

© Cengage Learning 2014

FIGURE 16-38 Connecting the traveler conductors between the two three-way switches.

travelers between the two three-way switches. The red and blue wires of the four-conductor cable will make this connection, FIGURE 16-38.

FOUR-WAY SWITCHES

Four-way switches are used to control a light from more than two locations. Four-way switches are actually double-pole double-throw (DPDT) switches with an internal criss-cross connection, FIGURE 16-39. Since the stationary contacts are connected inside the switch, only four screw terminals are required, FIGURE 16-40. When a four-way switch is thrown in one position,

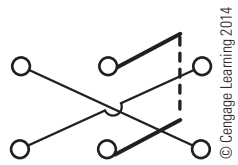
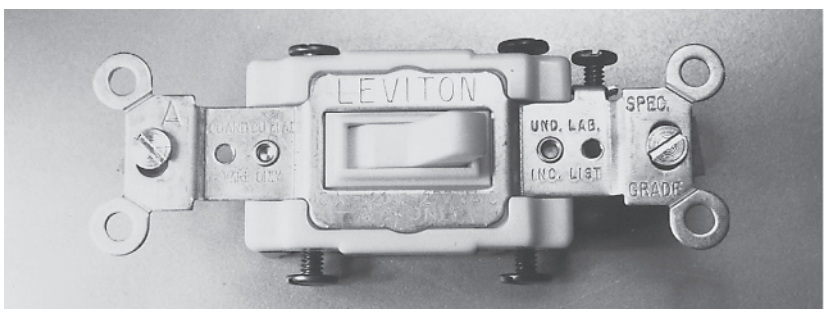

© Cengage Learning 2014

FIGURE 16-39 A four-way switch is a double-pole double-throw switch with an internal criss-cross connection.



© Cengage Learning 2014

FIGURE 16-40 Four-way switch.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

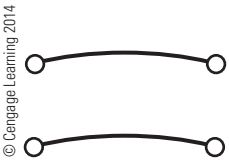

© Cengage Learning 2014

FIGURE 16-41 When thrown in one position, the four-way switch makes a connection straight across the terminals.

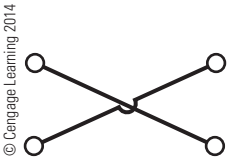

© Cengage Learning 2014

FIGURE 16-42 When thrown in the other position, the four-way switch makes a criss-cross connection.

the terminal screws will be connected as shown in FIGURE 16-41. In this position, the switch terminals are connected straight across. If the switch is thrown in the other direction, connection will be made in a criss-cross fashion, as shown in FIGURE 16-42.

When making a four-way switch connection, the same four rules that apply to making three-way switch connections can be used. The only difference is that the four-way switch is connected in the traveler conductors, FIGURE 16-43. If a current path is traced in this circuit, it will be seen that an open switch prevents the flow of current to the light, FIGURE 16-44. The light is, therefore, turned off at this time.

Now assume that the position of the four-way switch is changed, as shown in FIGURE 16-45. A current path now exists through the light, and it is turned on. If the position of any one of the three switches should change, the light will be turned off. Changing the position of any of the three switches will alternately toggle the light from on to off and from off to on. Anytime a light is to be controlled from more than one location, two three-way switches must be used. Any number of switches above two, however, must be four-way. Virtually any number of four-way switches can be inserted between the travelers of the two three-way switches, FIGURE 16-46.

Like the other types of switch circuits previously discussed, four-way switch connections are actually made with two- and three-conductor cable. In this example, the power wire is brought from the panel and enters one of the three-way switch boxes. A three-conductor cable is connected between the

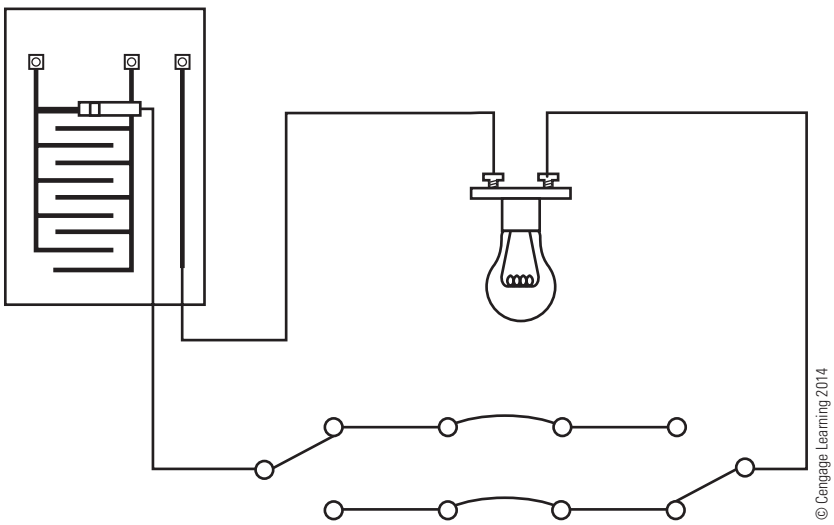

© Cengage Learning 2014

FIGURE 16-43 A four-way switch connects into the traveler conductors between the two three-way switches.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

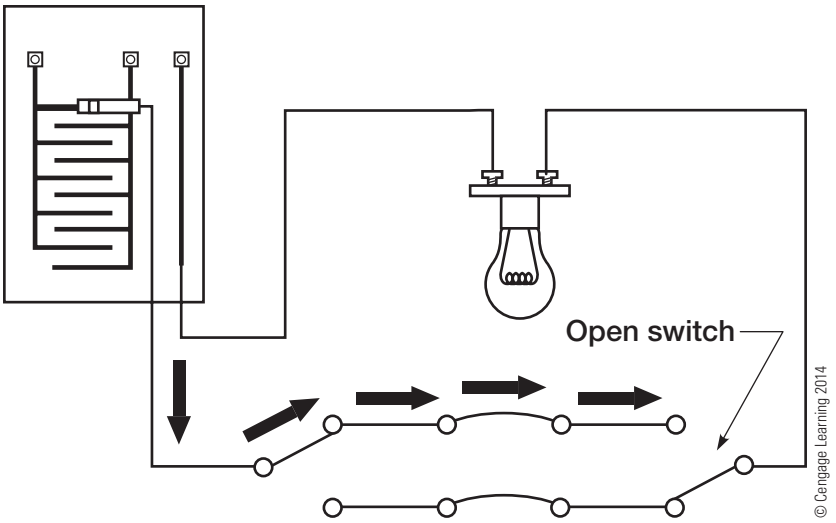


FIGURE 16-44 The current path is broken by an open switch.

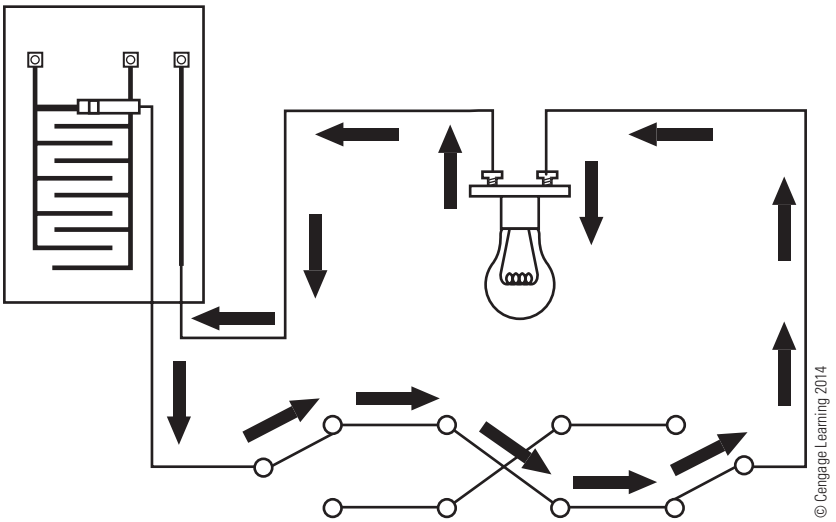


FIGURE 16-45 Changing the position of the four-way switch provides a current path for the circuit.

first three-way switch and the four-way switch, and a second three-conductor cable is connected between the four-way switch and the other three-way switch. A two-conductor cable is run from the second three-way switch to the lighting outlet box, FIGURE 16-47. The four rules for connecting three-way switches will be followed to make this connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

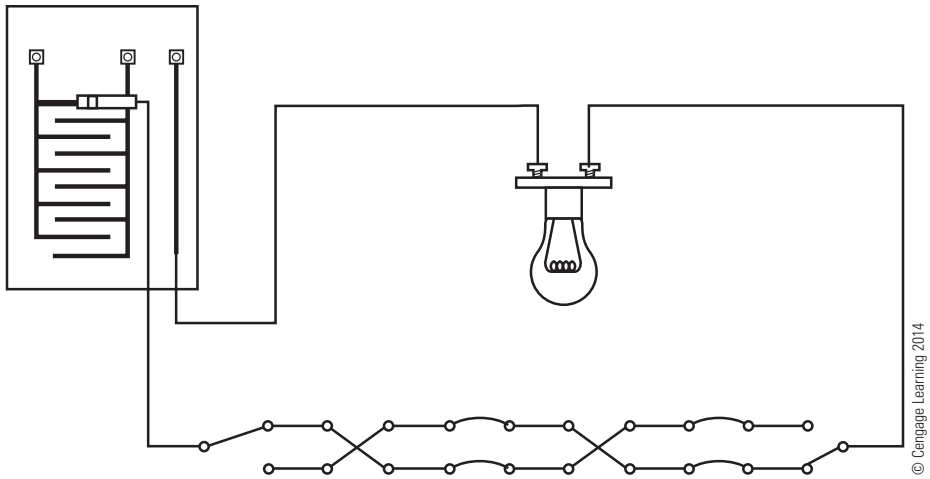


FIGURE 16-46 Any number of four-way switches can be connected between the travelers of two three-way switches.

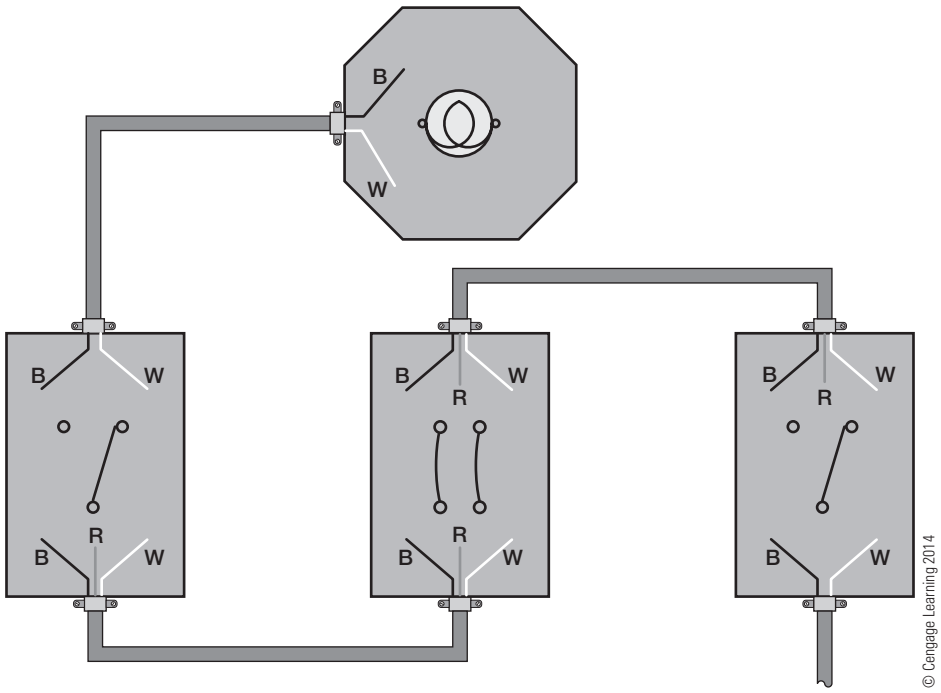


FIGURE 16-47 A four-way switch connection using two- and three-conductor cable.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The first step is to connect the neutral conductor to the light, FIGURE 16-48. The neutral conductor enters the three-way switch box on the right side. Since the *National Electrical Code*® requires that neutral, or grounded, conductors be white or gray, the white wire will be used to carry the neutral conductor through the circuit to the light. Because the neutral conductor passes through each switch location, the requirement of *NEC* 404.2(C) is met. Note that by connecting the power supply to one of the three-way switches and the lamp to the other, only three-conductor cable is required to make the connection. Four conductor cable is not required for this installation. As stated previously, planning how the cable is to be run and where power is applied to the circuit can reduce the cost and complexity of an installation.

The second step is to connect the ungrounded, or hot, conductor to the common terminal of one three-way switch. The black wire of the power cable

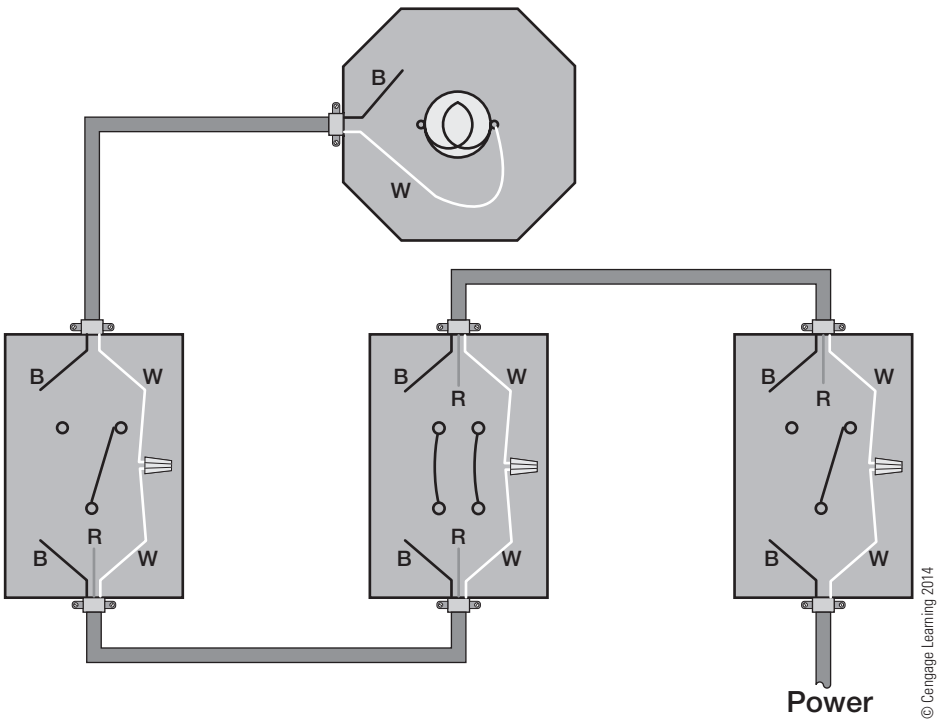


FIGURE 16-48 The neutral conductor is carried through the entire circuit and connected to the light.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

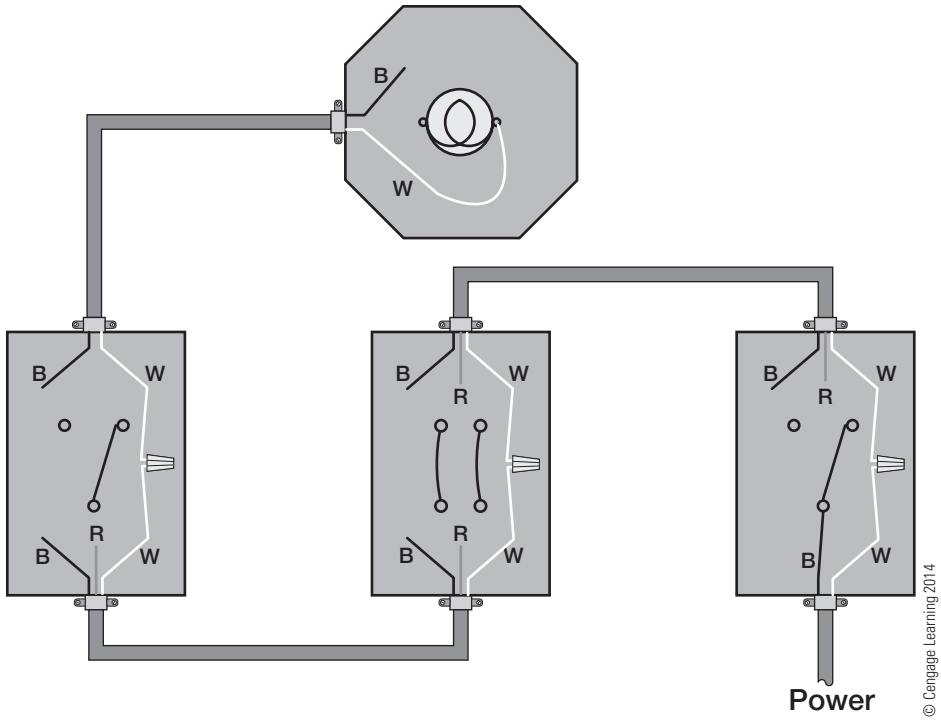


FIGURE 16-49 The ungrounded, or hot, conductor is connected to the common terminal of one three-way switch.

is connected to the common terminal of the three-way switch located on the right side, FIGURE 16-49.

The third step is to connect the other side of the light to the common terminal of the second three-way switch. The black wire of the two-conductor runs between the three-way switch located on the left side and the lighting outlet box will be used to make this connection, FIGURE 16-50.

The final step is to connect the travelers. In this circuit, the four-way switch will be connected between the traveler conductors, FIGURE 16-51. The red and black wires of the three-conductor cables will be used for this connection. When connecting the four-way switch into the circuit, it is important to connect the traveler conductors to the proper screw terminals. The traveler conductors from one of the three-conductor cables is generally connected to the two top screws, and the traveler conductors from the other three-conductor cables is connected to the two bottom screws. Some switches have the connection labeled on the switch, as shown in FIGURE 16-52, but some do not.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

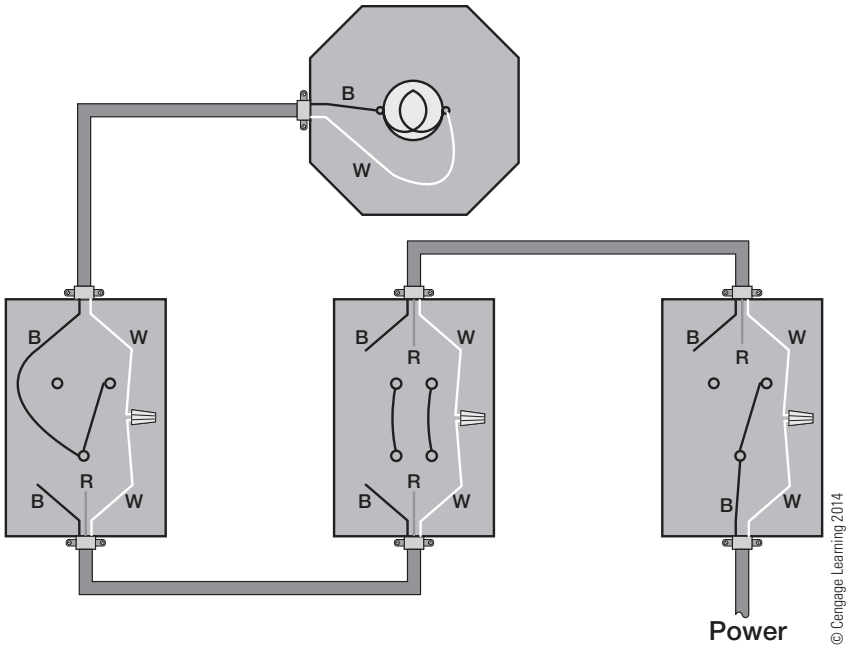


FIGURE 16-50 The other side of the light is connected to the common terminal of the second three-way switch.

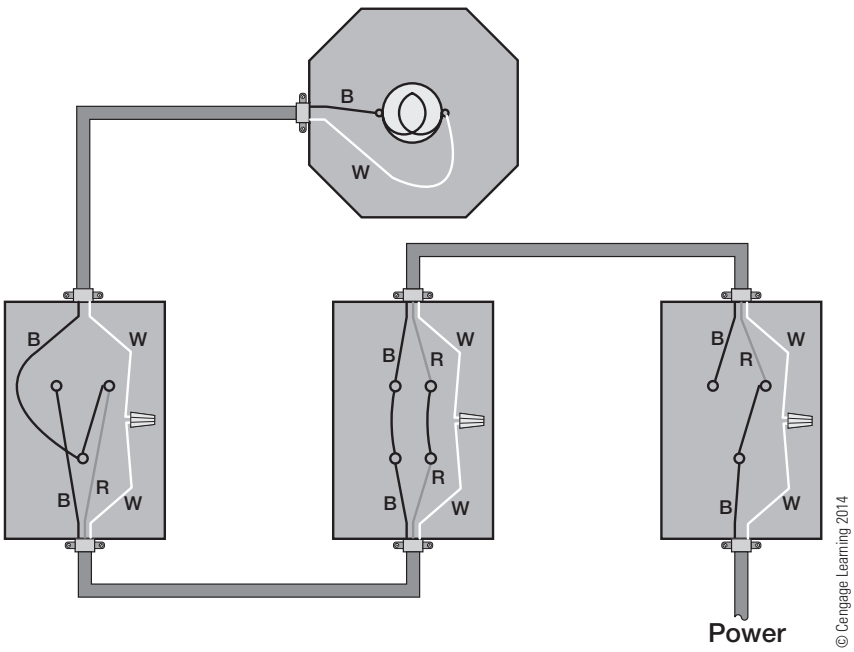
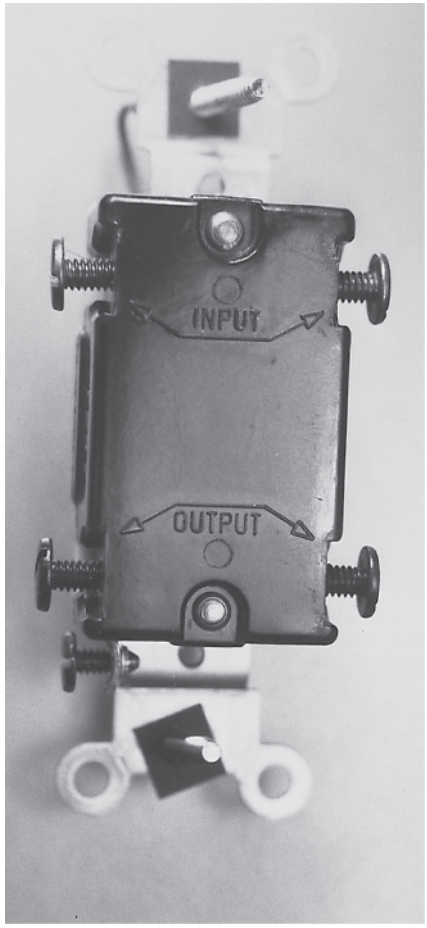


FIGURE 16-51 The four-way switch is connected in the travelers between the two three-way switches.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 16-52 Some switches have the screws labeled.

Summary

1. A residential occupancy is wired with two- and three-conductor cable.
2. Receptacles are connected in parallel.
3. When connecting a receptacle, the black conductor is connected to the brass or gold screw, the white conductor is connected to the silver screw, and the bare conductor is connected to the green screw.
4. The neutral conductor is referred to as the *grounded* conductor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. The bare conductor is referred to as the *grounding* conductor.
6. The hot conductor is referred to as the *ungrounded* conductor.
7. A duplex receptacle contains two outlets on the same strap.
8. Receptacles and switches can be connected quickly with stab-locks or quick-connects, but these do not make as good a connection as screws.
9. The leading cause of electrical fires is poor connection.
10. Single-pole switches use two terminal screws for connection and have ON and OFF printed on the switch lever.
11. Single-pole switches are used to control lights from one location.
12. Three-way switches use three terminal screws for connection.
13. When connecting three-way switches, three-conductor cable should be run between the switches.
14. Four rules for connecting three- and four-way switches are as follows:
    A. Connect the neutral to the light.
    B. Connect the hot (ungrounded) conductor to the common terminal of one three-way switch.
    C. Connect the other side of the light to the common terminal of the second three-way switch.
    D. Connect the travelers.
15. Four-way switches use four terminal screws for connection.
16. Four-way switches are used when it is necessary to control a light from more than two locations.
17. Four-way switches connect in the traveler conductors between two three-way switches.

Review Questions

1. A two-conductor cable actually contains three wires. Why is it called a two-conductor cable if it has three wires?
2. What are the colors of the wires in a three-conductor cable?
3. When installing a duplex receptacle, which wire should be connected to the gold or brass screw?
4. What is the advantage of stab-lock connectors?
5. What is the disadvantage of stab-lock connectors?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

6. What is the leading cause of electrical fires?
7. List four rules for connecting three-way switches.
8. What are traveler conductors?
9. What is a switch leg?
10. How is the common screw of a three-way switch generally identified?
11. A light is to be controlled from five different locations. How many single-pole, three-way, and four-way switches are required to make this connection?
12. List two ways of identifying a single-pole switch.
13. A circuit is to supply power to a number of duplex receptacles. The circuit is connected to a 20-A circuit breaker. What size copper wire should be used to make this connection?
14. What is the *National Electrical Code*® requirement when a white conductor is employed as a switch leg?
15. When conductors are connected to a light, the *National Electrical Code*® requires that the conductors be identified. Explain what is meant by identifying the conductors.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 17

General Wiring Practices Part 2—Protection Circuits, Dimmers, and Chimes

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the operation of a ground fault circuit.
- Install a ground fault circuit breaker.
- Install a ground fault receptacle.
- Discuss the operation of an arc-fault interrupter.
- Install an arc-fault circuit breaker.
- Discuss the operation of a dimmer switch.
- Install a dimmer switch.
- Discuss the operation of electric chime circuits.
- Install a chime circuit.

The *National Electrical Code*® requires the use of certain protective devices in dwellings. Two of these are the ground fault circuit interrupter (**GFCI**) and the arc-fault circuit interrupter (**AFCI**). These devices are intended to protect individuals from the hazards of electrical shock and fire.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

GROUND FAULT CIRCUIT INTERRUPTERS

There are two basic types of ground fault circuit interrupters (GFCIs). One type is designed to protect industrial equipment. This type is generally used on three-phase systems and is designed to disconnect the circuit if a ground should occur. It operates by passing all three-phase conductors through a toroid transformer, FIGURE 17-1. The circuit works on the principle that when current flows through a conductor, a magnetic field is developed around the conductor. As long as the current is the same in each of the three phases, the magnetic fields cancel each other. As a result there is no voltage induced in the toroid transformer. If one of the phase conductors becomes grounded, a large amount of current will flow in it, causing a more intense magnetic field in that conductor. The increased magnetic field induces a voltage into the transformer. The transformer then causes the control circuit to de-energize the power supplying the load. Ground fault detectors of this type generally require from several to 1,000 or more amperes to open the circuit. These detectors are intended to protect equipment, not people.

PERSONNEL GFCI DETECTORS

The articles concerning ground fault protection in the National Electrical Code® deal mainly with personnel protection. A ground fault interrupter can generally be purchased as a circuit breaker or as a receptacle. When the circuit breaker type of protector is used, all devices connected to that circuit are ground fault protected, FIGURE 17-2. GFCI circuit breakers are constructed differently than standard breakers. Standard single-pole circuit breakers contain only one

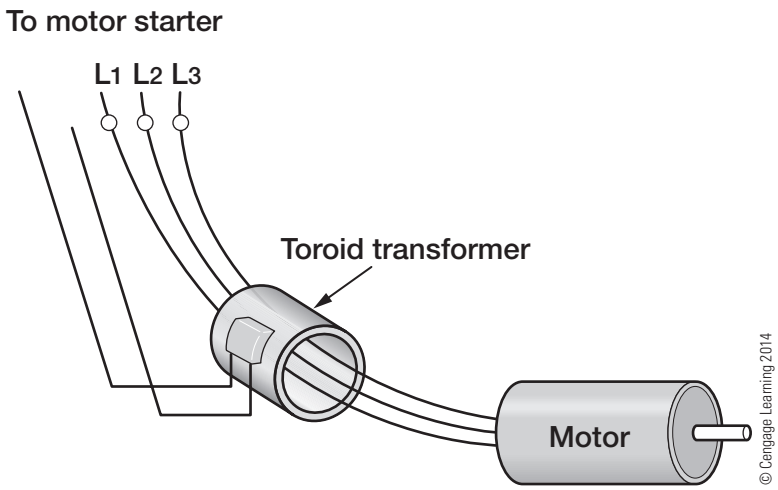


FIGURE 17-1 Industrial ground fault detectors protect equipment.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

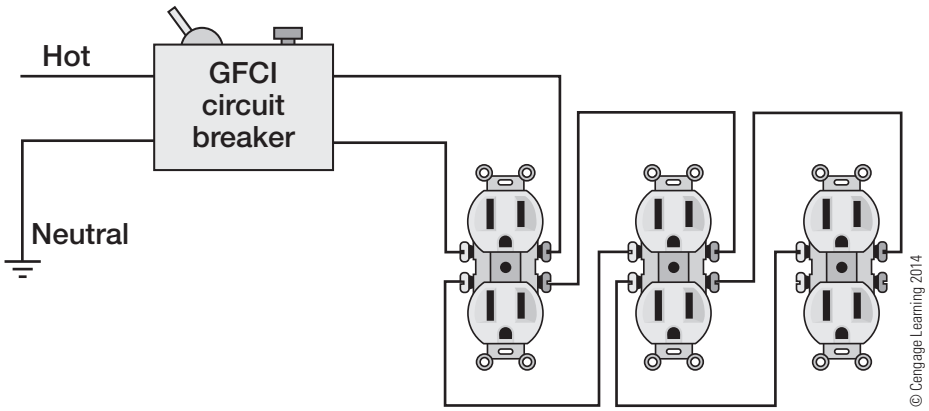


FIGURE 17-2 The GFCI circuit breaker protects all devices connected to it.

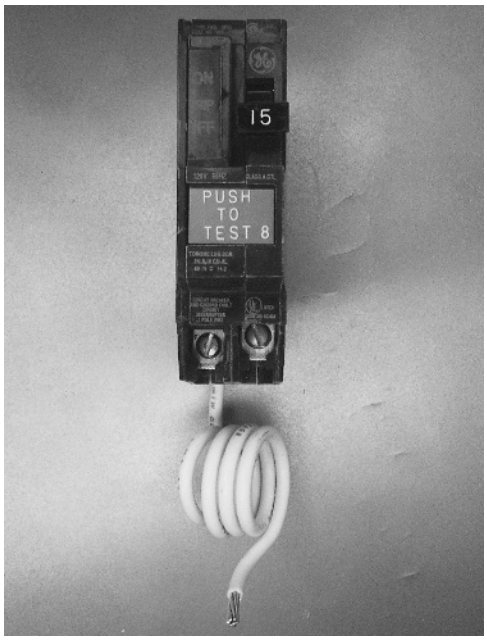


FIGURE 17-3 GFCI circuit breaker.

connection screw for termination of the branch circuit ungrounded, or hot, conductor. Single-pole GFCI circuit breakers contain two connection screws, FIGURE 17-3. The hot, or ungrounded, branch circuit conductor connects to the brass-colored screw, and the neutral conductor connects to the silver screw. The white pig tail attached to the circuit breaker connects to the neutral bus bar in the service panel. The reason the hot and neutral conductors must connect to the circuit breaker is because both conductors must pass through a

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

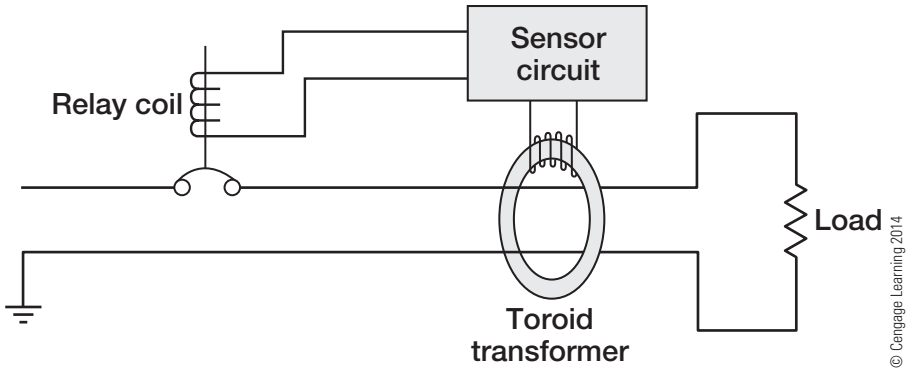


FIGURE 17-4 Both the hot and neutral conductors pass through the transformer.

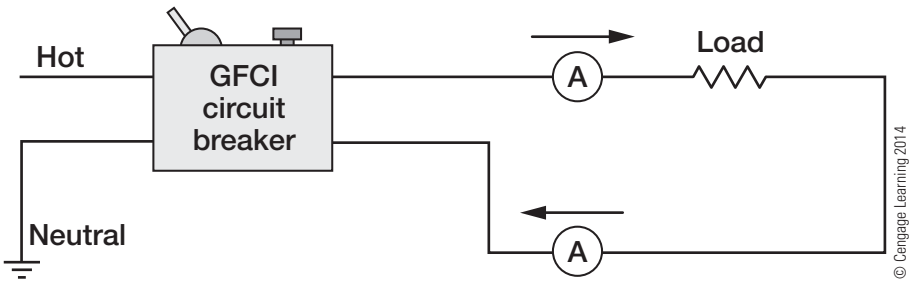


FIGURE 17-5 The current leaving the circuit breaker should be the same as the current returning.

toroid transformer, FIGURE 17-4. The ground fault circuit interrupter operates by sensing the amount of current flow in each conductor. Assume that current flows from the circuit breaker to the load and back to neutral, FIGURE 17-5. In a closed circuit, the amount of current leaving the circuit breaker should be the same as the amount of current returning. Therefore, the current should be the same in both the hot and neutral conductors but will flow in opposite directions. Since the two currents flow in opposite directions, the magnetic fields produced by the current in each conductor cancel each other. This results in no induced voltage in the toroid transformer.

A ground fault is an unintentional path to ground. Ground faults can be caused by many different conditions, such as bad insulation on an appliance cord where it enters the case of the appliance or the winding of a motor coming in contact with the motor case. These conditions can be hazardous, as when a person touches the case of the appliance and a grounded water line. At that moment a current path exists through the person to ground, FIGURE 17-6. Since there is now a separate current path to ground (other than the neutral conductor), more current flows in the hot, or ungrounded, conductor than in the neutral conductor. This produces a stronger magnetic field in the hot

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

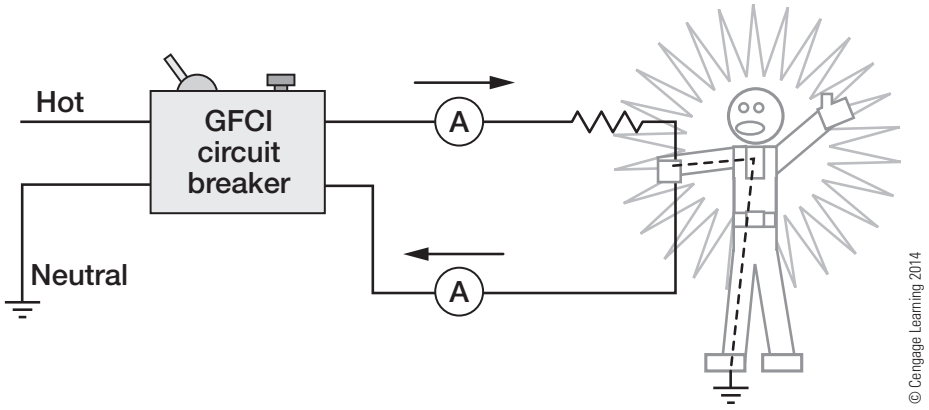


FIGURE 17-6 A ground fault is an unintended path to ground.

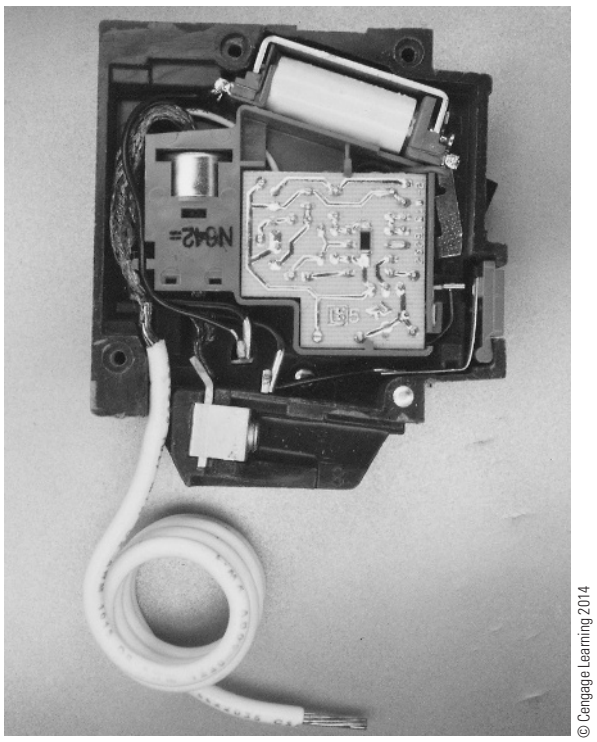


FIGURE 17-7 GFCI circuit breaker sensor circuit.

conductor. The extra field strength of the hot conductor induces a voltage into the toroid transformer. The toroid transformer signals the sensor circuit that there is a ground fault. The sensor circuit activates a small relay coil and opens the circuit breaker. The sensor circuit for a ground fault circuit breaker is shown in FIGURE 17-7. Ground fault circuit interrupters for personnel

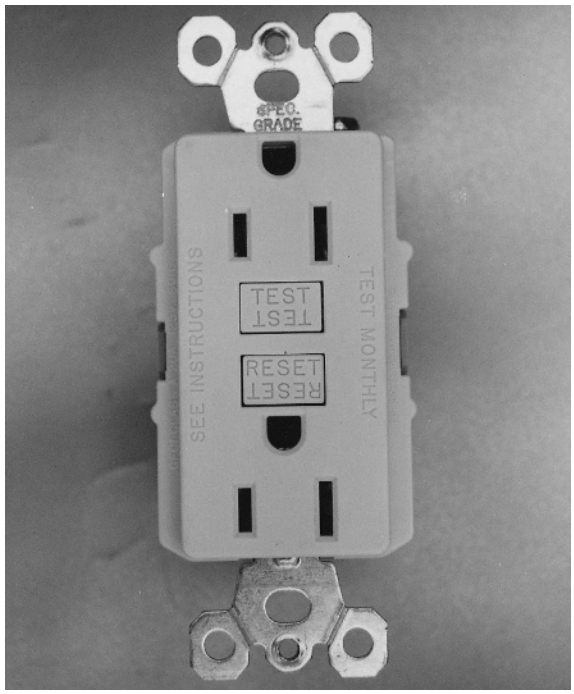
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

protection will open the circuit with a ground fault of approximately 5 mA (0.005 A). GFCI devices contain a test button that is used to check the device for proper operation. If the test button is pressed, the circuit breaker should trip open. The button should be tested periodically to ensure that the ground fault circuit operates properly.

GROUND FAULT RECEPTACLES

Another device used for ground fault protection of personnel is the GFCI receptacle, FIGURE 17-8. The receptacle has an advantage over the circuit breaker in that ground fault protection starts at the place of usage instead of in the service panel. Ground fault circuit breakers sometimes have a problem with nuisance tripping, caused mainly by long wire runs. Long wire runs can exhibit a fairly large amount of stray capacitance that causes leakage current to ground. The problem is generally more noticeable in damp weather than in dry and in areas close to the coast, because of salt content in the air.

Ground fault receptacles contain the same basic circuitry as the circuit breaker. They have a relay coil and a toroid transformer, FIGURE 17-9, and an electronic sensing circuit, FIGURE 17-10. When connecting GFCI receptacles,



© Cengage Learning 2014

FIGURE 17-8 GFCI receptacle.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

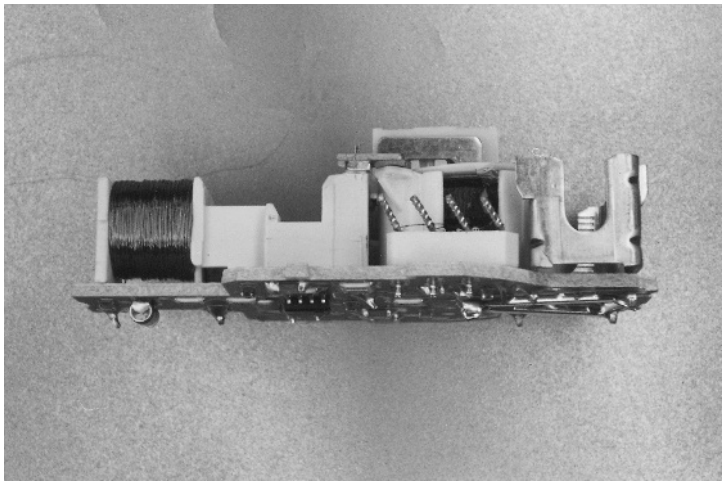

© Cengage Learning 2014

FIGURE 17-9 GFCI receptacles contain a relay coil and toroid transformer.

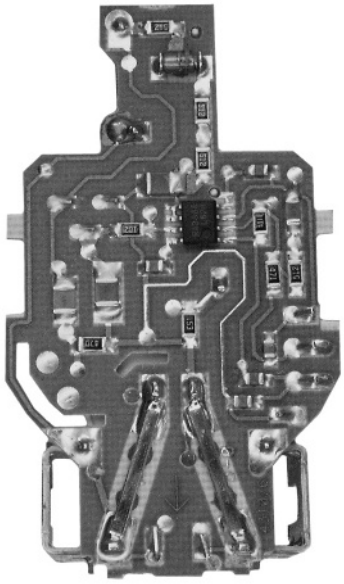
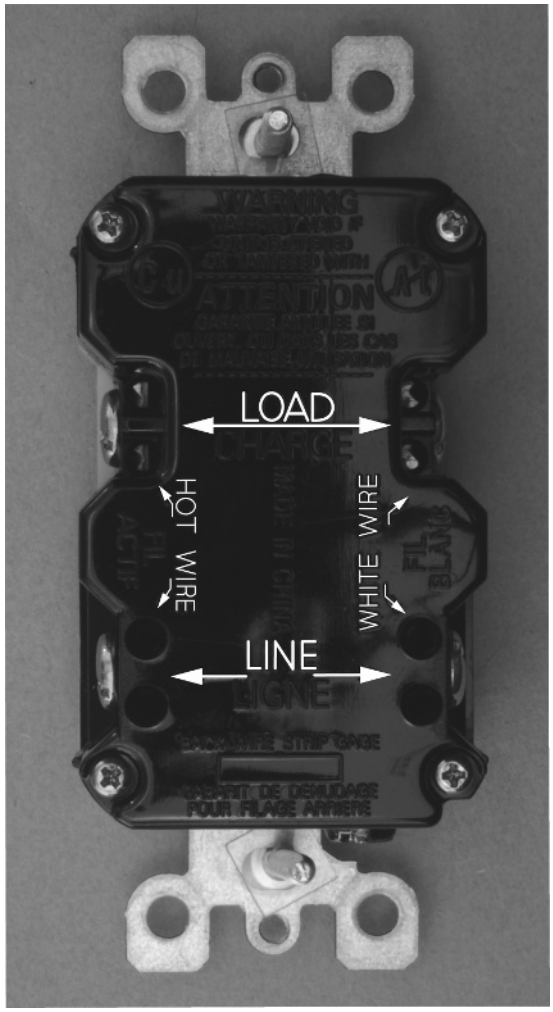

© Cengage Learning 2014

FIGURE 17-10 Electronic sensing circuit.

particular attention must be paid concerning how they are connected into the circuit. There are two important factors that must be considered.

1. The incoming power must be connected to the LINE side of the receptacle.
2. The hot and neutral conductors *must* be connected to the correct screws.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 17-11 The screw terminals are labeled LINE and LOAD.

The screw terminals on a ground fault receptacle are labeled LINE and LOAD, FIGURE 17-11. The incoming power must be connected to the LINE terminals and the hot and neutral conductors must be connected to the proper terminals, otherwise the device will not work. Any devices connected to the LOAD side of the receptacle are ground fault protected by the receptacle, FIGURE 17-12. Devices not connected to the load side are not protected.

The *National Electrical Code*® requires the use of ground fault interrupters on all outside receptacles and on receptacles in bathrooms, open garages, and boat docks; around swimming pools and fountains; within six feet of a kitchen sink; on snow-melting equipment; in crawl spaces and unfinished basements; and on recreational vehicles.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

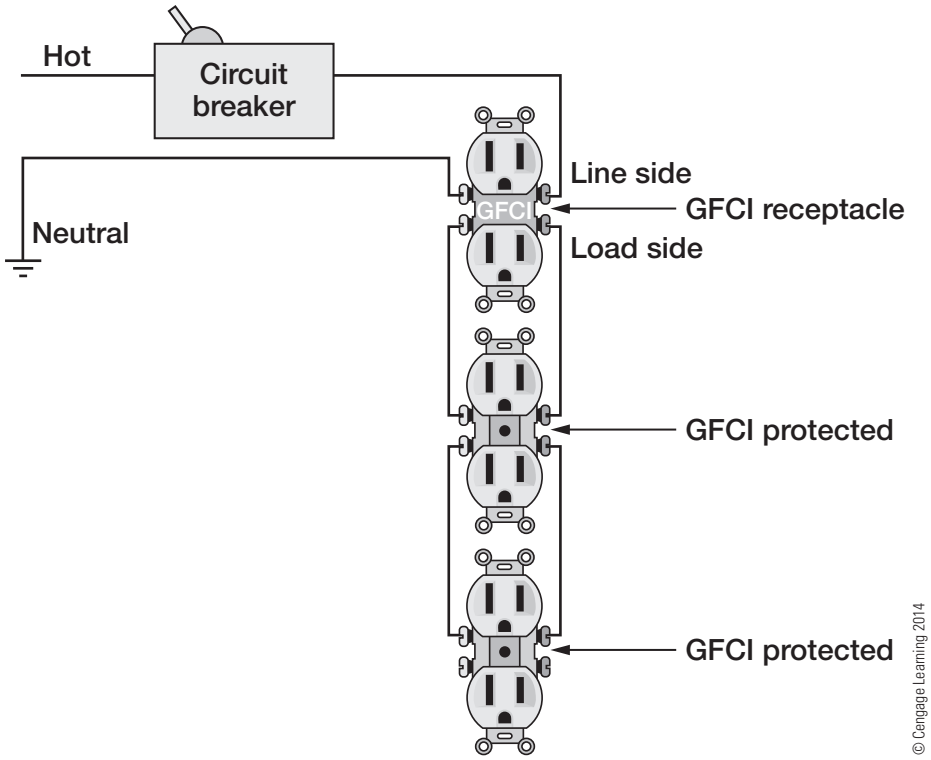


FIGURE 17-12 Devices connected to the LOAD side are GFCI protected.

ARC-FAULT CIRCUIT INTERRUPTERS

Arc-fault circuit interrupters (AFCIs) are similar to ground fault circuit interrupters in that they are designed to protect people from a particular hazard. The group fault interrupter is designed to protect against electrocution, whereas the arc-fault interrupter is intended to protect against fire. Studies have shown that one-third of electrical-related fires are caused by an arc-fault condition. The *National Electrical Code*® requires that arc-fault circuit interrupters be used on all 120-V, single-phase, 15- and 20-A circuits installed in dwelling units supplying power to family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, closets, hallways, or similar rooms or areas. An arc-fault is a plasma flame that can develop temperatures in excess of 6,000°C or 10,832°F. Arc-faults occur when an intermittent gap between two conductors or a conductor and ground permits current to "jump" between the two-conductive surfaces. There are two basic types of arc-faults, the parallel and the series.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

PARALLEL ARC-FAULTS

Parallel arc-faults are caused by two conductors becoming shorted together, FIGURE 17-13. A prime example of this is when the insulation of a lamp cord or extension cord has become damaged and permits the two conductors to short together. The current in this type of fault is limited by the resistance of the conductors in the circuit, and is generally much higher than the rated current of a typical thermo/magnetic circuit breaker. A continuous short will usually cause the circuit breaker to trip almost immediately because it will activate the magnetic part of the circuit breaker, but an intermittent short may take some time to heat the thermal part of the circuit breaker enough to cause it to trip open. Thermal/magnetic-type circuit breakers are generally effective in protecting against this type of arc-fault, but cords with small-size conductors, such as lamp and small extension cords, can add enough resistance to the circuit to permit the condition to exist long enough to produce sufficient heat to start a fire.

Parallel arc-faults are generally more hazardous than series arc-faults because they generate a greater amount of heat. Arc-faults of this type often cause hot metal to be ejected into combustible material. Parallel arc-faults, however, generally produce peak currents that are well above the normal current rating of a circuit breaker. This permits the electronic circuits in the arc-fault circuit interrupter to detect them very quickly and trip the breaker in a fraction of a second.

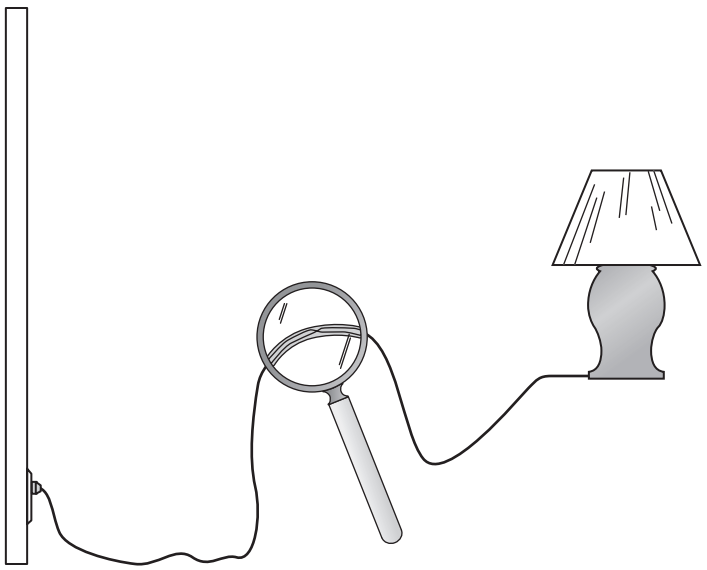


FIGURE 17-13 A parallel arc-fault is caused by two-conductors touching.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

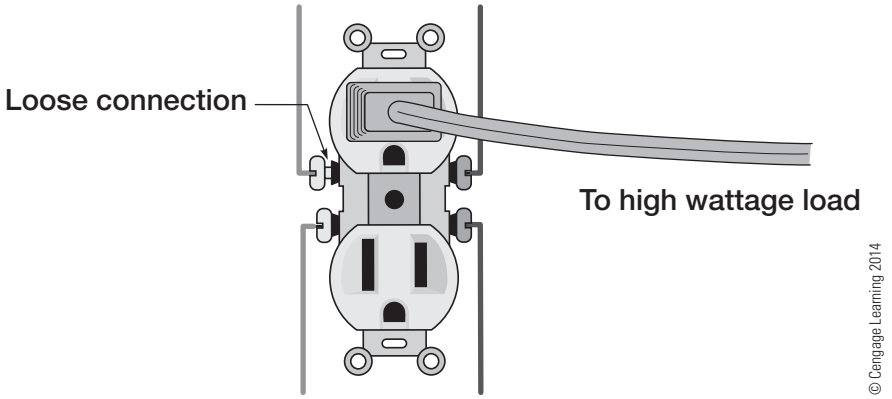


FIGURE 17-14 Loose connections are the cause of most series arc-faults.

SERIES ARC-FAULTS

Series arc-faults are generally caused by loose connections. A loose screw on an outlet terminal or an improperly made wire-nut connection are prime examples of this type of problem. They are called series arc-faults because the circuit contains some type of current-limiting resistance connected in series with the arc, FIGURE 17-14. Although the amount of electrical energy converted into heat is less than that of a parallel arc-fault, series arc-faults can be more dangerous. The fact that the current is limited by some type of load keeps the current below the thermal and magnetic trip rating of a common thermo/magnetic circuit breaker. Since the peak arc current is never greater than the normal steady current flow, series arcing is more difficult to detect than parallel arcing.

When the current of an arc remains below the normal range of a common thermo/magnetic circuit breaker it cannot provide protection. If a hair dryer, for example, normally has a current draw of 12 A, but the wall outlet has a loose screw at one terminal so that the circuit makes connection only one half of the time, the average circuit current is 6 A. This is well below the trip rating of a common circuit breaker. A 6-A arc, however, can produce a tremendous amount of heat in a small area.

ARC-FAULT DETECTION

There are conditions where arcing in an electrical circuit is normal, such as

- turning a light switch on or off;
- switching of a motor relay;
- plugging in an appliance that is already turned on;

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

- changing a light bulb with the power turned on;
- the arcs caused by motors that contain a commutator and brushes.

The arc-fault circuit interrupter is designed to be able to distinguish between normally occurring arcs and an arc-fault. An arc caused by a toggle switch being used to turn a light on or off will produce a current spike of short duration as shown in FIGURE 17-15. An arc-fault, however, is an intermittent connection and will generally produce current spikes of various magnitudes and lengths of time, FIGURE 17-16. In order for an arc-fault circuit interrupter to determine the difference between a normally occurring arc and an arc-fault, a microprocessor and other related electronic components are employed to detect these differences. The AFCI contains current and temperature sensors as well as a microprocessor and nonvolatile (retains its information when power is switched off) memory. The current and temperature sensors permit the AFCI to operate as a normal circuit breaker in the event of a circuit overload or short circuit. The microprocessor continuously monitors the current and compares the waveform to information stored in the memory. The microprocessor monitors the current for the magnitude, duration, and length of time between pulses, not for a particular waveform. For this reason, there are some appliances that can produce waveforms similar to that of an arc-fault and may cause the AFCI to trip. Appliances containing motors that employ the use of brushes and a commutator, such as vacuum cleaners and hand drills, will produce a similar waveform.

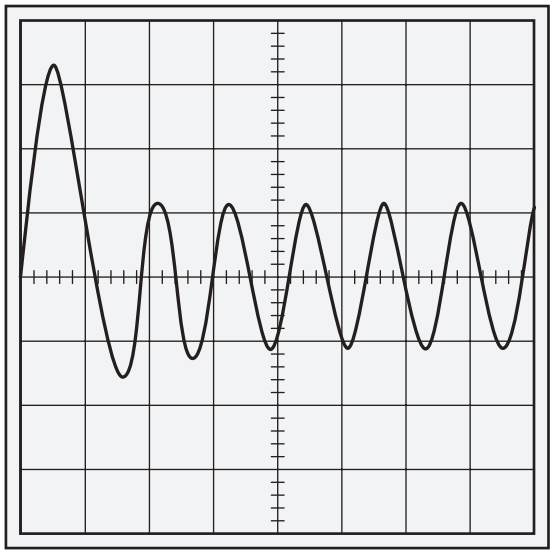

© Cengage Learning 2014

FIGURE 17-15 Typical current spike caused by turning a light switch on or off.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

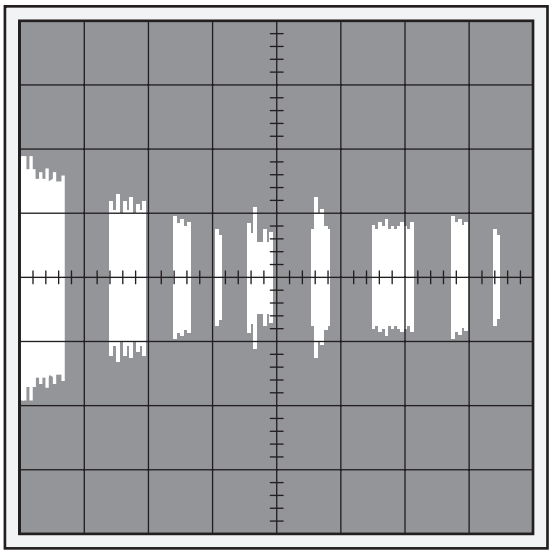

© Cengage Learning 2014

FIGURE 17-16 Typical waveform produced by an arc-fault.

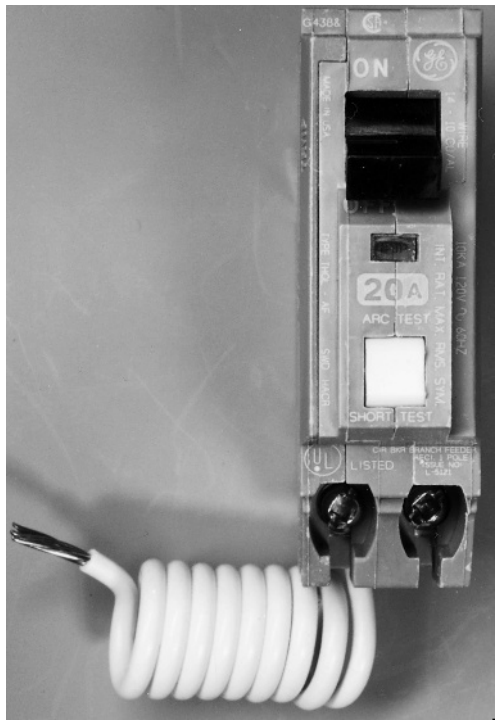
CONNECTING AN ARC-FAULT CIRCUIT INTERRUPTER

The AFCI is connected in the same manner as a ground fault circuit breaker. The AFCI contains a white pig tail, FIGURE 17-17, that is connected to the neutral bus bar in the panel box. Both the neutral and hot or ungrounded conductors of the branch circuit are connected to the arc-fault circuit breaker. The circuit breaker contains a silver-colored and a brass-colored screw. The neutral or white wire of the branch circuit is inserted under the silver screw and the black wire is inserted under the brass screw. A rocker switch located on the front of the AFCI permits the breaker to be tested for both short and arc condition. In addition to the manual test switch, the microprocessor performs a self-test about once every 10 minutes.

LIGHT DIMMERS

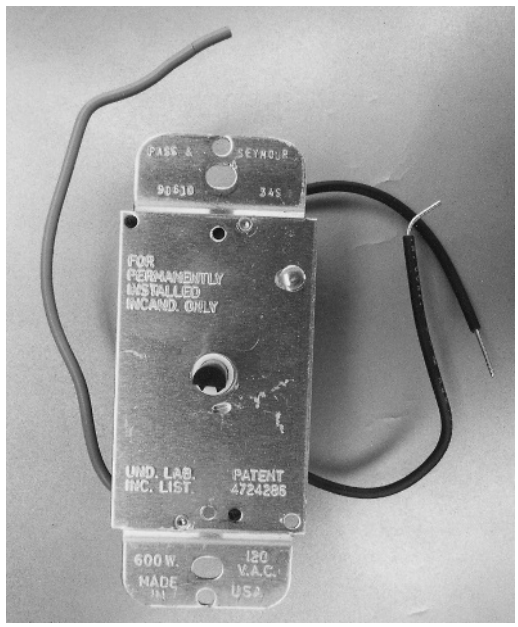
Another common device used in general wiring is the light dimmer, FIGURE 17-18. Dimmers can be obtained that employ single-pole or three-way switches. Single-pole dimmers generally have one green and two black pig-tail leads. The two black leads are connected to the switch terminals, and the green is for the grounding. Three-way switch dimmers commonly use one black and two red pig tails plus a green for grounding. The two red pig tails are the traveler connections, and the black is the common. Most dimmers are for use on incandescent lamps only and should not be used to control

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 17-17 Arc-fault circuit interrupter.



© Cengage Learning 2014

FIGURE 17-18 Light dimmer.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

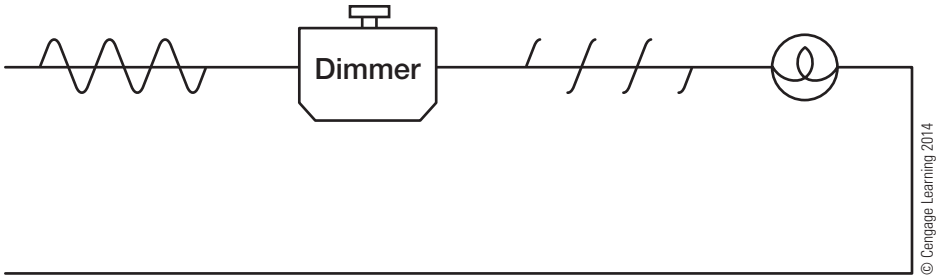


FIGURE 17-19 The dimmer operates by chopping the AC waveform.

fluorescent lights or ceiling fans. There are some fluorescent lights that can be dimmed, but they require a special ballast and dimmer control.

Light dimmers operate by chopping the AC waveform applied to the lamp, FIGURE 17-19. If the waveform is on for 50% of the time and off for 50% of the time, the voltage applied to the load will be one-half the applied voltage. If the waveform is permitted to remain on for 75% of the time and off for 25% of the time, the voltage applied to the load will be 75% of the line value, or 90 V if the circuit voltage is 120 V. A solid-state component called a triac is used to control the AC waveform. The triac is a bidirectional device in that it will permit current to flow through it in either direction. The triac is a member of the thyristor family of devices. Thyristors are solid-state devices that exhibit only two states of operation, on or off. To turn the triac on, current must be applied to the gate circuit. A simple triac control circuit is shown in FIGURE 17-20. The control knob on the dimmer switch is connected to the variable resistor, or pot. A second resistor is used to limit current to the base of the triac in the event that the control knob should be turned to zero resistance. A second solid-state component, called a diac, is used to control when gate current is applied to the triac. The diac is a bidirectional,

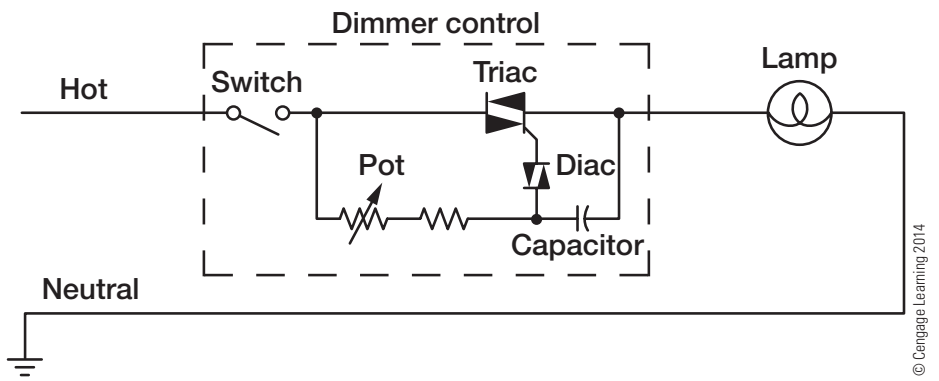


FIGURE 17-20 Basic dimmer switch control circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

voltage-activated diode. The diac will not turn on until the voltage applied to it reaches a certain value. In this circuit, that value will be assumed to be 15 V. When the diac turns on, it will remain on until the voltage drops to a value less than that needed to turn it on. That value will be assumed to be 5 V. The circuit operates as follows:

1. When the switch is closed, the triac is turned off but current flows through the pot (variable resistor) and current-limiting fixed resistor to the capacitor. The resistance value of the pot and current-limiting resistor determines the charge time of the capacitor.
2. When the capacitor charges to a value of 15 V, the diac turns on and discharges the capacitor through the gate of the triac, causing the triac to turn on and supply power to the lamp. When the capacitor discharges to a value of 5 V, the diac turns off and the capacitor begins charging again.
3. At the end of each half-cycle, the triac will turn off and remain off until it receives another pulse of gate current.
4. Since the value of the pot controls the charge time of the capacitor, the triac can be gated on at different times during the cycle of AC voltage.

The circuit board for a typical dimmer control is shown in FIGURE 17-21.

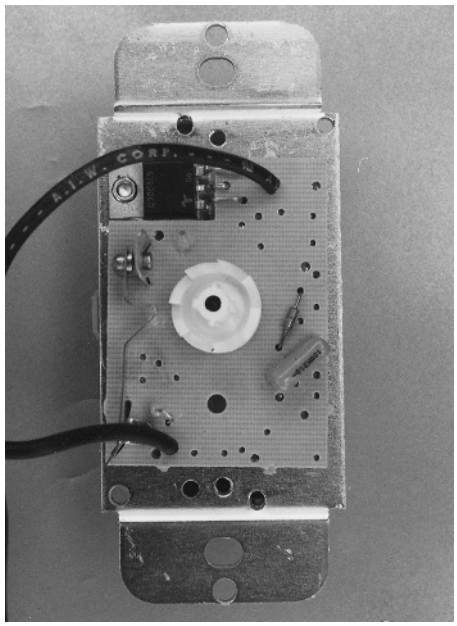


FIGURE 17-21 Typical dimmer control circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CHIMES

A device common to almost every home is the chime or doorbell. Chime circuits are operated on voltages that generally range from 24- to 16-V AC. A small transformer converts the standard 120 V to the chime voltage, FIGURE 17-22. The transformer is generally mounted to a standard square or octagon box, FIGURE 17-23. The *National Electrical Code*® requires that the 120-V connections be made inside a box, but the low-voltage circuit is not required to be inside a box. For this reason, low-voltage transformers supplying power to electric chime circuits are generally mounted outside the box.

Electric chimes can be obtained in a variety of styles. Some are single note, meaning that they will make the same tone when activated regardless of which button is pressed. Some are electronic and can be set to play different sounds or complete tunes. Most can be set to play different sounds depending on which button is pressed. A simple two-tone chime contains two solenoids, FIGURE 17-24. One side of each solenoid winding is connected together to form a common terminal. A basic connection for a chime



© Cengage Learning 2014

FIGURE 17-22 Typical 16-V chime transformer.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

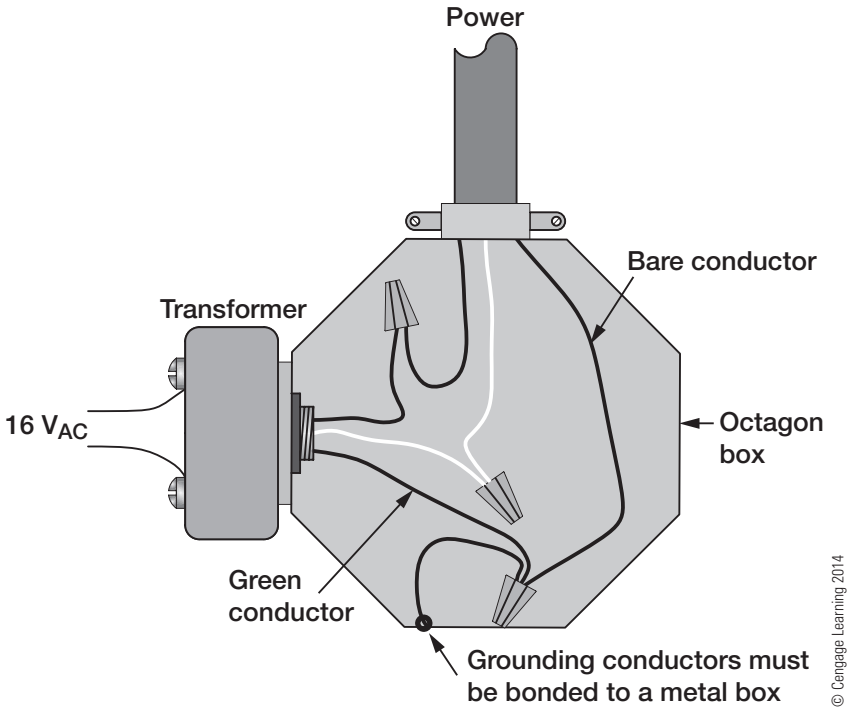


FIGURE 17-23 High-voltage connections must be made inside a box.

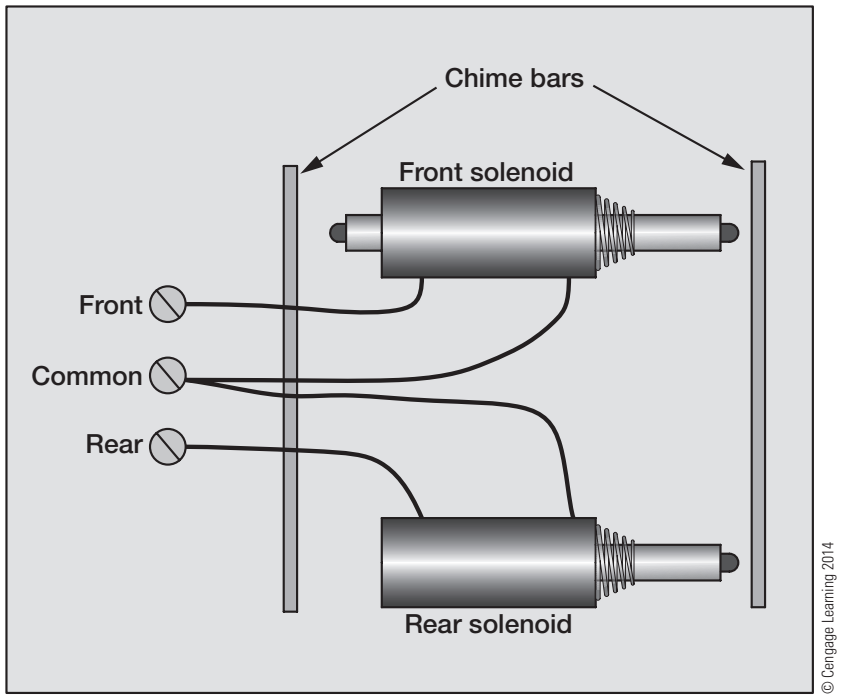


FIGURE 17-24 A two-tone chime contains two solenoids.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

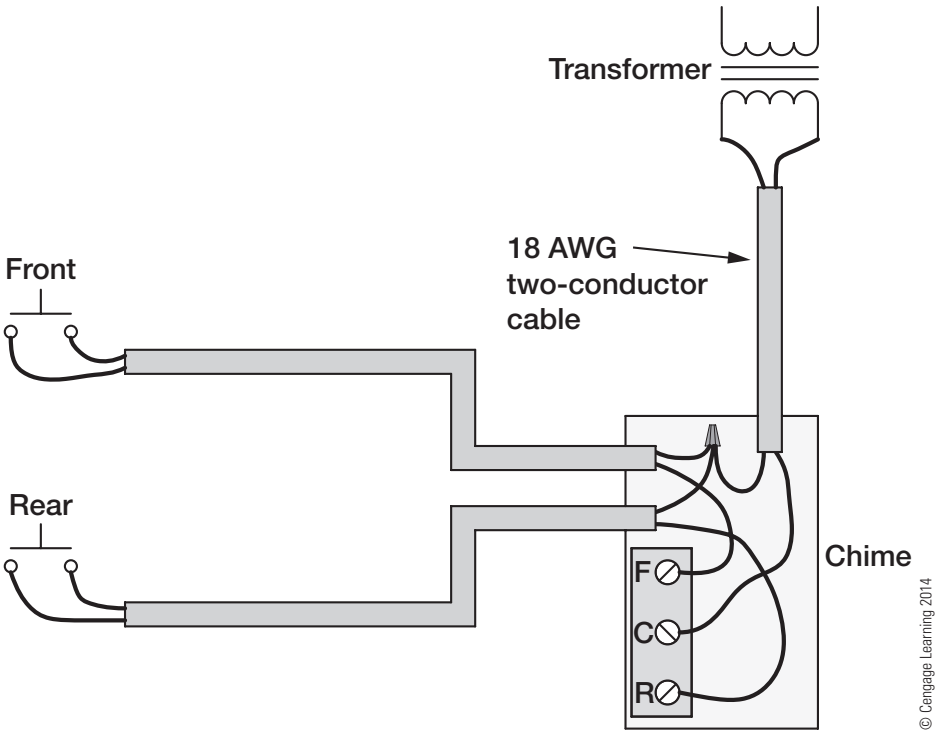


FIGURE 17-25 18-AWG two-conductor cable is used for low-voltage chime circuits.

circuit with two pushbuttons is shown in FIGURE 17-25. Chime circuits are generally made using 18-AWG two-conductor bell wire. The two-conductor cable is brought for the transformer and each pushbutton to the chime. Connection is made inside the chime. One side of the transformer is connected to the common terminal on the terminal board. The other side of the transformer supplies power to one side of each pushbutton. The other side of the pushbutton is connected to the appropriate front (F) or rear (R) terminal on the board. A schematic diagram of this basic circuit is shown in FIGURE 17-26.

Large homes often require more than one chime. This is accomplished by connecting the additional chimes in parallel with the master chime. The master chime is the one with the transformer and pushbutton connections, FIGURE 17-27. When additional chimes are connected to the circuit, a transformer with a larger volt-ampere rating than that used for a single chime is generally required.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

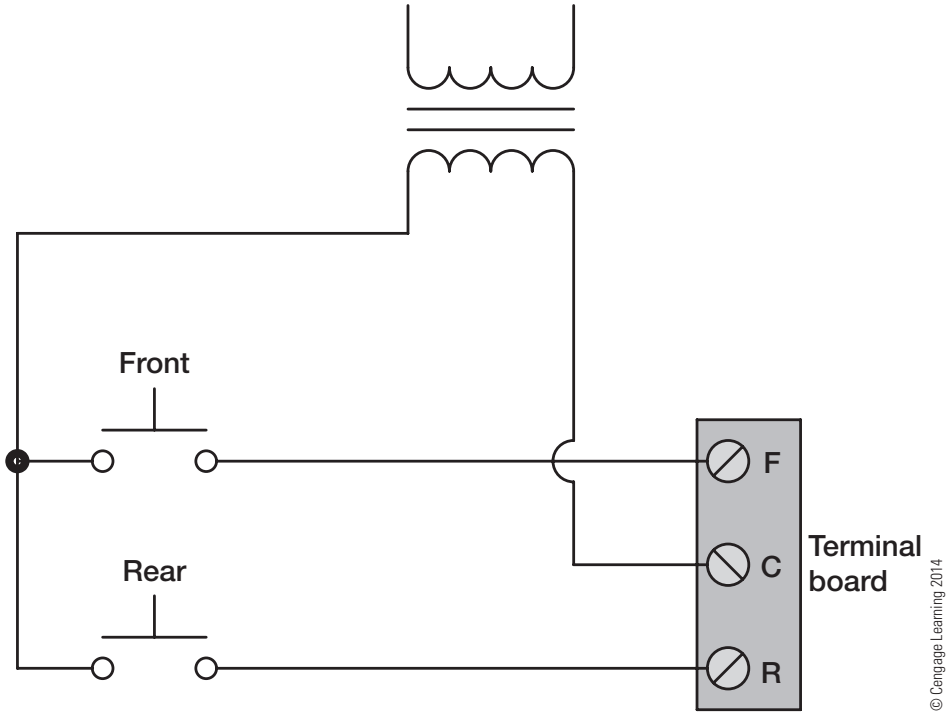


FIGURE 17-26 Schematic diagram of a chime circuit with two pushbuttons.

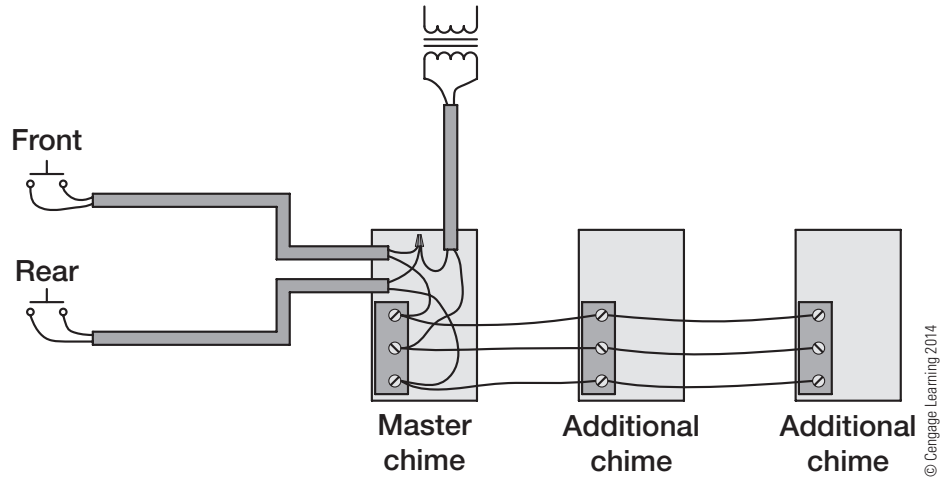


FIGURE 17-27 Additional chimes can be added to the master chime.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Summary

1. A ground fault is an unintended path to ground.
2. Ground fault detectors for personnel protection will open the circuit with a fault current of approximately 5 mA.
3. Ground fault detectors for personnel protection can be obtained as circuit breakers or receptacles.
4. GFCI circuit breakers have two screws, instead of one, for connection to branch circuit conductors.
5. When installing a GFCI circuit breaker, both the hot and neutral branch circuit conductors must be terminated at the circuit breaker.
6. All devices connected to a GFCI circuit breaker are ground fault protected.
7. When installing a GFCI receptacle, the incoming power must be connected to the LINE side of the receptacle.
8. Devices connected to the LOAD side of a GFCI receptacle are ground fault protected by the receptacle.
9. The *National Electrical Code*® requires GFCIs on outside receptacles and on receptacles around swimming pools and fountains; in unfinished basements, garages, bathrooms, and kitchens; on snow-melting equipment; and in recreational vehicles (RVs).
10. Light dimmers control the voltage applied to the lamp by chopping the AC waveform.
11. Light dimmers use a triac as the main control device.
12. Arc-fault circuit interrupters contain a microprocessor that examines the current waveform.
13. Arc-fault circuit interrupters are intended to protect people against fire.
14. Thirty-three percent of electrical fires are caused by arc-faults.
15. Chime circuits operate on 24- to 16-V AC.
16. 18-AWG two-conductor bell wire is used for connecting chime circuits.
17. Additional chimes can be connected in parallel with the master chime.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Review Questions

1. What part of the circuit is used to detect the presence of a fault current in a ground fault circuit interrupter device?
2. Ground fault circuit interrupters intended for personnel protection open the circuit with ____ A of fault current.
3. When installing a GFCI receptacle, should the incoming power be connected to the LINE or LOAD side of the receptacle?
4. When installing a GFCI receptacle, how is it possible to use the receptacle to provide ground fault protection to other receptacles on the same circuit?
5. What type of solid-state device does a light dimmer use to control the voltage to the light?
6. Both ground fault circuit interrupters and arc-fault circuit interrupters are intended to protect people from certain hazards. What hazard is each intended to protect people against?
7. Is it possible for a ground fault circuit interrupter to operate if the grounding conductor (bare or green wire) has not been connected? Explain your answer.
8. Arc-faults can develop temperatures in excess of ____°C.
9. The *National Electrical Code*® requires that arc-fault circuit interrupters be used in what type of circuits?
10. Between the parallel and series arc-faults, which is generally more dangerous and why?
11. How much voltage is supplied to most chime circuits?
12. What type and size conductors are generally used for wiring the low-voltage side of chime circuits?
13. In a home with multiple chimes, which chime is considerd the master chime?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 18

Three-Phase Motors

OBJECTIVES: After studying this unit, you should be able to:

- Discuss the basic operating principles of three-phase motors.
- List factors that produce a rotating magnetic field.
- List different types of three-phase motors.
- Discuss the operating principles of squirrel-cage motors.
- Connect dual-voltage motors for proper operation on the desired voltage.
- Discuss the operation of consequent pole motors.
- Discuss the operation of wound-rotor motors.
- Discuss the operation of synchronous motors.

Three-phase motors are used as the prime mover for industry throughout the United States and Canada. These motors convert the three-phase alternating current into mechanical energy to operate all types of machinery. Three-phase motors are smaller

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

in size and lighter in weight, and they have higher efficiencies per horsepower than single-phase motors. They are extremely rugged and require very little maintenance. Many of these motors operate twenty-four hours a day, seven days a week for many years without a problem.

THREE-PHASE MOTORS

There are three basic types of three-phase motors:

1. The squirrel-cage induction motor
2. The wound-rotor induction motor
3. The synchronous motor

All three motors operate on the same principle, and they all use the same basic design for the stator windings. The difference between these motors is the type of rotor used. Two of the three motors are induction motors and operate on the principle of electromagnetic induction in a manner similar to transformers. In fact, AC induction motors were patented as **rotating transformers** by Nikola Tesla. The stator winding of a motor is often referred to as the motor primary, and the rotor is referred to as the motor secondary.

rotating transformers
Nicola Tesla patented induction motors as rotating transformers.

THE ROTATING MAGNETIC FIELD

The principle of operation for all three-phase motors is the **rotating magnetic field.** There are three factors that cause the magnetic field to rotate:

rotating magnetic field
a magnetic field that rotates.

1. Voltages in a three-phase system that are 120° out of phase with each other
2. The three voltages changing polarity at regular intervals
3. The arrangement of the stator windings around the inside of the motor

SYNCHRONOUS SPEED

The speed at which the magnetic field rotates is called the **synchronous speed.** Two factors that determine the speed of the rotating magnetic field are as follows:

synchronous speed
speed of the rotating magnetic field of an AC induction motor.

1. The number of stator poles (per phase)
2. The frequency of the applied voltage

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The following chart shows the synchronous speed at 60 Hz for different numbers of stator poles.

RPM	STATOR POLES
3,600	2
1,800	4
1,200	6
900	8

The stator winding of a three-phase motor is shown in FIGURE 18-1. The synchronous speed can be calculated using the following formula:

$$S = \frac{120\ F}{P}$$

where

S = speed in RPM

F = frequency in Hz

P = number of stator poles (per phase)

EXAMPLE 1: What is the synchronous speed of a four-pole motor connected to 50 Hz?

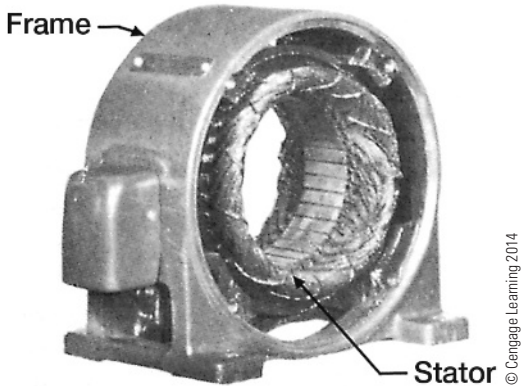


FIGURE 18-1 Stator of a three-phase motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Solution:

$$S = \frac{120 \times 50}{4}$$

$$S = 1500 \text{ RPM}$$

EXAMPLE 2: What frequency should be applied to a six-pole motor to produce a synchronous speed of 400 RPM?

Solution:
First change the base formula to find frequency. Once that is done, known values can be substituted in the formula.

$$F = \frac{PS}{120}$$

$$F = \frac{6 \times 400}{120}$$

$$F = 20 \text{ Hz}$$

KEY POINT
The direction of rotation of any three-phase motor can be changed by reversing two of its stator leads.

DIRECTION OF ROTATION FOR THREE-PHASE MOTORS

On many types of machinery, the direction of rotation of the motor is critical. **The direction of rotation of any three-phase motor can be changed by reversing two of its stator leads.** This causes the direction of the rotating magnetic field to reverse. When a motor is connected to a machine that will not be damaged when its direction of rotation is reversed, power can be momentarily applied to the motor to observe its direction of rotation. If the rotation is incorrect, any two-line leads can be interchanged to reverse the motor's rotation.

When a motor is to be connected to a machine that can be damaged by incorrect rotation, however, the direction of rotation must be determined before the motor is connected to its load. This can be accomplished in two basic ways. One way is to make electrical connection to the motor before it is mechanically connected to the load. The **direction of rotation** can then be tested by momentarily applying power to the motor before it is coupled to the load.

There may be occasions when this is not practical or is very inconvenient. It is possible to determine the direction of rotation of a motor before power is connected to it with the use of a **phase rotation meter.** The phase rotation meter is used to compare the phase rotation of two different three-phase

direction of rotation
direction the magnetic field rotates.

phase rotation meter
a device for determining the direction of field rotation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

connections. The meter contains six terminal leads. Three of the leads are connected to one side of the meter and labeled MOTOR. These three motor leads are labeled A, B, or C. The LINE leads are located on the other side of the meter, and are labeled A, B, or C.

To determine the direction of rotation of the motor, first zero the meter by following the instructions provided by the manufacturer. Then set the meter selector switch to MOTOR, and connect the three MOTOR leads of the meter to the T-leads of the motor as shown in FIGURE 18-2. The phase rotation meter contains a zero-center voltmeter. One side of the voltmeter is labeled INCORRECT, and the other side is labeled CORRECT. While observing the zero-center voltmeter, manually turn the motor shaft in the direction of desired rotation. The zero-center voltmeter will immediately swing in the CORRECT or INCORRECT direction. When the motor shaft stops turning, the needle may swing in the opposite direction. It is the first indication of the voltmeter that is to be used.

If the voltmeter needle indicated CORRECT, label the motor T-leads A, B, or C to correspond with the MOTOR leads from the phase rotation meter. If the voltmeter needle indicated INCORRECT, change any two of the MOTOR leads from the phase rotation meter and again turn the motor shaft. The voltmeter needle should now indicate CORRECT. The motor T-leads can now be labeled to correspond with the MOTOR leads from the phase rotation meter.

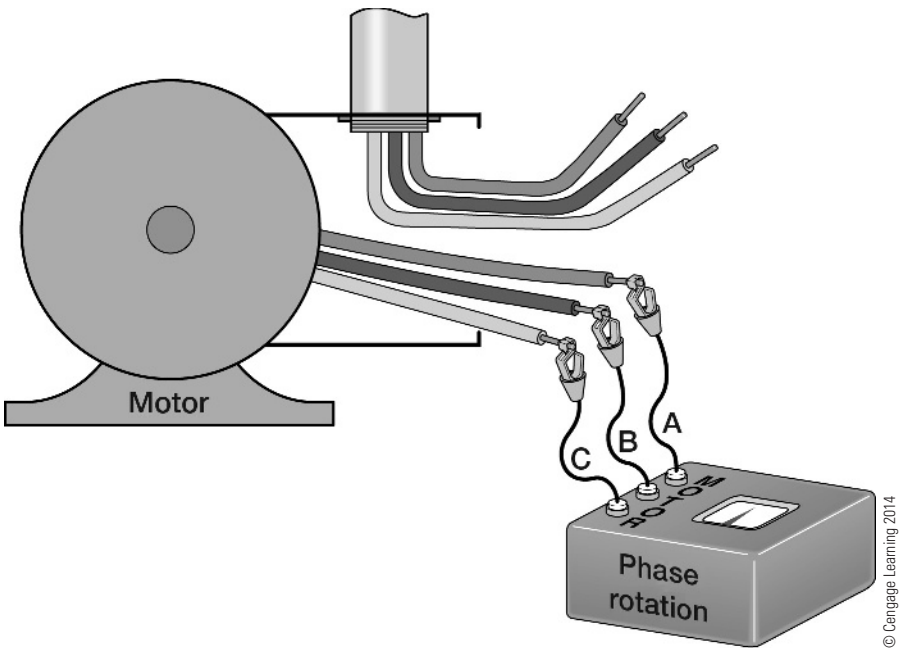


FIGURE 18-2 Connecting the phase rotation meter to the motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

After the motor T-leads have been labeled A, B, or C to correspond with the leads of the phase rotation meter, the rotation of the line supplying power to the motor must be determined. Set the selector switch on the phase rotation meter to the LINE position. After making certain the power has been turned off, connect the three LINE leads of the phase rotation meter to the incoming power line, FIGURE 18-3. Turn on the power and observe the zero-center voltmeter. If the meter is pointing in the CORRECT direction, turn off the power and label the line leads A, B, or C to correspond with the LINE leads of the phase rotation meter.

If the voltmeter is pointing in the INCORRECT direction, turn off the power and change any two of the leads from the phase rotation meter. When the power is turned on, the voltmeter should point in the CORRECT direction. Turn off the power and label the line leads A, B, or C to correspond with the leads from the phase rotation meter.

Now that the motor T-leads and the incoming power leads have been labeled, connect the line lead labeled A to the T-lead labeled A, the line lead labeled B to the T-lead labeled B, and the line lead labeled C to the T-lead labeled C. When power is connected to the motor, it will operate in the proper direction.

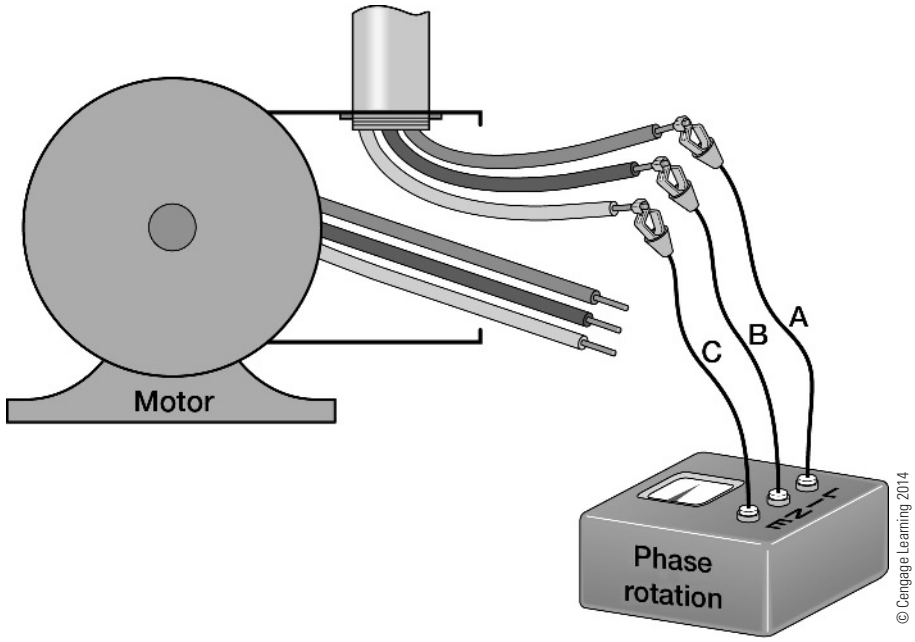


FIGURE 18-3 Connecting the phase rotation meter to the line.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CONNECTING DUAL-VOLTAGE THREE-PHASE MOTORS

Many of the three-phase motors used in industry are designed to be operated on two voltages, such as 240 V or 480 V. Motors of this type contain two sets of windings per phase. Most dual-voltage motors bring out nine T-leads at the terminal box. There is a standard method used to number these leads, as shown in FIGURE 18-4. Starting with terminal 1, the leads are numbered in a decreasing spiral as shown. Another method of determining the proper lead numbers is to add three to each terminal. For example, starting with lead 1, add three to one. Three plus one equals four. The phase winding that begins with 1 ends with 4. Now add three to four. Three plus four equals seven. The beginning of the second winding for phase 1 is 7. This method will work for the windings of all phases. If in doubt, draw a diagram of the phase windings and number them in a spiral.

HIGH-VOLTAGE CONNECTIONS

Three-phase motors can be constructed to operate in either wye or delta. If a motor is to be connected to high voltage, the phase windings will be connected in series. In FIGURE 18-5, a schematic diagram and terminal connection chart for high voltage are shown for a wye-connected motor. In FIGURE 18-6, a schematic diagram and terminal connection chart for high voltage are shown for a delta-connected motor. Notice that in both cases the windings are connected in series.

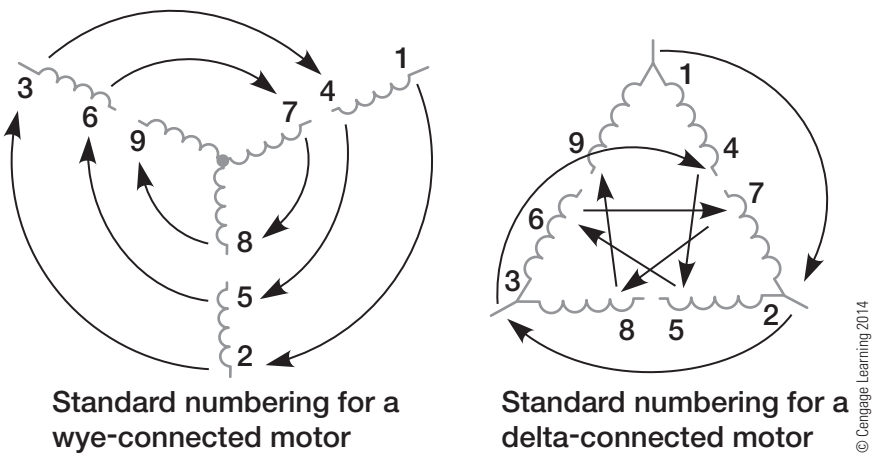


FIGURE 18-4 Standard numbering for three-phase motors.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

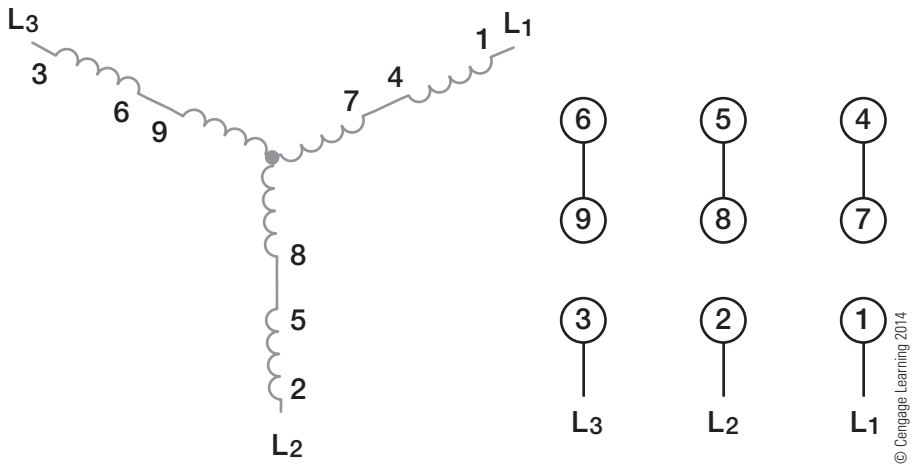


FIGURE 18-5 High-voltage wye connection.

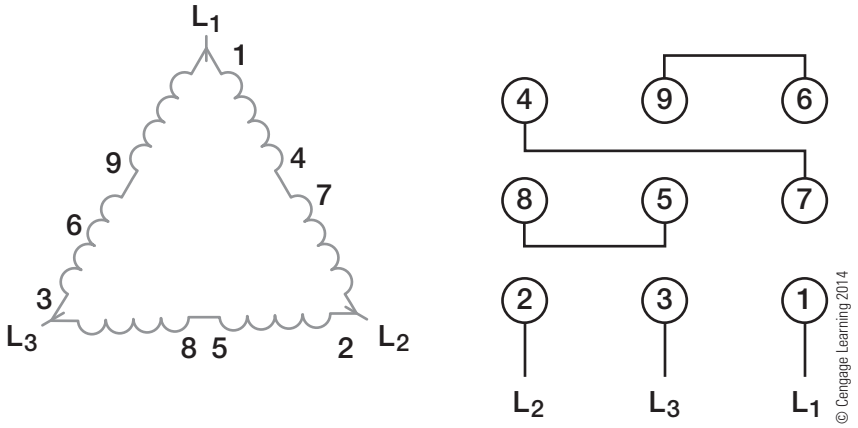


FIGURE 18-6 High-voltage delta connection.

LOW-VOLTAGE CONNECTIONS

When a motor is to be connected for low-voltage operation, the phase windings must connect in parallel. FIGURE 18-7 shows the basic schematic diagram for a wye-connected motor with parallel phase windings. In actual practice, however, it is not possible to make this exact connection with a nine-lead motor. The schematic shows that terminal 4 connects to the other end of the phase winding that starts with terminal 7. Terminal 5 connects to the other end of winding 8, and terminal 6 connects to the other end of winding 9. In actual motor construction, the opposite ends of windings 7, 8, and 9 are

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

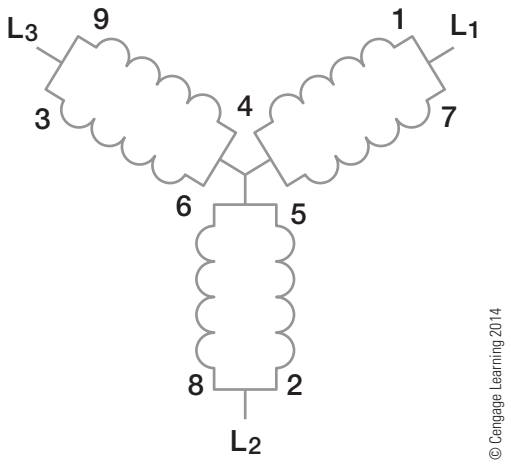


FIGURE 18-7 Stator windings connected in parallel.

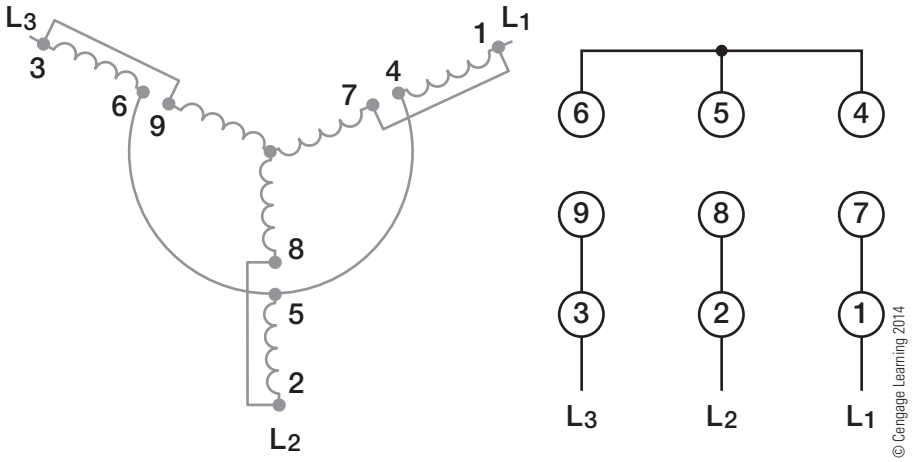


FIGURE 18-8 Low-voltage wye connection.

connected together inside the motor and are not brought outside the motor case. The problem is solved, however, by forming a second wye connection by connecting terminals 4, 5, and 6 as shown in FIGURE 18-8.

The phase windings of a delta-connected motor must also be connected in parallel for use on low voltage. A schematic for this connection is shown in FIGURE 18-9. A connection diagram and terminal connection chart for this hook-up are shown in FIGURE 18-10.

Some dual-voltage motors will contain twelve T-leads instead of nine. In this instance, the opposite ends of terminals 7, 8, and 9 are brought out for

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

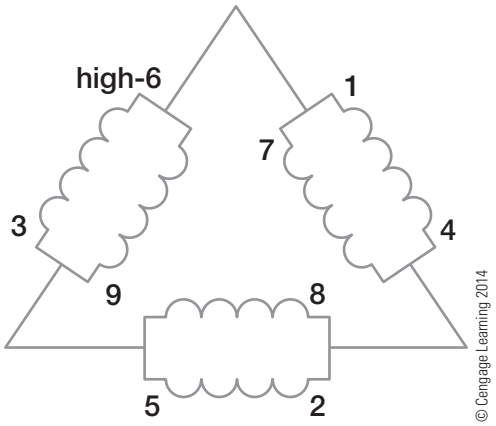


FIGURE 18-9 Parallel delta connection.

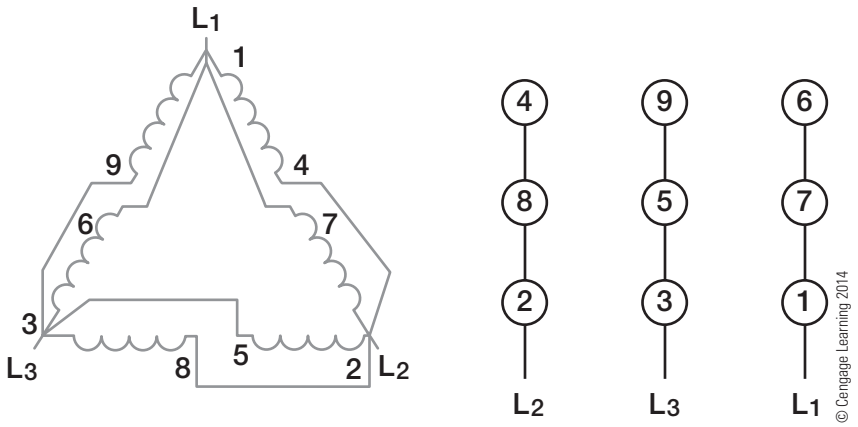


FIGURE 18-10 Low-voltage delta connection.

connection. FIGURE 18-11 shows the standard numbering for both delta- and wye-connected motors. Twelve leads are brought out if the motor is intended to be used for wye-delta starting. When this is the case, the motor must be designed for normal operation with its windings connected in delta. If the windings are connected in wye during starting, the starting current of the motor is reduced to one-third of what it will be if the motor is started as a delta.

VOLTAGE AND CURRENT RELATIONSHIPS FOR DUAL-VOLTAGE MOTORS

When a motor is connected to the higher voltage, the current flow will be half as much as when it is connected for low-voltage operation. The reason is that when the windings are connected in series for high-voltage operation,

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

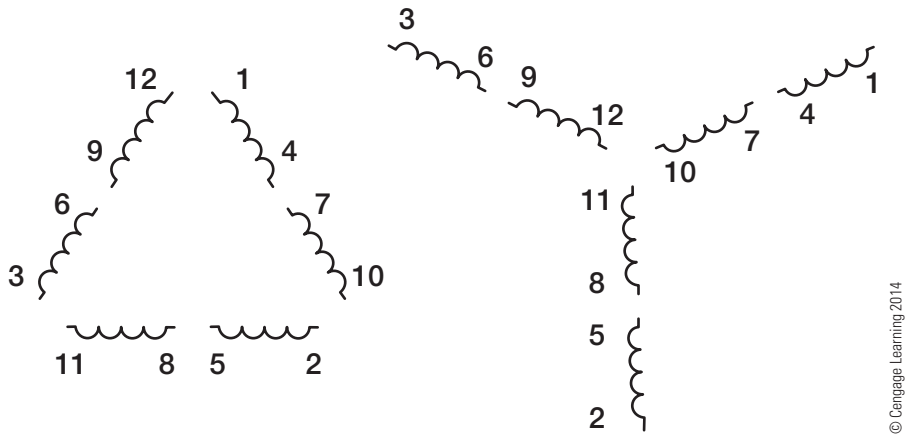


FIGURE 18-11 A twelve-lead motor.

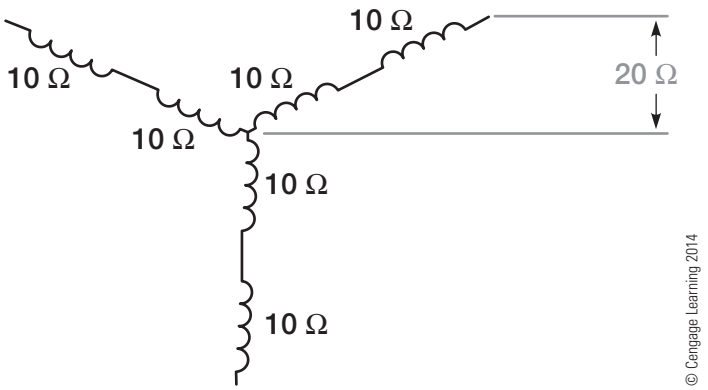


FIGURE 18-12 Impedance adds in series.

the impedance will be four times greater than when the windings are connected for low-voltage operation. For example, assume a dual-voltage motor is intended to operate on 480 V or 240 V. Also assume that during full load, the motor's windings exhibit an impedance of 10 Ω each. When the winding is connected in series, FIGURE 18-12, the impedance per phase will be 20 Ω (10 + 10 = 20).

If a voltage of 480 V is connected to the motor, the phase voltage will be

$$E_{PHASE} = \frac{E_{LINE}}{1.732}$$

$$E_{PHASE} = \frac{480}{1.732}$$

$$E_{PHASE} = 277 \text{ V}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The amount of current flow through the phase can be computed using Ohm's Law.

$$I = \frac{E}{Z}$$

$$I = \frac{277}{20}$$

$$I = 13.85 \text{ A}$$

If the stator windings are connected in parallel, the total impedance will be found by adding the reciprocals of the impedances of the windings, FIGURE 18-13.

$$Z_T = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}}$$

$$Z_T = 5\ \Omega$$

If a voltage of 240 V is connected to the motor, the voltage applied across each phase will be 138.6 V (240/1.732 = 138.6). The amount of phase current can now be computed using Ohm's Law.

$$I = \frac{E}{Z}$$

$$I = \frac{138.6}{5}$$

$$I = 27.72 \text{ A}$$

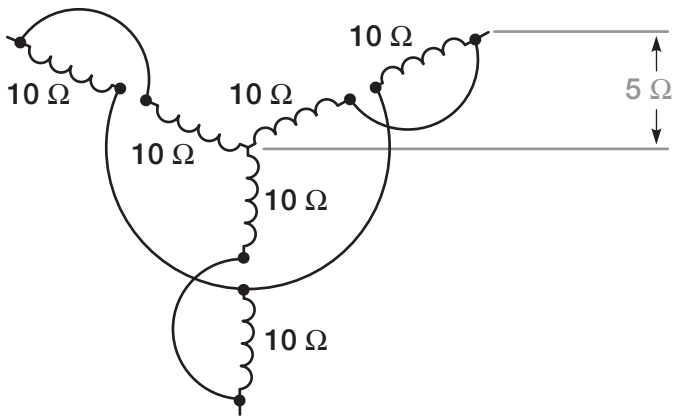


FIGURE 18-13 Impedance is less when in parallel.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

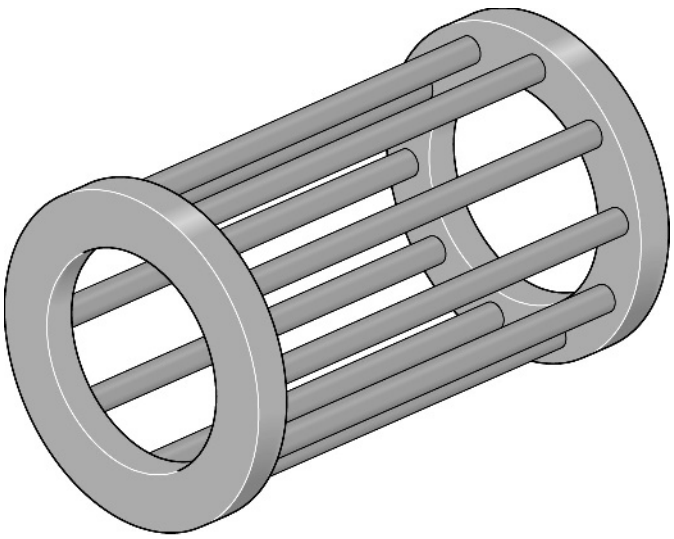
SQUIRREL-CAGE INDUCTION MOTORS

squirrel-cage motor a type of rotor used in induction motors.

The **squirrel-cage motor** receives its name from the type of rotor used in the motor. A squirrel-cage rotor is made by connecting bars to two end rings. If the metal laminations were to be removed from the rotor, the result would look very similar to a squirrel-cage, FIGURE 18-14. A squirrel-cage is a cylindrical device constructed of heavy wire. A shaft is placed through the center of the cage. This permits the cage to spin around the shaft. A squirrel cage is placed inside the cage of small pets, such as squirrels and hamsters, to permit them to exercise by running inside of the squirrel cage. A cutaway view of a squirrel-cage motor is shown in FIGURE 18-15. A cutaway view of a squirrel-cage rotor is shown in FIGURE 18-16. The major parts of a squirrel-cage motor are shown in FIGURE 18-17.

PRINCIPLES OF OPERATION

The squirrel-cage motor is an induction motor. This means that the current flow in the rotor is produced by induced voltage from the rotating magnetic field of the stator. In FIGURE 18-18, a squirrel-cage rotor is shown inside the stator of a three-phase motor. It will be assumed that the motor shown in Figure 18-18 contains four poles per phase, which produces a rotating magnetic field with a synchronous speed of 1,800 RPM when the stator is connected to a 60-Hz line. When power is first connected to the stator, the rotor is not turning. The magnetic field of the stator cuts the rotor bars at a rate of 1,800 RPM. This cutting action induces a voltage into the rotor bars. This induced voltage



© Cengage Learning 2014

FIGURE 18-14 Basic squirrel-cage rotor without laminations.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

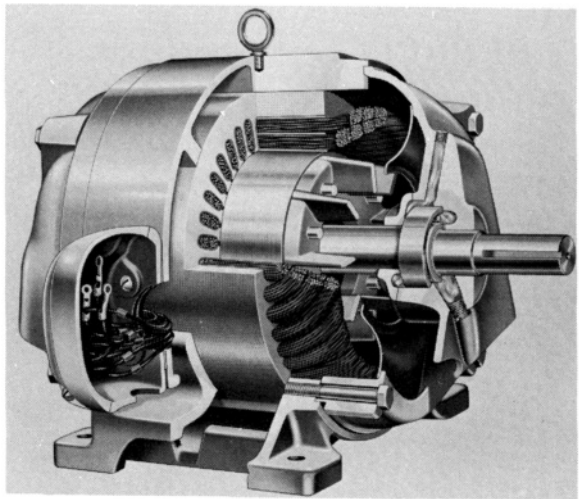

© Cengage Learning 2014

FIGURE 18-15 Cutaway view of a squirrel-cage motor.

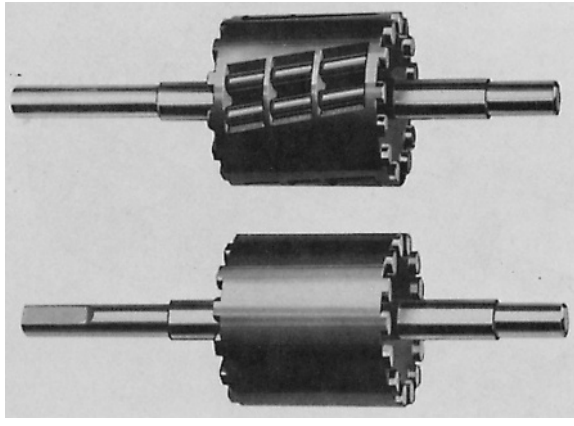

© Cengage Learning 2014

FIGURE 18-16 Cutaway view of a squirrel-cage rotor.

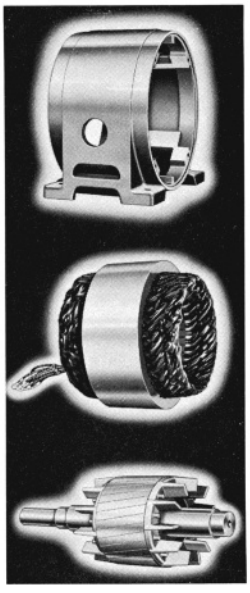

© Cengage Learning 2014

FIGURE 18-17 Squirrel-cage induction motor frame, stator winding, and rotor.

will be the same frequency as the voltage applied to the stator. The amount of induced voltage is determined by three factors:

1. The strength of the magnetic field of the stator
2. The number of turns of wire cut by the magnetic field (In the case of a squirrel-cage rotor this will be the number of bars in the rotor.)
3. The speed of the cutting action

Since the rotor is stationary at this time, maximum voltage is induced into the rotor. The induced voltage causes current to flow through the rotor bars.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

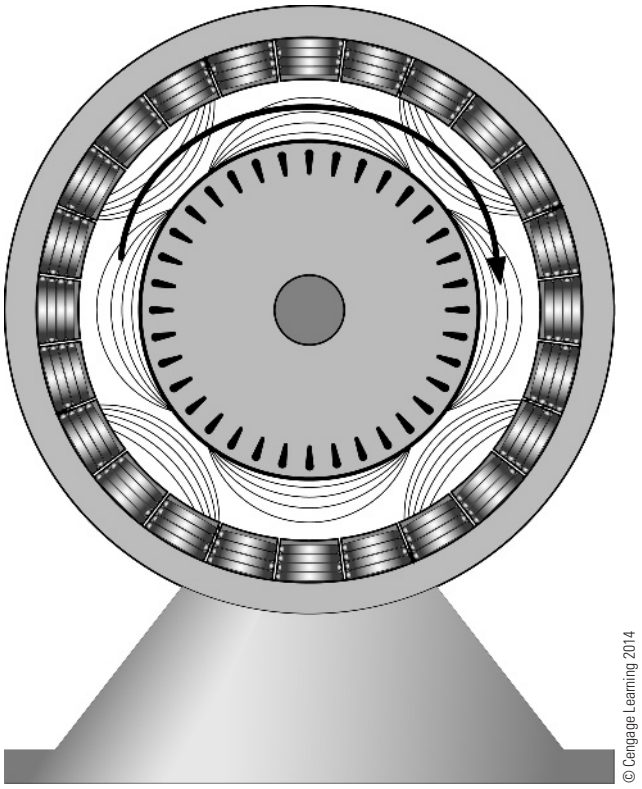


FIGURE 18-18 Voltage is induced in the rotor by the rotating magnetic field.

As current flows through the rotor, a magnetic field is produced around each bar, FIGURE 18-19.

The magnetic field of the rotor is attracted to the magnetic field of the stator, and the rotor begins to turn in the same direction as the rotating magnetic field.

As the speed of the rotor increases, the rotating magnetic field cuts the rotor bars at a slower rate. For example, assume the rotor has accelerated to a speed of 600 RPM. The synchronous speed of the rotating magnetic field is 1,800 RPM. Therefore, the rotor bars are now being cut at a rate of 1,200 RPM instead of 1,800 RPM (1,800 RPM − 600 RPM = 1,200 RPM). Since the rotor bars are being cut at a slower rate, less voltage is induced in the rotor, reducing rotor current. When the rotor current decreases, the stator current decreases also.

As the rotor continues to accelerate, the rotating magnetic field cuts the rotor bars at a decreasing rate. This reduces the amount of induced voltage and, therefore, the amount of rotor current. If the motor is operating without a load, the rotor will continue to accelerate until it reaches a speed close to that of the rotating magnetic field.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

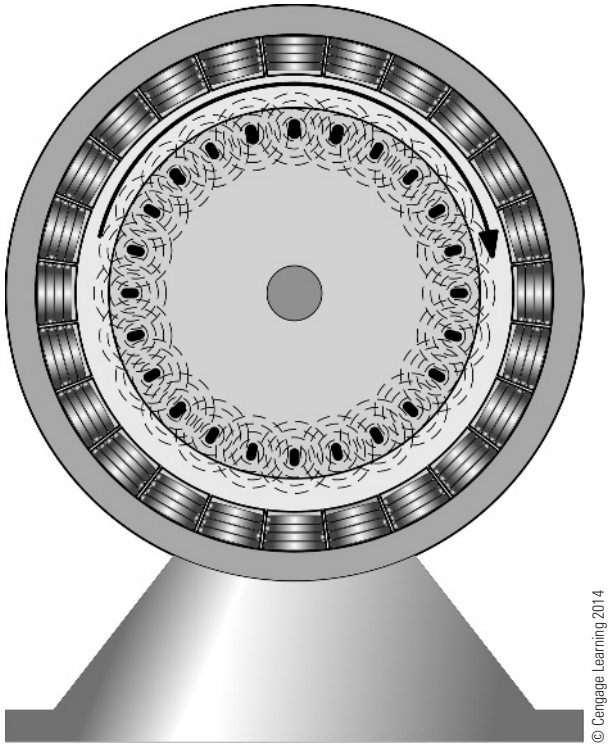


FIGURE 18-19 A magnetic field is produced around each rotor bar.

TORQUE

torque
turning force developed by a motor.

The amount of **torque** produced by an AC induction motor is determined by three factors:

1. The strength of the magnetic field of the stator
2. The strength of the magnetic field of the rotor
3. The phase angle difference between rotor and stator fields

$$T = K_T \times \varphi_S \times I_R \times \text{COS } \theta_R$$

where

T = torque in lb-ft

K_T = torque constant

φ_S = stator flux (constant at all speeds)

I_R = rotor current

COS θ_R = rotor power factor

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Notice that one of the factors that determines the amount of torque produced by an induction motor is the strength of the magnetic field of the rotor. **An induction motor can never reach synchronous speed.** If the rotor were to turn at the same speed as the rotating magnetic field, there would be no induced voltage in the rotor, and consequently no rotor current. Without rotor current there could be no magnetic field developed by the rotor and, therefore, no torque or turning force. A motor operating at no load will accelerate until the torque developed is proportional to the windage and bearing friction losses.

KEY POINT
An induction motor can never reach synchronous speed.

If a load is connected to the motor, it must furnish more torque to operate the load. This causes the motor to slow down. When the motor speed decreases, the rotating magnetic field cuts the rotor bars at a faster rate. This causes more voltage to be induced in the rotor and, therefore, more current. The increased current flow produces a stronger magnetic field in the rotor, which causes more torque to be produced. The increased current flow in the rotor causes increased current flow in the stator. This is why motor current will increase as load is added.

Another factor that determines the amount of torque developed by an induction motor is the phase angle difference between stator and rotor field flux. **Maximum torque is developed when the stator and rotor flux are in phase with each other.** Note in the previous formula that one of the factors that determines the torque developed by an induction motor is the cosine of the rotor power factor. The cosine function reaches its maximum value of 1 when the phase angle is 0 (COS 0° = 1).

KEY POINT
Maximum torque is developed when the stator and rotor flux are in phase with each other.

STARTING CHARACTERISTICS

When a squirrel-cage motor is first started, it will have a current draw several times greater than its normal running current. The actual amount of starting current is determined by the type of rotor bars, the horsepower rating of the motor, and the applied voltage. The type of rotor bars is indicated by the code letter found on the nameplate of a squirrel-cage motor. Table 430-7b of the *National Electrical Code®* can be used to compute the locked rotor current (starting current) of a squirrel-cage motor when the applied voltage, horsepower, and code letter are known. The table shown in FIGURE 18-20 lists values for locked currents.

EXAMPLE 3: An 800-hp three-phase squirrel-cage motor is connected to 2,300 V. The motor has a code letter of J. What is the starting current of this motor?

Solution:

The table in Figure 18-20 lists a value of 7.1–7.99 kVA per horsepower as the locked rotor current of a motor with a code letter J. An average value of 7.5 will be used for this calculation. The apparent power can be computed by

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CODE LETTER	KILO-VOLT-AMPERES PER HORSEPOWER WITH LOCKED ROTOR
A	0-3.14
B	3.15-3.54
C	3.55-3.99
D	4.0-4.49
E	4.5-4.99
F	5.0-5.59
G	5.6-6.29
H	6.3-7.09
J	7.1-7.99
K	8.0-8.99
L	9.0-9.99
M	10.0-11.9
N	11.2-12.49
P	12.5-13.49
R	14.0-15.99
S	16.0-17.99
T	18.0-19.99
U	20.0-22.39
V	22.4-and up

© Cengage Learning 2014

FIGURE 18-20 Table for determining starting current for squirrel-cage motors.

multiplying the 7.5 times the horsepower rating of the motor.

$$kVA = 7.5 \times 800$$

$$kVA = 6{,}000$$

The line current supplying the motor can now be computed using the formula

$$I_{(LINE)} = \frac{VA}{E_{(LINE)} \times 1.732}$$

$$I_{(LINE)} = \frac{6{,}000{,}000}{2300 \times 1.732}$$

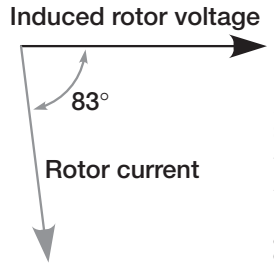
$$I_{(LINE)} = 1506.175 \text{ A}$$

This large starting current is caused by the fact that the rotor is not turning when power is first applied to the stator. Since the rotor is not turning, the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

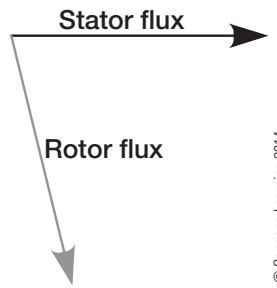
squirrel-cage bars are cut by the rotating magnetic field at a fast rate. Remember that one of the factors that determines the amount of induced voltage is the speed of the cutting action. This high induced voltage causes a large amount of current to flow in the rotor. The large current flow in the rotor causes a large amount of current flow in the stator. Since a large amount of current flows in both the stator and rotor, a strong magnetic field is established in both.

The starting torque of a squirrel-cage motor is high since the magnetic field of both the stator and rotor are strong at this point. The starting torque of a typical squirrel-cage motor can range from 200% to 300% of its full load-rated torque. Although the starting torque is high, the squirrel-cage motor does not develop as much starting torque per ampere of starting current as other types of three-phase motors. Recall that the third factor for determining the torque developed by an induction motor is the difference in phase angle between stator flux and rotor flux. Since the rotor is being cut at a high rate of speed by the rotating stator field, the bars in the squirrel-cage rotor appear to be very inductive at this point because of the high frequency of the induced voltage. This causes the phase angle difference between the induced voltage in the rotor and rotor current to be almost 90° out of phase with each other, producing a lagging power factor for the rotor, FIGURE 18-21. This causes the rotor flux to lag the stator flux by a large amount, and consequently a relatively weak starting torque per ampere of starting current, compared to other types of three-phase motors, is developed, FIGURE 18-22. A typical torque curve for a squirrel-cage motor is shown in FIGURE 18-23.



© Cengage Learning 2014

FIGURE 18-21 Rotor current is almost 90° out of phase with the induced voltage at the moment of starting.



© Cengage Learning 2014

FIGURE 18-22 Rotor flux lags the stator flux by a large amount during starting.

PERCENT SLIP

The speed performance of an induction motor is measured in **percent slip.** The percent slip can be determined by subtracting the synchronous speed from the speed of the rotor. For example, assume an induction motor has a synchronous speed of 1,800 RPM and at full load the rotor turns at a speed of 1,725 RPM. The difference between the two speeds is 75 RPM (1,800 − 1,725 = 75). The percent slip can be determined using the formula

percent slip
rotor frequency of the current inducted in the rotor.

$$\text{percent slip} = \frac{\text{synchronous speed} - \text{rotor speed}}{\text{synchronous speed}} \times 100$$

$$\text{percent slip} = \frac{75}{1{,}800} \times 100$$

$$\text{percent slip} = 4.16\%$$

A rotor slip of 2–5% is common for most squirrel-cage induction motors. The amount of slip for a particular motor is greatly affected by the type of rotor bars used in the construction of the rotor. Squirrel-cage motors are considered to

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

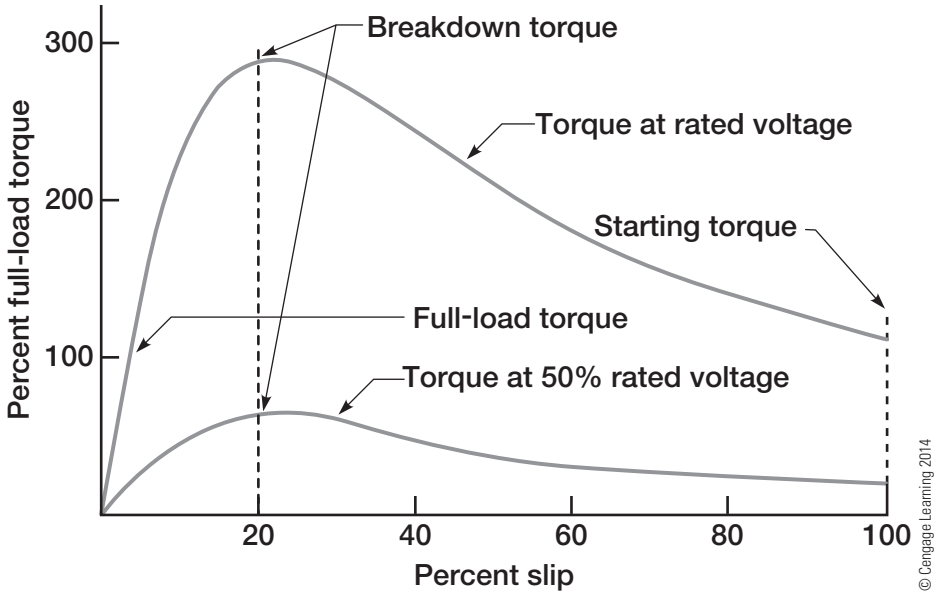


FIGURE 18-23 Typical torque curves for a squirrel-cage motor.

be constant speed motors because there is a small difference between no-load speed and full-load speed.

ROTOR FREQUENCY

In the previous example, the rotor slips behind the rotating magnetic field by 75 RPM. This means that at full load, the bars of the rotor are being cut by magnetic lines of flux at a rate of 75 RPM. Therefore, the voltage being induced in the rotor at this point in time is at a much lower frequency than when the motor was started. The **rotor frequency** can be determined using the formula

rotor frequency
frequency of the current inducted in the rotor.

$$F = \frac{P \times S_R}{120}$$

where

F = frequency in Hz

P = number of stator poles

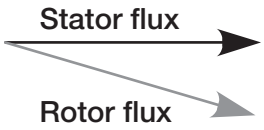
S_R = rotor slip in RPM

$$F = \frac{4 \times 75}{120}$$

F = 2.5 Hz

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Because the frequency of the current in the rotor decreases as the rotor approaches synchronous speed, the rotor bars become less inductive. The current flow through the rotor becomes limited more by the resistance of the bars and less by inductive reactance. The current flow in the rotor becomes more in phase with the induced voltage, which causes less phase angle shift between stator and rotor flux, FIGURE 18-24. This is the reason why squirrel-cage motors generally have a relatively poor starting torque per ampere of starting current but a good running torque, as compared to other types of three-phase motors.



© Cengage Learning 2014

FIGURE 18-24 Rotor and stator flux become more in phase with each other as motor speed increases.

REDUCED VOLTAGE STARTING

Due to the large amount of starting current required for many squirrel-cage motors, it is sometimes necessary to reduce the voltage during the starting period. When the voltage is reduced, the starting torque is reduced also. If the applied voltage is reduced to 50% of its normal value, the magnetic fields of both the stator and rotor are reduced to 50% of normal. This causes the starting torque to be reduced to 25% of normal. A chart of typical torque curves for squirrel-cage motors is shown in Figure 18-23.

The torque formula given earlier can be used to show why this large reduction of torque occurs. Both the stator flux, φ_S, and the rotor current, I_R, are reduced to half their normal value. The product of these two values, torque, is reduced to one-fourth. The torque varies as the square of the applied voltage for any given value of slip.

CODE LETTERS

Squirrel-cage rotors are not all the same. Rotors are made with different types of bars. The type of rotor bars used in the construction of the rotor determines the operating characteristics of the motor. AC squirrel-cage motors are given a code letter on their nameplate. The code letter indicates the type of bars used in the rotor. FIGURE 18-25 shows a rotor with A-type bars. An A-type rotor has the highest resistance of any squirrel-cage rotor. This means that the starting torque per ampere of starting current will be high since the rotor current is closer to being in phase with the induced voltage than any other type of rotor. Also, the high resistance of the rotor bars limits the amount of current flow in the rotor when starting. This produces a low starting current for the motor. A rotor with A-type bars has very poor running characteristics, however. Since the bars are resistive, a large amount of voltage will have to be induced into the rotor to produce an increase in rotor current and, therefore, an increase in the rotor magnetic field. This means that when load is added to the motor, the rotor must slow down a great amount to produce enough current in the rotor to increase the torque. Motors with A-type rotors have the highest percent slip

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

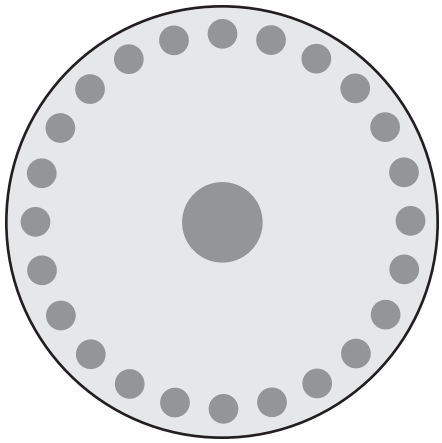


FIGURE 18-25 Type-A rotor.

of any squirrel-cage motor. Motors with A-type rotors are generally used in applications where starting is a problem, such as a motor that must accelerate a large flywheel from 0 RPM to its full speed. Flywheels can have a very large amount of inertia, which may require several minutes to accelerate them to their running speed when they are started.

FIGURE 18-26 shows a rotor with bars similar to those found in rotors with code letters B through E. These rotor bars have lower resistance than the A-type rotor. Rotors of this type have fair starting torque, low starting current, and fair speed regulation.

FIGURE 18-27 shows a rotor with bars similar to those found in rotors with code letters F through V. This rotor has low starting torque, high starting current, and good running torque. Motors containing rotors of this type generally have very good speed regulation and low percent slip.

THE DOUBLE SQUIRREL-CAGE ROTOR

Some motors use a rotor that contains two sets of squirrel-cage windings, FIGURE 18-28. The outer winding consists of bars with a relatively high resistance located close to the top of the iron core. Since these bars are located close to the surface, they have a relatively low reactance. The inner winding consists of bars with a large cross-sectional area, which gives them a low resistance. The inner winding is placed deeper in the core material, which causes it to have a much higher reactance.

When the double squirrel-cage motor is started, the rotor frequency is high. Since the inner winding is inductive, its impedance will be high as compared to the resistance of the outer winding. During this period, most of the rotor current flows through the outer winding. The resistance of the outer

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

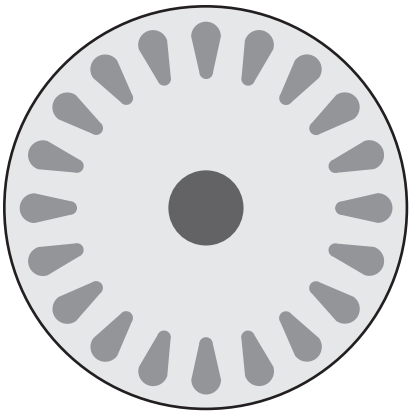

© Cengage Learning 2014

FIGURE 18-26 Type B–E rotor.

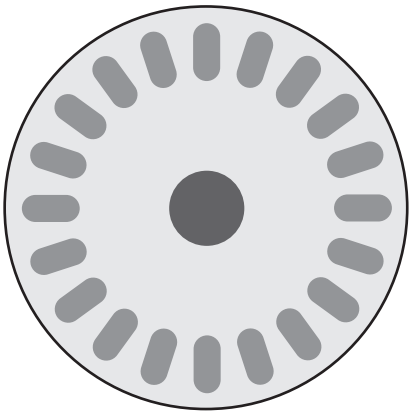

© Cengage Learning 2014

FIGURE 18-27 Type F–V rotor.

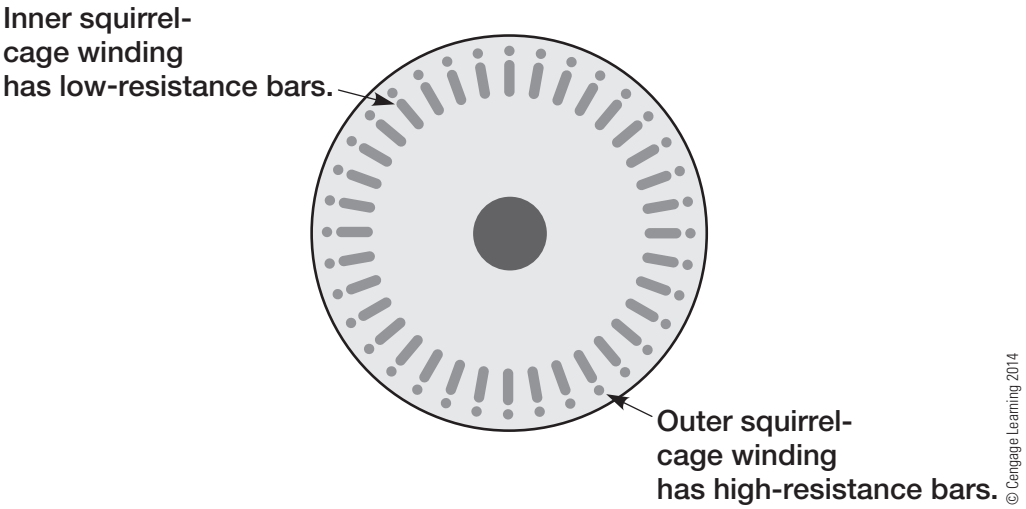


FIGURE 18-28 Double squirrel-cage rotor.

winding limits the current flow through the rotor, which limits the starting current to a relatively low value. Since the current is close to being in phase with the induced voltage, the rotor flux and stator flux are close to being in phase with each other and a strong starting torque is developed. The starting torque of a double squirrel-cage motor can be as high as 250% of rated full-load torque.

When the rotor reaches its full load speed, rotor frequency decreases to 2 or 3 Hz. The inductive reactance of the inner winding has now decreased to a low value. Most of the rotor current now flows through the low-resistance inner winding. This type of motor has good running torque and excellent speed regulation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

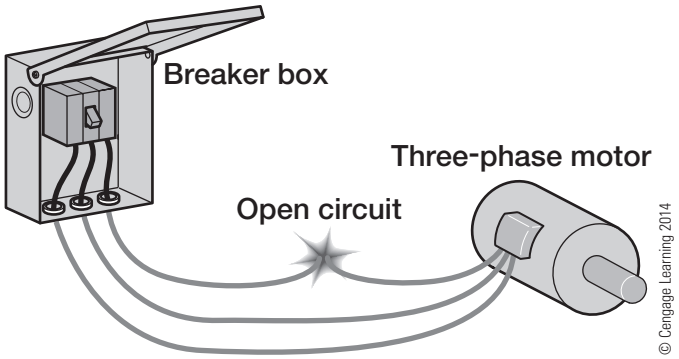


FIGURE 18-29 Single phasing occurs when one line of a three-phase system is open.

SINGLE PHASING

Three lines supply power to a three-phase motor. If one of these lines should open, the motor will be connected to single-phase power, FIGURE 18-29. This condition is known as **single phasing**.

single phasing
caused by the loss of one phase in a three-phase system.

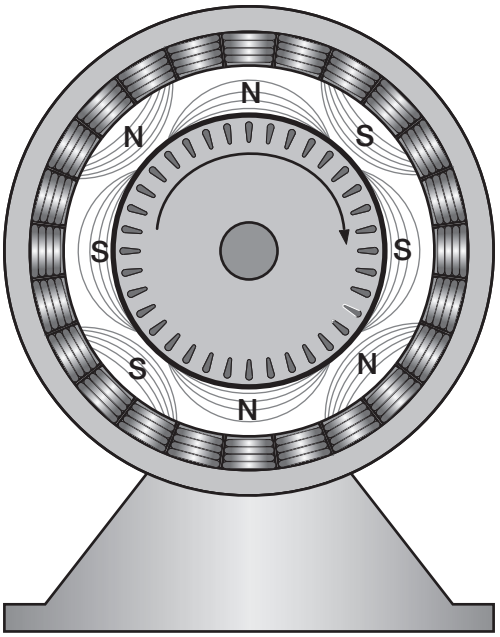
If the motor is not running and single-phase power is applied to the motor, the induced voltage in the rotor sets up a magnetic field in the rotor. This magnetic field opposes the magnetic field of the stator (Lenz's Law). As a result, practically no torque is developed in either the clockwise or counterclockwise direction, and the motor will not start. The current supplying the motor will be excessive, however, and damage to the stator windings can occur.

If the motor is operating under load at the time the single-phasing condition occurs, the rotor will continue to turn at a reduced speed. The moving bars of the rotor cut the stator field flux, which continues to induce voltage and current in the bars. Due to reduced speed, the rotor has high reactive and low resistive components, causing the rotor current to lag the induced voltage by almost 90°. This lagging current creates rotor fields midway between the stator poles, resulting in greatly reduced torque, FIGURE 18-30. This is the same operating principle of a single-phase squirrel-cage induction motor. The reduction in rotor speed causes high current flow and will most likely damage the stator winding if the motor is not disconnected from the power line.

THE NAMEPLATE

Electric motors have nameplates that give a great deal of information about the motor. FIGURE 18-31 illustrates the nameplate of a three-phase squirrel-cage induction motor. The nameplate shows that the motor is 10 hp, it is a three-phase motor, and operates on 240 V or 480 V. The full-load running current of the motor is 28 A when operated on 240 V and 14 A when operated on 480 V. The motor is designed to be operated on a 60-Hz AC voltage, and has a full-load speed of 1,745 RPM. This speed indicates that the motor has four poles per

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 18-30 A single-phasing condition creates magnetic poles in the rotor that are 90° out of phase with the magnetic field of the stator.

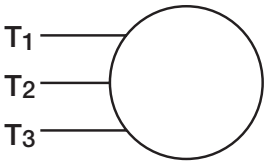
MANUFACTURER	
HP 10	Phase 3
Volts 240/480	Amps 28/14
Hz 60	Fl speed 1,745 RPM
Code J	SF 1.25
Frame XXXX	Model No. XXXX

© Cengage Learning 2014

FIGURE 18-31 Motor nameplate.

phase. Since the full-load speed is 1,745 RPM, the synchronous speed would be 1,800 RPM. The motor contains a J-type squirrel-cage rotor, and has a service factor of 1.25. The service factor is used to determine the amperage rating of the overload protection for the motor. Some motors indicate a marked temperature rise in celsius degrees instead of a service factor. The frame number

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 18-32
Schematic symbol of a three-phase squirrel-cage induction motor.

consequent pole
motors that changed the number of stator poles in order to change speed.

indicates the type of mounting the motor has. FIGURE 18-32 shows the schematic symbol used to represent a three-phase squirrel-cage motor.

CONSEQUENT POLE SQUIRREL-CAGE MOTORS

Consequent pole squirrel-cage motors permit the synchronous speed to be changed by changing the number of stator poles. If the number of poles is doubled, the synchronous speed will be reduced by one-half. A two-pole motor has a synchronous speed of 3,600 RPM when operated at 60 Hz. If the number of poles is doubled to four, the synchronous speed becomes 1,800 RPM. The number of stator poles can be changed by changing the direction of current flow through alternate pairs of poles.

FIGURE 18-33 illustrates this concept. In Figure 18-33A, two coils are connected in such a manner that current flows through them in the same direction. Both poles will produce the same magnetic polarity and are essentially one pole. In Figure 18-33B, the coils have been reconnected in such a manner that current flows through them in opposite directions. Each coil now produces the opposite magnetic polarity, and are essentially two different poles.

Consequent pole motors with one stator winding bring out six leads labeled T_1 through T_6. Depending on the application, the windings will be connected as a series delta or a parallel wye. If it is intended that the motor maintain the same horsepower rating for both high and low speed, the high-speed connection will be a series delta, FIGURE 18-34. The low-speed connection will be a parallel wye, FIGURE 18-35.

If it is intended that the motor maintain constant torque for both low and high speeds, the series delta connection will provide low speed and the parallel wye will provide high speed.

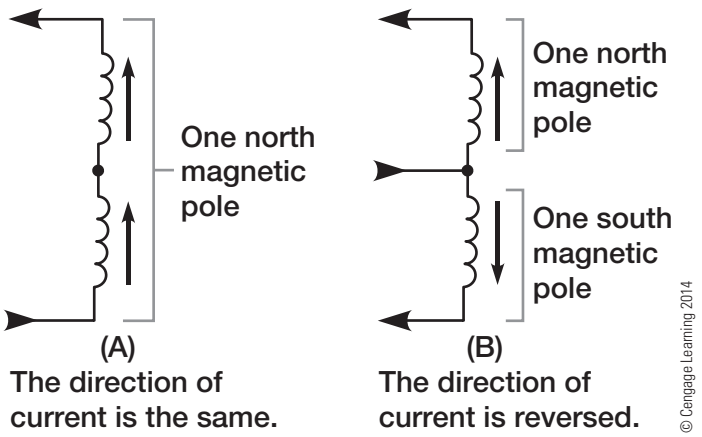
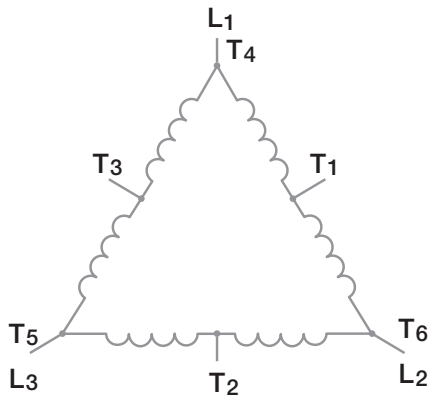


FIGURE 18-33 The number of poles can be changed by reversing the current flow through alternate poles.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

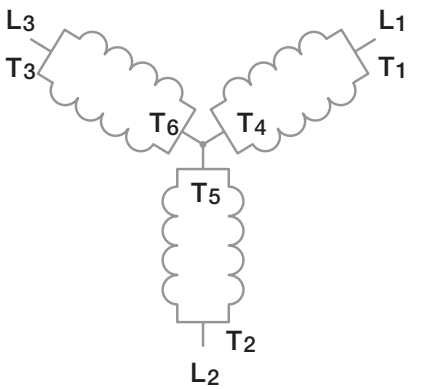
Since the speed range of a consequent pole motor is limited to a 1:2 ratio, motors intended to operate at more than two speeds contain more than one stator winding. A consequent pole motor with three speeds, for example, will have one stator winding for one speed only and a second winding with taps. The tapped winding may provide synchronous speeds of 1,800 and 900 RPM, and the separate winding may provide a speed of 1,200 RPM. Consequent pole



Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	———	T_4 T_5 T_6
High	T_6	T_4	T_5	All others	———

© Cengage Learning 2014

FIGURE 18-34 High-speed series delta connection.



Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	———	T_4 T_5 T_6
High	T_6	T_4	T_5	All others	———

© Cengage Learning 2014

FIGURE 18-35 Low-speed parallel wye connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

motors with four speeds contain two separate stator windings with taps. If the second stator winding of the motor in this example were to be tapped, the motor would provide synchronous speeds of 1,800, 1,200, 900, and 600 RPM.

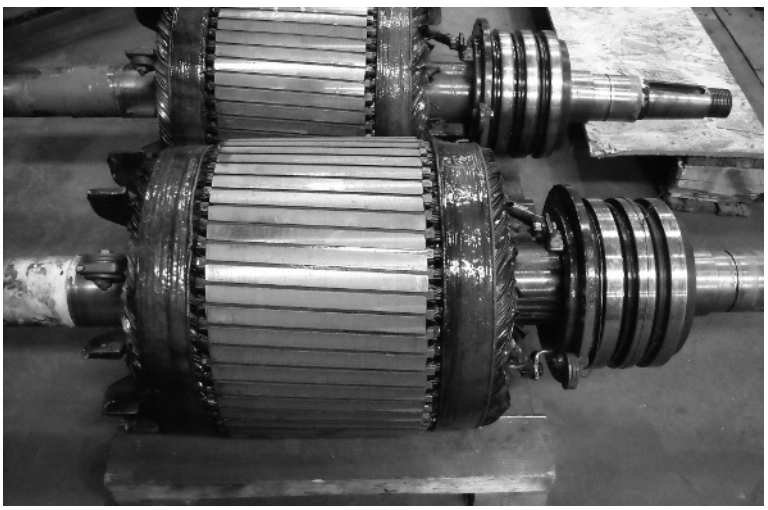
THE WOUND-ROTOR INDUCTION MOTOR

wound-rotor motor
three-phase motor containing a rotor with windings and sliprings. This rotor permits control of rotor current by connecting external resistance in series with the rotor winding.

The **wound-rotor** induction **motor** is very popular in industry because of its high starting torque and low starting current. The stator winding of the wound-rotor motor is the same as the squirrel-cage motor. The difference between the two motors lies in the construction of the rotor. Recall that the squirrel-cage rotor is constructed of bars connected together at each end by a shorting ring as shown in Figure 18-14.

The rotor of a wound-rotor motor is constructed by winding three separate coils on the rotor 120° apart. The rotor will contain as many poles per phase as the stator winding. These coils are then connected to three sliprings located on the rotor shaft as shown in FIGURE 18-36. Brushes, connected to the sliprings, provide external connection to the rotor. This permits the rotor circuit to be connected to a set of resistors, as shown in FIGURE 18-37.

The stator terminal connections are generally labeled T_1, T_2, and T_3. The rotor connections are commonly labeled M_1, M_2, and M_3. The M_2 lead is generally connected to the middle slipring and the M_3 lead is connected close to the rotor windings. The direction of rotation for the wound-rotor motor is reversed by changing any two stator leads. Changing the M-leads will have no effect on the direction of rotation. The schematic symbol for a wound-rotor motor is shown in FIGURE 18-38.



© Cengage Learning 2014

FIGURE 18-36 Rotor of a wound-rotor induction motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

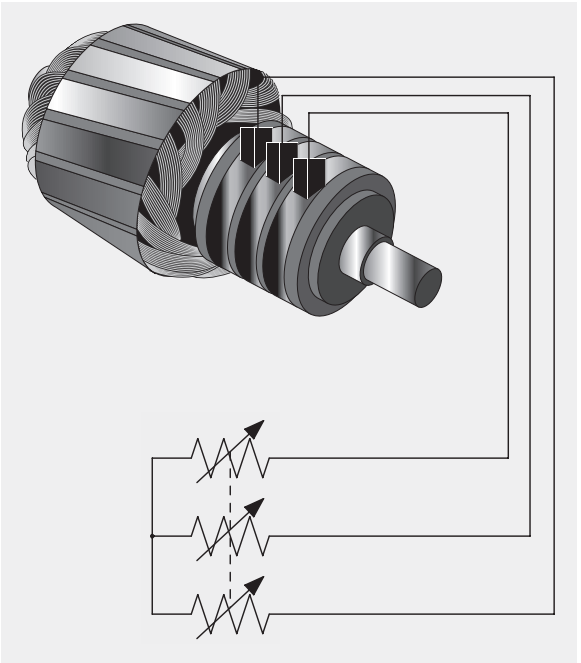


FIGURE 18-37 The rotor of a wound-rotor motor is connected to external resistors.

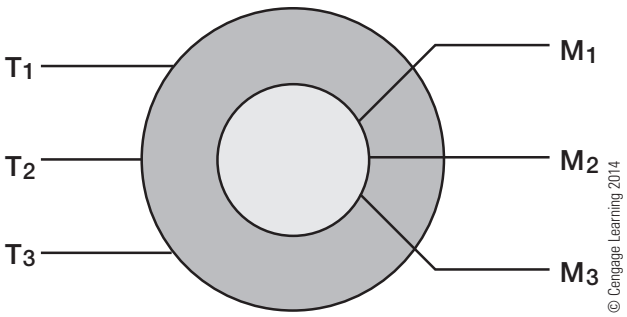


FIGURE 18-38 Schematic symbol for a wound-rotor induction motor.

WOUND-ROTOR MOTOR OPERATION

When power is applied to the stator winding, a rotating magnetic field is created in the motor. This magnetic field cuts through the windings of the rotor and induces a voltage into them. The amount of current flow in the rotor is determined by the amount of induced voltage and the total impedance of the rotor circuit ($I = E/Z$). The rotor impedance is a combination of inductive reactance created in the rotor windings and the external resistance. The impedance could be calculated using the formula for resistance and inductive reactance connected in series.

$$Z = \sqrt{R_2 + X_L^2}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

As the rotor speed increases, the frequency of the induced voltage will decrease just as it does in the squirrel-cage motor. The reduction in frequency causes the rotor circuit to become more resistive and less inductive, decreasing the phase angle between induced voltage and rotor current.

When current flows through the rotor, a magnetic field is produced. This magnetic field is attracted to the rotating magnetic field of the stator. As the rotor speed increases, the induced voltage decreases because of less cutting action between the rotor windings and rotating magnetic field. This produces less current flow in the rotor and, therefore, less torque. If rotor circuit resistance is reduced, more current can flow, which will increase motor torque, and the rotor will increase in speed. This action continues until all external resistance has been removed from the rotor circuit by shorting the M-leads together and the motor is operating at maximum speed. At this point, the wound-rotor motor is operating in the same manner as a squirrel-cage motor.

STARTING CHARACTERISTICS OF A WOUND-ROTOR MOTOR

The wound-rotor motor will have a higher starting torque and lower starting current per horsepower than a squirrel-cage motor. The starting current is less because resistance is connected in the rotor circuit during starting. This resistance limits the amount of current that can flow in the rotor circuit. Since the stator current is proportional to rotor current because of transformer action, the stator current is less also. The starting torque is high because of the resistance in the rotor circuit. Recall that one of the factors that determines motor torque is the phase angle difference between stator flux and rotor flux. Since resistance is connected in the rotor circuit, stator and rotor flux are close to being in phase with each other, producing a high starting torque for the wound-rotor induction motor. If an attempt is made to start the motor with no circuit connected to the rotor, the motor cannot start. If no resistance is connected to the rotor circuit, there can be no current flow and, consequently, no magnetic field developed in the rotor.

SPEED CONTROL

The speed of a wound-rotor motor can be controlled by permitting resistance to remain in the rotor circuit during operation. When this is done, the rotor and stator current is limited, which reduces the strength of both magnetic fields. The reduced magnetic field strength permits the rotor to slip behind the rotating magnetic field of the stator. The resistors of speed controllers must have higher power ratings than the resistors of starters because they operate for extended periods of time.

The operating characteristics of a wound-rotor motor with the sliprings shorted are almost identical to those of a squirrel-cage motor. The percent

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

slip, power factor, and efficiency are very similar for motors of equal horsepower rating.

SYNCHRONOUS MOTORS

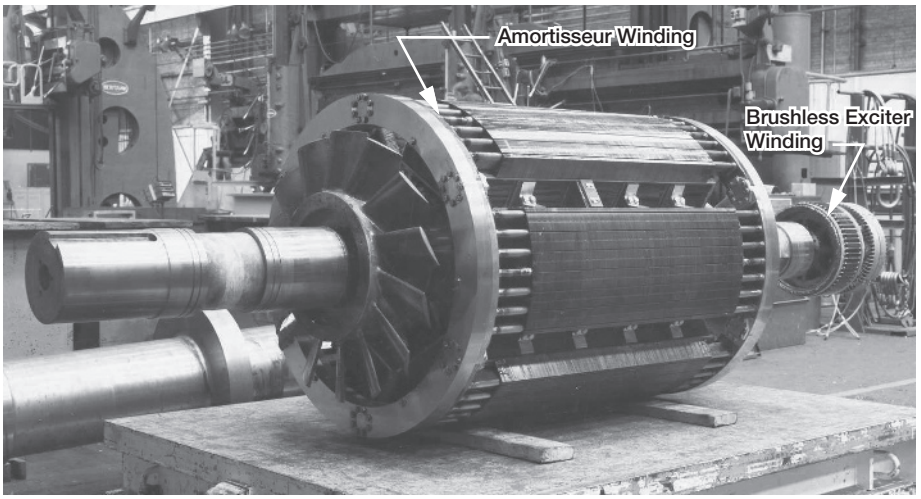
synchronous a type of three-phase motor.

The three-phase **synchronous** motor has several characteristics that separate it from other types of three-phase motors. Some of these characteristics are as follows:

1. The synchronous motor is not an induction motor. It does not depend on induced current in the rotor to produce a torque.
2. It will operate at a constant speed from full load to no load.
3. The synchronous motor must have DC excitation to operate.
4. It will operate at the speed of the rotating magnetic field (synchronous speed).
5. It has the ability to correct its own power factor and the power factor of other devices connected to the same line.

ROTOR CONSTRUCTION

The synchronous motor has the same type of stator windings as the other two three-phase motors. The rotor of a synchronous motor, however, contains both wound-pole pieces and a squirrel-cage winding, FIGURE 18-39. The wound pole pieces become electromagnets when direct current is applied to them. The excitation current can be applied to the rotor through two sliprings located on the rotor shaft or by a brushless exciter.



© Cengage Learning 2014

FIGURE 18-39 Rotor of a synchronous motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

STARTING A SYNCHRONOUS MOTOR

amortisseur winding
squirrel-cage winding on the rotor of a synchronous motor used for starting purposes only.

The rotor of a synchronous motor contains a set of squirrel-cage bars similar to those found in an A-type rotor. This set of squirrel-cage bars is used to start the motor and is known as the **amortisseur winding,** Figure 18-39. When power is first connected to the stator, the rotating magnetic field cuts through the squirrel-cage bars. The cutting action of the field induces a current into the squirrel-cage winding. The current flow through the amortisseur winding produces a rotor magnetic field that is attracted to the rotating magnetic field of the stator. This causes the rotor to begin turning in the direction of rotation of the stator field. When the rotor has accelerated to a speed that is close to the synchronous speed of the field, direct current is connected to the rotor through the sliprings on the rotor shaft or by a brushless exciter, FIGURE 18-40.

When DC current is applied to the rotor, the windings of the rotor become electromagnets. The electromagnetic field of the rotor locks in step with the rotating magnetic field of the stator. The rotor will now turn at the same speed as the rotating magnetic field. When the rotor turns at the synchronous speed of the field, there is no more cutting action between the stator field and the amortisseur winding. This causes the current flow in the amortisseur winding to cease.

Notice that the synchronous motor starts as a squirrel-cage induction motor. Since the rotor uses bars that are similar to those used in an A-type rotor, they have a relatively high resistance, which gives the motor

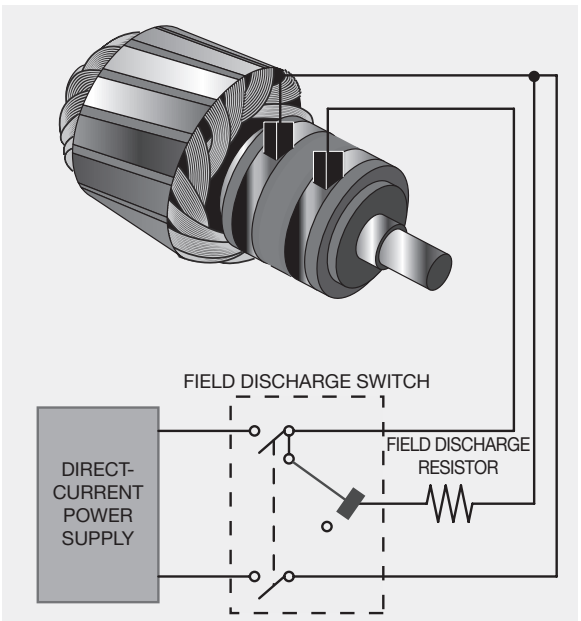


FIGURE 18-40 DC excitation current supplied through sliprings.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

good starting torque and low starting current. **A synchronous motor must never be started with DC current connected to the rotor.** If DC current is applied to the rotor, the field poles of the rotor become electromagnets. When the stator is energized, the rotating magnetic field begins turning at synchronous speed. The electromagnets are alternately attracted and repelled by the stator field. As a result, the rotor does not turn. The rotor and power supply can be damaged by high induced voltages, however.

KEY POINT
A synchronous motor must never be started with DC current connected to the rotor.

THE FIELD DISCHARGE RESISTOR

When the stator winding is first energized, the rotating magnetic field cuts through the rotor winding at a fast rate of speed. This causes a large amount of voltage to be induced into the winding of the rotor. To prevent this from becoming excessive, a resistor is connected across the winding. This resistor is known as the field discharge resistor, FIGURE 18-41. It also helps to reduce the voltage induced into the rotor by the collapsing magnetic field when the DC current is disconnected from the rotor. The field discharge resistor is connected in parallel with the rotor winding during starting. If the motor is manually started, a field discharge switch is used to connect the excitation current to the rotor. If the motor is automatically started, a special type of relay is used to connect excitation current to the rotor and disconnect the field discharge resistor.

CONSTANT SPEED OPERATION

Although the synchronous motor starts as an induction motor, it does not operate as one. After the amortisseur winding has been used to accelerate the rotor to about 95% of the speed of the rotating magnetic field, direct current is connected to the rotor, and the electromagnets lock in step with the rotating

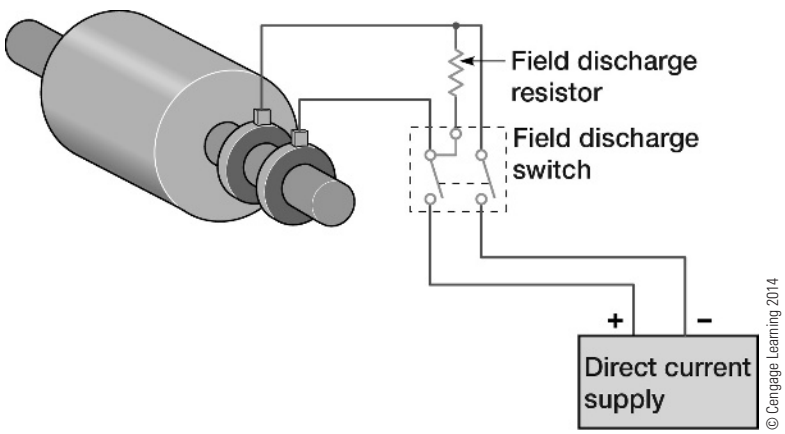


FIGURE 18-41 The field discharge resistor is connected in parallel with the rotor winding during starting.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

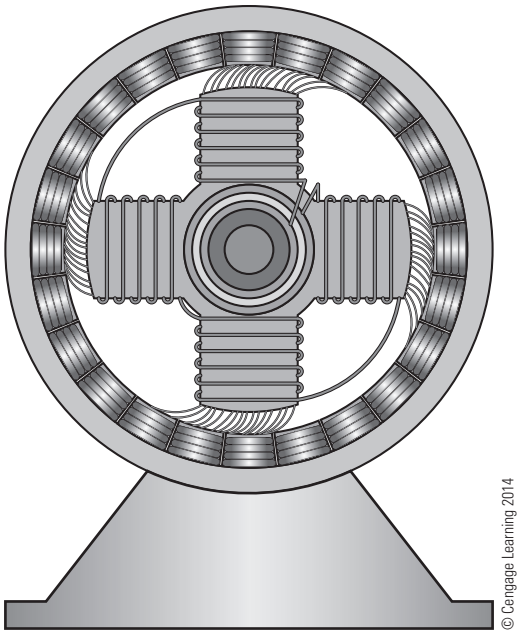


FIGURE 18-42 The magnetic field becomes stressed as load is added.

field. Notice that the synchronous motor does not depend on induced voltage from the stator field to produce a magnetic field in the rotor. The magnetic field of the rotor is produced by external DC current applied to the rotor. This is the reason why the synchronous motor has the ability to operate at the speed of the rotating magnetic field.

As load is added to the motor, the magnetic field of the rotor remains locked with the rotating magnetic field of the stator and the rotor continues to turn at the same speed. The added load, however, causes the magnetic fields of the rotor and stator to become stressed, FIGURE 18-42. The action is similar to connecting the north and south ends of two magnets and then trying to pull them apart. If the force being used to pull the magnets apart becomes greater than the strength of the magnetic attraction, the magnetic coupling will be broken and the magnets can be separated. The same is true for the synchronous motor. If the load on the motor becomes too great, the rotor will be pulled out of sync with the rotating magnetic field. The amount of torque necessary to cause this condition is called the **pull-out torque.** The pull-out torque for most synchronous motors will range from 150% to 200% of rated full-load torque. If this should happen, the motor must be stopped and restarted. The schematic symbol for a synchronous motor is shown in FIGURE 18-43.

pull-out torque
the amount of torque necessary for the magnetic attraction between the rotor and stator magnetic fields to pull apart.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

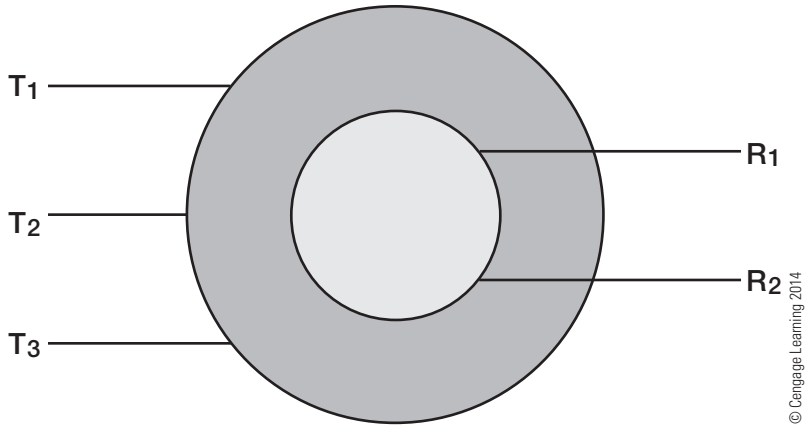


FIGURE 18-43 Schematic symbol for a synchronous motor.

THE POWER SUPPLY

The DC power supply of a synchronous motor can be provided by several methods. The most common are to use either a small DC generator mounted to the shaft of the motor or an electronic power supply that converts the AC line voltage into DC voltage.

Summary

1. Three basic types of three-phase motors are the following:
   A. Squirrel-cage induction motor
   B. Wound-rotor induction motor
   C. Synchronous motor
2. All three-phase motors operate on the principle of a rotating magnetic field.
3. Three factors that cause a magnetic field to rotate are as follows:
   A. The voltages of a three-phase system are 120° out of phase with each other.
   B. The voltages change polarity at regular intervals.
   C. The arrangement of the stator windings.
4. The speed of the rotating magnetic field is called the synchronous speed.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

5. Two factors that determine the synchronous speed are as follows:
   A. Number of stator poles per phase
   B. Frequency of the applied voltage
6. The direction of rotation of any three-phase motor can be changed by reversing the connection of any two stator leads.
7. The direction of rotation of a three-phase motor can be determined with a phase rotation meter before power is applied to the motor.
8. Dual-voltage motors will have nine or twelve leads brought out at the terminal connection box.
9. Dual-voltage motors intended for high-voltage connection have their phase windings connected in series.
10. Dual-voltage motors intended for low-voltage connection have their phase windings connected in parallel.
11. Motors that bring out twelve leads are generally intended for wye-delta starting.
12. Three factors that determine the torque produced by an induction motor are as follows:
    A. The strength of the magnetic field of the stator
    B. The strength of the magnetic field of the rotor
    C. The phase angle difference between rotor and stator flux
13. Maximum torque is developed when stator and rotor flux are in phase with each other.
14. The code letter on the nameplate of a squirrel-cage motor indicates the type of rotor bars used in the construction of the rotor.
15. The A-type rotor has the lowest starting current, highest starting torque, and poorest speed regulation of any type of squirrel-cage rotor.
16. The double squirrel-cage rotor contains two sets of squirrel-cage windings in the same rotor.
17. Consequent pole squirrel-cage motors change speed by changing the number of stator poles.
18. Wound-rotor induction motors have wound rotors that contain three-phase windings.
19. Wound-rotor motors have three sliprings on the rotor shaft to provide external connection to the rotor.
20. Wound-rotor motors have higher starting torque and lower starting current than squirrel-cage motors of the same horsepower.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

21. The speed of a wound-rotor motor can be controlled by permitting resistance to remain in the rotor circuit during operation.
22. Synchronous motors operate at synchronous speed.
23. Synchronous motors operate at a constant speed from no load to full load.
24. When load is connected to a synchronous motor, stress develops between the magnetic fields of the rotor and stator.
25. Synchronous motors must have DC excitation for an external source.
26. DC excitation is provided to some synchronous motors through two sliprings located on the rotor shaft, and other motors use a brushless exciter.
27. Synchronous motors have the ability to produce a leading power factor by overexcitation of the DC current supplied to the rotor.
28. Synchronous motors have a set of A-type squirrel-cage bars used for starting. This squirrel-cage winding is called the amortisseur winding.
29. A field discharge resistor is connected across the rotor winding during starting to prevent high voltage in the rotor due to induction.
30. Changing the DC excitation current does not affect the speed of the motor.

Review Questions

1. What are the three basic types of three-phase motors?
2. What is the principle of operation of all three-phase motors?
3. What is synchronous speed?
4. What two factors determine synchronous speed?
5. Name three factors that cause the magnetic field to rotate.
6. Name three factors that determine the torque produced by an induction motor.
7. Is the synchronous motor an induction motor?
8. What is the amortisseur winding?
9. Why must a synchronous motor never be started when DC excitation current is applied to the rotor?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

10. Name three characteristics that make the synchronous motor different from an induction motor.
11. What is the function of the field discharge resistor?
12. Why can an induction motor never operate at synchronous speed?
13. What is the difference between a squirrel-cage motor and a wound-rotor motor?
14. What is the advantage of the wound-rotor motor over the squirrel-cage motor?
15. Name three factors that determine the amount of voltage induced in the rotor of a wound-rotor motor.
16. Why will the rotor of a wound-rotor motor not turn if the rotor circuit is left open with no resistance connected to it?
17. Why is the starting torque of a wound-rotor motor higher per ampere of starting current than that of a squirrel-cage motor?
18. What determines when a synchronous motor is at normal excitation?
19. How can a synchronous motor be made to have a leading power factor?
20. Is the excitation current of a synchronous motor AC or DC?
21. How is the speed of a consequent pole squirrel-cage motor changed?
22. A three-phase squirrel-cage motor is connected to a 60-Hz line. The full load speed is 870 RPM. How many poles per phase does the stator have?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 19

Single-Phase Motors

OBJECTIVES: After studying this unit, you should be able to:

- List the different types of split-phase motors.
- Discuss the operation of split-phase motors.
- Reverse the direction of rotation of a split-phase motor.
- Discuss the operation of multispeed split-phase motors.
- Discuss the operation of shaded-pole type of motors.
- Discuss the operation of universal motors.

Although most of the large motors used in industry are three-phase, there are times when single-phase motors must be used. Single-phase motors are used almost exclusively to operate home appliances such as air conditioners, refrigerators, well pumps, and fans. They are designed to operate on 120 V or 240 V. They range in size from fractional horsepower to several horsepower depending on the application.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

SINGLE-PHASE MOTORS

In Unit 17, it was stated that there are three basic types of three-phase motors and that all operate on the principle of a rotating magnetic field. While this is true for three-phase motors, it is not true for single-phase motors. There are not only many different types of single-phase motors, but they have different operating principles.

SPLIT-PHASE MOTORS

Split-phase motors fall into three general classifications:

1. The resistance-start induction-run motor
2. The capacitor-start induction-run motor
3. The capacitor-start capacitor-run motor (This motor is also known as a permanent-split capacitor motor in the air conditioning and refrigeration industry.)

Split-phase motors
type of single-phase motor that uses resistance or capacitance to cause a shift in the phase of the current in the run winding and the current in the start winding. The three primary types of split-phase motors are: resistance-start induction-run, capacitor-start induction-run, and permanent split-capacitor motor.

Although all of these motors have different operating characteristics, they are similar in construction and use the same operating principle. **Split-phase motors** receive their name from the manner in which they operate. Like three-phase motors, split-phase motors operate on the principle of a rotating magnetic field. A rotating magnetic field, however, cannot be produced with only one phase. Split-phase motors, therefore, split the current flow through two separate windings to simulate a two-phase power system. A rotating magnetic field can be produced with a two-phase system.

THE TWO-PHASE SYSTEM

two-phase
a power system that produces two voltages that are 90 degrees out of phase with each other.

In some parts of the world two-phase power is produced. A **two-phase** system is produced by having an alternator with two sets of coils wound 90° apart, FIGURE 19-1. The voltages of a two-phase system are, therefore, 90° out of phase with each other. These two out-of-phase voltages can be used to produce a rotating magnetic field in a manner similar to that of producing a rotating magnetic field with the voltages of a three-phase system. Since there have to be two voltages, or currents, out of phase with each other to produce a rotating magnetic field, split-phase motors use two separate windings to create a phase difference between the currents in each of these windings. These motors literally split one phase and produce a second phase, hence the name split-phase motor.

STATOR WINDINGS

start winding
a single phase motor winding used to produce a rotating magnetic field.

run winding
the winding in a single phase motor that remains energized after the motor has started.

The stator of a split-phase motor contains two separate windings, the **start winding** and the **run winding.** The start winding is made of small wire and is placed near the top of the stator core. The run winding is

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

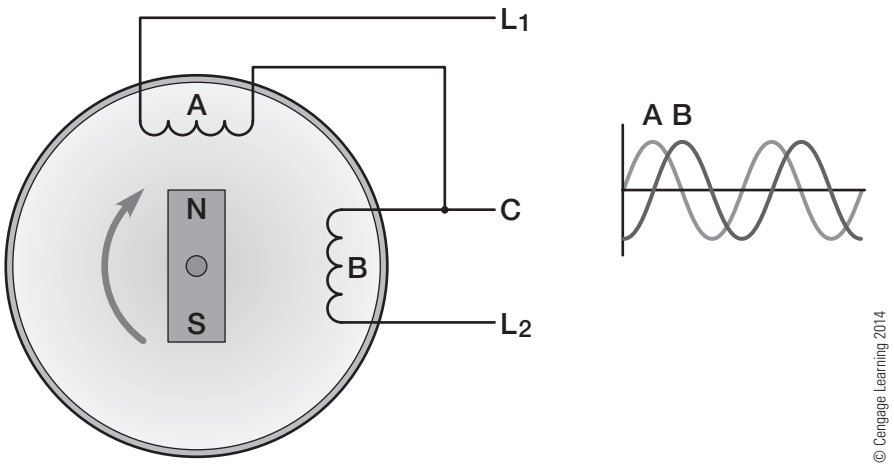


FIGURE 19-1 A two-phase alternator produces voltages that are 90° out of phase with each other.

made of relatively large wire and is placed in the bottom of the stator core. FIGURE 19-2A shows a photograph of a split-phase stator. This stator is used for a resistance-start induction-run motor or a capacitor-start induction-run motor. The stator shown in FIGURE 19-2B is used for a capacitor-start capacitor-run motor. Both stators contain four poles, and the start winding is placed at a 90° angle from the run winding.

Notice the difference in size and position of the two windings of the stator shown in FIGURE 19-2A. The start winding is made from small wire and is placed near the top of the stator core. This causes it to have a higher resistance than the run winding. The start winding is located between the poles of the run winding. The run winding is made with larger wire and placed near the

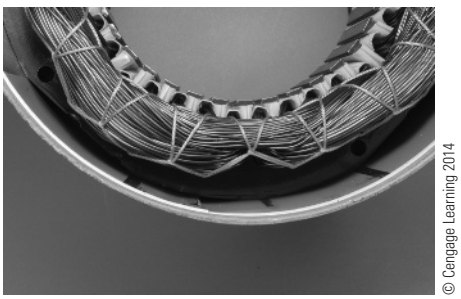


FIGURE 19-2A Stator winding of a resistance-start induction or capacitor-start induction-run motor.

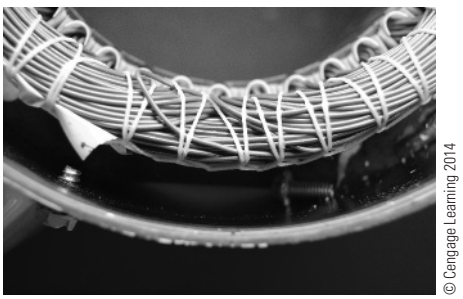


FIGURE 19-2B Stator winding of a capacitor-start capacitor-run motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

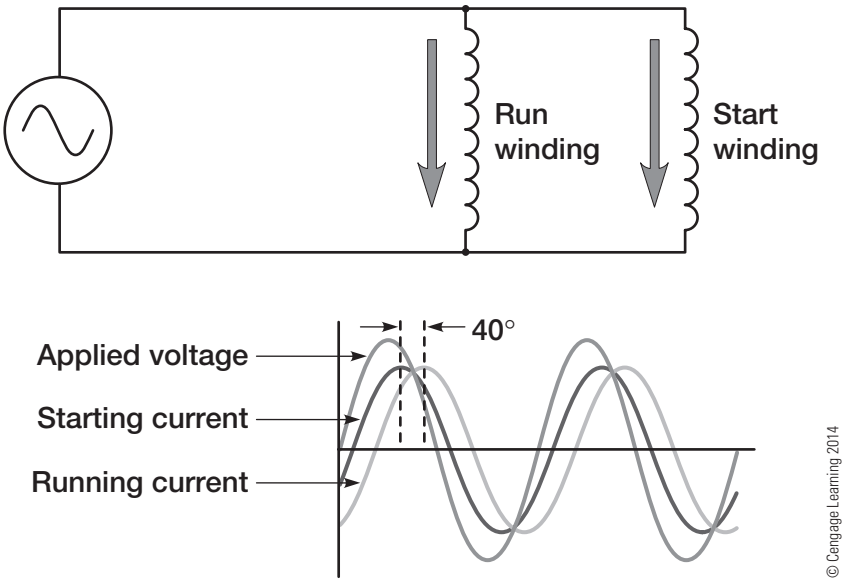


FIGURE 19-3 The start and run windings are connected in parallel with each other.

bottom of the core. This gives it higher inductive reactance and less resistance than the start winding. These two windings are connected in parallel with each other, FIGURE 19-3.

When power is applied to the stator, current will flow through both windings. Since the start winding is more resistive, the current flow will be more in phase with the applied voltage. The current flow through the run winding will lag the applied voltage due to inductive reactance. These two out-of-phase currents are used to create a rotating magnetic field in the stator. The speed of this rotating magnetic field is called **synchronous speed** and is determined by the same two factors that determined the synchronous speed for a three-phase motor:

synchronous speed speed of the rotating magnetic field of an AC induction motor.

1. Number of stator poles per phase
2. Frequency of the applied voltage

THE RESISTANCE-START INDUCTION-RUN MOTOR

The resistance-start induction-run motor receives its name from the fact that the out-of-phase condition between start and run winding current is caused by the start winding being more resistive than the run winding. The amount of starting torque produced by a split-phase motor is determined by three factors:

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

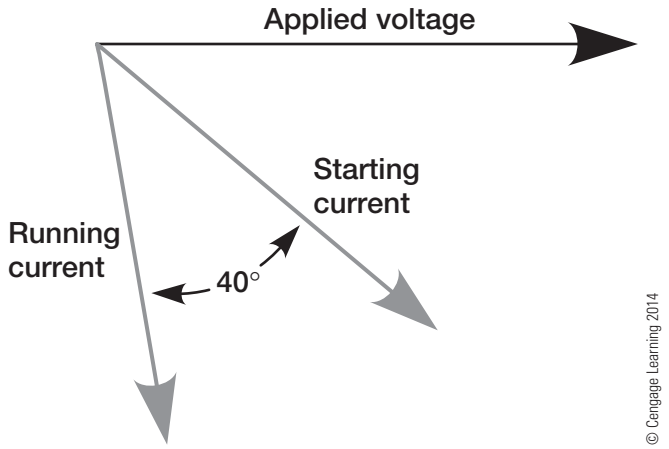


FIGURE 19-4 The running current and starting current are 35°–40° out of phase with each other.

1. The strength of the magnetic field of the stator
2. The strength of the magnetic field of the rotor
3. The phase angle difference between current in the start winding and current in the run winding (Maximum torque is produced when these two currents are 90° out of phase with each other.)

Although these two currents are out of phase with each other, they are not 90° out of phase. The run winding is more inductive than the start winding, but it does have some resistance, which prevents the current from being 90° out of phase with the voltage. The start winding is more resistive than the run winding, but it does have some inductive reactance, preventing the current from being in phase with the applied voltage. Therefore, a phase angle difference of 35°–40° is produced between these two currents, resulting in a rather poor starting torque, FIGURE 19-4.

DISCONNECTING THE START WINDING

A stator rotating magnetic field is necessary only to start the rotor turning in both the resistance-start induction-run and capacitor-start induction-run motors. Once the rotor has accelerated to approximately 75% of rated speed, the start winding can be disconnected from the circuit, and the motor will continue to operate with only the run winding energized. Motors that are not hermetically sealed (most refrigeration and air conditioning compressors are hermetically sealed), use a **centrifugal switch** to disconnect the start windings from the circuit. The contacts of the centrifugal switch are connected in series with the start winding, FIGURE 19-5. The centrifugal switch contains a

centrifugal switch switch used to disconnect the start winding when the motor reaches a predetermined speed.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

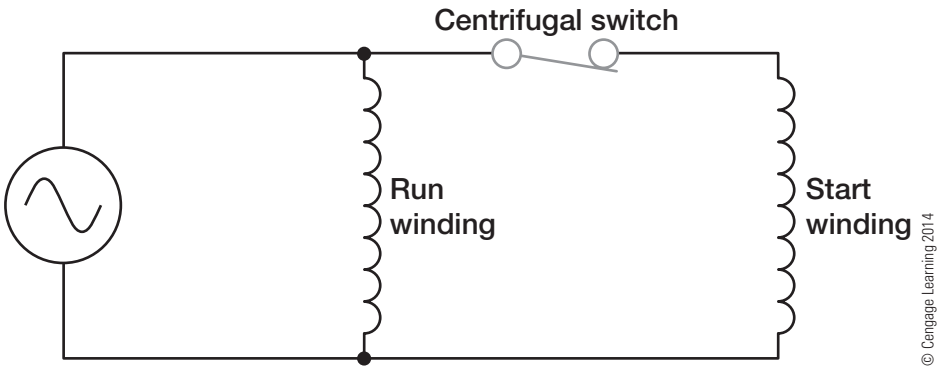


FIGURE 19-5 A centrifugal switch is used to disconnect the start winding from the circuit.

set of spring-loaded weights that control the operation of a fiber brushing and a switch assembly, FIGURE 19-6. When the shaft is not turning, the springs hold a fiber washer in contact with the movable contact of the switch, FIGURE 18-7. The fiber washer causes the movable contact to complete a circuit with a stationary contact.

When the rotor accelerates to about 75% of rated speed, centrifugal force causes the weights to overcome the force of the springs. The fiber washer retracts and permits the contacts to open and disconnect the start winding from the circuit. The start winding of this type of motor is intended to be energized only during the period of time that the motor is actually starting. If the start winding is not disconnected, it will be damaged by excessive current flow.

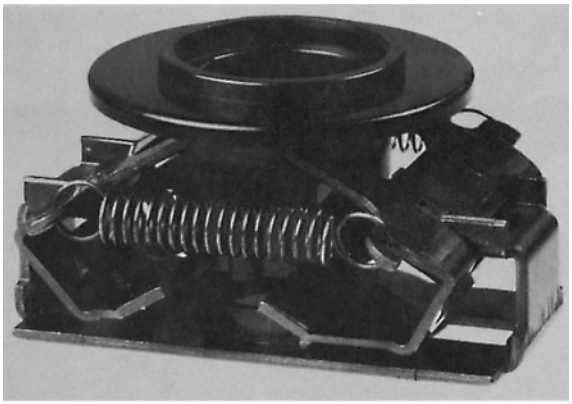
STARTING HERMETICALLY SEALED MOTORS

Resistance-start induction-run and capacitor-start induction-run motors are sometimes hermetically sealed as is the case with air conditioning and refrigeration compressors. When these motors are hermetically sealed, a centrifugal switch cannot be used to disconnect the start winding. A device that can be mounted externally must be used to disconnect the start windings from the circuit. Starting relays are used to perform this function. There are two basic types of starting relays used with the resistance start and capacitor start motors:

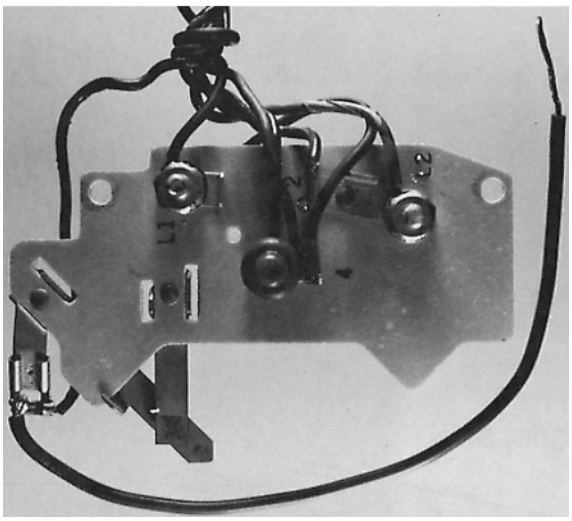
1. The hot-wire relay
2. The current relay

Although the *hot-wire relay* is seldom used, it is still found on some older units that are still in service. The hot-wire relay functions as both a starting

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

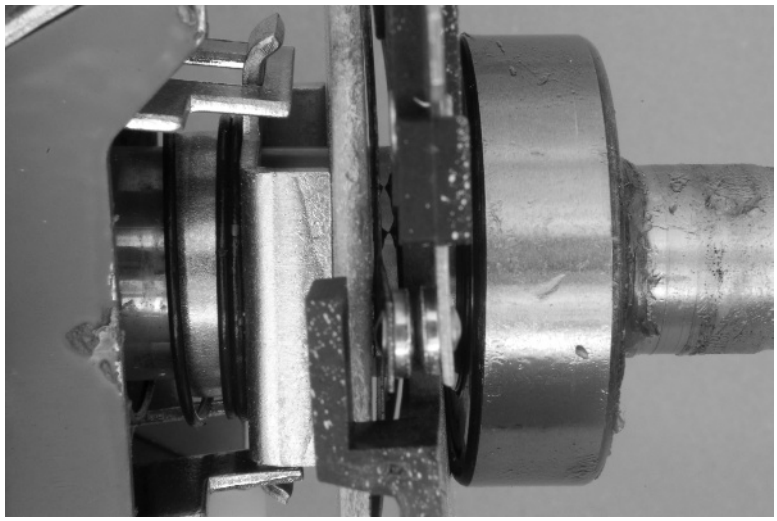


© Cengage Learning 2014

FIGURE 19-6 Centrifugal switch.

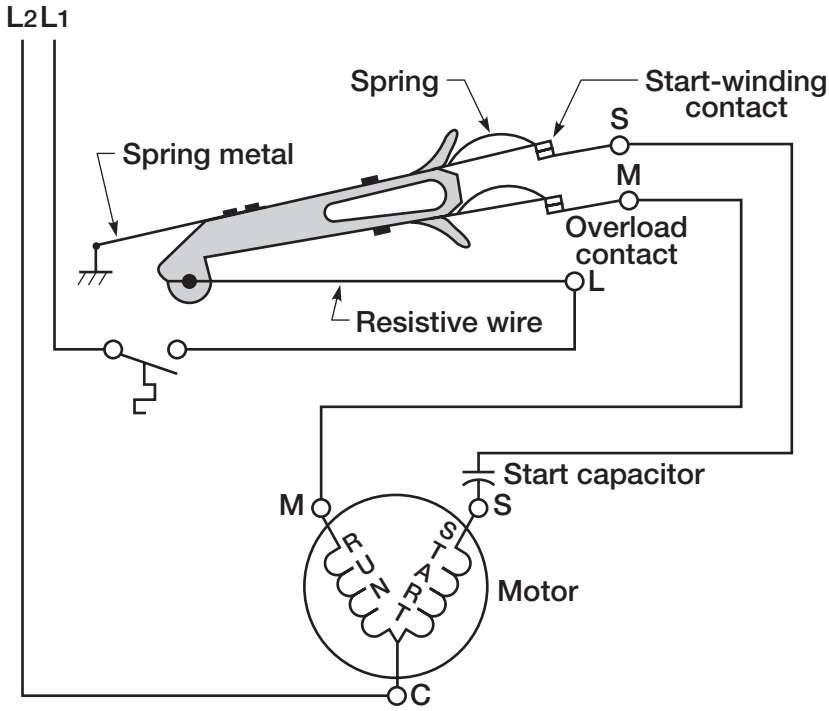
relay and an overload relay. In the circuit shown in FIGURE 19-8, it is assumed that a thermostat controls the operation of the motor. When the thermostat closes, current flows through a resistive wire and two normally closed contacts connected to the start and run windings of the motor. The starting current of the motor is high and rapidly heats the resistive wire, causing it to expand. The expansion of the wire causes the spring-loaded start winding contact to open and disconnect the start winding from the circuit, reducing motor current. If the motor is not overloaded, the resistive wire never becomes hot enough to cause the overload contact to open and the motor continues to run. If the motor should become overloaded, however, the resistive wire will expand

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 19-7 The centrifugal switch is closed when the rotor is not turning.



© Cengage Learning 2014

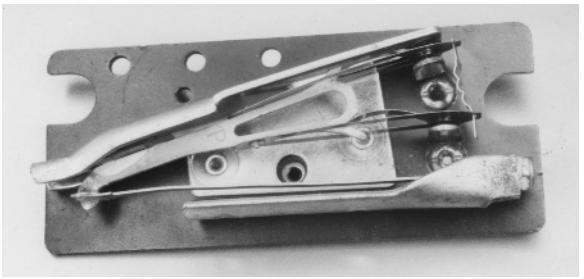
FIGURE 19-8 Hot-wire relay connection.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

enough to open the overload contact and disconnect the motor from the line. A photograph of a hot-wire starting relay is shown in FIGURE 19-9.

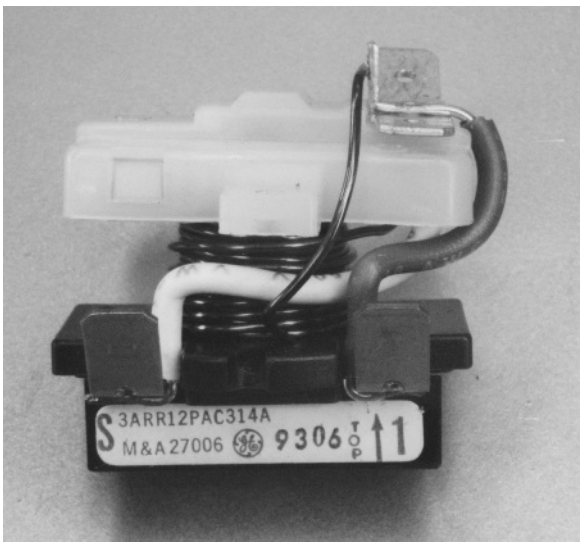
The **current relay** also operates by sensing the amount of current flow in the circuit. This type of relay operates on the principle of a magnetic field instead of expanding metal. The current relay contains a coil with a few turns of large wire and a set of normally open contacts, FIGURE 19-10. The coil of the relay is connected in series with the run winding of the motor, and the contacts are connected in series with the start winding as shown in FIGURE 19-11. When the thermostat contact closes, power is applied to the run winding of the motor. Since the start winding is open, the motor cannot start. This causes a high current to flow in the run winding circuit. This high current flow produces a strong magnetic field in the coil of the relay, causing

current relay
relay that is operated by a predetermined amount of current flow. Current relays are often used as one type of starting relay for air conditioning and refrigeration equipment.



© Cengage Learning 2014

FIGURE 19-9 Hot-wire type of starting relay.



© Cengage Learning 2014

FIGURE 19-10 Current type of starting relay.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

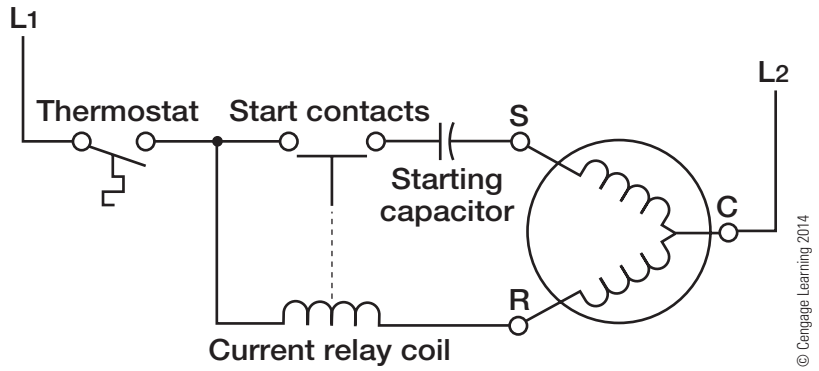


FIGURE 19-11 Current relay connection.

the normally open contacts to close and connect the start winding to the circuit. When the motor starts, the run winding current is greatly reduced, permitting the start contacts to reopen and disconnect the start winding from the circuit.

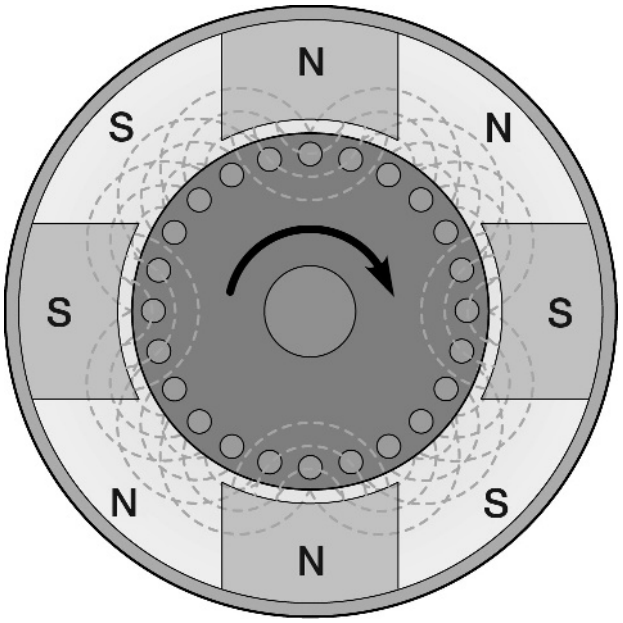
RELATIONSHIP OF STATOR AND ROTOR FIELDS

The split-phase motor contains a squirrel-cage rotor very similar to those used with three-phase squirrel-cage motors. When power is connected to the stator windings, the rotating magnetic field induces a voltage into the bars of the squirrel-cage rotor. The induced voltage causes current to flow in the rotor, and a magnetic field is produced around the rotor bars. The magnetic field of the rotor is attracted to the stator field and the rotor begins to turn in the direction of the rotating magnetic field. After the centrifugal switch opens, only the run winding induces voltage into the rotor. This induced voltage is in phase with the stator current. The inductive reactance of the rotor is high, causing the rotor current to be almost 90° out of phase with the induced voltage. This causes the pulsating magnetic field of the rotor to lag the pulsating magnetic field of the stator by 90°. Magnetic poles are created in the rotor and are located midway between the stator poles, FIGURE 19-12. These two pulsating magnetic fields produce a rotating magnetic field of their own, and the rotor continues to rotate.

DIRECTION OF ROTATION

The direction of rotation for the motor is determined by the direction of rotation of the rotating magnetic field created by the run and start windings when the motor is first started. The direction of motor rotation can be changed by reversing the connection of either the start winding or the run winding, but

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 19-12 A rotating magnetic field is produced by the stator and rotor flux.

not both. If the start winding is disconnected, the motor can be operated in either direction by manually turning the rotor shaft in the desired direction of rotation.

THE CAPACITOR-START INDUCTION-RUN MOTOR

The capacitor-start induction-run motor is very similar in construction and operation to the resistance-start induction-run motor. The capacitor-start induction-run motor, however, has an AC electrolytic capacitor connected in series with the centrifugal switch and start winding, FIGURE 19-13. Although the running characteristics of both the capacitor-start induction-run motor and the resistance-start induction-run motor are identical, the starting characteristics are not. The capacitor-start induction-run motor produces a starting torque that is substantially higher than the resistance-start induction-run motor. Recall that one of the factors that determines the starting torque for a split-phase motor is the phase angle difference between start-winding current and run-winding current. The starting torque of a resistance-start induction-run motor is low because the phase angle difference between these two currents is only about 40°, Figure 19-4.

When a capacitor of the proper size is connected in series with the start winding, it causes the start winding current to lead the applied voltage. This

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

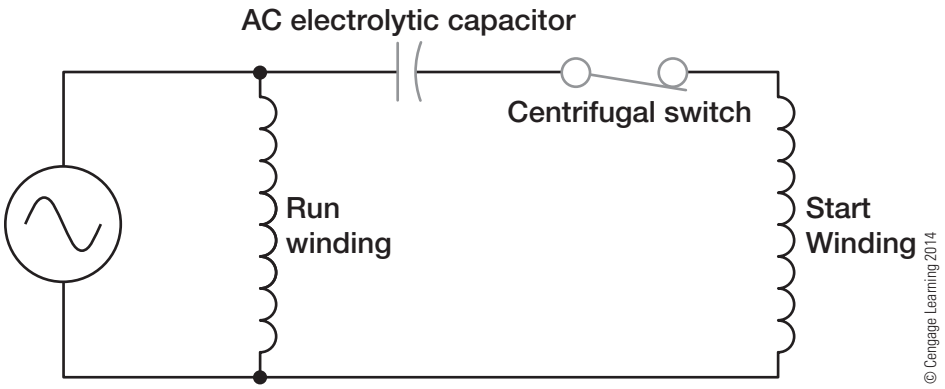


FIGURE 19-13 An AC electrolytic capacitor is connected in series with the start winding.

leading current produces a 90° phase shift between run-winding current and start-winding current, FIGURE 19-14. Maximum starting torque is developed at this point.

KEY POINT

Although the capacitor-start induction-run motor has a high starting torque, the motor should not be started more than about eight times per hour.

Although the capacitor-start induction-run motor has a high starting torque, the motor should not be started more than about eight times per hour. Frequent starting can damage the start capacitor due to overheating. If the capacitor must be replaced, care should be taken to use a capacitor of the correct microfarad rating. If a capacitor with too little capacitance is used, the starting current will be less than 90° out of phase with the running current, and the starting torque will be reduced. If the capacitance value is too

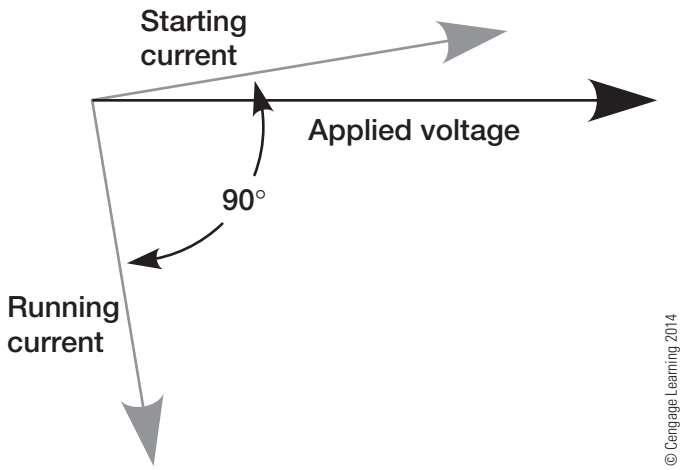


FIGURE 19-14 Run-winding current and start-winding current are 90° out of phase with each other.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

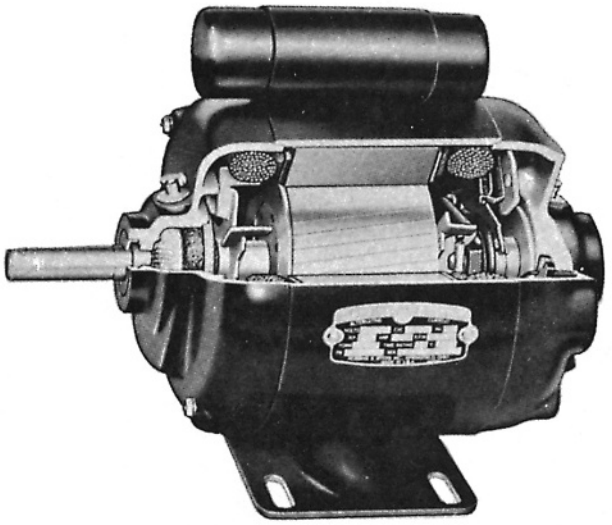

© Cengage Learning 2014

FIGURE 19-15 Capacitor-start induction-run motor.

great, the starting current will be more than 90° out of phase with the running current, and the starting torque will again be reduced. A capacitor-start induction-run motor is shown in FIGURE 19-15.

DUAL-VOLTAGE SPLIT-PHASE MOTORS

Many split-phase motors are designed for operation on 120 V or 240 V. FIGURE 19-16 shows the schematic diagram of a split-phase motor designed for dual-voltage operation. This particular motor contains two run windings and two start windings. The lead numbers for single-phase motors are numbered in a standard manner also. One of the run windings has lead numbers of T_1 and T_2. The other run winding has its leads numbered T_3 and T_4. This particular motor uses two different sets of start winding leads. One set is labeled T_5 and T_6, and the other set is labeled T_7 and T_8.

If the motor is to be connected for high-voltage operation, the run windings and start windings will be connected in series as shown in FIGURE 19-17. The start windings are then connected in parallel with the run windings. It should be noted that if the opposite direction of rotation is desired, T_5 and T_8 will be changed.

For low-voltage operation, the windings must be connected in parallel as shown in FIGURE 19-18. This connection is made by first connecting the run windings in parallel by hooking T_1 and T_3 together, and T_2 and T_4 together. The start windings are paralleled by connecting T_5 and T_7 together, and T_6 and T_8 together. The start windings are then connected in parallel with the run windings. If the opposite direction of rotation is desired, T_5 and T_6 should be reversed.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

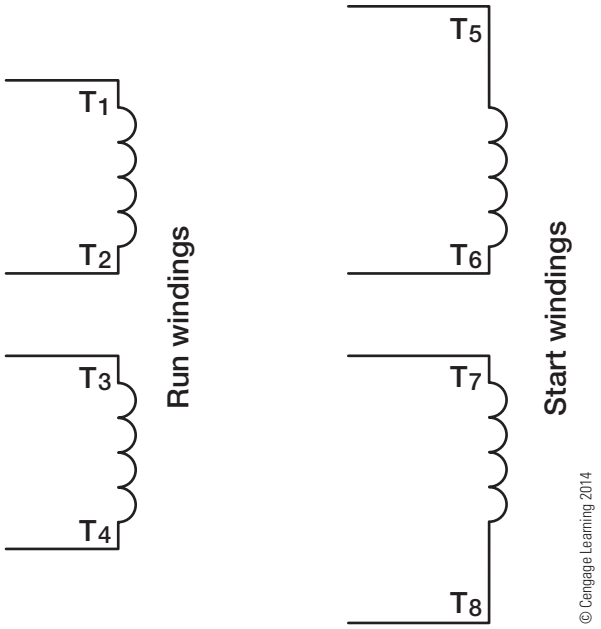


FIGURE 19-16 Dual-voltage windings for a split-phase motor.

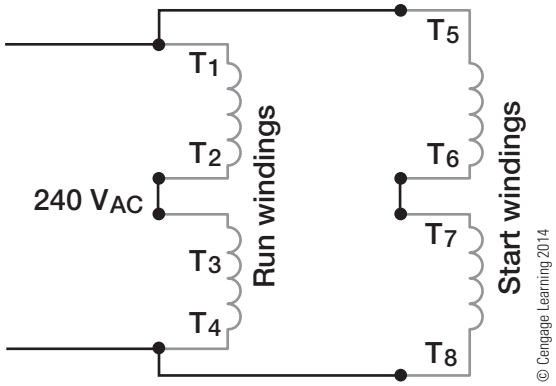


FIGURE 19-17 High-voltage connection for a split-phase motor with two run and two start windings.

Not all dual-voltage single-phase motors contain two sets of start windings. FIGURE 19-19 shows the schematic diagram of a motor that contains two sets of run windings and only one start winding. In this illustration, the start winding is labeled T_5 and T_6. It should be noted, however, that some motors identify the start winding by labeling it T_5 and T_8 as shown in FIGURE 19-20.

Regardless of which method is used to label the terminal leads of the start winding, the connection will be the same. If the motor is to be connected for

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

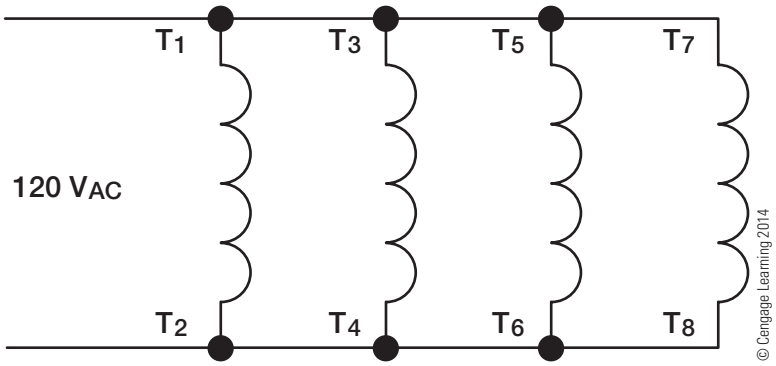


FIGURE 19-18 Low-voltage connection for a split-phase motor with two run and two start windings.

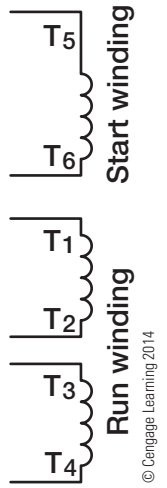


FIGURE 19-19 Dual-voltage motor with one start winding labeled T_5 and T_6.

high-voltage operation, the run windings will be connected in series, and the start winding will be connected in parallel with one of the run windings, as shown in FIGURE 19-21. In this type of motor, each winding is rated at 120 V. If the run windings are connected in series across 240 V, each winding will have a voltage drop of 120 V. By connecting the start winding in parallel across only one run winding, it will receive only 120 V when power is applied to the motor. If the opposite direction of rotation is desired, T_5 and T_8 should be changed.

If the motor is to be operated on low voltage, the windings are connected in parallel as shown in FIGURE 19-22. Since all windings are connected in parallel, each will receive 120 V when power is applied to the motor.

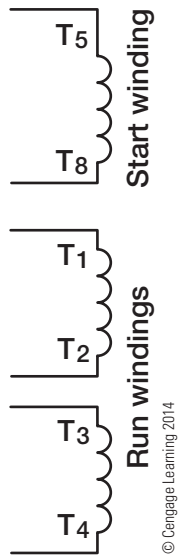


FIGURE 19-20 Dual-voltage motor with one start winding labeled T_5 and T_8.

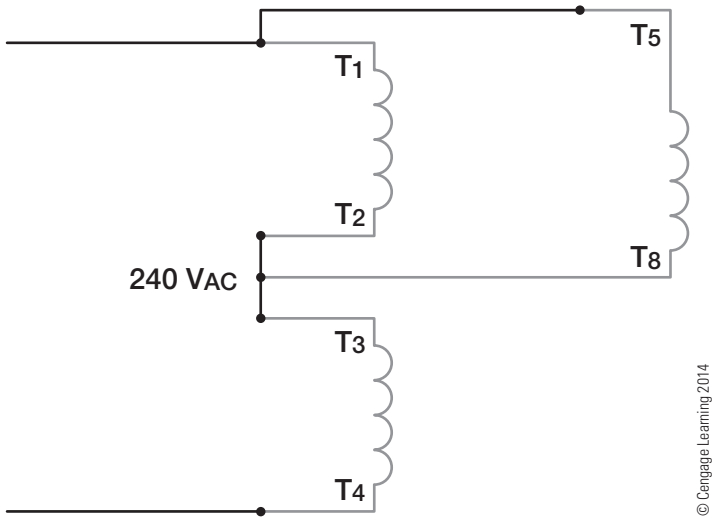


FIGURE 19-21 High-voltage connection with one start winding.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

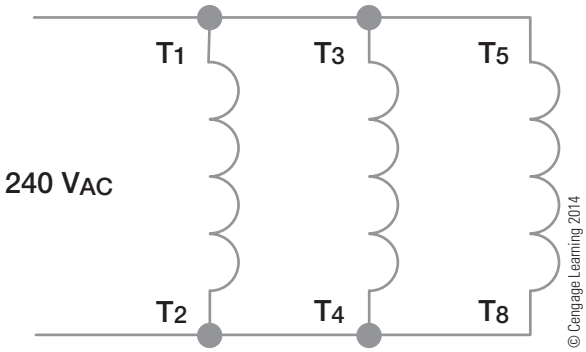


FIGURE 19-22 Low-voltage connection for a split-phase motor with one-start winding.

DETERMINING THE DIRECTION OF ROTATION FOR SPLIT-PHASE MOTORS

The direction of rotation of a single-phase motor can generally be determined when the motor is connected. The direction of rotation is determined by facing the back or rear of the motor. FIGURE 19-23 shows a connection diagram for rotation. If clockwise rotation is desired, T_5 should be connected to T_1. If counterclockwise rotation is desired, T_8 (or T_6) should be connected to T_1. It should be noted that this connection diagram assumes the motor contains two sets of run and two sets of start windings. The type of motor used will determine the actual connection. For example, Figure 19-21 shows the connection of a motor with two run windings and only one-start winding. If this motor were to be connected for clockwise rotation, terminal T_5 would be

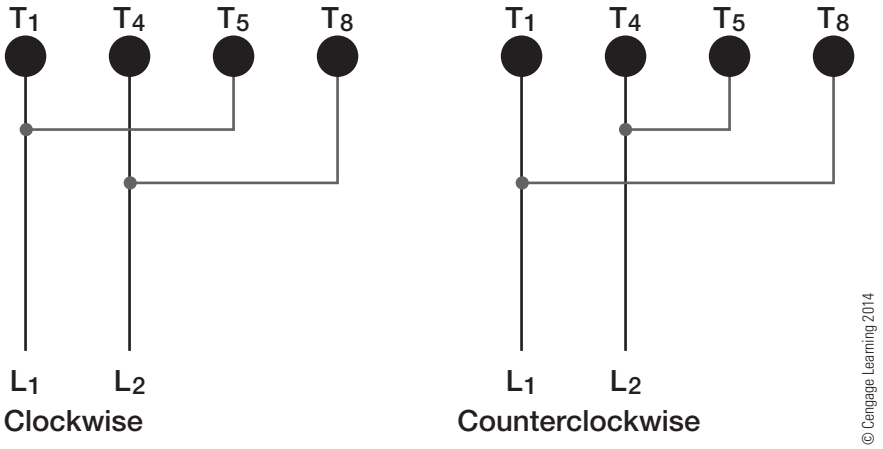


FIGURE 19-23 Determining the direction of rotation for a split-phase motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

connected to T_1 and terminal T_8 would be connected to T_2 and T_3. If counterclockwise rotation is desired, terminal T_8 would be connected to T_1 and terminal T_5 would be connected to T_2 and T_3.

CAPACITOR-START CAPACITOR-RUN MOTOR (PERMANENT SPLIT-CAPACITOR MOTOR)

Although the capacitor-start capacitor-run motor is a split-phase motor, it operates on a different principle than the resistance-start induction-run motor or the capacitor-start induction-run motor. The capacitor-start capacitor-run motor is designed so that its start winding remains energized at all times. A capacitor is connected in series with the winding to provide a continuous leading current in the start winding, FIGURE 19-24. Since the start winding remains energized at all times, no centrifugal switch is needed to disconnect the start winding as the motor approaches full speed. Because the start winding remains in the circuit when the motor is in operation, the wire used to form the start winding is the same size as the wire that forms the run winding as seen in FIGURE 19-2B. The phase shift of the run and start winding currents is produced mainly by the capacitor connected in series with the start winding, not an increase of resistance in the start winding due to smaller size wire. The capacitor used in this type of motor will generally be of the oil-filled type since it is intended for continuous use. An exception to this general rule are small fractional horsepower motors used in reversible ceiling fans. These fans have a low current draw and use an AC electrolytic capacitor to help save space.

The capacitor-start capacitor-run motor actually operates on the principle of a rotating magnetic field in the stator. Since both run and start windings remain energized at all times, the stator magnetic field continues to rotate and the motor operates as a two-phase motor. This motor has excellent starting and running torque. It is quiet in operation and has a high efficiency. Since the capacitor remains connected in the circuit at all times, the motor power factor is close to unity.

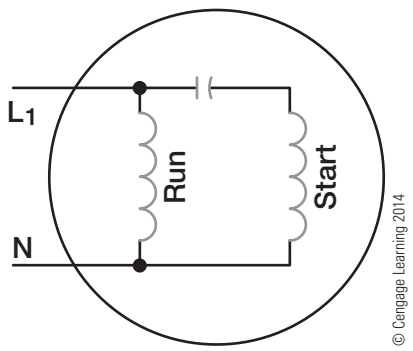
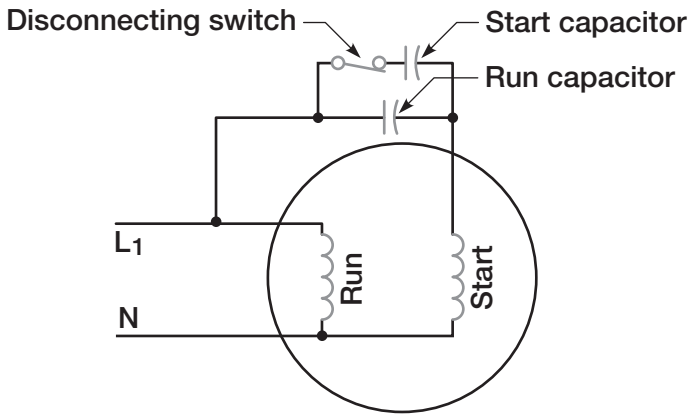


FIGURE 19-24 A capacitor-start capacitor-run motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Although the capacitor-start capacitor-run motor does not require a centrifugal switch to disconnect the capacitor from the start winding, there are some motors that use a second capacitor during the starting period to help improve starting torque, FIGURE 19-25. Capacitor-start capacitor-run motors that are not hermetically sealed contain a centrifugal switch to disconnect the start capacitor when the motor reaches about 75% of its full load speed.

Hermetically sealed motors, such as the compressor of a central air conditioning unit designed for operation on single-phase power, use an external starting relay to disconnect the starting capacitor. This type of motor generally employs a potential starting relay, FIGURE 19-26. The potential starting relay operates by sensing an increase in the voltage developed in the start winding when the motor is operating. A schematic diagram of a potential starting relay circuit is shown in FIGURE 19-27. In this circuit, the potential relay



© Cengage Learning 2014

FIGURE 19-25 Capacitor-start capacitor-run motor with additional starting capacitor.

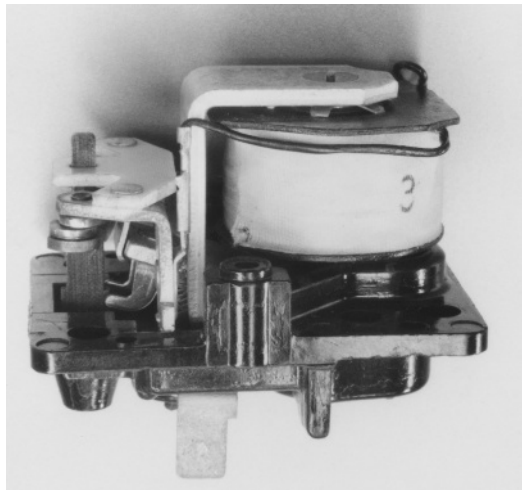

© Cengage Learning 2014

FIGURE 19-26 Potential starting relay.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

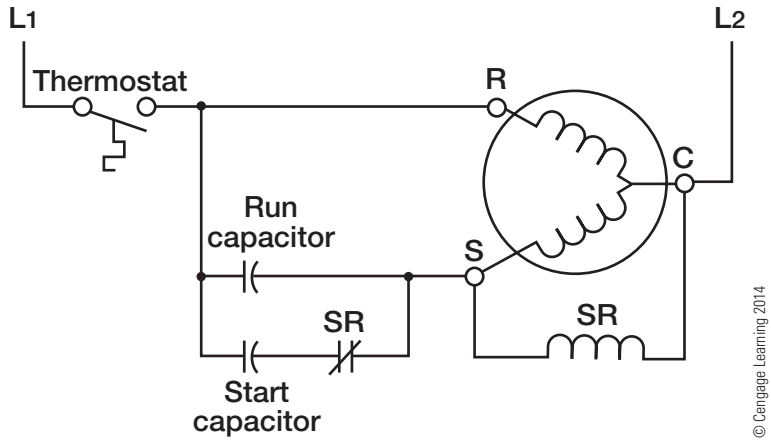


FIGURE 19-27 Potential relay connection.

is used to disconnect the starting capacitor from the circuit when the motor reaches about 75% of its full speed. The starting relay coil, SR, is connected in parallel with the start winding of the motor. A normally closed SR contact is connected in series with the starting capacitor. When the thermostat contact closes, power is applied to both the run and start windings. At this point in time, both the start and run capacitors are connected in the circuit.

As the rotor begins to turn, its magnetic field induces a voltage into the start winding, producing a higher voltage across the start winding than the applied voltage. When the motor has accelerated to about 75% of its full speed, the voltage across the start winding is high enough to energize the coil of the potential relay. This causes the normally closed SR contact to open and disconnect the start capacitor from the circuit.

SHADED-POLE INDUCTION MOTORS

The **shaded-pole induction motor** is popular because of its simplicity and long life. This motor contains no start windings or centrifugal switch. It contains a squirrel-cage rotor and operates on the principle of a rotating magnetic field. The rotating magnetic field is created by a **shading coil** wound on one side of each pole piece. Shaded-pole motors are generally fractional-horsepower motors and used for low-torque applications such as operating fans and blowers.

shaded-pole induction motor
a type of single phase motor.

shading coil
a shorted loop around part of a pole piece.

THE SHADING COIL

The shading coil is wound around one end of the pole piece, FIGURE 19-28. The shading coil is actually a large loop of copper wire or a copper band. Both ends are connected to form a complete circuit. The shading coil acts in

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

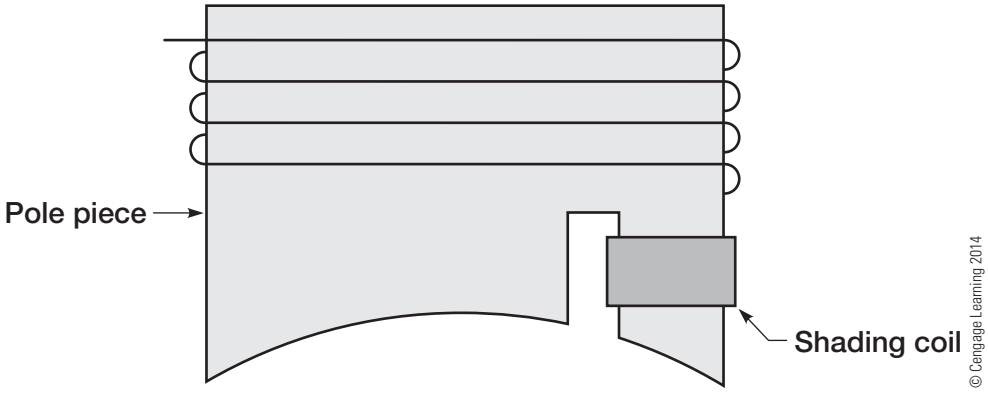


FIGURE 19-28 A shaded pole.

the same manner as a transformer with a shorted secondary winding. When the current of the AC waveform increases from zero toward its positive peak, a magnetic field is created in the pole piece. As magnetic lines of flux cut through the shading coil, a voltage is induced in the coil. Since the coil is a low-resistance short circuit, a large amount of current flows in the loop. This current causes an opposition to the change of magnetic flux, FIGURE 19-29. As long as voltage is induced into the shading coil, there will be an opposition to the change of magnetic flux.

When the AC current reaches its peak value, it is no longer changing, and no voltage is being induced into the shaded coil. Since there is no current flow in the shading coil, there is no opposition to the magnetic flux. The magnetic flux of the pole piece is now uniform across the pole face, FIGURE 19-30.

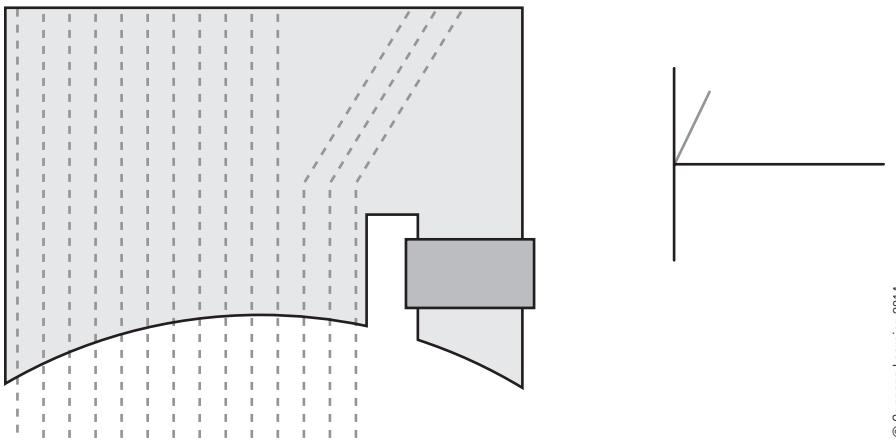


FIGURE 19-29 The shading coil opposes a change of flux as current increases.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

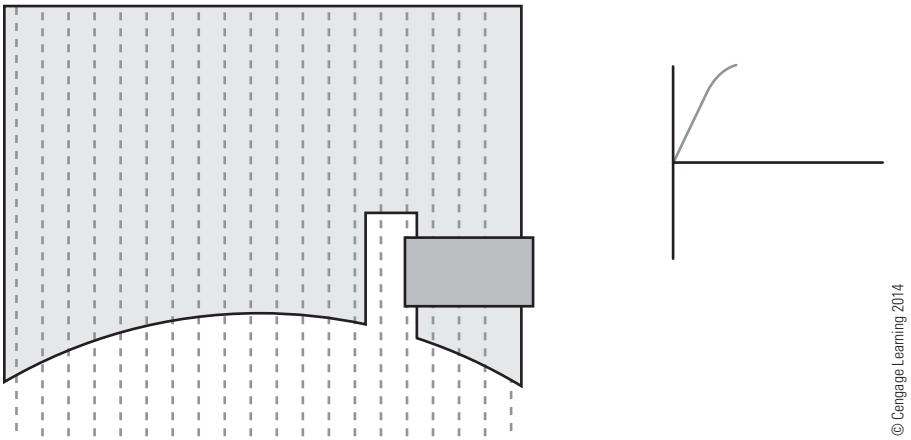


FIGURE 19-30 There is no opposition to magnetic flux when the current is not changing.

When the AC current begins to decrease from its peak value back toward zero, the magnetic field of the pole piece begins to collapse. A voltage is again induced into the shading coil. This induced voltage creates a current that opposes the change of magnetic flux, FIGURE 19-31. This causes the magnetic flux to be concentrated in the shaded section of the pole piece.

When the AC current passes through zero and begins to increase in the negative direction, the same set of events happen, except that the polarity of the magnetic field is reversed. If these events were to be viewed in rapid order, the magnetic field would be seen to rotate across the face of the pole piece.

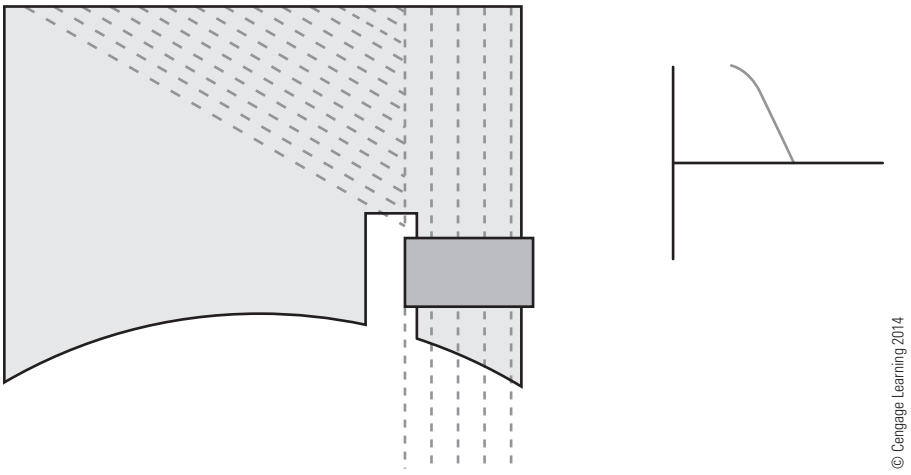


FIGURE 19-31 The shading coil opposes a change of flux when the current decreases.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

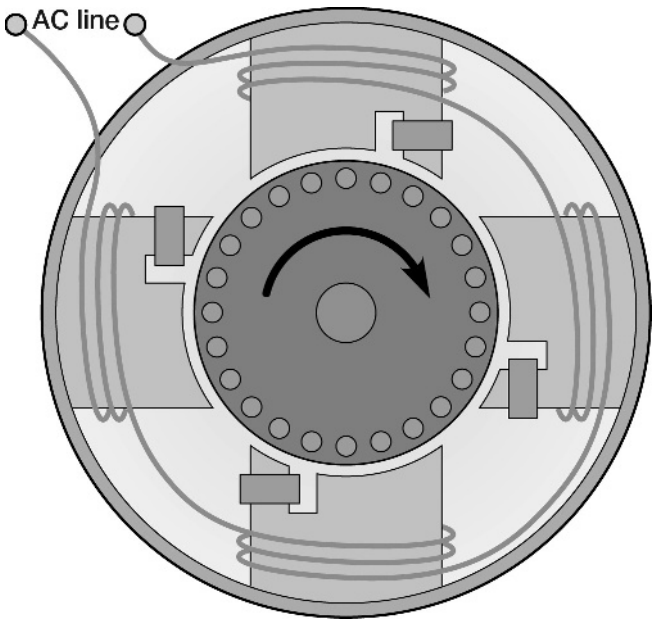
SPEED

The speed of the shaded-pole induction motor is determined by the same factors that determine the synchronous speed of other induction motors: frequency and number of stator poles. Shaded-pole motors are commonly wound as four or six pole motors. FIGURE 19-32 shows a drawing of a four-pole shaded-pole induction motor.

GENERAL OPERATING CHARACTERISTICS

The shaded-pole motor contains a standard squirrel-cage rotor. The amount of torque produced is determined by the strength of the magnetic field of the stator, the strength of the magnetic field of the rotor, and the phase angle difference between rotor and stator flux. The shaded-pole induction motor has low starting and running torque.

The direction of rotation is determined by the direction in which the rotating magnetic field moves across the pole face. The rotor will turn in the direction shown by the arrow in Figure 19-32. If the direction must be changed, it can be done by removing the stator winding and turning it around. This is not a common practice, however. As a general rule the shaded-pole induction motor is considered to be nonreversible. FIGURE 19-33 shows a photograph of the stator winding and rotor of a shaded-pole induction motor.



© Cengage Learning 2014

FIGURE 19-32 Four-pole shaded-pole induction motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

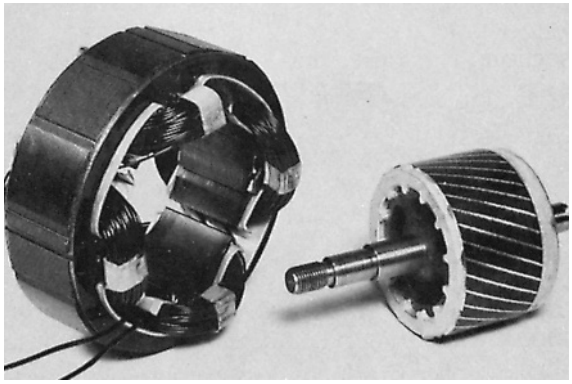

© Cengage Learning 2014

FIGURE 19-33 Stator winding and rotor of a shaded-pole induction motor.

MULTISPEED MOTORS

multispeed motors motor that can be operated at more than one speed.

consequent-pole motor motors that change speed by changing the number of stator poles.

There are two basic types of **multispeed** single-phase **motors.** One is the **consequent-pole motor** and the other is a specially wound capacitor-start capacitor-run motor or shaded-pole induction motor. The consequent-pole single-phase motor operates in the same basic way as the three-phase consequent-pole discussed in Unit 17. The speed is changed by reversing the current flow through alternate poles and increasing or decreasing the total number of stator poles. The consequent-pole motor is used where high running torque must be maintained at different speeds. A good example of where this type of motor is used is in two-speed compressors for central air conditioning units.

MULTISPEED FAN MOTORS

Multispeed fan motors have been used for many years. These motors are generally wound for two to five steps of speed and operate fans and squirrel-cage blowers. A schematic drawing of a three-speed motor is shown in FIGURE 19-34. Notice that the run winding has been tapped to produce low, medium, and high speed. The start winding is connected in parallel with the run winding section. The other end of the start winding lead is connected to an external oil-filled capacitor. This motor obtains a change of speed by inserting inductance in series with the run winding. The actual run winding for this motor is between the terminals marked *high* and *common*. The winding shown between *high* and *medium* is connected in series with the main run winding. When the rotary switch is connected to the medium speed position, the inductive reactance of this coil limits the amount of current flow through the run winding. When the current of the run winding is reduced, the

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

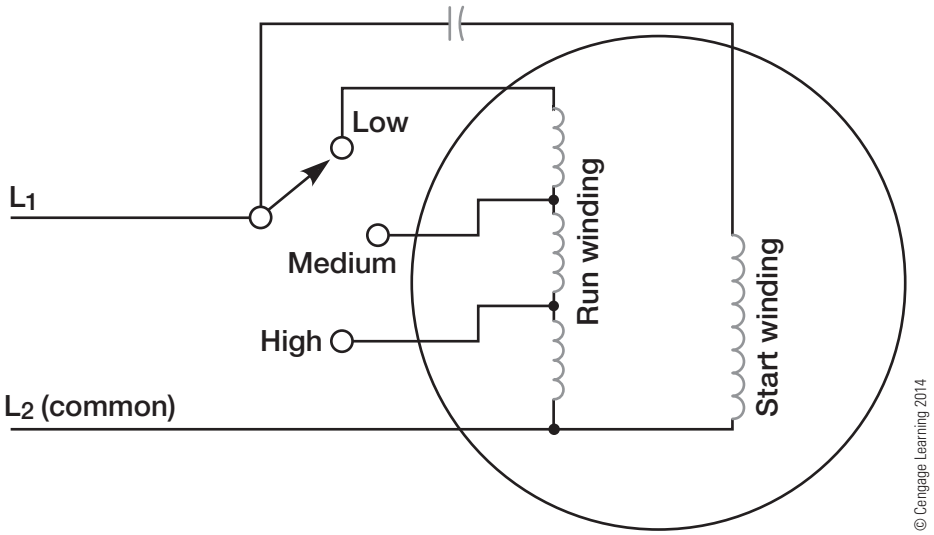


FIGURE 19-34 A three-speed motor.

strength of the magnetic field of the run winding is reduced and the motor produces less torque. This causes a greater amount of slip and the motor speed to decrease.

If the rotary switch is changed to the low position, more inductance is inserted in series with the run winding. This causes less current to flow through the run winding and another reduction in torque. When the torque is reduced the motor speed decreases again.

Common speeds for a four-pole motor of this type are 1625, 1500, and 1350 RPM. Notice that this motor does not have wide ranges between speeds as would be the case with a consequent-pole motor. Most induction motors would overheat and damage the motor winding if the speed were to be reduced to this extent. This type of motor, however, has much higher-impedance windings than most motors. The run windings of most split-phase motors have a wire resistance of 1–4 Ω. This motor will generally have a resistance of 10–15 Ω in its run winding. It is the high-impedance of the windings that permits the motor to be operated in this manner without damage.

Since this motor is designed to slow down when load is added, it is not used to operate high-torque loads. This type of motor is generally used to operate only low-torque loads such as fans and blowers.

SINGLE-PHASE SYNCHRONOUS MOTORS

synchronous motors a type of fractional horsepower single phase motor.

Single-phase **synchronous motors** are small and develop only fractional horsepower. They operate on the principle of a rotating magnetic field

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

developed by a shaded-pole stator. Although they will operate at synchronous speed, they do not require DC excitation current. They are used in applications where constant speed is required such as clock motors, timers, and recording instruments. They also are used as the driving force for small fans because they are small and inexpensive to manufacture. There are two basic types of synchronous motors: the Warren or General Electric motor, and the Holtz motor. These motors are also referred to as hysteresis motors.

WARREN MOTORS

Warren motor
a type of single phase synchronous motor.

The **Warren motor** is constructed with a laminated stator core and a single coil. The coil is generally wound for 120-V AC operation. The core contains two poles, which are divided into two sections each. One-half of each pole piece contains a shading coil to produce a rotating magnetic field, FIGURE 19-35. Since the stator is divided into two poles, the synchronous field speed will be 3,600 RPM when connected to 60 Hz.

The difference between the Warren and Holtz motors is the type of rotor used. The rotor of the Warren motor is constructed by stacking hardened steel laminations onto the rotor shaft. These disks have high hysteresis loss. The

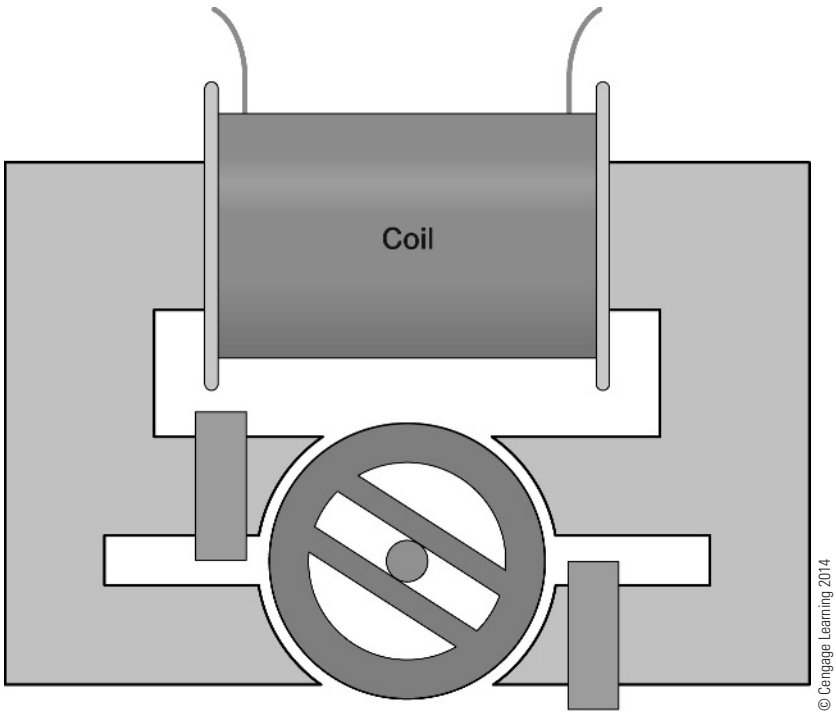


FIGURE 19-35 A Warren motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

laminations form two crossbars for the rotor. When power is connected to the motor, the rotating magnetic field induces a voltage into the rotor and a strong starting torque is developed, causing the rotor to accelerate to near synchronous speed. Once the motor has accelerated to near synchronous speed, the flux of the rotating magnetic field will follow the path of minimum reluctance (magnetic resistance) through the two crossbars. This causes the rotor to lock in step with the rotating magnetic field and the motor operates at 3,600 RPM. These motors are often used with small gear trains to reduce the speed to the desired level.

HOLTZ MOTORS

Holtz motor
a type of single phase synchronous motor.

The **Holtz motor** uses a different type of rotor, FIGURE 19-36. This rotor is cut in such a manner that six slots are formed. These slots form six salient (projecting or jutting) poles for the rotor. A squirrel-cage winding is constructed by inserting a metal bar at the bottom of each slot. When power is connected to the motor, the squirrel-cage winding provides the torque necessary to start

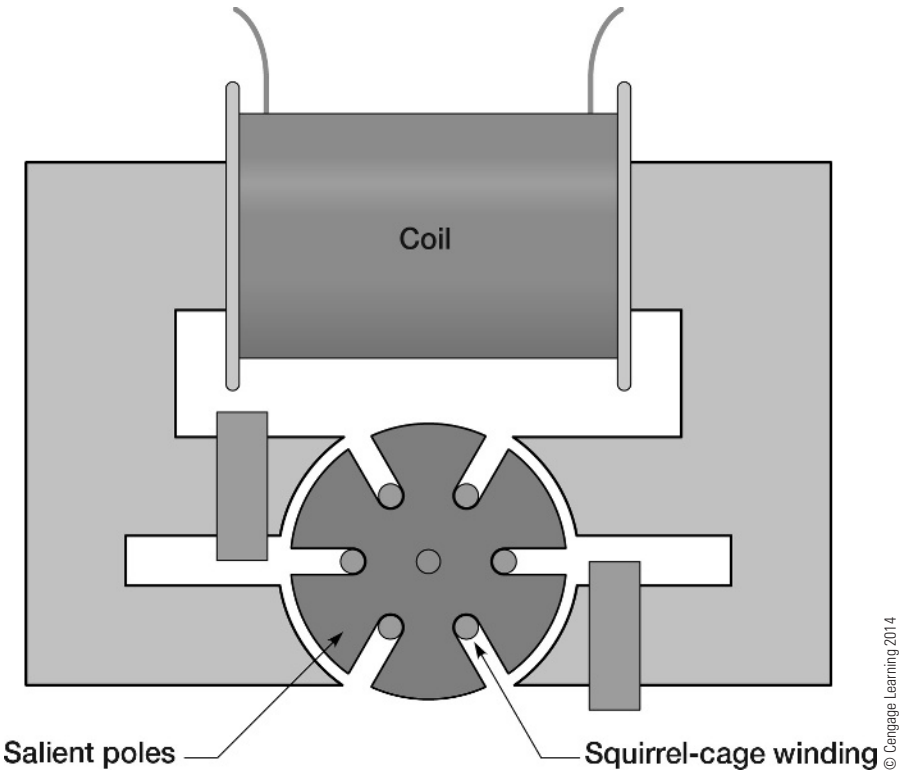


FIGURE 19-36 A Holtz motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

the rotor turning. When the rotor approaches synchronous speed, the salient poles will lock in step with the field poles each half cycle. This produces a rotor speed of 1,200 RPM (one-third of synchronous speed) for the motor.

UNIVERSAL MOTORS

The **universal motor** is often referred to as an AC series motor. This motor is very similar to a DC series motor in its construction because it contains a wound armature and brushes, FIGURE 19-37. The universal motor, however, has the addition of a **compensating winding.** The universal motor is so named because it can be operated on AC or DC voltage.

universal motor
a type of single phase motor that can operate on AC or DC power.

compensating winding
winding embedded in the main field poles of a DC machine. The compensating winding is used to help overcome armature reaction.

SPEED REGULATION

The speed regulation of the universal motor is very poor. If the universal motor is connected to a light load or no load, its speed is almost unlimited. It is not unusual for this motor to be operated at several thousand RPM. Universal motors are used in a number of portable appliances where high horsepower and light weight is needed, such as drill motors, skill saws, and vacuum cleaners. The universal motor is able to produce a high horsepower for its size and weight. To change the direction of rotation, change the armature leads with respect to the field leads.

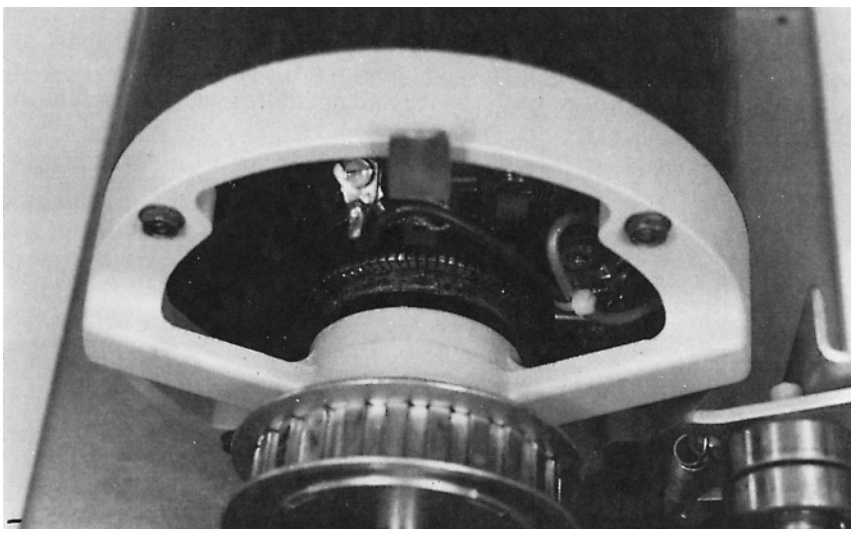

© Cengage Learning 2014

FIGURE 19-37 Armature and brushes of a universal motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Summary

1. Not all single-phase motors operate on the principle of a rotating magnetic field.
2. Split-phase motors start as two-phase motors by producing an out-of-phase condition for the current in the run winding and the current in the start winding.
3. The resistance of the wire in the start winding of a resistance-start induction-run motor is used to produce a phase angle difference between the current in the start winding and the current in the run winding.
4. The capacitor-start induction-run motor uses an AC electrolytic capacitor to increase the phase angle difference between starting and running current. This causes an increase in starting torque.
5. Maximum starting torque for a split-phase motor is developed when the start-winding current and run-winding current are 90° out of phase with each other.
6. Most resistance-start induction-run motors and capacitor-start induction-run motors use a centrifugal switch to disconnect the start windings when the motor reaches approximately 75% of full load speed.
7. The capacitor-start capacitor-run motor operates like a two-phase motor because both the start and run windings remain energized during motor operation.
8. Most capacitor-start capacitor-run motors use an AC oil-filled capacitor connected in series with the start winding.
9. The capacitor of the capacitor-start capacitor-run motor does help to correct the power factor.
10. Shaded-pole induction motors operate on the principle of a rotating magnetic field.
11. The rotating magnetic field of a shaded-pole induction motor is produced by placing shading loops or coils on one side of the pole piece.
12. The synchronous field speed of a single-phase motor is determined by the number of stator poles and the frequency of the applied voltage.
13. Consequent-pole motors are used when a change of motor speed is desired and high torque must be maintained.
14. Multispeed fan motors are constructed by connecting windings in series with the main run winding.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

15. Multispeed fan motors have high-impedance stator windings to prevent them from overheating when their speed is reduced.
16. Hermetically sealed resistance-start induction-run and capacitor-start induction-run motors use a starting relay to disconnect the start windings from the circuit when the motor approaches about 75% of its full speed.
17. Two types of starting relays used for the resistance-start induction-run and capacitor-start induction-motors are the hot-wire relay and the current relay.
18. A potential starting relay is generally used to disconnect the start capacitor from the line for a hermetically sealed capacitor-start capacitor-run motor.
19. The capacitor-start capacitor-run motor is also known as a permanent-split capacitor motor.
20. Shaded-pole motors are generally considered to be not reversible.
21. There are two type of single-phase synchronous motors: the Warren and the Holtz.
22. Single-phase synchronous motors are sometimes called hysteresis motors.
23. The Warren motor operates at a speed of 3,600 RPM.
24. The Holtz motor operates at a speed of 1,200 RPM.
25. Universal motors operate on direct or alternating current.
26. Universal motors contain a wound armature and brushes.
27. Universal motors are also called AC series motors.
28. The direction of rotation for a universal motor can be changed by reversing the armature leads with respect to the field leads.
29. Universal motors develop a large amount of horsepower for their size and weight because of their high operating speed.

Review Questions

1. What are the three basic types of split-phase motors?
2. The voltages of a two-phase system are how many degrees out of phase with each other?
3. How are the start and run windings of a split-phase motor connected in relation to each other?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

4. In order to produce maximum starting torque in a split-phase motor, how many degrees out of phase should the start and run winding currents be with each other?
5. What is the advantage of the capacitor-start induction-run motor over the resistance-start induction-run motor?
6. On the average, how many degrees out of phase with each other are the start and run winding currents in a resistance-start induction-run motor?
7. What device is used to disconnect the start windings for the circuit in most non-hermetically sealed capacitor-start induction-run motors?
8. Why does a split-phase motor continue to operate after the start windings have been disconnected from the circuit?
9. How can the direction of rotation of a split-phase motor be reversed?
10. If a dual-voltage split-phase motor is to be operated on high voltage, how are the run windings connected in relation to each other?
11. When determining the direction of rotation for a split-phase motor, should that motor be faced from the front or from the rear?
12. What type of split-phase motor does not generally contain a centrifugal switch?
13. What type of single-phase motor develops the highest starting torque?
14. Name two types of starting relays used with hermetically sealed capacitor-start induction-run motors.
15. What is the principle of operation of a capacitor-start capacitor-run motor?
16. What causes the magnetic field to rotate in a shaded-pole induction motor?
17. How can the direction of rotation of a shaded-pole induction motor be changed?
18. How is the speed of a consequent-pole motor changed?
19. Why can a multispeed fan motor be operated at lower speed than most induction motors without harm to the motor windings?
20. What is the speed of operation of the Warren motor?
21. What is the speed of operation of the Holtz motor?
22. Why is the AC series motor often referred to as a universal motor?
23. How is the direction of rotation of the universal motor reversed?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 20

Schematics and Wiring Diagrams

OBJECTIVES: After studying this unit, you should be able to:

- Place wire numbers on a schematic diagram.
- Place the corresponding numbers on control components.
- Draw a wiring diagram from a schematic diagram.
- Define the difference between a schematic, or ladder, diagram, and a wiring diagram.
- Discuss the operation of a start-stop pushbutton circuit.
- Connect a start-stop pushbutton control circuit.

A schematic diagram shows components in their electrical sequence without regard for the physical location of any component, FIGURE 20-1. A wiring diagram is a pictorial representation of components with connecting wires.

The pictorial representation of the components is shown in FIGURE 20-2. Schematic diagrams are generally preferred over wiring diagrams for troubleshooting a circuit because they illustrate circuit

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

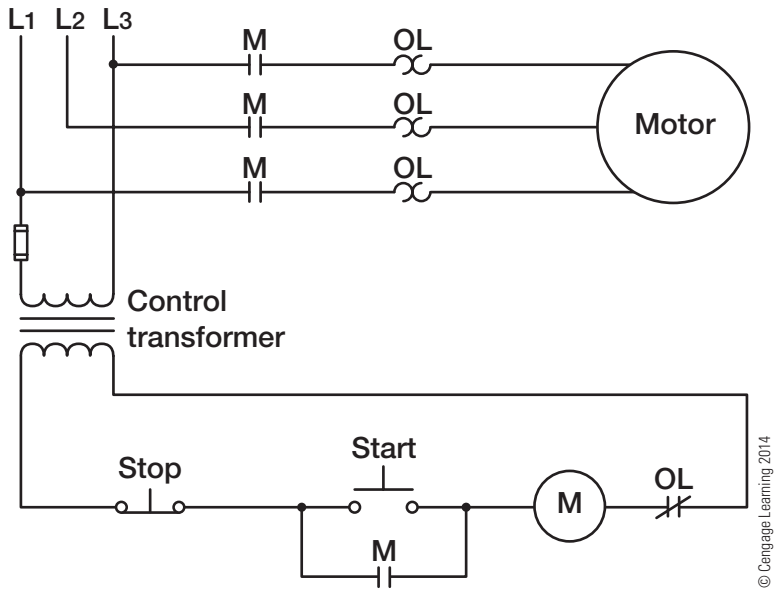


FIGURE 20-1 Basic diagram of a basic start-stop pushbutton control circuit.

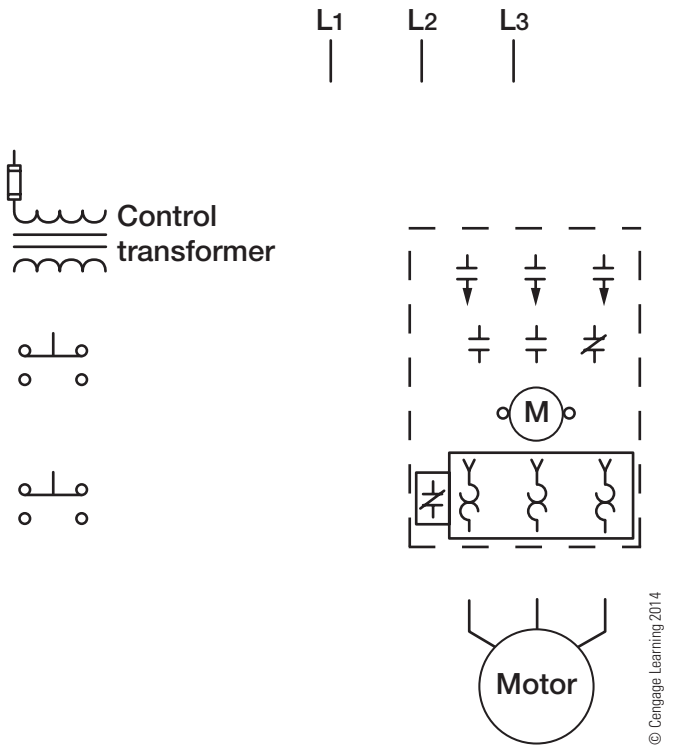


FIGURE 20-2 Components of the basic start-stop control circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

logic better. However, some people prefer to use wiring diagrams when making actual circuit connections because they show the placement of the wires.

When viewing a schematic diagram, there are several rules that should be understood:

1. Schematics are always shown in the off, or de-energized, condition. The states of all contacts and components are shown as they would be if the machine were turned off and not operating.
2. Schematic diagrams are generally read like a book, from left to right and from top to bottom.
3. Schematic symbols are generally drawn to represent the components they symbolize. A list of symbols is shown in FIGURE 20-3. While there are no actual standards for symbols, the most frequently employed are those used by the *National Electrical Manufacturers Association* (NEMA).
4. Coils are generally labeled with letters and/or numbers. Contacts with the same labels are controlled by one coil.
5. When a coil is energized, all contacts controlled by that coil will change condition. Contacts shown normally open will close and contacts shown normally closed will open.

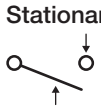
ANALYZING THE CIRCUIT

The circuit shown in Figure 20-1 is a basic start-stop pushbutton control circuit. This circuit is the basis on which many other control circuits are built. Understanding how this circuit works is imperative to understanding more complicated control circuits. The schematic in Figure 20-1 shows both the load and control circuits. The load circuit consists of the motor, overload heaters, load contacts controlled by the M starter, and the three-phase power lines labeled L_1, L_2, and L_3. Motor starters are used to connect a motor to the power line. They contain several parts.

COIL

In the schematic, the coil is shown as a circle with an M in the center of it. A motor starter is basically an electrically operated switch or solenoid with multiple contacts connected to it. When the coil is energized (power applied), all contacts controlled by the coil change position. When the coil is de-energized, all the contacts return to their normal position.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



Normally Open Switch
The switch is normally open because the movable contact is drawn below and does not touch the stationary contact.



Normally Closed Switch
The switch is normally closed because the movable contact is drawn above and touches the stationary contact.



Normally Open Held-Closed Switch
The switch is normally open because the movable contact is drawn below the stationary contact. It is held closed because the movable contact is touching the stationary contact.



Normally Closed Held-Open Switch
The switch is normally closed because the movable contact is drawn above the stationary contact. It is held open because the movable contact is not touching the stationary contact.

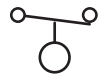
Symbols for particular components can be added to the contact symbols to illustrate different types of switches shown in different states. A float switch symbol, for example, is a line with a circle on the end of it. The circle represents a ball float. The float switch symbol can be used with any of the above switch symbols.



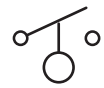
Normally Open Float Switch



Normally Closed Float Switch



Normally Open Held-Closed Float Switch



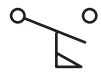
Normally Closed Held-Open Float Switch



Normally Open Limit Switch



Normally Open Pressure Switch



Normally Open Flow Switch



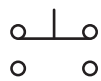
Normally Open Temperature Switch (Thermostat)



Normally Open Pushbutton



Normally Closed Pushbutton



Double Acting Pushbutton



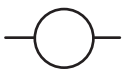
Overload Heater



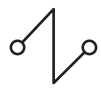
Normally Open Contacts



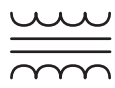
Normally Closed Contacts



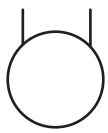
Coil



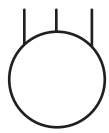
Solenoid Coil



Transformer



Single-Phase Squirrel-Cage Motor



Three-Phase Squirrel-Cage Motor



Lamp

© Cengage Learning 2014

FIGURE 20-3 Basic schematic symbols.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

LOAD CONTACTS

The load contacts are large and intended to control large amounts of current. The load contacts are used to connect the motor to the power line.

AUXILIARY CONTACTS

Most motor starters contain small contacts intended to be used as part of the control circuit. These contacts are generally called auxiliary contacts. They can be used to control small current loads such as those required for pilot lights and the coils of motor starters and relays.

OVERLOAD RELAY

The overload relay is used to sense motor current. It is divided into two separate sections: the heater section and the contact section. The heater section employs nichrome heaters that are inserted in series with the motor. Since motor current must pass through them, the amount of heat they produce is proportional to motor current. The contact section contains a normally closed contact that is connected in series with the starter coil. If the motor current becomes too great, the overload contact will open and de-energize the motor starter. The load contacts then open and disconnect the motor from the power line.

The schematic in Figure 20-1 also contains a transformer that is used to change the line voltage to control voltage. In this circuit it will be assumed that the three-phase lines are providing 480 V to operate the motor and that the control circuit operates on 120 V. The control transformer changes the 480 V to 120 V.

The control circuit also contains a stop pushbutton and a start pushbutton. The stop button is normally closed. This means that when the button is not pressed, there will be a circuit through the button. When the button is pressed, the circuit will open. The start button is shown normally open. When the button is not pressed, there is no circuit across the stationary contacts. When the button is pressed, the movable contact bridges the gap between the two stationary contacts and completes a circuit to the M coil.

To understand circuit operation, assume that the start button is pressed, FIGURE 20-4. This completes a circuit to the M coil, causing all M contacts to close. The three M load contacts connect the motor to the line. The M auxiliary contact connected in parallel with the start button closed in order to maintain a circuit to the M coil when the start button was released, FIGURE 20-5. Since this contact holds the current path to the starter coil, it is often referred to as the holding, maintaining, or sealing contact. The circuit will continue to operate until the stop button is pressed, de-energizing the M coil.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

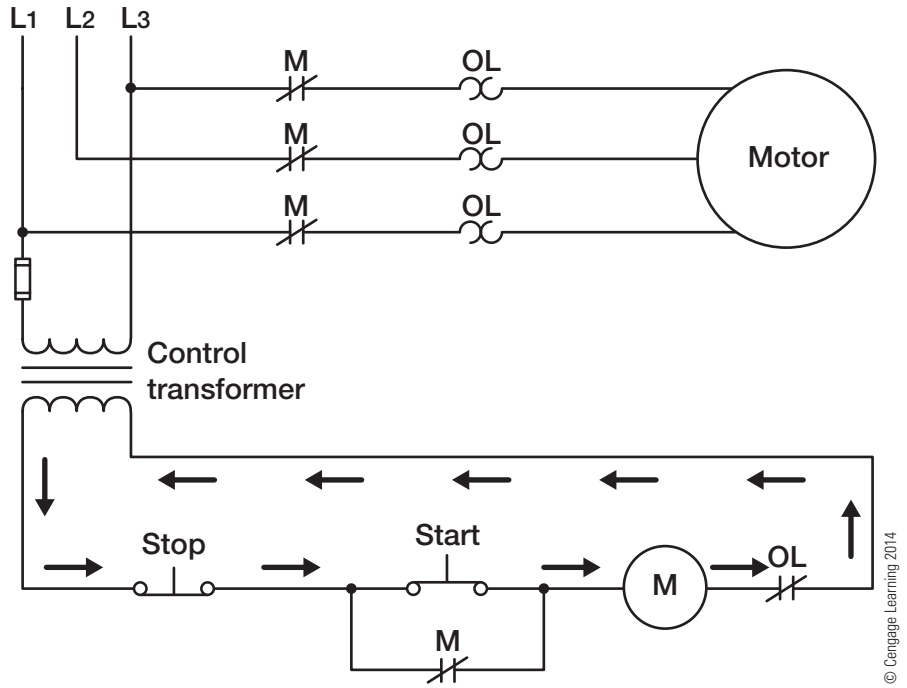


FIGURE 20-4 Pressing the start button completes a circuit to M coil.

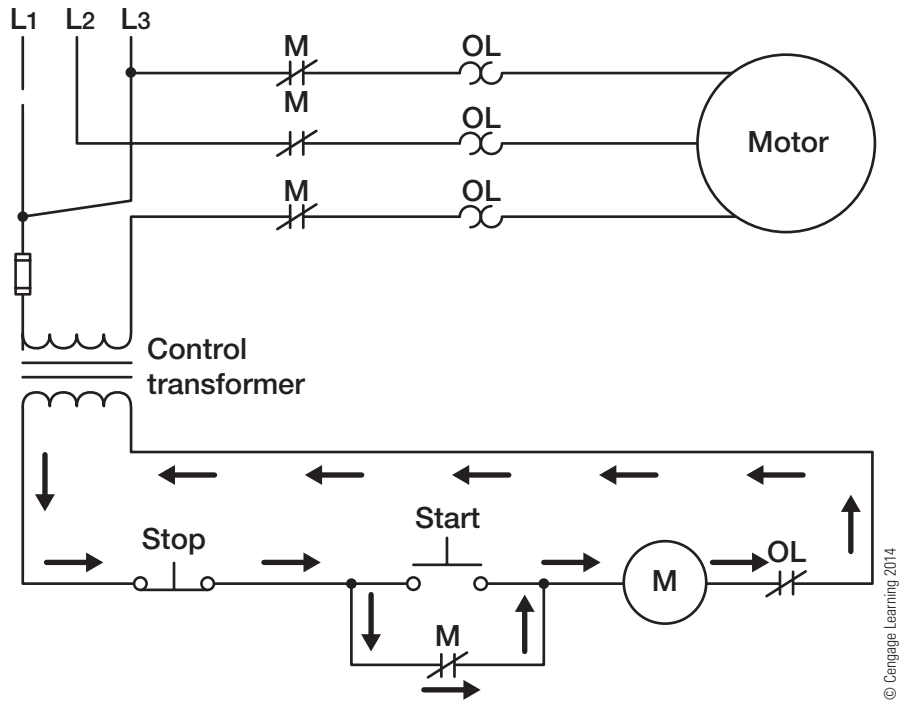


FIGURE 20-5 M auxiliary contacts maintain the circuit when the start button is released.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

If the motor should become overloaded while in operation, the overload contact connected in series with the starter coil will open and de-energize the starter. This will cause the load contacts to open and disconnect the motor from the power line.

CONNECTING THE CIRCUIT

As stated previously, schematic diagrams show components in their electrical sequence, without regard for physical location. They are superior for interpreting the logic of a circuit but bear no resemblance to a connected circuit. Experienced electricians generally prefer using schematic diagrams for connecting circuits, but students find this difficult because they are not familiar with looking at a component on a schematic and recognizing where that component is physically located. The best method for learning to connect control circuits is to learn how to change a schematic diagram into a wiring diagram.

To simplify the task of converting a schematic diagram into a wiring diagram, wire numbers will be added to the schematic diagram. These numbers will then be transferred to the control components shown in Figure 20-2. The rules for numbering a schematic diagram are as follows:

1. A set of numbers can be used only once.
2. Each time you go through a component, the number set must change.
3. All components that are connected together will have the same number.

To begin the numbering procedure, start at Line 1 (L_1) with the number 1 and place a number 1 beside each component connected to L_1, FIGURE 20-6. The number 2 is placed beside each component connected to L_2, FIGURE 20-7, and a 3 is placed beside each component connected to L_3, FIGURE 20-8. The number 4 is placed on the other side of the M load contact that already has a number 1 on one side and also on one side of the overload heater, FIGURE 20-9. The number 5 is placed on the other side of the M load contact that has one side already numbered with a 2 and also beside the second overload heater. The other side of the M load contact that has been numbered with a 3 is numbered with a 6, as is one side of the third overload heater. The numbers 7, 8, and 9 are placed between the other sides of the overload heaters and the motor T leads.

The number 10 begins at one side of the control transformer secondary and goes to one side of the normally closed stop pushbutton. The number 11 is placed on the other side of the stop button; it is also placed on one side of the normally open start pushbutton and the normally open M auxiliary

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

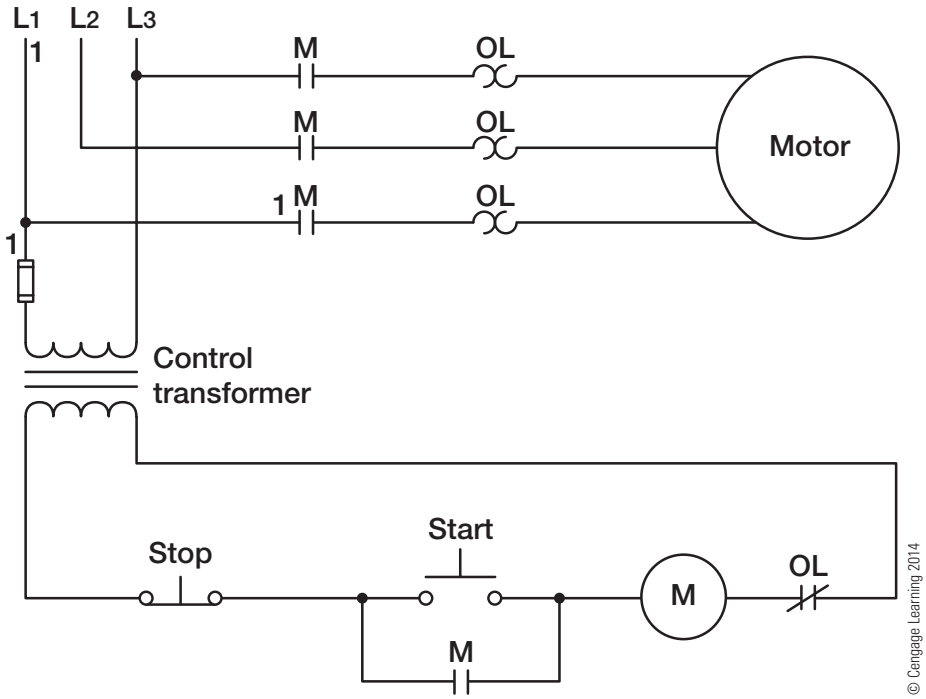


FIGURE 20-6 The number 1 is placed beside each component connected to L_1.

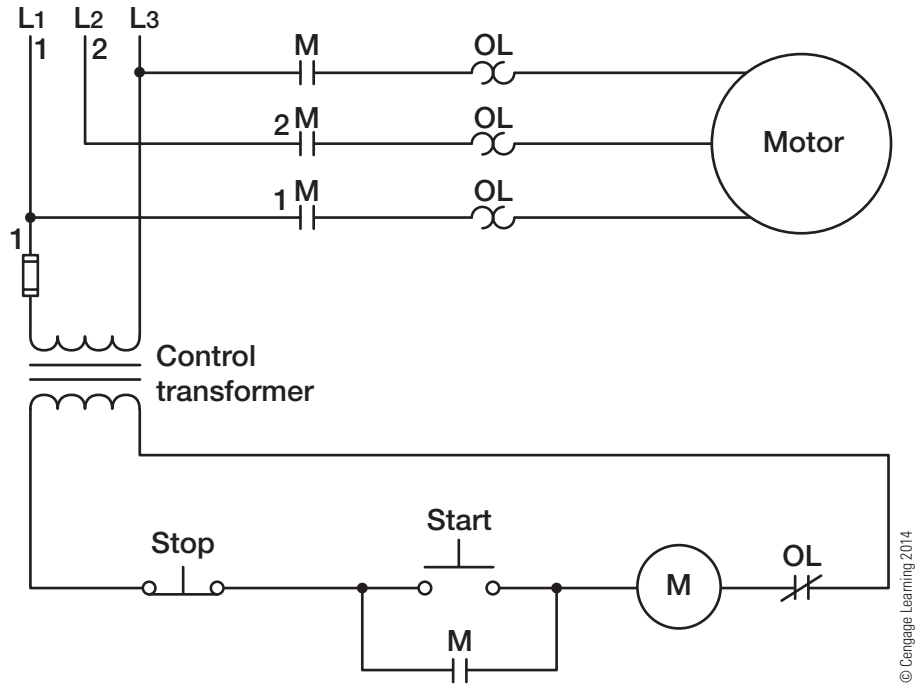


FIGURE 20-7 The number 2 is placed beside each component connected to L_2.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

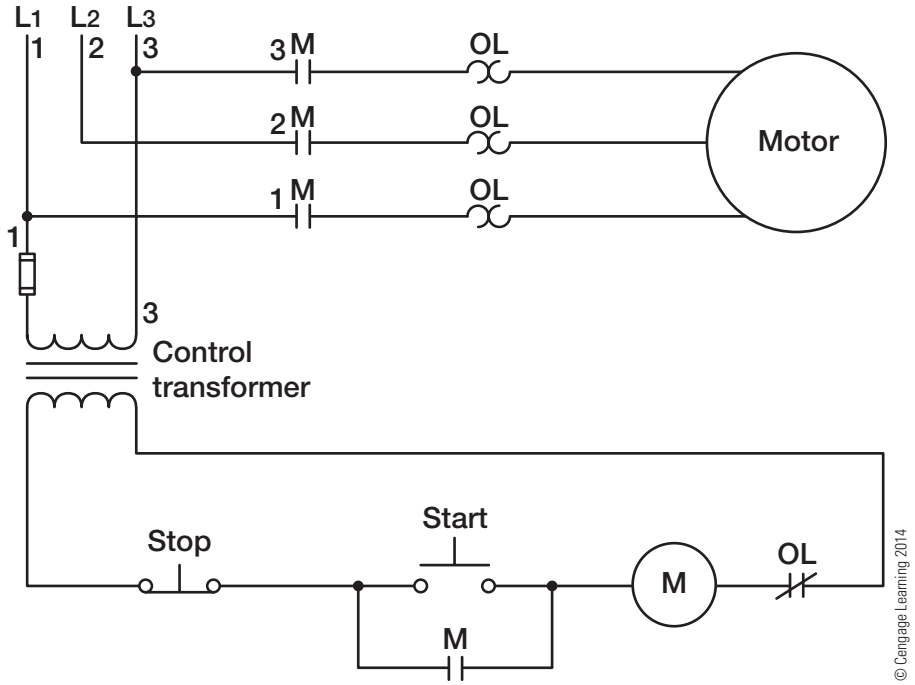


FIGURE 20-8 The number 3 is placed beside each component connected to L_3.

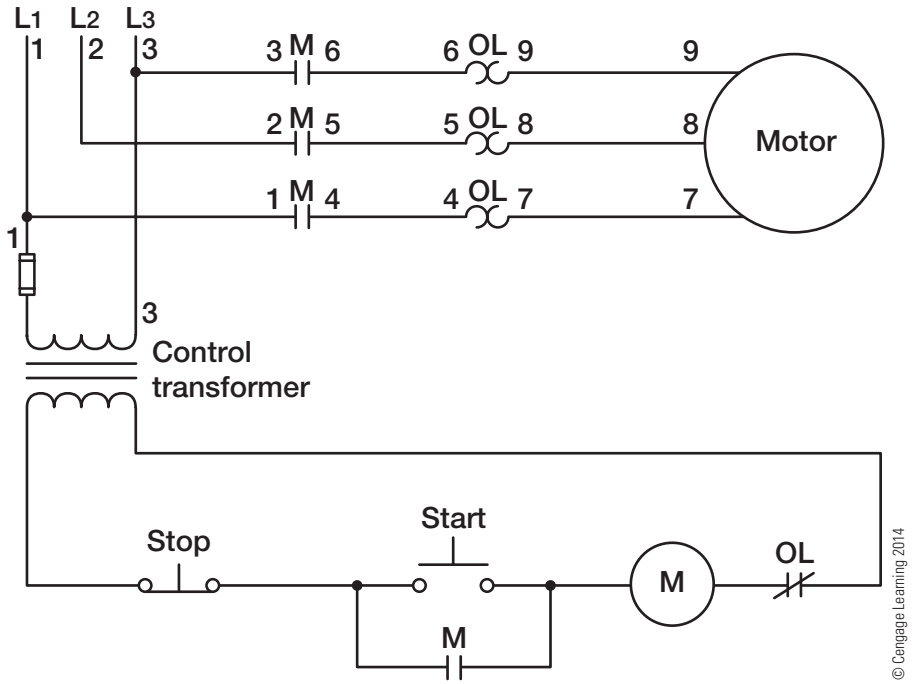


FIGURE 20-9 The number changes each time you proceed across a component.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

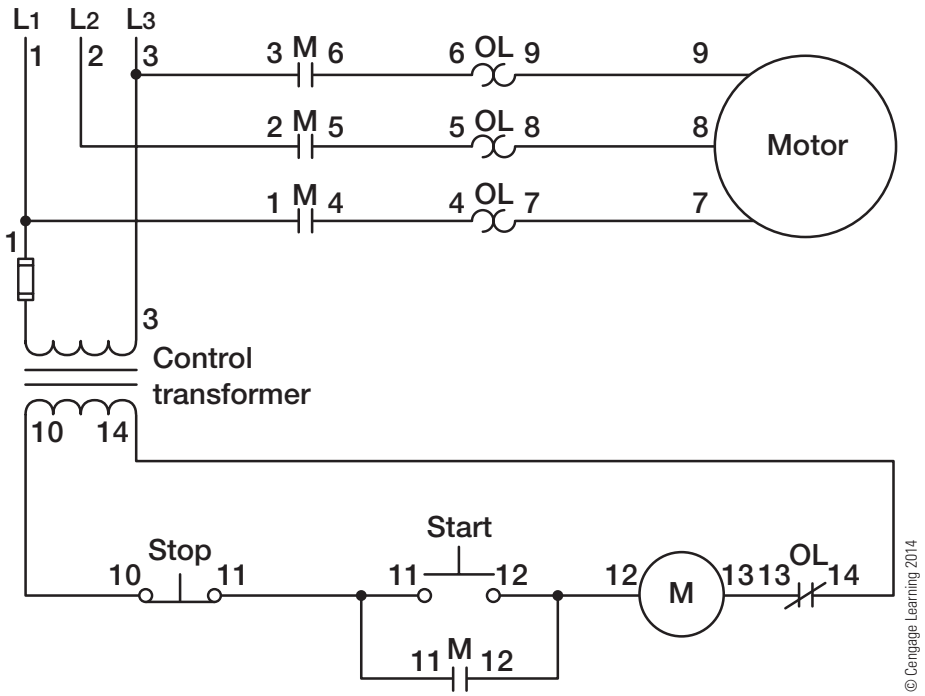


FIGURE 20-10 Numbers are placed beside all components.

contact. The number 12 is placed on the other side of the start button and the M auxiliary contact on one side of the M coil. The number 13 is placed on the other side of the coil, to one side of the normally closed overload contact. The number 14 is placed on the other side of the normally closed overload contact and on the other side of the control transformer secondary winding, FIGURE 20-10.

NUMBERING THE COMPONENTS

Now that the components on the schematic have been numbered, the next step is to place the same numbers on the corresponding components of the wiring diagram. The schematic diagram in Figure 20-10 shows that the number 1 has been placed beside L_1, the fuse on the control transformer, and one side of a load contact on the M starter, FIGURE 20-11. The number 2 is placed beside L_2 and on the second load contact on the M starter, FIGURE 20-12. The number 3 is placed beside L_3, the third load contact on the M starter, and on

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

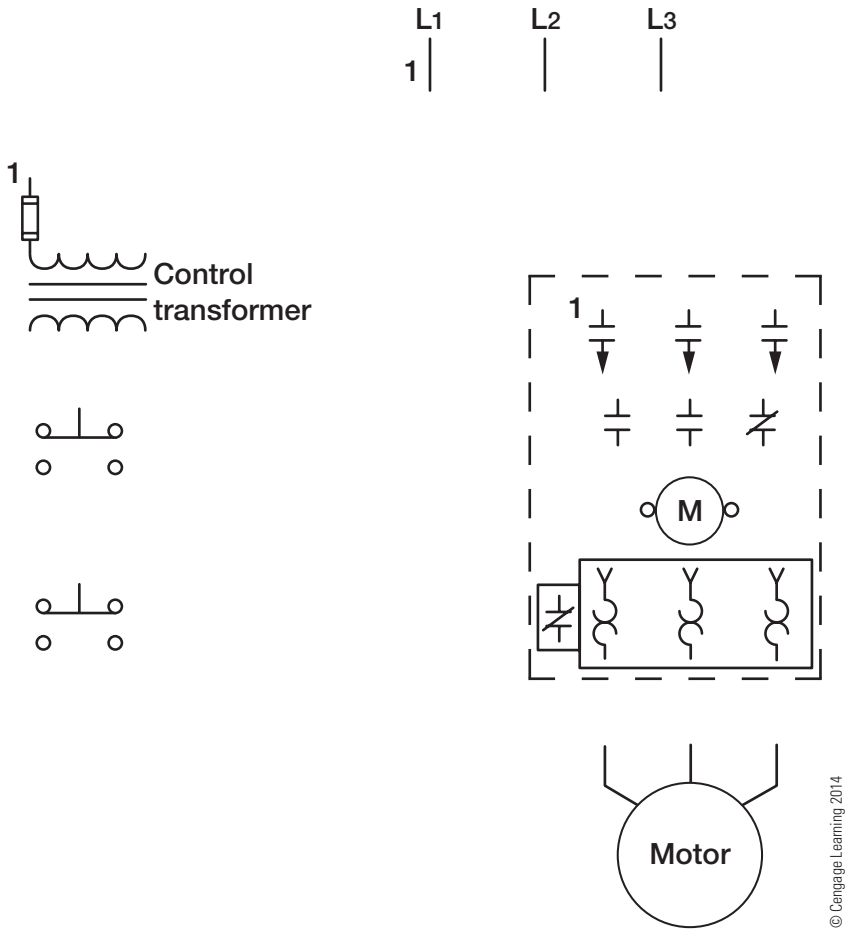


FIGURE 20-11 The number is placed beside L_1, the control transformer fuse, and M load contacts.

the other side of the primary winding on the control transformer. The numbers 4, 5, 6, 7, 8, and 9 are placed beside the corresponding components on the schematic diagram, FIGURE 20-13. Note on connection points 4, 5, and 6, from the output of the load contacts to the overload heaters, that these connections are factory made on a motor starter and do not have to be made in the field. For the sake of simplicity, these connections are not shown in the diagram. If a separate contactor and overload relay are being used, however, these connections will have to be made. Recall that a motor starter is a contactor and an overload relay combined.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

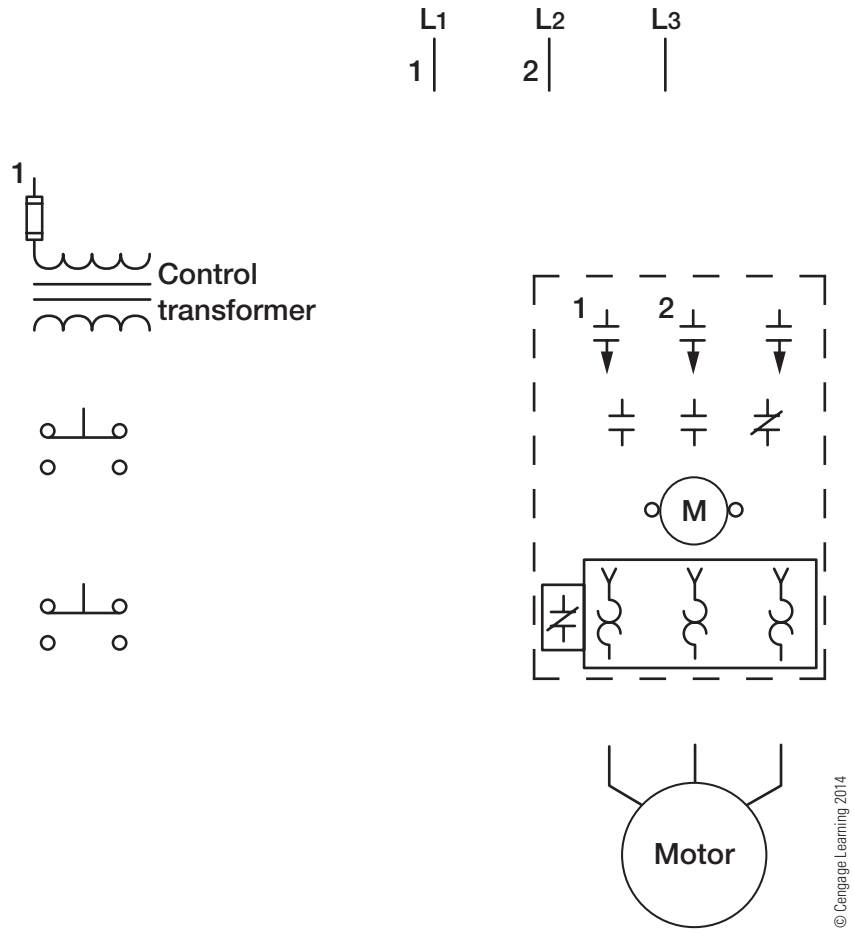


FIGURE 20-12 The number 2 is placed beside L_2 and the second load contact on M starter.

The number 10 starts at the secondary winding of the control transformer and goes to one side of the normally closed stop pushbutton. When making this connection, care must be taken to make certain that connection is made to the normally closed side of the pushbutton. Since this is a double-acting pushbutton, it contains both normally closed and normally open contacts, FIGURE 20-14.

The number 11 starts at the other side of the normally closed stop-button and goes to one side of the normally open start pushbutton and to one side

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

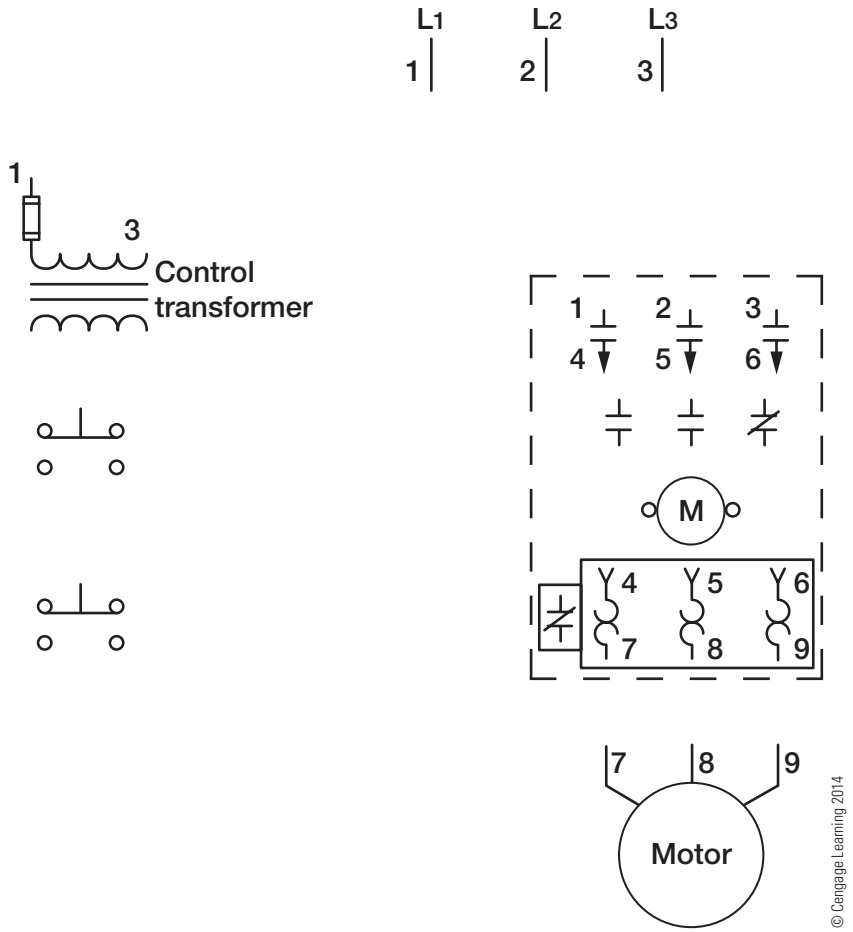


FIGURE 20-13 Placing numbers 3, 4, 5, 6, 7, 8, and 9 beside the proper components.

of a normally open M auxiliary contact, FIGURE 20-15. The starter in this example shows three auxiliary contacts: two normally open and one normally closed. It makes no difference which normally open contact is used.

This same procedure is followed until all circuit components have been numbered with the number that corresponds to the same component on the schematic diagram, FIGURE 20-16.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

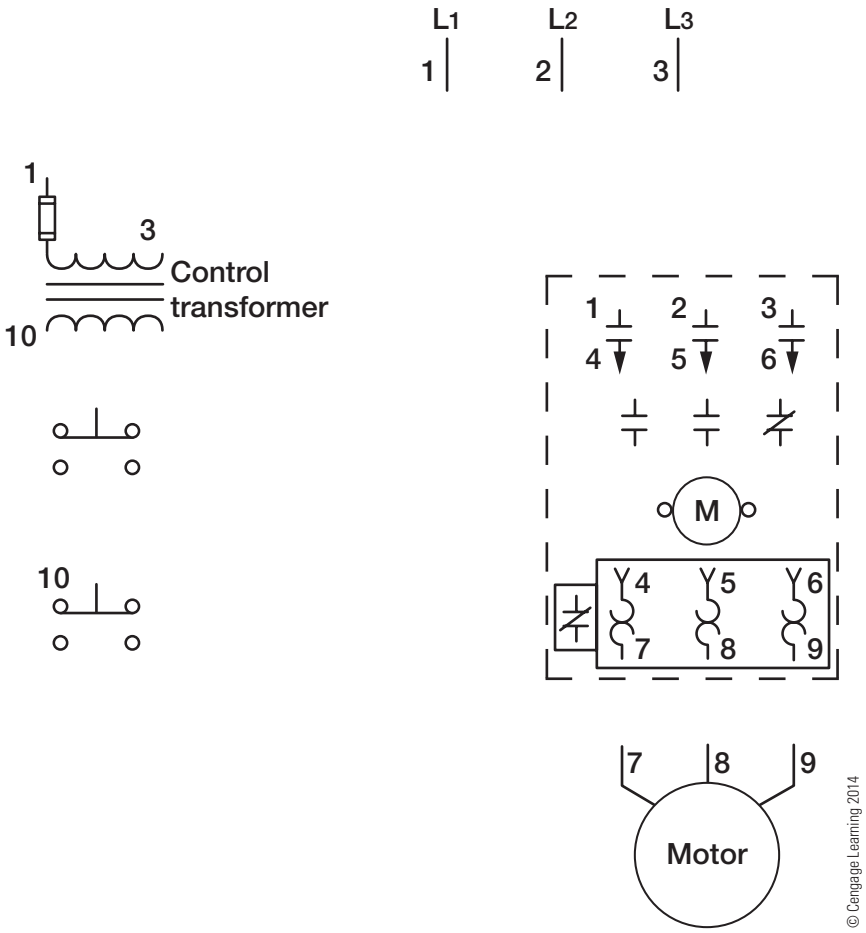


FIGURE 20-14 Wire number 10 connects from the transformer secondary to the stop button.

CONNECTING THE WIRES

Now that numbers have been placed beside the components, wiring the circuit becomes a matter of connecting numbers. First, connect all components labeled with a number 1 together, FIGURE 20-17. Then, all components numbered with a 2 are connected together, FIGURE 20-18. Next, all components numbered with a 3 are connected together, FIGURE 20-19. This procedure is followed until all the numbered components are connected together with the exception of 4, 5, and 6 (which are assumed to be factory connected), FIGURE 20-20.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

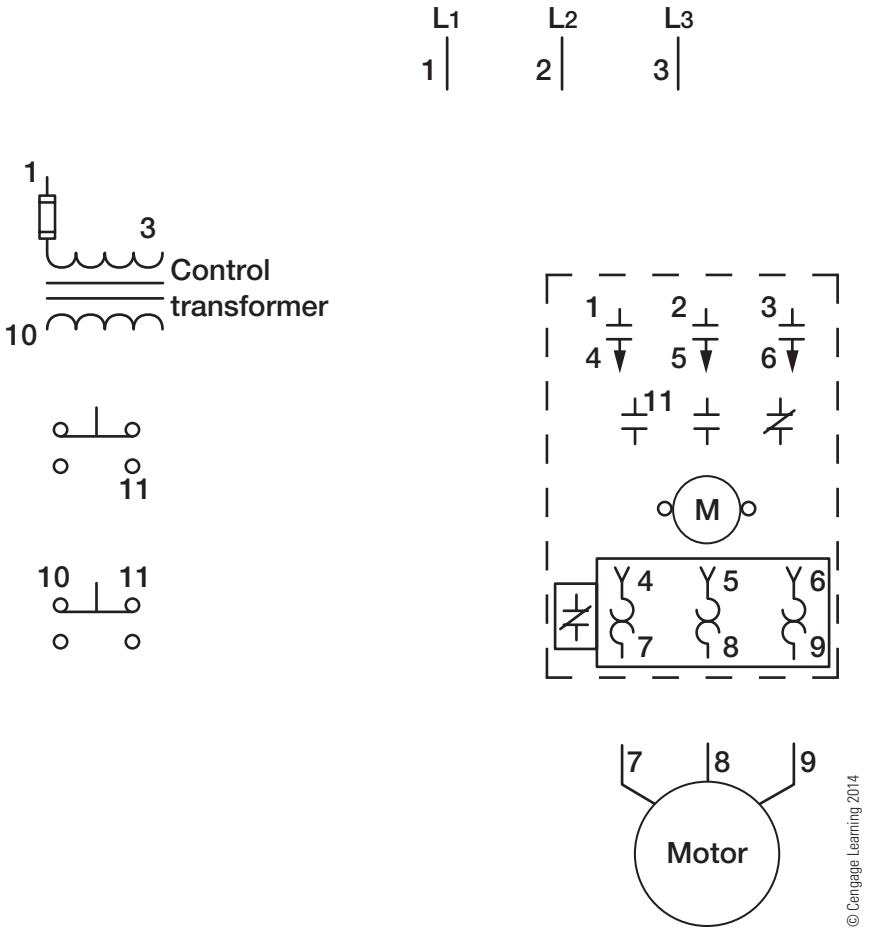


FIGURE 20-15 Number 11 connects to the stop button, start button, and holding contact.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

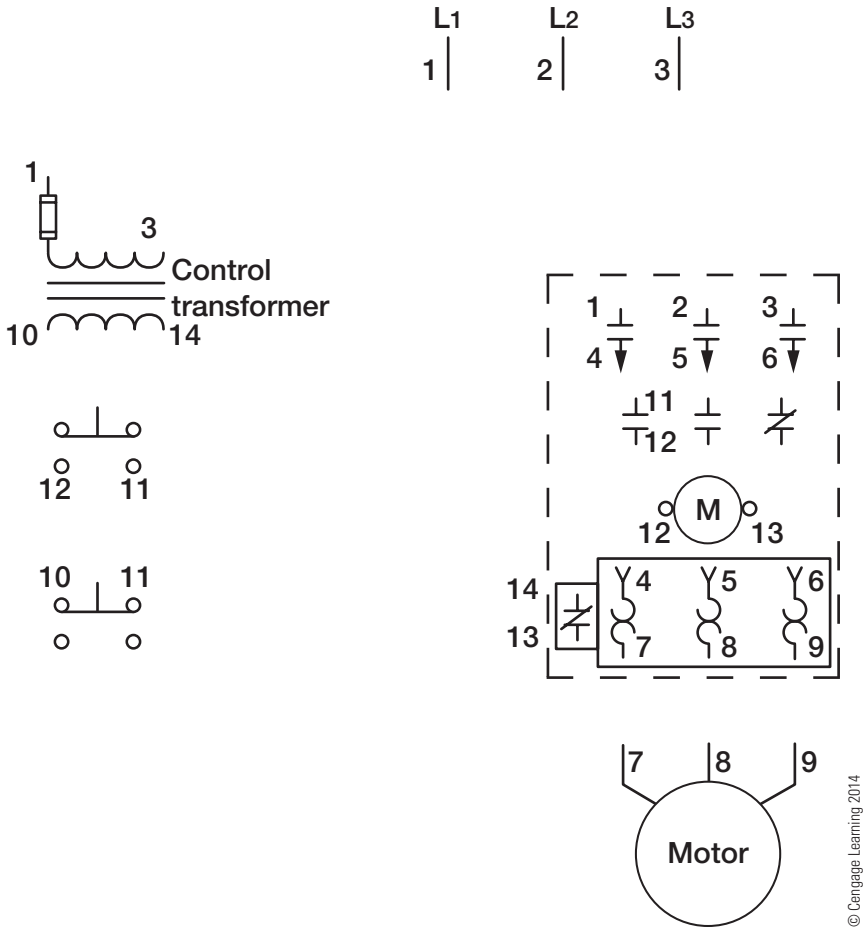


FIGURE 20-16 All components have been numbered.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

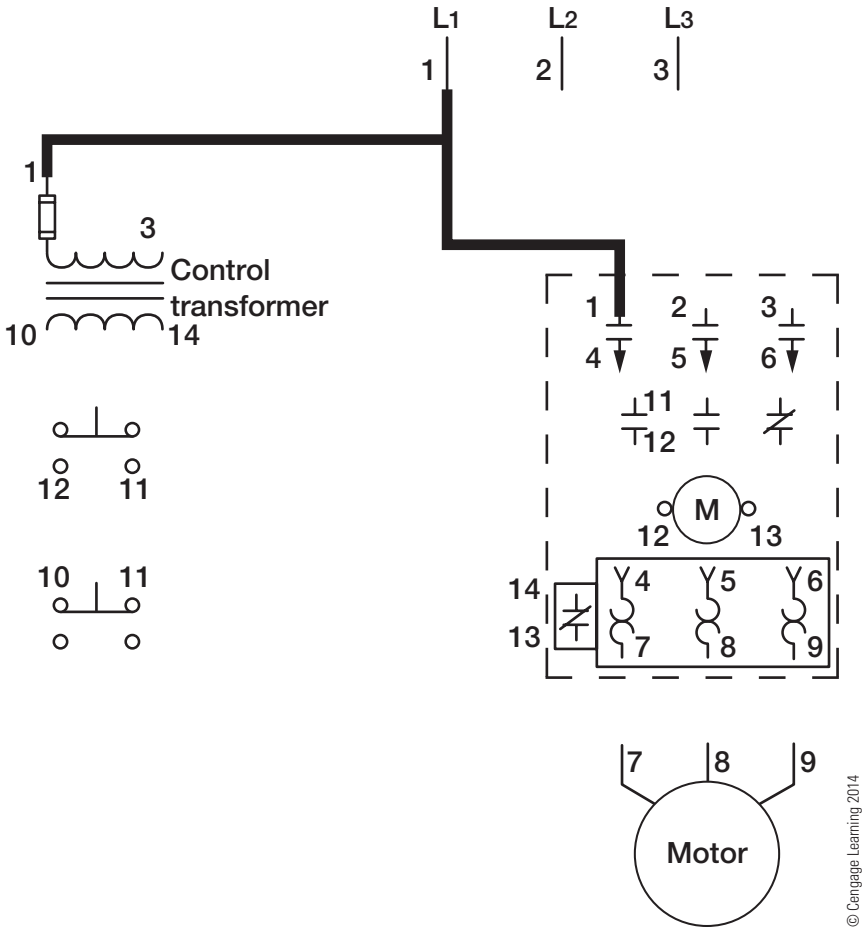


FIGURE 20-17 Connecting all components numbered with a 1.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

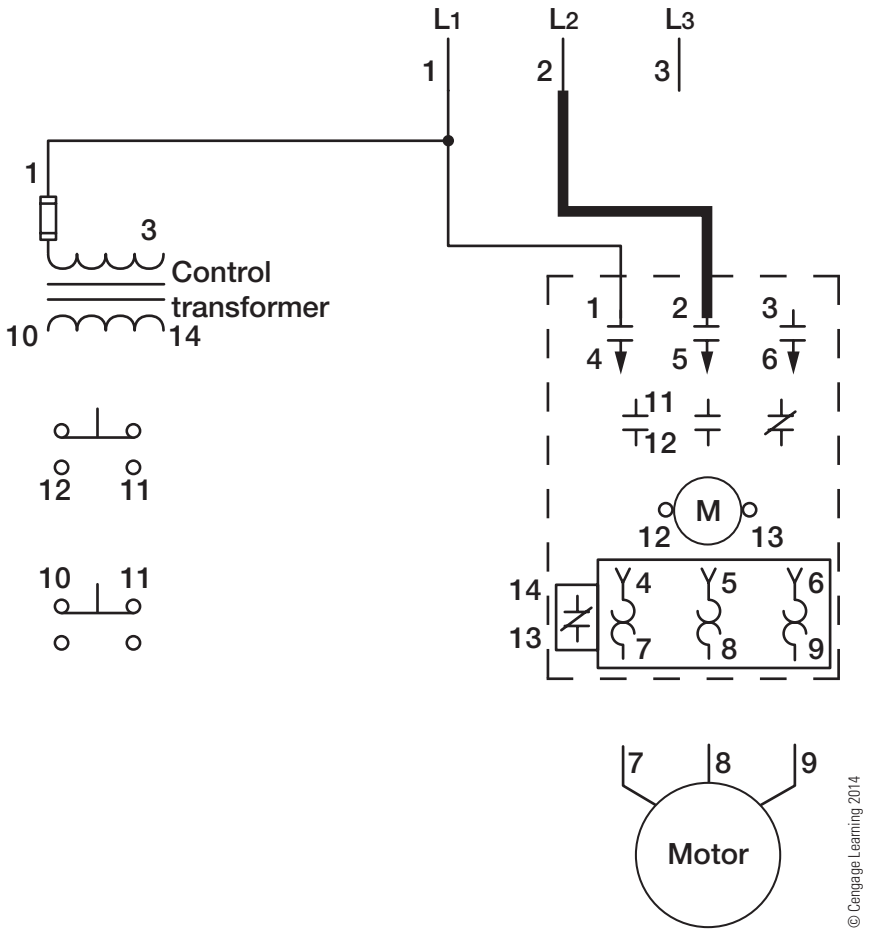


FIGURE 20-18 Connecting all components numbered with a 2.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

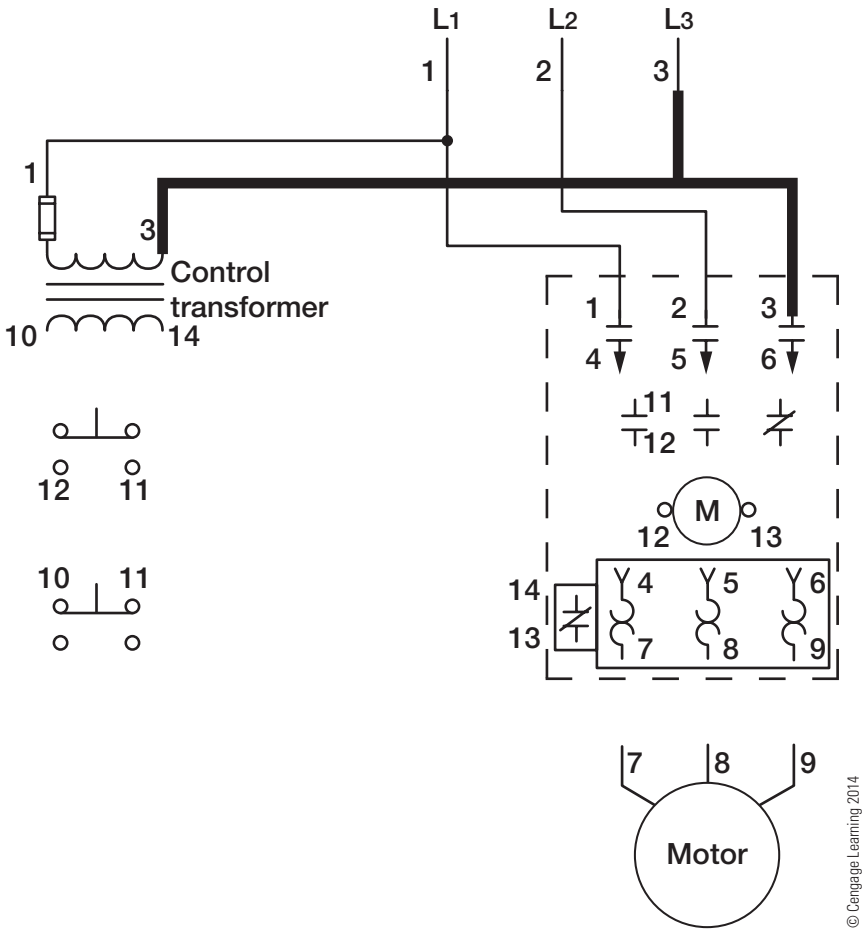


FIGURE 20-19 Connecting all components numbered with a 3.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

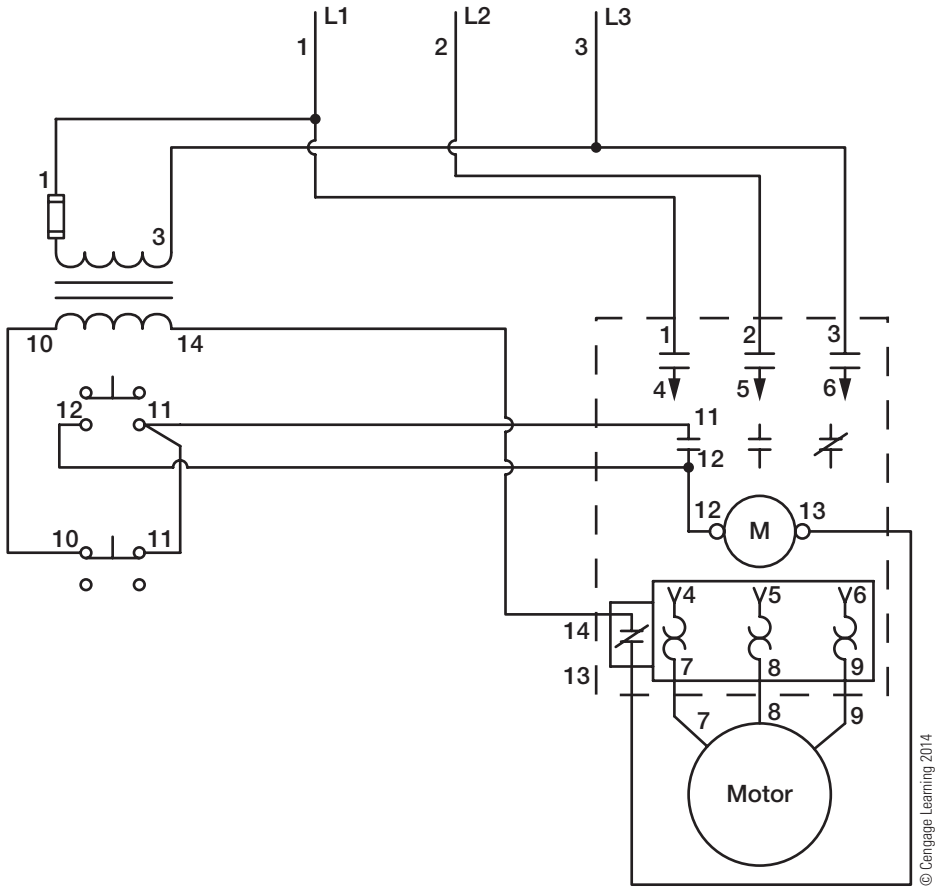


FIGURE 20-20 Completing the wiring diagram.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Summary

1. Schematic diagrams show components in their electrical sequence, without regard for physical location.
2. Wiring diagrams show a pictorial representation of the components, with connecting wires.
3. Schematic, or ladder, diagrams are generally used for troubleshooting because they illustrate the circuit logic better than a wiring diagram.
4. The most often used control symbols are the NEMA symbols.
5. Control symbols are generally drawn to represent the device they depict.
6. Normally open switches are drawn with their movable contact below and not touching the stationary contact.
7. Normally closed switches are drawn with their movable contact above and touching the stationary contact.
8. Normally open, held-closed switches are drawn with the movable contact below and touching the stationary contact.
9. Normally closed, held-open switches are shown with the movable contact above and not touching the stationary contact.
10. Motor starters generally contain both load and auxiliary contacts.
11. Load contacts are large and are designed to connect the load to the line.
12. Auxiliary contacts are small and operate on a small current load.
13. Motor starters contain overload relays.
14. Most overload relays sense motor current by connecting an electric heating element in series with the motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Review Questions

1. Refer to the circuit shown in Figure 20-10. If wire number 11 were disconnected at the normally open auxiliary M contact, how would the circuit operate?
2. Assume that when the start button is pressed, the M starter does not energize. List seven possible causes for this problem.

   A. _____

   B. _____

   C. _____

   D. _____

   E. _____

   F. _____

   G. _____
3. Explain the difference between a motor starter and a contactor.
4. Refer to the schematic in Figure 20-10. Assume that when the start button is pressed, the control transformer fuse blows. What is the most likely cause of this trouble?
5. Explain the difference between load and auxiliary contacts.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



UNIT 21

Motor Installation

OBJECTIVES: After studying this unit, you should be able to:

- Determine the full-load current rating of different types of motors using the *National Electrical Code® (NEC®)*.
- Determine the conductor size for installing motors.
- Determine the overload size for different types of motors.
- Determine the size of the short-circuit protective device for individual motors and multimotor connections.
- Select the proper size starter for a particular motor.

Many service people working in the field are faced with the responsibility of installing electric motors. Many packaged units such as central air conditioners have the circuit size printed on the nameplate. In these instances it is a matter of choosing the proper conductor size for the ampere rating of the circuit. A 30 A circuit, for example, would require a #10 AWG copper conductor. The only exception to this is in the event of an excessively long wire run from the service panel to the unit. If the unit is located over 100 feet from the panel, the conductor size in this example should be increased from a #10 AWG to a #8 AWG to prevent problems with voltage drop.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

When individual motors are installed, the service person must choose the proper conductor size, circuit breaker or fuse size, overload size, and starter size for each motor. This unit is based on the requirements of the *National Electrical Code*® (*NEC*®) that governs the installation of motors. The information presented in this unit is for general-use motors and does not cover the installation of special motors such as torque motors or multispeed motors.

DETERMINING MOTOR CURRENT

There are different types of motors, such as direct current, single-phase AC, two-phase AC, and three-phase AC. Different tables from the *NEC*® are used to determine the running current for these different types of motors. Table 430.247, FIGURE 21-1, is used to determine the full-load running current for a direct current motor. Table 430.248, FIGURE 21-2, is used to determine the full-load running current for single-phase motors; Table 430.249, FIGURE 21-3, is used to determine the running current for two-phase motors; and Table 430.250, FIGURE 21-4, is used to determine the full-load running current for three-phase motors. Note that the tables list the amount of current that the motor is expected to draw under a full-load condition. The motor will exhibit less current draw if it is not under full load. These tables list the ampere rating of the motors according to horsepower (hp) and connected voltage. It should also be noted that *NEC*® Section 430.6(A)(1) states these tables are to be used in determining *conductor size, short-circuit protection size, and ground fault protection size* instead of the nameplate rating of the motor. The motor overload size, however, is to be determined by the nameplate rating of the motor.

DIRECT CURRENT MOTORS

Table 430.247 lists the full-load running currents for direct current motors. The horsepower rating of the motor is given in the far left-hand column. Rated voltages are listed across the top of the table. The table shows that a 1-hp motor will have a full-load current of 12.2 A when connected to 90-V DC. If a 1-hp motor is designed to be connected to 240 V, it will have a current draw of 4.7 A.

SINGLE-PHASE AC MOTORS

The current ratings for single-phase AC motors are given in Table 430.248. Particular attention should be paid to the statement preceding the table. The statement asserts that the values listed in this table are for motors that operate under normal speeds and torques. Motors especially designed for low speed and high torque, or multispeed motors, shall have their running current determined from the nameplate rating of the motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Table 430.247 Full-Load Current in Amperes, Direct-Current Motors
The following values of full-load currents* are for motors running at base speed.

	Armature Voltage Rating*					
Horsepower	**90 Volts**	**120 Volts**	**180 Volts**	**240 Volts**	**500 Volts**	**550 Volts**
¼	4.0	3.1	2.0	1.6	—	—
⅓	5.2	4.1	2.6	2.0	—	—
½	6.8	5.4	3.4	2.7	—	—
¾	9.6	7.6	4.8	3.8	—	—
1	12.2	9.5	6.1	4.7	—	—
1½	—	13.2	8.3	6.6	—	—
2	—	17	10.8	8.5	—	—
3	—	25	16	12.2	—	—
5	—	40	27	20	—	—
7½	—	58	—	29	13.6	12.2
10	—	76	—	38	18	16
15	—	—	—	55	27	24
20	—	—	—	72	34	31
25	—	—	—	89	43	38
30	—	—	—	106	51	46
40	—	—	—	140	67	61
50	—	—	—	173	83	75
60	—	—	—	206	99	90
75	—	—	—	255	123	111
100	—	—	—	341	164	148
125	—	—	—	425	205	185
150	—	—	—	506	246	222
200	—	—	—	675	330	294

*These are average dc quantities.

FIGURE 21-1 *NEC*® Table 430.247 lists the full-load current of direct current motors. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

Table 430.248 Full-Load Currents in Amperes, Single-Phase Alternating-Current Motors

The following values of full-load currents are for motors running at usual speeds and motors with normal torque characteristics. The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120 and 220 to 240 volts.

Horsepower	**115 Volts**	**200 Volts**	**208 Volts**	**230 Volts**
⅙	4.4	2.5	2.4	2.2
¼	5.8	3.3	3.2	2.9
⅓	7.2	4.1	4.0	3.6
½	9.8	5.6	5.4	4.9
¾	13.8	7.9	7.6	6.9
1	16	9.2	8.8	8.0
1½	20	11.5	11.0	10
2	24	13.8	13.2	12
3	34	19.6	18.7	17
5	56	32.2	30.8	28
7½	80	46.0	44.0	40
10	100	57.5	55.0	50

FIGURE 21-2 *NEC*® Table 430.248 lists the full-load current of single-phase motors. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Table 430.249 Full-Load Current, Two-Phase Alternating-Current Motors (4-Wire)

The following values of full-load current are for motors running at speeds usual for belted motors and motors with normal torque characteristics. Current in the common conductor of a 2-phase, 3-wire system will be 1.41 times the value given. The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)				
Horsepower	115 Volts	230 Volts	460 Volts	575 Volts	2300 Volts
½	4.0	2.0	1.0	0.8	—
¾	4.8	2.4	1.2	1.0	—
1	6.4	3.2	1.6	1.3	—
1½	9.0	4.5	2.3	1.8	—
2	11.8	5.9	3.0	2.4	—
3	—	8.3	4.2	3.3	—
5	—	13.2	6.6	5.3	—
7½	—	19	9.0	8.0	—
10	—	24	12	10	—
15	—	36	18	14	—
20	—	47	23	19	—
25	—	59	29	24	—
30	—	69	35	28	—
40	—	90	45	36	—
50	—	113	56	45	—
60	—	133	67	53	14
75	—	166	83	66	18
100	—	218	109	87	23
125	—	270	135	108	28
150	—	312	156	125	32
200	—	416	208	167	43

FIGURE 21-3 *NEC*® Table 430.249 is used to determine the full-load current of two-phase motors. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

The voltages listed in the table are 115, 200, 208, and 230. The last sentence of the preceding statement says that the currents listed shall be permitted for voltages of 110–120 V and 220–240 V. This means that if the motor is connected to a 120-V line, it is permissible to use the currents listed in the 115-V column. If the motor is connected to a 220-V line, the 230-V column can be used.

EXAMPLE: A 3-hp single-phase AC motor is connected to a 208-V line. What will be the full-load running current of this motor?

Locate 3 hp in the far left-hand column. Follow across to the 208-V column. The full-load current will be 18.7 A.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Table 430.250 Full-Load Current, Three-Phase Alternating-Current Motors
The following values of full-load currents are typical for motors running at speeds usual for belted motors and motors with normal torque characteristics.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)							Synchronous-Type Unity Power Factor* (Amperes)			
Horsepower	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts	2300 Volts	230 Volts	460 Volts	575 Volts	2300 Volts
½	4.4	2.5	2.4	2.2	1.1	0.9	—	—	—	—	—
¾	6.4	3.7	3.5	3.2	1.6	1.3	—	—	—	—	—
1	8.4	4.8	4.6	4.2	2.1	1.7	—	—	—	—	—
1½	12.0	6.9	6.6	6.0	3.0	2.4	—	—	—	—	—
2	13.6	7.8	7.5	6.8	3.4	2.7	—	—	—	—	—
3	—	11.0	10.6	9.6	4.8	3.9	—	—	—	—	—
5	—	17.5	16.7	15.2	7.6	6.1	—	—	—	—	—
7½	—	25.3	24.2	22	11	9	—	—	—	—	—
10	—	32.2	30.8	28	14	11	—	—	—	—	—
15	—	48.3	46.2	42	21	17	—	—	—	—	—
20	—	62.1	59.4	54	27	22	—	—	—	—	—
25	—	78.2	74.8	68	34	27	—	53	26	21	—
30	—	92	88	80	40	32	—	63	32	26	—
40	—	120	114	104	52	41	—	83	41	33	—
50	—	150	143	130	65	52	—	104	52	42	—
60	—	177	169	154	77	62	16	123	61	49	12
75	—	221	211	192	96	77	20	155	78	62	15
100	—	285	273	248	124	99	26	202	101	81	20
125	—	359	343	312	156	125	31	253	126	101	25
150	—	414	396	360	180	144	37	302	151	121	30
200		552	528	480	240	192	49	400	201	161	40
250	—	—	—	—	302	242	60	—	—	—	—
300	—	—	—	—	361	289	72	—	—	—	—
350	—	—	—	—	414	336	83	—	—	—	—
400	—	—	—	—	477	382	95	—	—	—	—
450	—	—	—	—	515	412	103	—	—	—	—
500	—	—	—	—	590	472	118	—	—	—	—

*For 90 and 80 percent power factor, the figures shall be multiplied by 1.1 and 1.25, respectively.

FIGURE 21-4 *NEC*® Table 430.250 is used to determine the full-load current of three-phase motors. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

TWO-PHASE MOTORS

Although two-phase motors are seldom used, Table 430.249 lists the full-load running currents for these motors. Like single-phase motors, two-phase motors, which are especially designed for low-speed, high-torque applications and multispeed motors, use the nameplate rating instead of the values shown in the table. When using a two-phase, three-wire system, the size of the neutral conductor must be increased by the square root of 2 or 1.41. The reason for this is that the voltages of a two-phase system are 90° out of phase with each other as shown in FIGURE 21-5. The principle of two-phase power generation is shown in FIGURE 21-6. In a two-phase alternator, the phase windings

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

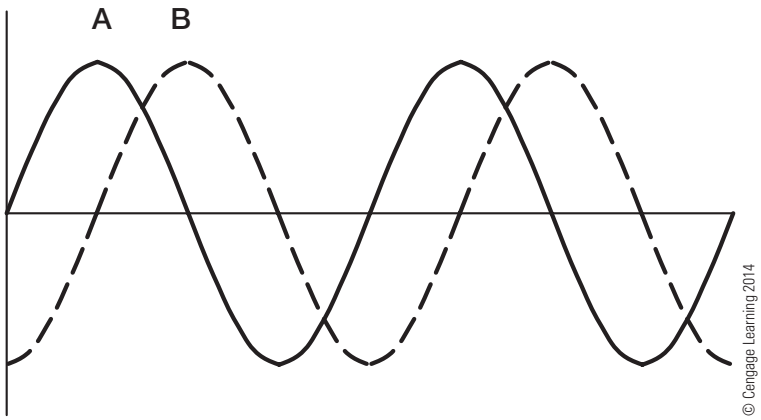


FIGURE 21-5 The voltages of a two-phase system are 90° out of phase with each other.

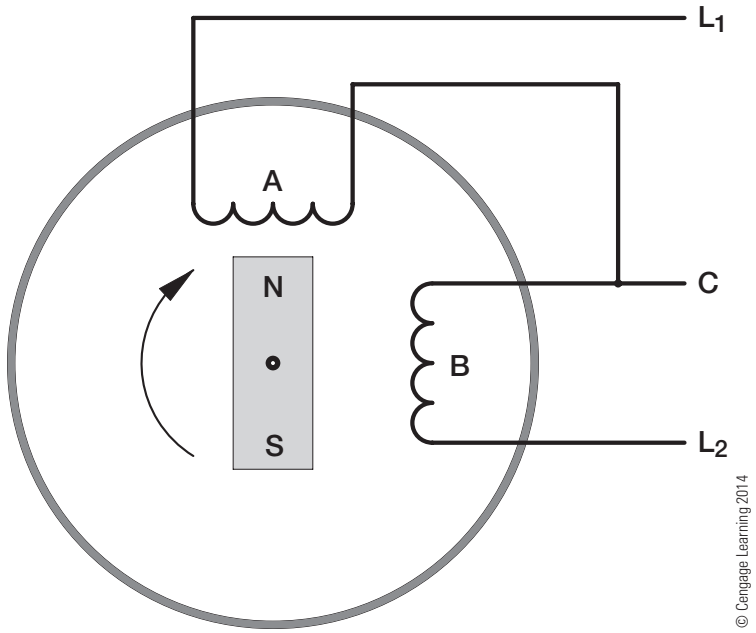


FIGURE 21-6 A two-phase alternator produces voltages that are 90° out of phase with each other.

are arranged 90° apart. The magnet is the rotor of the alternator. When the rotor turns, it induces voltage into the phase windings, which are 90° apart. When one end of each phase winding is joined to form a common terminal, or neutral, the current in the neutral conductor will be greater than the current in either of the two-phase conductors. An example of this is shown in FIGURE 21-7. In this example, a two-phase alternator is connected to a

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

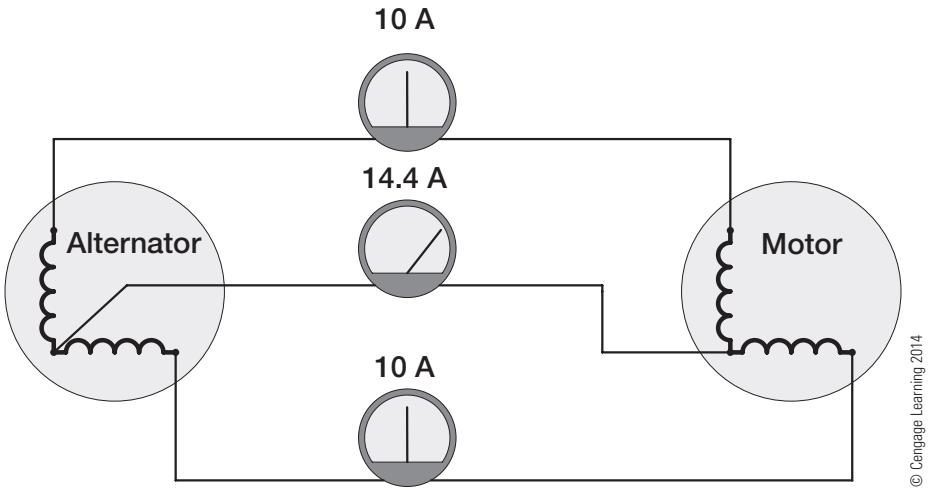


FIGURE 21-7 The neutral current of a two-phase system is 1.41 times greater than the line currents.

two-phase motor. The current draw on each of the phase windings is 10 A. The current flow in the neutral, however, is 1.41 times greater than the current flow in the phase windings, or 14.1 A.

EXAMPLE: Compute the phase current and neutral current for a 60-hp, 460-V two-phase motor.

The phase current can be taken from Table 430.249.

$$\text{Phase current} = 67 \text{ A}$$

The neutral current will be 1.41 times higher than the phase current.

$$\text{Neutral current} = 67 \times 1.41$$
$$\text{Neutral current} = 94.5 \text{ amperes}$$

THREE-PHASE MOTORS

Table 430.250 is used to determine the full-load current of three-phase motors. The notes at the top of the table are very similar to the notes of Tables 430.248 and 430.249. The full-load current of low-speed, high-torque, and multispeed motors is to be determined from the nameplate rating instead of from the values listed in the table. Table 430.250 has an extra note that deals with synchronous motors. Notice that the right side of Table 430.250 is devoted to the full-load currents of synchronous-type motors. The currents listed are for synchronous-type motors that are to be operated at unity, or

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

100% power factor. Since synchronous motors are often made to have a leading power factor by over-excitation of the rotor current, the full-load current rating must be increased when this is done. If the motor is to be operated at 90% power factor, the rated full-load current in the table must be increased by 10%. If the motor is to be operated at 80% power factor, the full-load current is to be increased by 25%.

EXAMPLE: A 150-hp, 460-V synchronous motor is to be operated at 80% power factor. What will be the full-load current rating of the motor?

The table indicates a current value of 151 amperes for this motor. To determine the running current at 80% power factor multiply this current by 125%, or 1.25. (Multiplying by 1.25 results in the same answer that would be obtained by dividing by 0.80.)

$$151 \times 1.25 = 188.75, \text{ or } 189 \text{ A}$$

EXAMPLE: A 200-hp, 2300-V synchronous motor is to be operated at 90% power factor. What will be the full-load current rating of this motor?

Locate 200 hp in the far left-hand column. Follow across to the 2300-V column listed under synchronous-type motors. Increase this value by 10%

$$40 \times 1.10 = 44 \text{ A}$$

DETERMINING CONDUCTOR SIZE FOR A SINGLE MOTOR

NEC® Section 430.6(A)(1) states that the conductor for a motor connection shall be based on the values from Tables 430.247, 430.248, 430.249, and 430.250 instead of the motor nameplate current. Section 430.22(A) states that conductors supplying a single motor shall have an ampacity of not less than 125% of the motor full-load current. *NEC*® Section 310 is used to select the conductor size after the ampacity has been determined. The exact table employed will be determined by the wiring conditions. Probably the most frequently used is Table 310.15(B)(16), FIGURE 21-8.

TERMINATION TEMPERATURE

Determining the amount of current a conductor is rated to carry and determining the proper size conductor for a specific installation are not the same thing. A factor that must be taken into consideration when determining the conductor size for a specific installation is the temperature rating of the devices and

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Table 310.15(B)(16) (formerly Table 310.16) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)*

	Temperature Rating of Conductor [See Table 310.104(A).]						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
Size AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Size AWG or kcmil
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	350	420	475	285	340	385	600
700	385	460	520	315	375	425	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	445	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	525	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	555	665	750	470	560	630	2000

*Refer to 310.15(B)(2) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F).
**Refer to 240.4(D) for conductor overcurrent protection limitations.

FIGURE 21-8 *NEC*® Table 310.15(B)(16) lists ampacity ratings for common conductors. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

terminals as specified in *NEC*® Section 110.14(C). This section states that the conductor is to be selected and coordinated so as to not exceed the lowest temperature rating of any connected termination, any connected conductor, or any connected device. This means that regardless of the temperature rating of the conductor, the ampacity must be selected from a column that does not exceed the temperature rating of the termination. The conductors listed in the first column of Table 310.15(B)(16) have a temperature rating of 60°C, the conductors in the second column have a rating of 75°C, and the conductors in the third column have a rating of 90°C. The temperature ratings of devices such as circuit breakers, fuses, and terminals are often found in the UL (Underwriters Laboratories) product directories. Occasionally, the temperature rating may be found on the piece of equipment, but this is the exception and not the rule. As a general rule the temperature rating of most devices will not exceed 75°C.

When the termination temperature rating is not listed or known, NEC® Section 110.14(C)(1)(a) states that for circuits rated at 100 A or less, or for #14 AWG through #1 AWG conductors, the ampacity of the wire, regardless of the temperature rating, will be selected from the 60°C column. This does not mean that only those types of insulations listed in the 60°C column can be used, but that the *ampacities* listed in the 60°C column must be used to select the conductor size. For example, assume that a copper conductor with type XHHW insulation is to be connected to a 50-A circuit breaker that does not have a listed temperature rating. According to *NEC*® Table 310.15(B)(16), a #8 AWG copper conductor with XHHW insulation is rated to carry 55 A of current. Type XHHW insulation is located in the 90°C column, but the temperature rating of the circuit breaker is not known. Therefore, the wire size must be selected from the ampacity ratings in the 60°C column. A #6 AWG copper conductor with type XHHW insulation would be used.

NEC® Section 110.14(C)(1)(a)(4) has a special provision for motors with marked NEMA design codes B, C, or D. This section states that conductors rated at 75°C or higher may be selected from the 75°C column even if the ampacity is 100 A or less. This code will not apply to motors that do not have a NEMA design code marked on their nameplate. Most motors manufactured before 1996 will not have a NEMA design code. The NEMA design code letter should not be confused with the code letter that indicates the type of squirrel-cage rotor used in the motor.

EXAMPLE: A 30-hp three-phase squirrel-cage induction motor is connected to a 480-V line. The conductors are run in conduit to the motor. The motor does not have a NEMA design code listed on the nameplate. The termination temperature rating of the devices is not known. Copper conductors

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

with THWN insulation are to be used for this motor connection. What size conductors should be used?

The first step is to determine the full-load current of the motor. This is determined from Table 430.250. The table indicates a current of 40 A for this motor. The current must be increased by 25% according to Section 430.22(A).

$$40 \times 1.25 = 50 \text{ A}$$

Table 310.15(B)(16) is used to determine the conductor size. Locate the column that contains THWN insulation in the copper section of the table. THWN is located in the 75°C column. Since this circuit is less than 100 A and the termination temperature is not known, and the motor does not contain a NEMA design code letter, the conductor size must be selected from the ampacities listed in the 60°C column. A #6 AWG copper conductor with type THWN insulation will be used.

For circuits rated over 100 A, or for conductor sizes larger than #1 AWG, Section 110.14(C)(1)(b) states that the ampacity ratings listed in the 75°C column may be used to select wire sizes unless conductors with a 60°C temperature rating have been selected for use. For example, types TW and UF insulation are listed in the 60°C column. If one of these two insulation types has been specified, the wire size must be chosen from the 60°C column regardless of the ampere rating of the circuit.

OVERLOAD SIZE

When determining the overload size for a motor the *nameplate* current rating of the motor is used instead of the current values listed in the tables *(NEC®* Section 430.6(A)(1)*)*. Other factors such as the service factor (SF) or temperature rise (°C) of the motor are also to be considered when determining the overload size for a motor. The temperature rise of the motor is an indication of the amount of temperature increase the motor should experience under a full-load condition and should not be confused with termination temperature discussed in Section 110.14(C). *NEC®* Section 430.32, FIGURE 21-9, is used to determine the overload size for motors of 1 hp or more. The overload size is based on a percentage of the full-load current of the motor listed on the motor nameplate.

EXAMPLE: A 25-hp three-phase induction motor has a nameplate rating of 32 A. The nameplate also shows a temperature rise of 30°C. Determine the ampere rating of the overload for this motor.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

430.32 Continuous-Duty Motors.

(A) More Than 1 Horsepower. Each motor used in a continuous duty application and rated more than 1 hp shall be protected against overload by one of the means in 430.32(A)(1) through (A)(4).

(1) Separate Overload Device. A separate overload device that is responsive to motor current. This device shall be selected to trip or shall be rated at no more than the following percent of the motor nameplate full-load current rating:

Motors with a marked service factor 1.15 or greater	125%
Motors with a marked temperature rise 40°C or less	125%
All other motors	115%

FIGURE 21-9 *NEC*® Section 430.32 is used to determine the overload size of motors rated 1 hp or more. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

NEC® Section 430.32(A)(1) indicates the overload size is 125% of the full-load current rating of the motor.

$$32 \times 1.25 = 40 \text{ A}$$

If for some reason this overload size does not permit the motor to start without tripping out, Section 430.32(C) permits the overload size be increased to a maximum of 140% for this motor. If this increase in overload size does not solve the starting problem, the overload may be shunted out of the circuit during the starting period in accordance with Section 430.35(A)&(B).

DETERMINING LOCKED-ROTOR CURRENT

There are two basic methods for determining the locked-rotor current (starting current) of a squirrel-cage induction motor depending on the information available. If the motor nameplate lists code letters that range from A to V, they indicate the type of rotor bars used when the rotor was made. Different types of bars are used to make motors with different operating characteristics. The type of rotor bars largely determines the maximum starting current of the motor. *NEC*® Table 430.7(B) FIGURE 21-10 lists the different code letters and gives the locked-rotor kilovolt-amperes (kVA) per horsepower. The starting current can be determined by multiplying the kVA rating by the horsepower rating and then dividing by the applied voltage.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Table 430.7(B) Locked-Rotor Indicating Code Letters

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0–3.14
B	3.15–3.54
C	3.55–3.99
D	4.0–4.49
E	4.5–4.99
F	5.0–5.59
G	5.6–6.29
H	6.3–7.09
J	7.1–7.99
K	8.0–8.99
L	9.0–9.99
M	10.0–11.19
N	11.2–12.49
P	12.5–13.99
R	14.0–15.99
S	16.0–17.99
T	18.0–19.99
U	20.0–22.39
V	22.4 and up

FIGURE 21-10 *NEC*® Table 430.7(B) is used to determine the locked-rotor current of motors that do not contain NEMA code letters. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

EXAMPLE: A 15-hp, three-phase squirrel-cage motor with a code letter of K is connected to a 240-V line. Determine the locked-rotor current.

Table 430.7(B) lists 8.0–8.99 kVA per horsepower for a motor with a code letter of K. An average value of 8.5 will be used.

$$8.5 \times 15 = 127.5 \text{ kVA or } 127{,}500 \text{ VA}$$

$$\frac{12{,}7500}{240 \times \sqrt{3}} = 306.7 \text{ A}$$

The second method of determining locked-rotor current is to use Table 430.251(A) and Table 430.251(B), FIGURE 21-11, if the motor nameplate lists NEMA design codes. Table 430.251(A) lists the locked-rotor currents for single-phase motors and Table 430.251(B) lists the locked-rotor currents for polyphase motors.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

(a) **Table 430.251(A) Conversion Table of Single-Phase Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating**

For use only with 430.110, 440.12, 440.41, and 455.8(C).

Rated Horsepower	Maximum Locked-Rotor Current in Amperes, Single Phase		
	115 Volts	208 Volts	230 Volts
½	58.8	32.5	29.4
¾	82.8	45.8	41.4
1	96	53	48
1½	120	66	60
2	144	80	72
3	204	113	102
5	336	186	168
7½	480	265	240
10	600	332	300

(b) **Table 430.251(B) Conversion Table of Polyphase Design B, C, and D Maximum Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating and Design Letter**

For use only with 430.110, 440.12, 440.41 and 455.8(C).

Rated Horsepower	Maximum Motor Locked-Rotor Current in Amperes, Two- and Three-Phase, Design B, C, and D*					
	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts
	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
½	40	23	22.1	20	10	8
¾	50	28.8	27.6	25	12.5	10
1	60	34.5	33	30	15	12
1½	80	46	44	40	20	16
2	100	57.5	55	50	25	20
3	—	73.6	71	64	32	25.6
5	—	105.8	102	92	46	36.8
7½	—	146	140	127	63.5	50.8
10	—	186.3	179	162	81	64.8
15	—	267	257	232	116	93
20	—	334	321	290	145	116
25	—	420	404	365	183	146
30	—	500	481	435	218	174
40	—	667	641	580	290	232
50	—	834	802	725	363	290
60	—	1001	962	870	435	348
75	—	1248	1200	1085	543	434
100	—	1668	1603	1450	725	580
125	—	2087	2007	1815	908	726
150	—	2496	2400	2170	1085	868
200	—	3335	3207	2900	1450	1160
250	—	—	—	—	1825	1460
300	—	—	—	—	2200	1760
350	—	—	—	—	2550	2040
400	—	—	—	—	2900	2320
450	—	—	—	—	3250	2600
500	—	—	—	—	3625	2900

*Design A motors are not limited to a maximum starting current or locked rotor current.

FIGURE 21-11 *NEC*® Tables 430.251(a&b) are used to determine the locked-rotor current of motors that contain NEMA code letters. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

SHORT-CIRCUIT PROTECTION

The rating of the short-circuit protective device is determined by *NEC*® Table 430.52, FIGURE 21-12. The far left-hand column lists the type of motor that is to be protected. To the right of this are four columns that list different types of short-circuit protective devices; non-time-delay fuses, dual-element time-delay fuses, instantaneous-trip circuit breakers, and inverse time circuit

Table 430.52 Maximum Rating or Setting of Motor Branch-Circuit Short-Circuit and Ground-Fault Protective Devices

	Percentage of Full-Load Current			
Type of Motor	Nontime Delay Fuse[1]	Dual Element (Time-Delay) Fuse[1]	Instantaneous Trip Breaker	Inverse Time Breaker[2]
Single-phase motors	300	175	800	250
AC polyphase motors other than wound-rotor	300	175	800	250
Squirrel cage — other than Design B energy-efficient	300	175	800	250
Design B energy-efficient	300	175	1100	250
Synchronous[3]	300	175	800	250
Wound rotor	150	150	800	150
Direct current (constant voltage)	150	150	250	150

Note: For certain exceptions to the values specified, see 430.54.
[1]The values in the Nontime Delay Fuse column apply to Time-Delay Class CC fuses.
[2]The values given in the last column also cover the ratings of nonadjustable inverse time types of circuit breakers that may be modified as in 430.52(C)(1), Exception No. 1 and No. 2.
[3]Synchronous motors of the low-torque, low-speed type (usually 450 rpm or lower), such as are used to drive reciprocating compressors, pumps, and so forth, that start unloaded, do not require a fuse rating or circuit-breaker setting in excess of 200 percent of full-load current.

FIGURE 21-12 *NEC*® Table 430.52 is used to determine the rating of the short-circuit protective device for a motor. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

breakers. Although it is permissible to use non-time-delay fuses and instantaneous-trip circuit breakers, most motor circuits are protected by dual-element time-delay fuses or inverse-time circuit breakers.

Each of these columns lists the percentage of motor current that is to be used in determining the ampere rating of the short-circuit protective device. The current listed in the appropriate motor table is to be used instead of the nameplate current. *NEC*® Section 430.52(C)(1) states that the protective device is to have a rating or setting not exceeding the value calculated in accord with Table 430.52. Exception No. 1 of this section, however, states that if the calculated value does not correspond to a standard size or rating of a fuse or circuit breaker, it shall be permissible to use the next higher standard size. The standard sizes of fuses and circuit breakers are listed in *NEC*® Section 240.6, FIGURE 21-13.

As of 1996, Table 430.52 lists squirrel-cage motor types by NEMA design letters instead of code letters. Section 430.7(A)(9) requires that motor nameplates be marked with design letters B, C, or D. Motors manufactured before this requirement, however, do not list design letters on the nameplate. Most common squirrel-cage motors used in industry actually fall in the Design B classification and for purposes of selecting the short-circuit protective device are considered to be Design B unless otherwise listed.

EXAMPLE: A 100-hp three-phase squirrel-cage induction motor is connected to a 240-V line. The motor does not contain a NEMA design code. A dual-element time-delay fuse is to be used as the short-circuit protective device. Determine the size needed.

Table 340.250 lists a full-load current of 248 A for this motor. Table 430.52 indicates that a dual-element time-delay fuse is to be calculated at

> **(a) 240.6 Standard Ampere Ratings.**
>
> **(A) Fuses and Fixed-Trip Circuit Breakers.** The standard ampere ratings for fuses and inverse time circuit breakers shall be considered 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 700, 800, 1000, 1200, 1600, 2000, 2500, 3000, 4000, 5000, and 6000 amperes. Additional standard ampere ratings for fuses shall be 1, 3, 6, 10, and 601. The use of fuses and inverse time circuit breakers with nonstandard ampere ratings shall be permitted.

FIGURE 21-13 *NEC*® Section 240.6 (a) lists the standard fuse and circuit breaker sizes. (Reprinted with permission from NFPA 70®-2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

175% of the full-load current rating for an AC polyphase (more than one phase) squirrel-cage motor, other than Design code E. Since the motor does not list a NEMA design code on the nameplate, it will be assumed that the motor is Design B.

$$248 \times 1.75 = 434 \text{ A}$$

The nearest standard fuse size above the computed value listed in Section 240.6 is 450 A. 450-ampere Fuses of 450 A will be used to protect this motor.

If for some reason this fuse will not permit the motor to start without blowing, *NEC*® Section 430.52(C)(1) Exception 2(b) states that the rating of a dual-element time-delay fuse may be increased to a maximum of 225% of the full-load motor current.

STARTER SIZE

Another factor that must be considered when installing a motor is the size starter used to connect the motor to the line. Starter sizes are rated by motor type, horsepower, and connected voltage. The two most common ratings are NEMA and IEC. A chart showing common NEMA size starters for alternating current motors is shown in FIGURE 21-14. A chart showing IEC starters for alternating current motors is shown in FIGURE 21-15. Each of these charts lists the minimum size starter designed to connect the listed motors to the line. It is not uncommon to employ larger size starters than those listed. This is especially true when using IEC type starters because of their smaller load contact size. In practice, IEC type starters are often sized from one to two sizes larger than those listed in the chart.

EXAMPLE: A 40-hp three-phase squirrel-cage motor is connected to a 208-V line. What are the minimum size NEMA and IEC starters that should be used to connect this motor to the line?

NEMA: The 200-V listing is used for motors rated at 208 V. Locate the NEMA size starter that corresponds to 200 V and 40 hp. Since the motor is three-phase, 40 hp will be in the polyphase column. A NEMA size-4 starter is the minimum size for this motor.

EXAMPLE PROBLEMS: IEC: As with the NEMA chart, the IEC chart lists 200 V instead of 208 V. A size-N starter lists 200 V and 40 hp in the three-phase column.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Motor Starter Sizes and Ratings

NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Poly Phase
	115	½	. . .
	200	. . .	1½
	230	1	1½
00	380	. . .	1½
	460	. . .	2
	575	. . .	2
	115	1	. . .
	200	. . .	3
	230	2	3
0	380	. . .	5
	460	. . .	5
	575	. . .	5
	115	2	. . .
	200	. . .	7½
	230	3	7½
1	380	. . .	10
	460	. . .	10
	575	. . .	10
	115	3	. . .
*1P	230	5	. . .
	115	3	. . .
	200	. . .	10
	230	7½	15
2	380	. . .	25
	460	. . .	25
	575	. . .	25
	115	7½	. . .
	200	. . .	25
	230	15	30
3	380	. . .	50
	460	. . .	50
	575	. . .	50
	200	. . .	40
	230	. . .	50
	380	. . .	75
4	460	. . .	100
	575	. . .	100
	200	. . .	75
	230	. . .	100
	380	. . .	150
5	460	. . .	200
	575	. . .	200
	200	. . .	150
	230	. . .	200
6	380	. . .	300
	460	. . .	400
	575	. . .	400
	230	. . .	300
7	460	. . .	600
	575	. . .	600
	230	. . .	450
8	460	. . .	900
	575	. . .	900

Tables are taken from NEMA Standards.

*1¾, 10 hp is available.

© Cengage Learning 2014

FIGURE 21-14 NEMA table of standard starter sizes.
Source: National Electrical Manufacturers Association

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

IEC Motor Starters (60 Hz)

SIZE	MAX AMPS	MOTOR VOLTAGE	MAXIMUM HORSEPOWER	
			1 Ø	3 Ø
A	7	115 200 230 460 575	1/4 1/2 	 1 1/2 1 1/2 3 5
B	10	115 200 230 460 575	1/2 1 	 2 2 5 7 1/2
C	12	115 200 230 460 575	1/2 2 	 3 3 7 1/2 10
D	18	115 200 230 460 575	1 3 	 5 5 10 15
E	25	115 200 230 460 575	2 3 	 5 7 1/2 15 20
F	32	115 200 230 460 575	2 5 	 7 1/2 10 20 25
G	37	115 200 230 460 575	3 5 	 7 1/2 10 25 30
H	44	115 200 230 460 575	3 7 1/2 	 10 15 30 40
J	60	115 200 230 460 575	5 10 	 15 20 40 40
K	73	115 200 230 460 575	5 10 	 20 25 50 50
L	85	115 200 230 460 575	7 1/2 10 	 25 30 60 75
M	105	115 200 230 460 575	10 10 	 30 40 75 100
N	140	115 200 230 460 575	10 10 	 40 50 100 125
P	170	115 200 230 460 575	 	 50 60 125 125
R	200	115 200 230 460 575	 	 60 75 150 150
S	300	115 200 230 460 575	 	 75 100 200 200
T	420	115 200 230 460 575	 	 125 125 250 250
U	520	115 200 230 460 575	 	 150 150 350 250
V	550	115 200 230 460 575	 	 150 200 400 400
W	700	115 200 230 460 575	 	 200 250 500 500
X	810	115 200 230 460 575	 	 250 300 600 600
Z	1215	115 200 230 460 575	 	 450 450 900 900

© Cengage Learning 2014

FIGURE 21-15 IEC motor starter sizes.

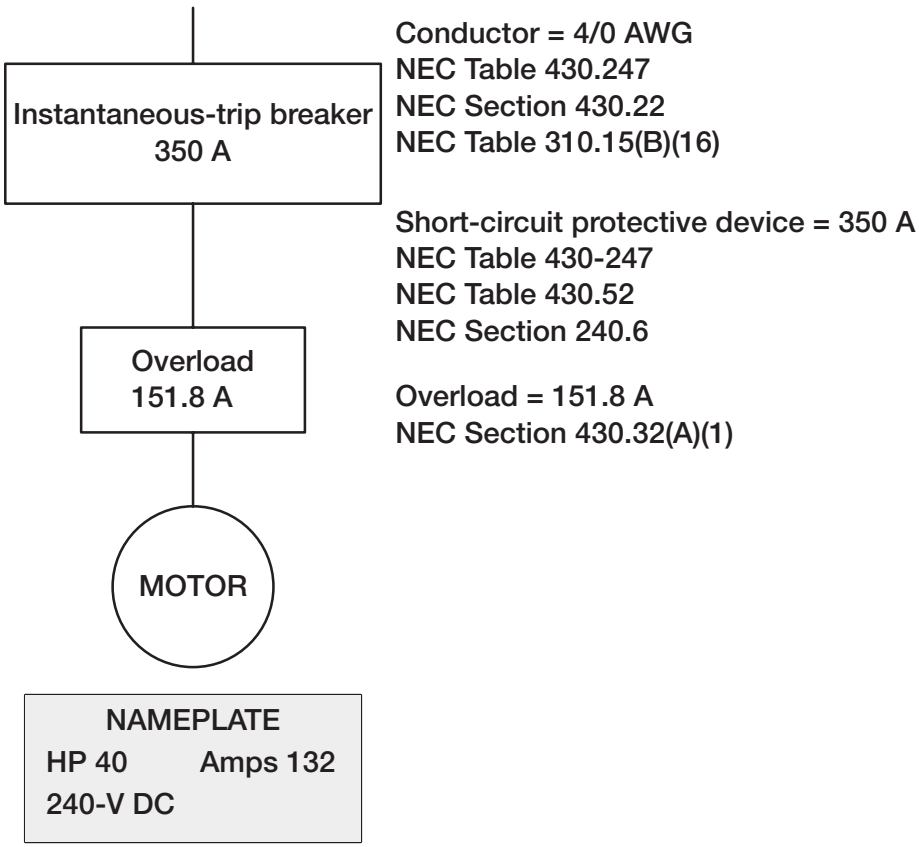
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

EXAMPLE 1: A 40-hp, 240-V DC motor has a nameplate current rating of 132 A. The conductors are to be copper with type TW insulation. The short-circuit protective device is to be an instantaneous-trip circuit breaker. The termination temperature rating of the connected devices is not known. Determine the conductor size, overload size, and circuit breaker size for this installation. Refer to FIGURE 21-16.

The conductor size must be determined from the current listed in Table 430.247. This value is to be increased by 25%. (Note: Multiplying by 1.25 has the same effect as multiplying by 0.25 and then adding the product back to the original number (140 × 0.25 = 35) (35 + 140 = 175 A).

$$140 \times 1.25 = 175 \text{ A}$$

Table 310.15(B)(16) is used to find the conductor size. Although section 110.14(C) states that for currents of 100 A or greater, the ampacity rating of the conductor is to be determined from the 75°C column, in this instance



© Cengage Learning 2014

FIGURE 21-16 Example circuit #1.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

type TW insulation is located in the 60°C column. Therefore, the conductor size must be determined using the 60°C column instead of the 75°C column. A 4/0 AWG copper conductor with type TW insulation will be used.

The overload size is determined from *NEC*® Section 430.32(A)(1). Since there is no service factor or temperature rise listed on the motor nameplate, the heading *ALL OTHER MOTORS* will be used. The motor nameplate current will be increased by 15%.

$$132 \times 1.15 = 151.8 \text{ A}$$

Depending on the manufacturer of the starter, different methods are used to choose the proper overload heater size. All heater sizes are chosen from a chart supplied by the starter manufacturer. Some charts list heater sizes in accord with the overload current as determined by the method just discussed. Others use the motor full-load current rating and the heater size is chosen on the basis of whether the heater rating is 115% or 125% of the full-load current. A typical overload heater chart is shown in FIGURE 21-17.

Overload heater selection for NEMA starter sizes 00–1. Heaters are calibrated for 115% of motor full load current. For heaters that correspond to 125% of motor full load current use the next size larger heater.

Heater Code	Motor Full-Load Current	Heater Code	Motor Full-Load Current	Heater Code	Motor Full-Load Current
XX01	.25–.27	XX18	1.35–1.47	XX35	6.5–7.1
XX02	.28–.31	XX19	1.48–1.62	XX36	7.2–7.8
XX03	.32–.34	XX20	1.63–1.78	XX37	7.9–8.5
XX04	.35–.38	XX21	1.79–1.95	XX38	8.6–9.4
XX05	.39–.42	XX22	1.96–2.15	XX39	9.5–10.3
XX06	.43–.46	XX23	2.16–2.35	XX40	10.4–11.3
XX07	.47–.50	XX24	2.36–2.58	XX41	11.4–12.4
XX08	.51–.55	XX25	2.59–2.83	XX42	12.5–13.5
XX09	.56–.62	XX26	2.84–3.11	XX43	13.6–14.9
XX10	.63–.68	XX27	3.12–3.42	XX44	15.0–16.3
XX11	.69–.75	XX28	3.43–3.73	XX45	16.4–18.0
XX12	.76–.83	XX29	3.74–4.07	XX46	18.1–19.8
XX13	.84–.91	XX30	4.08–4.39	XX47	19.9–21.7
XX14	.92–1.00	XX31	4.40–4.87	XX48	21.8–23.9
XX15	1.01–1.11	XX32	4.88–5.3	XX49	24.0–26.2
XX16	1.12–1.22	XX33	5.4–5.9		
XX17	1.23–1.34	XX34	6.0–6.4		

© Cengage Learning 2014

FIGURE 21-17 Typical overload heater chart.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The circuit breaker size is determined from Table 430.52. The current value listed in Table 430.247 is used instead of the nameplate current. Under DC motors (constant voltage), the instantaneous-trip circuit breaker rating is given at 250%.

$$140 \times 2.50 = 350 \text{ A}$$

Since 350 A is one of the standard sizes of circuit breakers listed in *NEC*® Section 240.6, that size breaker will be employed as the short-circuit protective device.

EXAMPLE 2: A 150-hp three-phase squirrel-cage induction motor is connected to a 440-V line. The motor nameplate lists the following information:

Amps 175

SF 1.25

Code D

NEMA code B

The conductors are to be copper with type THHN insulation. The short-circuit protective device is to be an inverse-time circuit breaker. The termination temperature rating is not known. Determine the conductor size, overload size, circuit breaker size, minimum NEMA starter size, and IEC starter size. Refer to FIGURE 21-18.

The conductor size is determined from the current listed in Table 430.250 and increased by 25%.

$$180 \times 1.25 = 225 \text{ A}$$

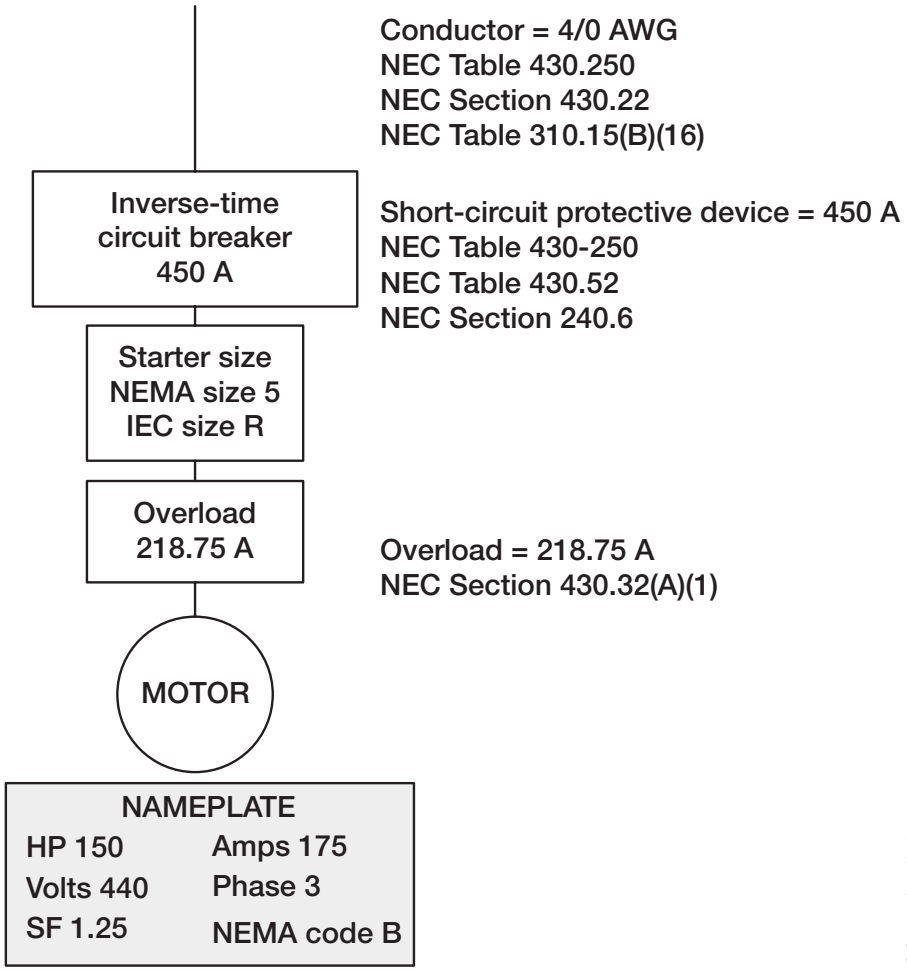
Table 310.15(B)(16) is used to determine the conductor size. Type THHN insulation is located in the 90°C column. Since the motor nameplate lists NEMA code B, and the amperage is over 100 A, the conductor will be selected from the 75°C column. The conductor size will be 4/0 AWG.

The overload size is determined from the nameplate current and *NEC*® Section 430.32(A)(1). The motor has a marked service factor of 1.25. The motor nameplate current will be increased by 25%.

$$175 \times 1.25 = 218.75 \text{ A}$$

The circuit breaker size is determined by Table 430.250 and Table 430.52. Table 430.52 indicates a factor of 250% for squirrel-cage motors

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 21-18 Example circuit #2.

with NEMA design code B. The value listed in Table 430.250 will be increased by 250%.

$$180 \times 2.50 = 450 \text{ A}$$

One of the standard circuit breaker sizes listed in *NEC*® Section 240.6 is 450 A. A 450-A inverse-time circuit breaker will be used as the short-circuit protective device.

The proper motor starter sizes are selected from the NEMA and IEC charts shown in Figure 21-14 and Figure 21-15. The minimum size NEMA starter is 5 and the minimum size IEC starter is R.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

MULTIPLE MOTOR CALCULATIONS

The main feeder short-circuit protective devices and conductor sizes for multiple motor connections are set forth in *NEC*® Section 430.62(A) and Section 430.24. In this example, three motors are connected to a common feeder. The feeder is 480-V three-phase and the conductors are to be copper with type THHN insulation. Each motor is to be protected with dual-element time-delay fuses and a separate overload device. The main feeder is also protected by dual-element time-delay fuses. The termination temperature rating of the connected devices is not known. The motor nameplates state the following:

MOTOR #1

Phase 3	HP 20
SF 1.25	NEMA code C
Volts 480	Amperes 23
Type Induction	

MOTOR #2

Phase 3	HP 60
Temp. 40°C	Code J
Volts 480	Amperes 72
Type Induction	

MOTOR #3

Phase 3	HP 100
Code A	Volts 480
Amperes 96	PF 90%
Type Synchronous	

MOTOR #1 CALCULATION: The first step is to calculate the values for motor amperage, conductor size, overload size, short-circuit protection size, and starter size for each motor. Both NEMA and IEC starter sizes will be determined. The values for motor #1 are shown in FIGURE 21-19.

The ampere rating from Table 430.250 is used to determine the conductor and fuse size. The amperage rating must be increased by 25% for the conductor size.

$$27 \times 1.25 = 33.75 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

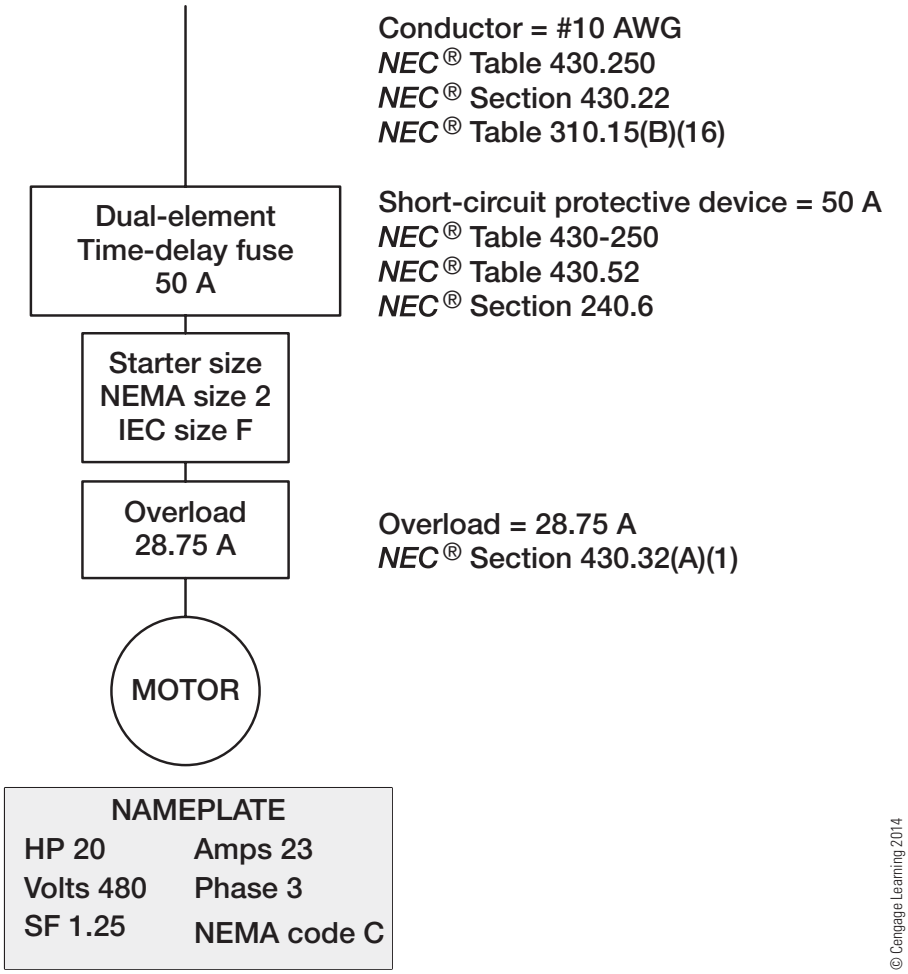


FIGURE 21-19 Motor #1 calculation.

The conductor size is chosen from Table 310.16. Although type THHN insulation is located in the 90°C column, the conductor size will be chosen from the 75°C column. Although the current is less than 100 A, *NEC*® Section 110.14(C)(1)(d) permits the conductors to be chosen from the 75°C column if the motor has a NEMA design code.

$$33.75 \text{ A} = \#10 \text{ AWG}$$

The overload size is computed from the nameplate current. The demand factors in Section 430.32(A)(1) are used for the overload calculation.

$$23 \times 1.25 = 28.75 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The fuse size is determined by using the motor current listed in Table 430.250 and the demand factor from Table 430.52. The percent of full-load current for a dual-element time-delay fuse protecting a squirrel-cage motor listed as Design C is 175%. The current listed in Table 430.250 will be increased by 175%.

$$27 \times 1.75 = 47.25 \text{ A}$$

The nearest standard fuse size listed in Section 240.6 is 50 A. 50-A fuses will be used.

The starter sizes are determined from the NEMA and IEC charts shown in Figure 21-14 and Figure 21-15. A 20-hp motor connected to 480 V would require a NEMA size-2 starter and an IEC size-F starter.

MOTOR #2 CALCULATION: FIGURE 21-20 shows an example for the calculation for motor #2. Table 430.250 lists a full-load current of 77 A for this motor. This value of current is increased by 25% for the calculation of the conductor current.

$$77 \times 1.25 = 96.25 \text{ A}$$

Table 310.15(B)(16) indicates a #1 AWG conductor should be used for this motor connection. The conductor size is chosen from the 60°C column because the circuit current is less than 100 A in accord with Section 110.14(C), and the motor nameplate does not indicate a NEMA design code. (The code J indicates the type of bars used in the construction of the rotor).

The overload size is determined from Section 430.32(A)(1). The motor nameplate lists a temperature rise of 40°C for this motor. The nameplate current will be increased by 25%.

$$72 \times 1.25 = 90 \text{ A}$$

The fuse size is determined from Table 430.52. The table current is increased by 175% for squirrel-cage motors other than design E.

$$77 \times 1.75 = 134.25 \text{ A}$$

The nearest standard fuse size listed in Section 240.6 is 150 A. The circuit will be protected by 150-A fuses.

The starter sizes are chosen from the NEMA and IEC starter charts. This motor would require a NEMA size-4 starter or an IEC size-L starter.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

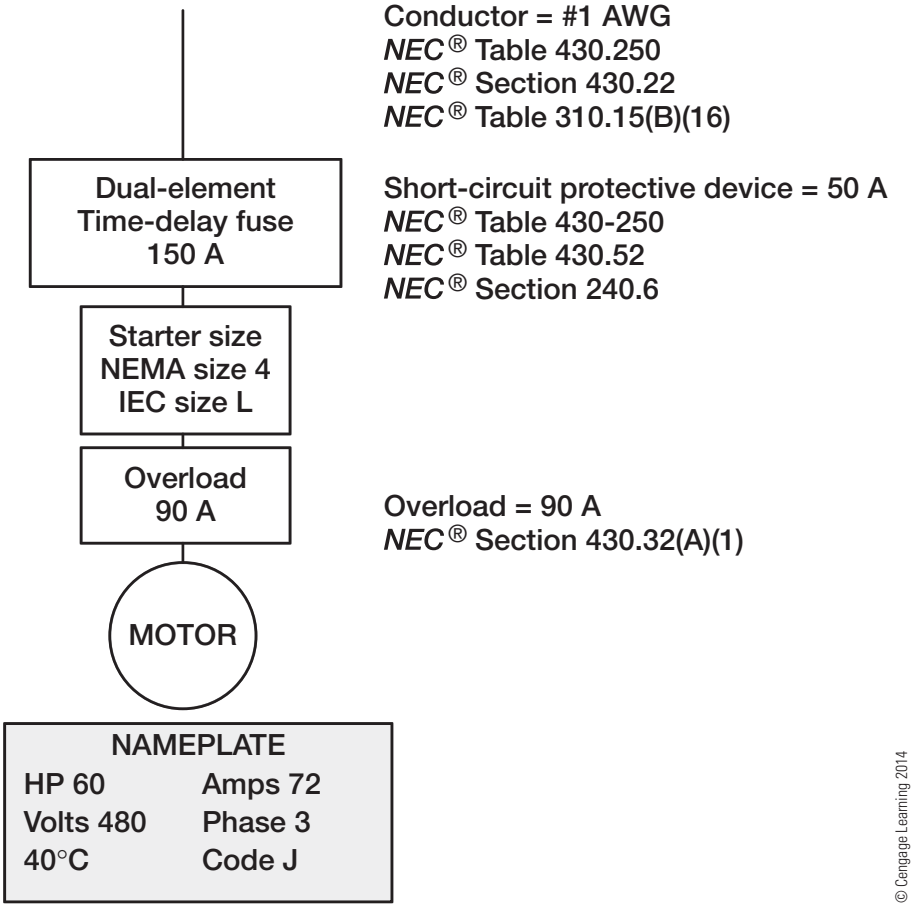


FIGURE 21-20 Motor #2 calculation.

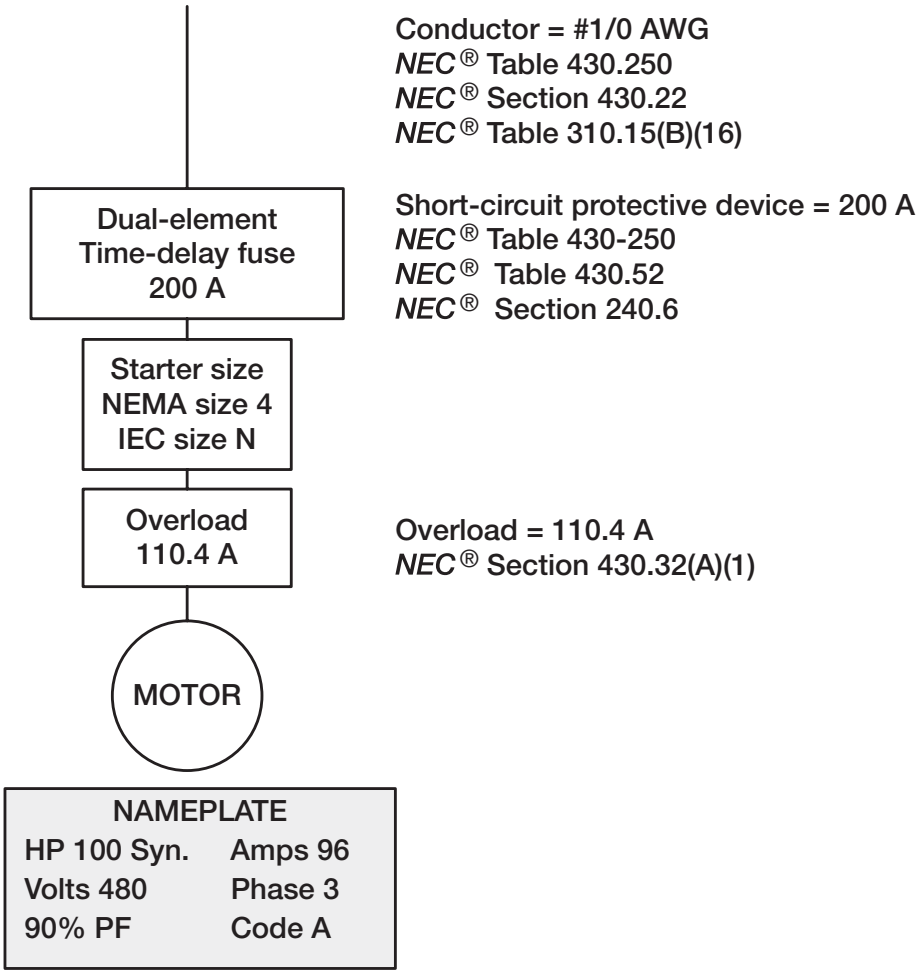
MOTOR #3 CALCULATION: Motor #3 is a synchronous motor intended to operate with a 90% power factor. FIGURE 21-21 shows an example of this calculation. The notes at the bottom of Table 430.250 indicate that the listed current is to be increased by 10% for synchronous motors with a listed power factor of 90%.

$$101 \times 1.10 = 111 \text{ A}$$

The conductor size is computed by using this current rating and increasing it by 25%.

$$111 \times 1.25 = 138.75 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 21-21 Motor #3 calculation.

Table 310.15(B)(16) indicates that a #1/0 AWG conductor will be used for this circuit. Since the circuit current is over 100 A, the conductor size is chosen from the 75°C column.

This motor does not have a marked service factor or a marked temperature rise. The overload size will be calculated by increasing the nameplate current by 15% as indicated in Section 430.32(A)(1) under the heading "All Other Motors."

$$96 \times 1.15 = 110.4 \text{ A}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

The fuse size is determined from Table 430.52. The percent of full-load current for a synchronous motor is 175%.

$$111 \times 1.75 = 194.25 \text{ A}$$

The nearest standard size fuse listed in Section 240.6 is 200 A. 200-ampere Fuses of 200 A will be used to protect this circuit.

The NEMA and IEC starter sizes are chosen from the charts shown in Figures 21-14 and 21-15. The motor will require a NEMA size-4 starter and an IEC size-N starter.

MAIN FEEDER CALCULATION

An example of the main feeder connections is shown in FIGURE 21-22. The conductor size is computed in accord with *NEC*® Section 430.24 by increasing the largest amperage rating of the motors connected to the feeder by 25% and then adding the ampere rating of the other motors to this amount. In this example, the 100-hp synchronous motor has the largest running current. This current will be increased by 25% and then the running currents of the other motors as determined from Table 430.250 will be added.

$$111 \times 1.25 = 138.75 \text{ A}$$

$$138.75 + 77 + 27 = 242.75 \text{ A}$$

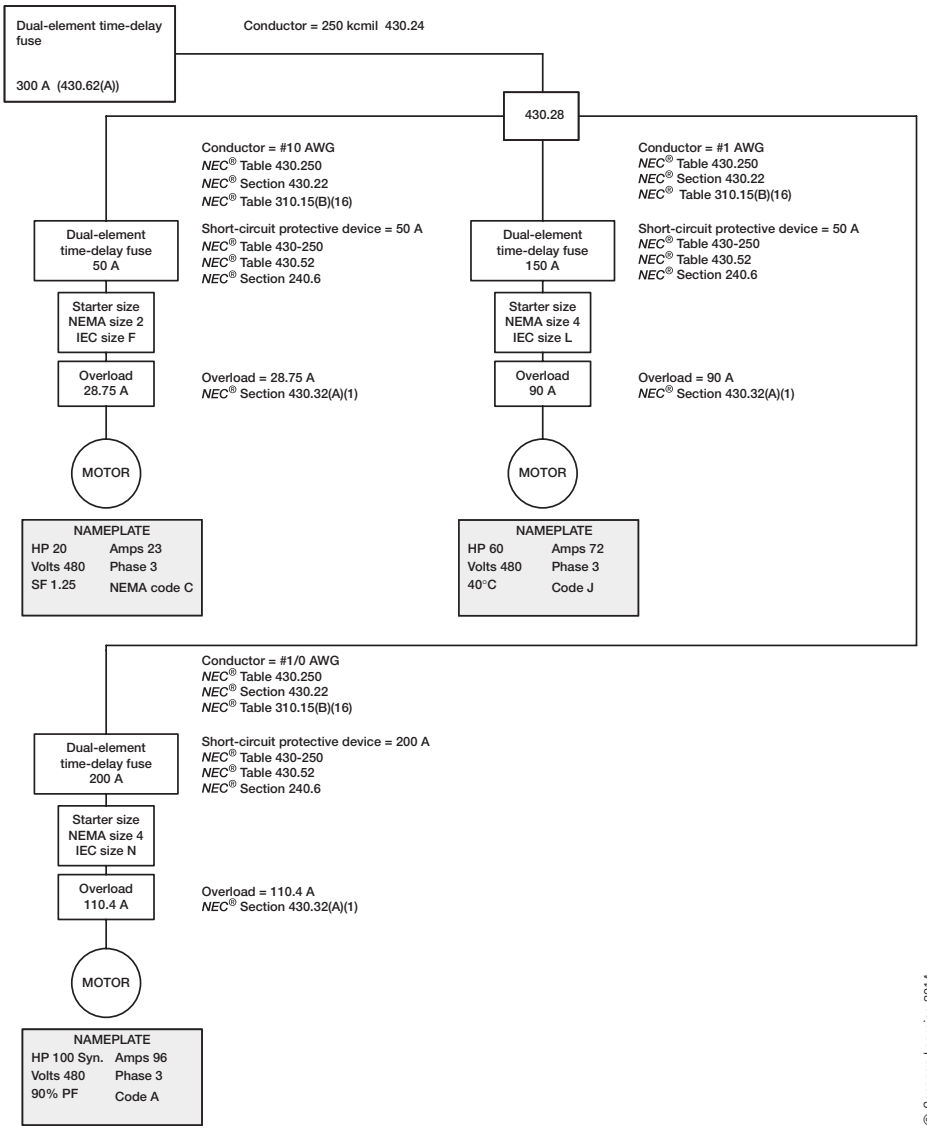
Table 310.15(B)(16) lists that 250 kcmil copper conductors are to be used as the main feeder conductors. The conductors were chosen from the 75°C column.

The size of the short-circuit protective device is determined by Section 430.62(A). The code states that the rating or setting of the short-circuit protective device ***shall not be greater than*** the largest rating or setting of the largest branch circuit short-circuit and ground fault protective device for any motor supplied by the feeder plus the sum of the full-load running currents of the other motors connected to the feeder. The largest fuse size in this example is the 100-hp synchronous motor. The fuse calculation for this motor is 200 A. The running currents of the other two motors will be added to this value to determine the fuse size for the main feeder.

$$200 + 77 + 27 = 304 \text{ A}$$

The closest standard fuse size listed in Section 240.6 without going over 304 A is 300 A. 300-ampere Fuses of 300 A will be used to protect this circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



© Cengage Learning 2014

FIGURE 21-22 Main feeder calculation.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Review Questions

1. A 20-hp DC motor is connected to a 500-V DC line. What is the full-load running current of this motor?
2. What rating is used to find the full-load running current of a torque motor?
3. A ¾-hp single-phase squirrel-cage motor is connected to a 240-V AC line. What is the full-load current rating of this motor and what is the minimum size of NEMA and IEC starters that should be used?
4. A 30-hp two-phase motor is connected to a 230-V AC line. What is the rated current of the phase conductors and the rated current of the neutral?
5. A 125-hp synchronous motor is connected to a 230-V three-phase AC line. The motor is intended to operate at 80% power factor. What is the full-load running current of this motor? What is the minimum size of NEMA and IEC starters that should be used to connect this motor to the line?
6. What is the full-load running current of a three-phase, 50-hp motor connected to a 560-V line? What minimum size NEMA and IEC starters should be used to connect this motor to the line?
7. A 125-hp three-phase squirrel-cage induction motor is connected to 560 V. The nameplate current is 115 A. It has a marked temperature rise of 40°C and a code letter J. The conductors are to be type THHN copper and they are run in conduit. The short-circuit protective device is dual-element time-delay fuses. Find the conductor size, overload size, fuse size, minimum NEMA and IEC starter sizes, and the upper and lower range of starting currents for this motor.
8. A 7.5-hp single-phase squirrel-cage induction motor is connected to 120 VAC. The motor has a code letter of H. The nameplate current is 76 A. The conductors are copper with type TW insulation. The short-circuit protection device is a non-time-delay fuse. Find the conductor size, overload size, fuse size, minimum NEMA and IEC starter sizes, and upper and lower starting currents.
9. A 75-hp three-phase synchronous motor is connected to a 230-V line. The motor is to be operated at 80% power factor. The motor nameplate lists a full-load current of 185 A, a temperature rise of 40°C, and a code letter A. The conductors are to be made of copper and have type THHN insulation. The short-circuit protective device

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

is to be an inverse-time circuit breaker. Determine the conductor size, overload size, circuit breaker size, minimum size NEMA and IEC starters, and the upper and lower starting currents.

10. Three motors are connected to a single branch circuit. The motors are connected to a 480-V three-phase line. Motor #1 is a 50-hp induction motor with a NEMA code B. Motor #2 is 40 hp with a code letter of H, and motor #3 is 50 hp with a NEMA code C. Determine the conductor size needed for the branch circuit supplying these three motors. The conductors are copper with type THWN-2 insulation.
11. The short-circuit protective device supplying the motors in question #10 is an inverse-time circuit breaker. What size circuit breaker should be used?
12. Five 5-hp three-phase motors with NEMA code B are connected to a 240-V line. The conductors are copper with type THWN insulation. What size conductor should be used to supply all of these motors?
13. If dual-element time-delay fuses are to be used as the short-circuit protective device, what size fuses should be used to protect the circuit in question #12?
14. A 75-hp three-phase squirrel-cage induction motor is connected to 480 V. The motor has a NEMA code D. What is the starting current for this motor?
15. A 20-hp three-phase squirrel-cage induction motor has a NEMA code B. The motor is connected to 208 V. What is the starting current for this motor?

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

APPENDIX A

American Wire Gauge Table

AMERICAN WIRE GAUGE TABLE

B & S Gauge No.	Diam. in Mils	Area in Circular Mils	Ohms per 1000 Ft. (ohms per 100 m)			Pounds per 1,000 Ft. (kg per 100 m)	
			Copper* 68°F (20°C)	Copper* 167°F (75°C)	Aluminum 68°F (20°C)	Copper	Aluminum
0000	460	211 600	0.049 (0.016)	0.0596 (0.0195)	0.0804 (0.0263)	640 (95.2)	195 (29.0)
000	410	167 800	0.0618 (0.020)	0.0752 (0.0246)	0.101 (0.033)	508 (75.5)	154 (22.9)
00	365	133 100	0.078 (0.026)	0.0948 (0.031)	0.128 (0.042)	403 (59.9)	122 (18.1)
0	325	105 500	0.0983 (0.032)	0.1195 (0.0392)	0.161 (0.053)	320 (47.6)	97 (14.4)
1	289	83 690	0.1239 (0.0406)	0.151 (0.049)	0.203 (0.066)	253 (37.6)	76.9 (11.4)
2	258	66 370	0.1563 (0.0512)	0.190 (0.062)	0.526 (0.084)	201 (29.9)	61.0 (9.07)
3	229	52 640	0.1970 (0.0646)	0.240 (0.079)	0.323 (0.106)	159 (23.6)	48.4 (7.20)
4	204	41 740	0.2485 (0.0815)	0.302 (0.099)	0.408 (0.134)	126 (18.7)	38.4 (5.71)
5	182	33 100	0.3133 (0.1027)	0.381 (0.125)	0.514 (0.168)	100 (14.9)	30.4 (4.52)
6	162	26 250	0.395 (1.29)	0.481 (0.158)	0.648 (0.212)	79.5 (11.8)	24.1 (3.58)
7	144	20 820	0.498 (0.163)	0.606 (0.199)	0.817 (0.268)	63.0 (9.37)	19.1 (2.84)
8	128	16 510	0.628 (0.206)	0.764 (0.250)	1.03 (0.338)	50.0 (7.43)	15.2 (2.26)
9	114	13 090	0.792 (0.260)	0.963 (0.316)	1.30 (0.426)	39.6 (5.89)	12.0 (1.78)
10	102	10 380	0.999 (0.327)	1.215 (0.398)	1.64 (0.538)	31.4 (4.67)	9.55 (1.42)
11	91	8 234	1.260 (0.413)	1.532 (0.502)	2.07 (0.678)	24.9 (3.70)	7.57 (1.13)
12	81	6 530	1.588 (0.520)	1.931 (0.633)	2.61 (0.856)	19.8 (2.94)	6.00 (0.89)
13	72	5 178	2.003 (0.657)	2.44 (0.80)	3.29 (1.08)	15.7 (2.33)	4.8 (0.71)
14	64	4 107	2.525 (0.828)	3.07 (1.01)	4.14 (1.36)	12.4 (1.84)	3.8 (0.56)
15	57	3 257	3.184 (0.043)	3.98 (1.27)	5.22 (1.71)	9.86 (1.47)	3.0 (0.45)
16	51	2 583	4.016 (0.316)	4.88 (1.60)	6.59 (2.16)	7.82 (1.16)	2.4 (0.36)
17	45.3	2 048	5.06 (1.66)	6.16 (2.02)	8.31 (2.72)	6.20 (0.922)	1.9 (0.28)
18	40.3	1 624	6.39 (2.09)	7.77 (2.55)	10.5 (3.44)	4.92 (0.731)	1.5 (0.22)
19	35.9	1 288	8.05 (2.64)	9.79 (3.21)	13.2 (4.33)	3.90 (0.580)	1.2 (0.18)
20	32.0	1 022	10.15 (3.33)	12.35 (4.05)	16.7 (5.47)	3.09 (0.459)	0.94 (0.14)
21	28.5	810	12.8 (4.2)	15.6 (5.11)	21.0 (6.88)	2.45 (0.364)	0.745 (0.110)
22	25.4	642	16.1 (5.3)	19.6 (6.42)	26.5 (8.69)	1.95 (0.290)	0.591 (0.09)
23	22.6	510	20.4 (6.7)	24.8 (8.13)	33.4 (10.9)	1.54 (0.229)	0.468 (0.07)
24	20.1	404	25.7 (8.4)	31.2 (10.2)	42.1 (13.8)	1.22 (0.181)	0.371 (0.05)
25	17.9	320	32.4 (10.6)	39.4 (12.9)	53.1 (17.4)	0.97 (0.14)	0.295 (0.04)
26	15.9	254	40.8 (13.4)	49.6 (16.3)	67.0 (22.0)	0.77 (0.11)	0.234 (0.03)
27	14.2	202	51.5 (16.9)	62.6 (20.5)	84.4 (27.7)	0.61 (0.09)	0.185 (0.03)
28	12.6	160	64.9 (21.3)	78.9 (25.9)	106 (34.7)	0.48 (0.07)	0.147 (0.02)
29	11.3	126.7	81.8 (26.8)	99.5 (32.6)	134 (43.9)	0.384 (0.06)	0.117 (0.02)
30	10.0	100.5	103.2 (33.8)	125.5 (41.1)	169 (55.4)	0.304 (0.04)	0.092 (0.01)
31	8.93	79.7	130.1 (42.6)	158.2 (51.9)	213 (69.8)	0.241 (0.04)	0.073 (0.01)
32	7.95	63.2	164.1 (53.8)	199.5 (65.4)	269 (88.2)	0.191 (0.03)	0.058 (0.01)
33	7.08	50.1	207 (68)	252 (82.6)	339 (111)	0.152 (0.02)	0.046 (0.01)
34	6.31	39.8	261 (86)	317 (104)	428 (140)	0.120 (0.02)	0.037 (0.01)
35	5.62	31.5	329 (108)	400 (131)	540 (177)	0.095 (0.01)	0.029
36	5.00	25.0	415 (136)	505 (165)	681 (223)	0.076 (0.01)	0.023
37	4.45	19.8	523 (171)	636 (208)	858 (281)	0.0600 (0.01)	0.0182
38	3.96	15.7	660 (216)	802 (263)	1080 (354)	0.0476 (0.01)	0.0145
39	3.53	12.5	832 (273)	1012 (332)	1360 (446)	0.0377 (0.01)	0.0115
40	3.15	9.9	1049 (344)	1276 (418)	1720 (564)	0.0299 (0.01)	0.0091
41							
42	2.50	6.3					
43							
44	1.97	3.9					

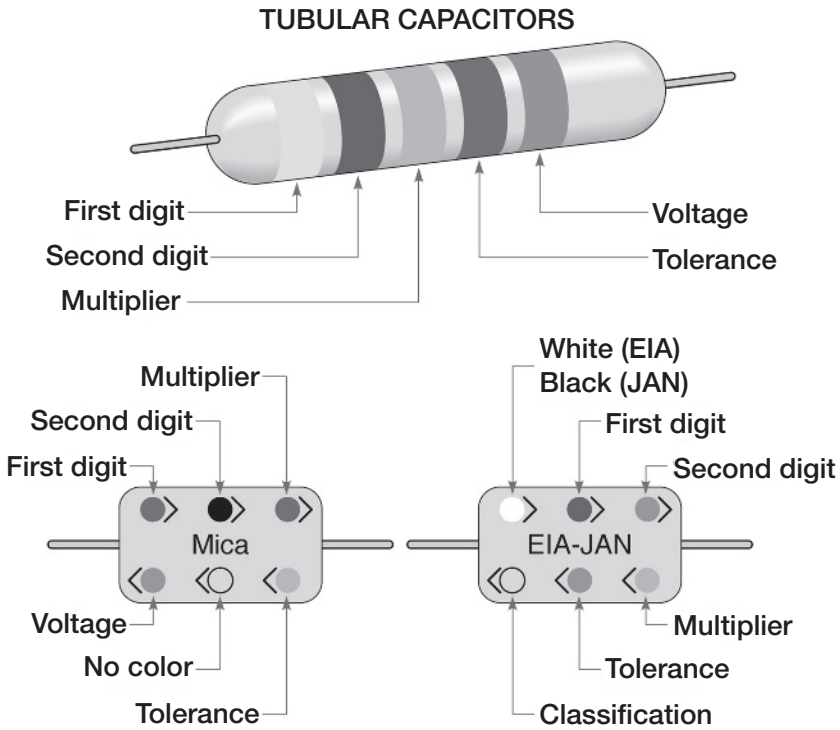
*Resistance figures are given for standard annealed copper. For hard-drawn copper add 2%

© Cengage Learning 2014

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

APPENDIX **B**

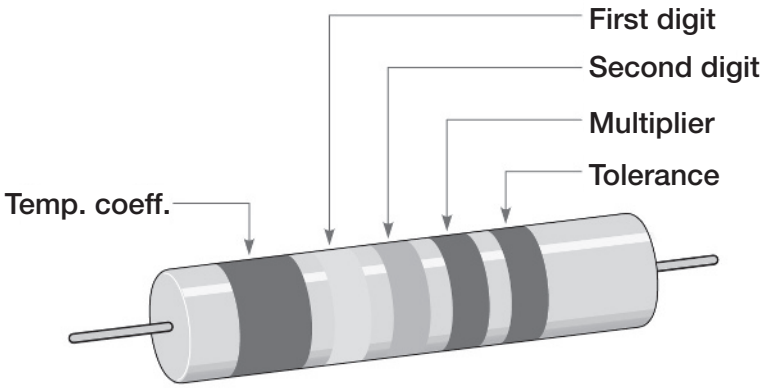
Identification of Mica and Tubular Capacitors



COLOR	NUMBER	MULTIPLIER	TOLERANCE %	VOLTAGE
No color			20	500
Black	0	1		
Brown	1	10	1	100
Red	2	100	2	200
Orange	3	1000	3	300
Yellow	4	10,000	4	400
Green	5	100,000	5 (EIA)	500
Blue	6	1,000,000	6	600
Violet	7	10,000,000	7	700
Gray	8	100,000,000	8	800
White	9	1,000,000,000	9	900
Gold		0.1	5 (JAN)	1000
Silver		0.01	10	2000

© Cengage Learning 2014

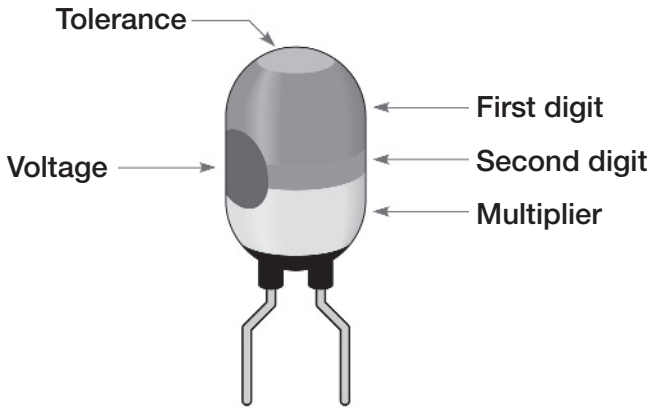
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



COLOR	NUMBER	MULTIPLIER	TOLERANCE OVER 10 pF	TOLERANCE 10 pF OR LESS	TEMP. COEFF.
Black	0	1	20%	2.0 pF	0
Brown	1	10	1%		N30
Red	2	100	2%		N80
Orange	3	1000			N150
Yellow	4				N220
Green	5				N330
Blue	6		5%	0.5 pF	N470
Violet	7				N750
Gray	8	0.01		0.25 pF	P30
White	9	0.1	10%	1.0 pF	P500

© Cengage Learning 2014

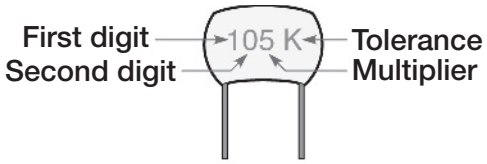
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



COLOR	NUMBER	MULTIPLIER	TOLERANCE %	VOLTAGE
			No dot 20	
Black	0			4
Brown	1			6
Red	2			10
Orange	3			15
Yellow	4	10,000		20
Green	5	100,000		25
Blue	6	1,000,000		35
Violet	7	10,000,000		50
Gray	8			
White	9			3
Gold			5	
Silver			10	

© Cengage Learning 2014

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.



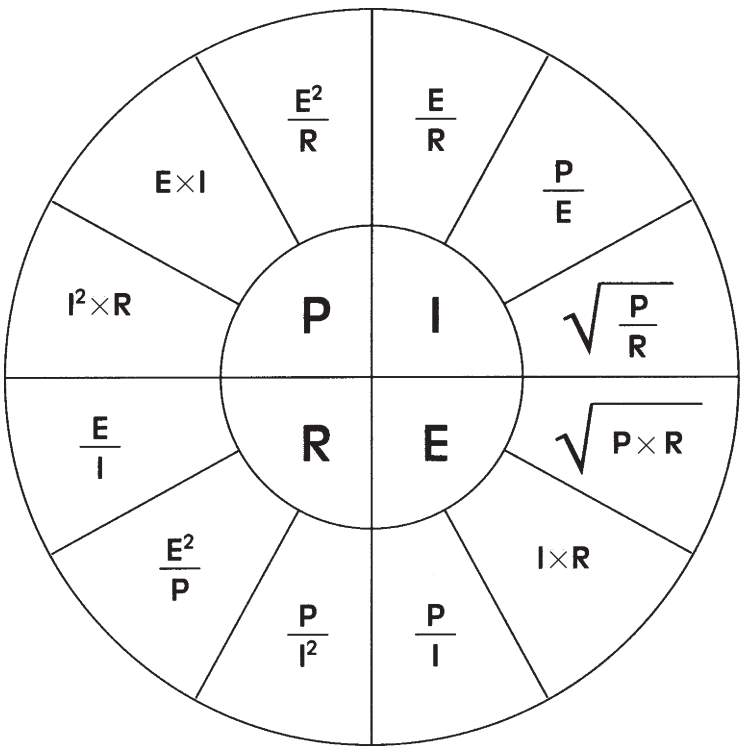
NUMBER	MULTIPLIER	TOLERANCE		
			10 pF or less	Over 10 pF
0	1	B	0.1 pF	
1	10	C	0.25 pF	
2	100	D	0.5 pF	
3	1000	F	1.0 pF	1%
4	10,000	G	2.0 pF	2%
5	100,000	H		3%
6		J		5%
7		K		10%
8	0.01	M		20%
9	0.1			

© Cengage Learning 2014

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

APPENDIX C

Alternating Current Formulas



© Cengage Learning 2014

INSTANTANEOUS AND MAXIMUM VALUES

The instantaneous value of voltage and current for a sine wave is equal to the peak, or maximum, value of the waveform times the sine of the angle. For example, a waveform has a peak value of 300 V. What is the voltage at an angle of 22°?

$$E_{(INST)} = E_{(MAX)} \times \text{SIN} \angle$$

$$E_{(INST)} = 300 \times 0.3746 \text{ (SIN of 22°)}$$

$$E_{(INST)} = 112.328 \text{ V}$$

$$E_{MAX} = \frac{E_{INST}}{\text{SIN} \angle}$$

$$\text{SIN} \angle = \frac{E_{INST}}{E_{MAX}}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

CHANGING PEAK, RMS, AND AVERAGE VALUES

To change	To	Multiply by
Peak	RMS	0.707
Peak	Average	0.637
Peak	Peak-to-Peak	2
RMS	Peak	1.414
Average	Peak	1.567
RMS	Average	0.9
Average	RMS	1.111

PURE RESISTIVE CIRCUIT

$E = I \times R$ $\quad I = \frac{E}{R}$ $\quad R = \frac{E}{I}$ $\quad P = E \times I$

$E = \frac{P}{I}$ $\quad I = \frac{P}{R}$ $\quad R = \frac{E^2}{P}$ $\quad P = I^2 \times R$

$E = \sqrt{P \times R}$ $\quad I = \sqrt{\frac{P}{R}}$ $\quad R = \frac{P}{I^2}$ $\quad P = \frac{E^2}{R}$

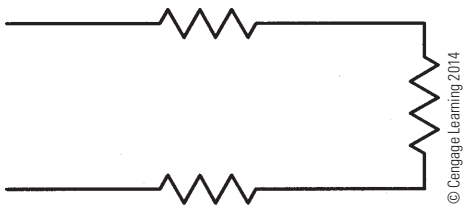
SERIES RESISTIVE CIRCUITS

$R_T = R_1 + R_2 + R_3$

$I_T = I_1 = I_2 = I_3$

$E_T = E_1 + E_2 + E_3$

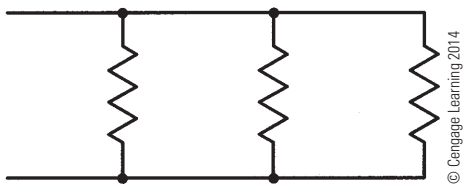
$P_T = P_1 + P_2 + P_3$


© Cengage Learning 2014

PARALLEL RESISTIVE CIRCUITS

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$


© Cengage Learning 2014

$I_T = I_1 + I_2 + I_3$

$E_T = E_1 = E_2 = E_3$

$P_T = P_1 + P_2 + P_3$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

PURE INDUCTIVE CIRCUITS

In a pure inductive circuit, the current lags the voltage by 90°. Therefore, there is no true power, or watts, and the power factor is 0. VARs are the reactive equivalent of watts.

$$L = \frac{X_L}{2\pi F} \qquad XL = 2\pi FL$$

$$E_L = I_L \times X_L \qquad I_L = \frac{E_L}{X_L} \qquad X_L = \frac{E_L}{I_L} \qquad VARs_L = E_L \times I_L$$

$$E_L = \sqrt{VARs_L \times X_L} \qquad I_L = \frac{VARs_L}{E_L} \qquad X_L = \frac{E_L^2}{VARs_L} \qquad VARs_L = I_L^2 \times X_L$$

$$E_L = \frac{VARs_L}{I_L} \qquad I_L = \sqrt{\frac{VARs_L}{X_L}} \qquad X_L = \frac{VARs_L}{I_L^2} \qquad VARs_L = \frac{E_L^2}{X_L}$$

SERIES INDUCTIVE CIRCUITS

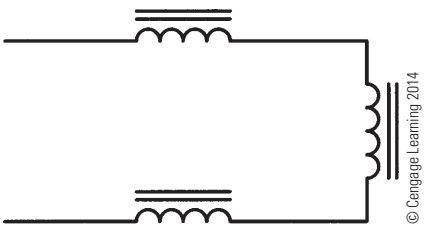
$$E_{LT} = E_{L1} + E_{L2} + E_{L3}$$

$$X_{LT} = X_{L1} + X_{L2} + X_{L3}$$

$$I_{LT} = I_{L1} = I_{L2} = I_{L3}$$

$$VARs_{LT} = VARs_{L1} + VARs_{L2} + VARs_{L3}$$

$$L_T = L_1 + L_2 + L_3$$

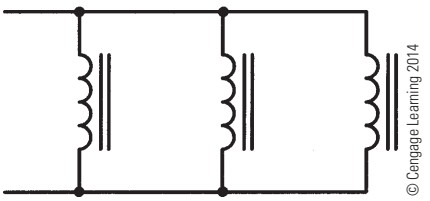

© Cengage Learning 2014

PARALLEL INDUCTIVE CIRCUITS

$$E_{LT} = E_{L1} = E_{L2} = E_{L3}$$

$$I_{LT} = I_{L1} + I_{L2} + I_{L3}$$

$$X_{LT} = \frac{X_{L1} \times X_{L2}}{X_{L1} + X_{L2}}$$


© Cengage Learning 2014

$$X_{LT} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}} \qquad L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}} \qquad L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

$$VARs_{LT} = VARs_{L1} + VARs_{L2} + VARs_{L3}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

PURE CAPACITIVE CIRCUITS

In a pure capacitive circuit, the current leads the voltage by 90°. For this reason there is no true power, or watts, and no power factor. VARs is the equivalent of watts in a pure capacitive circuit.

The value of C in the formula for finding capacitance is in farads and must be changed into the capacitive units being used.

$$C = \frac{1}{2\pi F X_C} \qquad X_C = \frac{1}{2\pi F C}$$

$$E_C = I_C \times X_C \qquad I_C = \frac{E_C}{X_C} \qquad X_C = \frac{E_C}{I_C} \qquad VARs_C = E_C \times I_C$$

$$E_C = \sqrt{VARs_C \times X_C} \qquad I_C = \frac{VARs_C}{E_C} \qquad X_C = \frac{E_C^2}{VARs_C} \qquad VARs_C = I_C^2 \times X_C$$

$$E_C = \frac{VARs_C}{I_C} \qquad I_C = \sqrt{\frac{VARs_C}{X_C}} \qquad X_C = \frac{VARs_C}{I_C^2} \qquad VARs_C = \frac{E_C^2}{X_C}$$

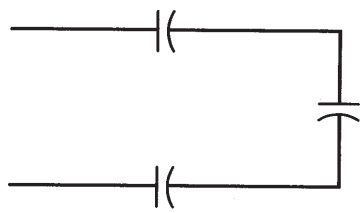
SERIES CAPACITIVE CIRCUITS

$$E_{CT} = E_{C1} + E_{C2} + E_{C3}$$

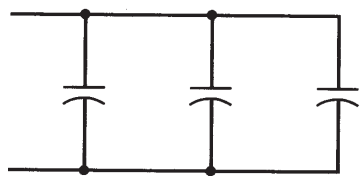
$$I_{CT} = I_{C1} = I_{C2} = I_{C3}$$

$$X_{CT} = X_{C1} + X_{C2} + X_{C3}$$

$$VARs_{CT} = VARs_{C1} + VARs_{C2} + VARs_{C3}$$


© Cengage Learning 2014

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} \qquad C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$


© Cengage Learning 2014

PARALLEL CAPACITIVE CIRCUITS

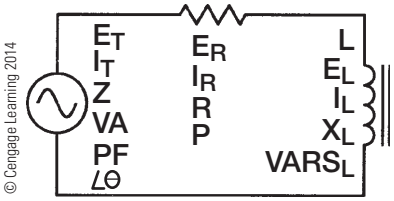
$$E_{CT} = E_{C1} = E_{C2} = E_{C3}$$

$$X_{CT} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}}} \qquad X_{CT} = \frac{X_{C1} \times X_{C2}}{X_{C1} + X_{C2}} \qquad I_{CT} = I_{C1} + I_{C2} + I_{C3}$$

$$C_T = C_1 + C_2 + C_3 \qquad VARs_{CT} = VARs_{C1} + VARs_{C2} + VARs_{C3}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-INDUCTIVE SERIES CIRCUITS



© Cengage Learning 2014

To find values for the resistor, use the formulas in the "Pure Resistive Circuit" section.

To find values for the inductor, use the formulas in the "Pure Inductive Circuits" section.

$E_T = \sqrt{E_R^2 + E_L^2}$

$E_T = I_T \times Z$

$E_T = \frac{VA}{I_T}$

$E_T = \frac{E_R}{PF}$

$PF = \frac{R}{Z}$

$PF = \frac{P}{VA}$

$PF = \frac{E_R}{E_T}$

$PF = \text{Cos} \angle\theta$

$R = \sqrt{Z^2 - X_L^2}$

$R = \frac{E_R}{I_R}$

$R = \frac{E_R^2}{P}$

$R = \frac{P}{I_R^2}$

$R = Z \times PF$

$VARs_L = \sqrt{VA^2 - P^2}$

$Z = \sqrt{R^2 + X_L^2}$

$Z = \frac{E_T}{I_T}$

$Z = \frac{VA}{I_T^2}$

$Z = \frac{R}{PF}$

$P = E_R \times I_R$

$P = \sqrt{VA^2 - VARs_L^2}$

$P = \frac{E_R^2}{R}$

$P = I^2_R \times R$

$P = VA \times PF$

$E_L = I_L \times X_L$

$E_L = \sqrt{E_T^2 - E_R^2}$

$E_L = \sqrt{VARs_L \times X_L}$

$E_L = \frac{VARs_L}{I_L}$

$VARs_L = E_L \times I_L$

$VA = E_T \times I_T$

$VA = I_T^2 \times Z$

$VA = \frac{E_T^2}{Z}$

$VA = \sqrt{P^2 + VARs_L^2}$

$Z = \frac{E_T^2}{VA}$

$E_R = I_R \times R$

$E_R = \sqrt{P \times R}$

$E_R = \frac{P}{I_R}$

$E_R = \sqrt{E_T^2 - E_L^2}$

$E_R = E_T \times PF$

$I_L = I_R = I_T$

$I_L = \frac{E_L}{X_L}$

$I_L = \frac{VARs_L}{E_L}$

$I_L = \sqrt{\frac{VARs_L}{X_L}}$

$VARs_L = \frac{E_L^2}{X_L}$

$L = \frac{X_L}{2\pi F}$

$I_T = I_R = I_L$

$I_T = \frac{E_T}{Z}$

$I_T = \frac{VA}{E_T}$

$VA = \frac{P}{PF}$

$I_R = I_T \times I_L$

$I_R = \frac{E_R}{R}$

$I_R = \frac{P}{E_R}$

$I_R = \sqrt{\frac{P}{R}}$

$X_L = \sqrt{Z^2 - R^2}$

$X_L = \frac{E_L}{I_L}$

$X_L = \frac{E_L^2}{VARs_L}$

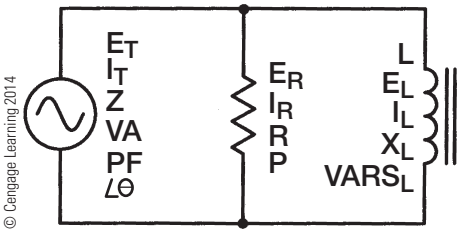
$X_L = \frac{VARs_L}{I_L^2}$

$X_L = 2\pi FL$

$VARs_L = I_L^2 \times X_L$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-INDUCTIVE PARALLEL CIRCUITS



© Cengage Learning 2014

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}} \qquad Z = \frac{VA}{I_T^2}$$

$$Z = \frac{E_T}{I_T} \qquad Z = \frac{E_T^2}{VA} \qquad Z = R \times PF$$

$$VA = E_T \times I_T \qquad PF = \frac{Z}{R}$$

$$VA = I_T^2 \times Z \qquad PF = \frac{P}{VA}$$

$$VA = \frac{E_T^2}{Z} \qquad PF = \frac{I_R}{I_T}$$

$$VA = \sqrt{P^2 + VARs_L^2} \qquad PF = \text{Cos} \angle\theta$$

$$VA = \frac{P}{PF} \qquad VA = \frac{E_T^2}{Z} \qquad VARs_L = \sqrt{VA^2 - P^2}$$

$$VARs_L = I_L^2 \times X_L$$

$$X_L = \frac{E_L}{I_L} \qquad X_L = \frac{1}{\sqrt{\left(\frac{1}{Z}\right)^2 - \left(\frac{1}{R}\right)^2}}$$

$$X_L = \frac{E_L^2}{VARs_L} \qquad X_L = 2\pi FL$$

$$X_L = \frac{VARs_L}{I_L^2} \qquad R = \frac{E_R}{I_R}$$

$$E_T = E_R = E_L \qquad E_T = \frac{VA}{I_T}$$

$$E_T = I_T \times Z \qquad E_T = \sqrt{VA \times Z}$$

$$L = \frac{X_L}{2\pi F}$$

$$I_T = \sqrt{I_R^2 + I_L^2} \qquad I_T = \frac{VA}{E_T} \qquad I_T = \sqrt{\frac{VA}{Z}}$$

$$I_T = \frac{E_T}{Z} \qquad I_T = \frac{I_R}{PF}$$

$$E_L = I_L \times X_L \qquad I_L = \sqrt{I_T^2 - I_R^2}$$

$$E_L = E_T = E_R \qquad I_L = \frac{E_L}{X_L}$$

$$E_L = \sqrt{VARs_L \times X_L} \qquad I_L = \frac{VARs_L}{E_L}$$

$$E_L = \frac{VARs_L}{I_L} \qquad I_L = \sqrt{\frac{VARs_L}{X_L}}$$

$$VARs_L = E_L \times I_L \qquad VARs_L = \frac{E_L^2}{X_L}$$

$$E_R = I_R \times R \qquad I_R = \sqrt{I_T^2 - I_L^2}$$

$$E_R = \sqrt{P \times R} \qquad I_R = \frac{E_R}{R}$$

$$E_R = \frac{P}{I_R} \qquad I_R = \frac{P}{E_R}$$

$$E_R = E_T = E_L \qquad I_R = \sqrt{\frac{P}{R}}$$

$$R = \frac{P}{I_R^2} \qquad I_R = I_T \times PF$$

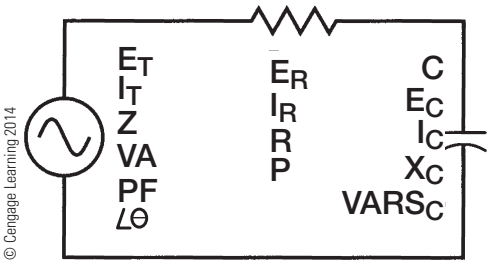
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-INDUCTIVE PARALLEL CIRCUITS (CONTINUED)

$$R = \frac{1}{\sqrt{\left(\frac{1}{Z}\right)^2 - \left(\frac{1}{X_L}\right)^2}} \qquad R = \frac{E_R^2}{P} \qquad R = \frac{Z}{PF} \qquad P = \sqrt{VA^2 - VARs_L^2}$$

$$P = E_R \times I_R \qquad P = \frac{E_R^2}{R} \qquad P = I_R^2 \times R \qquad P = VA \times PF$$

RESISTIVE-CAPACITIVE SERIES CIRCUITS



© Cengage Learning 2014

$$E_T = \sqrt{E_R^2 + E_C^2} \qquad I_T = I_R = I_C$$

$$E_T = I_T \times Z \qquad I_T = \frac{E_T}{Z}$$

$$E_T = \frac{VA}{I_T} \qquad I_T = \frac{VA}{E_T}$$

$$E_T = \frac{E_R}{PF}$$

$$Z = \sqrt{R^2 + X_C^2} \qquad Z = \frac{VA}{I_T^2} \qquad Z = \frac{E_T^2}{VA}$$

$$Z = \frac{E_T}{I_T} \qquad Z = \frac{R}{PF} \qquad C = \frac{1}{2\pi F X_C}$$

$$VA = E_T \times I_T \qquad PF = \frac{R}{Z} \qquad P = E_R \times I_R \qquad E_R = I_R \times R$$

$$VA = I_T^2 \times Z \qquad PF = \frac{P}{VA} \qquad P = \sqrt{VA^2 - VARs_C^2} \qquad E_R = \sqrt{P \times R}$$

$$VA = \frac{E_T^2}{Z} \qquad PF = \frac{E_R}{E_T} \qquad P = \frac{E_R^2}{R} \qquad E_R = \frac{P}{I_R}$$

$$VA = \sqrt{P^2 + VARs_C^2} \qquad PF = \text{Cos } \angle\theta \qquad P = I_R^2 \times R \qquad E_R = \sqrt{E_T^2 - E_C^2}$$

$$VA = \frac{P}{PF} \qquad R = \sqrt{Z^2 - X_C^2} \qquad P = VA \times PF \qquad E_R = E_T \times PF$$

$$I_R = I_T = I_C \qquad R = \frac{E_R}{I_R} \qquad E_C = I_C \times X_C \qquad I_C = I_R = I_T$$

$$I_R = \frac{E_R}{R} \qquad R = \frac{E_R^2}{P} \qquad E_C = \sqrt{E_T^2 - E_R^2} \qquad I_C = \frac{E_C}{X_C}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-CAPACITIVE SERIES CIRCUITS (CONTINUED)

$I_R = \frac{P}{E_R}$ $\quad R = \frac{P}{I_R^2}$ $\quad E_C = \sqrt{VARs_C \times X_C}$ $\quad I_C = \frac{VARs_C}{E_C}$

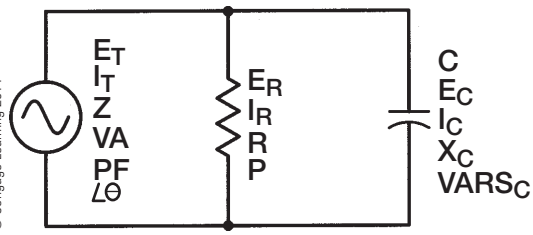
$I_R = \sqrt{\frac{P}{R}}$ $\quad R = Z \times PF$ $\quad E_C = \frac{VARs_C}{I_C}$ $\quad I_C = \sqrt{\frac{VARs_C}{X_C}}$

$X_C = \sqrt{Z^2 - R^2}$ $\quad X_C = \frac{E_C^2}{VARs_C}$ $\quad X_C = \frac{1}{2\pi FC}$ $\quad VARs_C = I_C^2 \times X_C$

$X_C = \frac{E_C}{I_C}$ $\quad X_C = \frac{VARs_C}{I_C^2}$ $\quad VARs_C = E_C \times I_C$ $\quad VARs_C = \frac{E_C^2}{X_C}$

$VARs_C = \sqrt{VA^2 - P^2}$

RESISTIVE-CAPACITIVE PARALLEL CIRCUITS



© Cengage Learning 2014

$E_T = E_R = E_C$

$E_T = I_T \times Z$

$E_T = \frac{VA}{I_T}$

$C = \frac{1}{2\pi FX_C}$ $\quad E_T = \sqrt{VA \times Z}$

$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C}\right)^2}}$ $\quad Z = \frac{VA}{I_T^2}$ $\quad Z = \frac{E_T}{I_T}$ $\quad Z = \frac{E_T^2}{VA}$ $\quad Z = R \times PF$

$I_T = \sqrt{I_R^2 + I_C^2}$ $\quad VA = E_T \times I_T$ $\quad PF = \frac{Z}{R}$ $\quad P = E_R \times I_R$

$I_T = \frac{E_T}{Z}$ $\quad VA = I_T^2 \times Z$ $\quad PF = \frac{P}{VA}$ $\quad P = \sqrt{VA^2 - VARs_C^2}$

$I_T = \frac{VA}{E_T}$ $\quad VA = \frac{E_T^2}{Z}$ $\quad PF = \frac{E_I}{E_R}$ $\quad P = \frac{E_R^2}{R}$

$I_T = \frac{I_R}{PF}$ $\quad VA = \sqrt{P^2 + VARs_C^2}$ $\quad PF = \text{Cos} \angle\theta$ $\quad P = I_R^2 \times R$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-CAPACITIVE PARALLEL CIRCUITS (CONTINUED)

$$I_T = \sqrt{\frac{VA}{Z}} \qquad VA = \frac{P}{PF} \qquad P = VA \times PF$$

$$E_R = I_R \times R \qquad I_R = \sqrt{I_T^2 - I_C^2} \qquad R = \frac{1}{\sqrt{\left(\frac{1}{Z}\right)^2 - \left(\frac{1}{X_C}\right)^2}} \qquad E_C = I_C \times X_C$$

$$E_R = \sqrt{P \times R} \qquad I_R = \frac{E_R}{R} \qquad R = \frac{E_R}{I_R} \qquad E_C = E_T = E_R$$

$$E_R = \frac{P}{I_R} \qquad I_R = \frac{P}{E_R} \qquad R = \frac{E_R^2}{P} \qquad E_C = \sqrt{VARs_C \times X_C}$$

$$E_R = E_T = E_C \qquad I_R = \sqrt{\frac{P}{R}} \qquad R = \frac{P}{I_R^2} \qquad E_C = \frac{VARs_C}{I_C}$$

$$E_R = E_T \times PF \qquad R = \frac{Z}{PF} \qquad VARs_C = I_C^2 \times X_C$$

$$I_C = \sqrt{I_T^2 - I_R^2} \qquad X_C = \frac{E_C^2}{VARs_C} \qquad VARs_C = \frac{E_C^2}{X_C}$$

$$I_C = \frac{E_C}{X_C} \qquad X_C = \frac{1}{\sqrt{\left(\frac{1}{Z}\right)^2 - \left(\frac{1}{R}\right)^2}} \qquad X_C = \frac{VARs_C}{I_C^2} \qquad VARs_C = E_C \times I_C$$

$$I_C = \frac{VARs_C}{E_C} \qquad X_C = \frac{E_C}{I_C} \qquad X_C = \frac{1}{2\pi FC} \qquad VARs_C = \sqrt{VA^2 - P^2}$$

$$I_C = \sqrt{\frac{VARs_C}{X_C}}$$

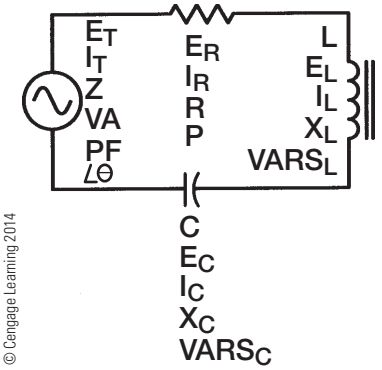
RESISTIVE-INDUCTIVE-CAPACITIVE SERIES CIRCUITS

$$E = \sqrt{E_R^2 + (E_L - E_C)^2} \qquad E_T = \frac{VA}{I_T} \qquad Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad Z = \frac{VA}{I_T^2}$$

$$E_T = I_T \times Z \qquad E_T = \frac{E_R}{PF} \qquad Z = \frac{E_R}{I_T} \qquad Z = \frac{R}{PF}$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-INDUCTIVE-CAPACITIVE SERIES CIRCUITS (CONTINUED)



© Cengage Learning 2014

$I_T = I_R = I_L = I_C$

$I_T = \frac{VA}{E_T}$

$I_T = \frac{E_T}{Z}$

$I_T = \sqrt{\frac{VA}{Z}}$

$VA = E_T \times I_T$

$VA = \frac{P}{PF}$

$VA = I_T^2 \times Z$

$VA = \frac{E_T^2}{Z}$

$VA = \sqrt{P^2 + (VARs_L - VARs_C)^2}$

$PF = \frac{R}{Z}$

$P = E_R \times I_R$

$P = VA \times PF$

$E_R = I_R \times R$

$PF = \frac{P}{VA}$

$P = \sqrt{VA^2 - (VARs_L - VARs_C)^2}$

$E_R = \frac{P}{I_R}$

$PF = \frac{E_R}{E_T}$

$P = \frac{E_R^2}{R}$

$E_R = \sqrt{P \times R}$

$E_R = \sqrt{E_T^2 - (E_L - E_C)^2}$

$PF = \text{Cos} \angle\theta$

$P = I_R^2 \times R$

$E_R = E_T \times PF$

$I_R = I_T = I_C = I_L$

$R = \sqrt{Z^2 - (X_L - X_C)^2}$

$E_C = I_C \times X_C$

$I_R = \frac{E_R}{R}$

$R = \frac{E_R}{I_R}$

$R = Z \times PF$

$E_C = \sqrt{VARs_C \times X_C}$

$I_R = \frac{P}{E_R}$

$R = \frac{E_R^2}{P}$

$R = \frac{P}{I_R^2}$

$E_C = \frac{VARs_C}{I_C}$

$I_R = \sqrt{\frac{P}{R}}$

$X_C = \frac{1}{2\pi FC}$

$C = \frac{1}{2\pi FX_C}$

$I_C = I_R = I_T = I_L$

$X_C = \frac{E_C^2}{VARs_C}$

$X_C = \frac{VARs_C}{I_C^2}$

$VARs_C = E_C \times I_C$

$I_C = \frac{E_C}{X_C}$

$X_C = \frac{E_C}{I_C}$

$L = \frac{X_L}{2\pi F}$

$X_L = 2\pi FL$

$I_C = \frac{VARs_C}{E_C}$

$VARs_C = I_C^2 \times X_C$

$X_L = \frac{E_L}{I_L}$

$X_L = \frac{VARs_L}{I_L^2}$

$I_C = \sqrt{\frac{VARs_C}{X_C}}$

$VARs_C = \frac{E_C^2}{X_C}$

$X_L = \frac{E_L^2}{VARs_L}$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-INDUCTIVE-CAPACITIVE SERIES CIRCUITS (CONTINUED)

$E_L = I_L \times X_L$

$I_L = I_R = I_T = I_C$

$I_L = \dfrac{VARs_L}{E_L}$

$VARs_L = E_L \times I_L$

$E_L = \sqrt{VARs_L \times X_L}$

$I_L = \dfrac{E_L}{X_L}$

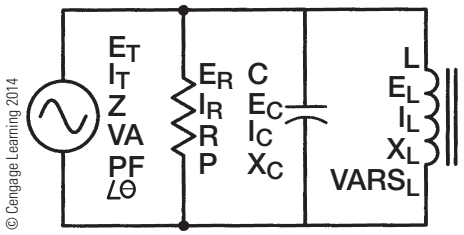
$I_L = \sqrt{\dfrac{VARs_L}{X_L}}$

$VARs_L = \dfrac{E_L^2}{X_L}$

$E_L = \dfrac{VARs_L}{I_L}$

$VARs_L = I_L^2 \times X_L$

RESISTIVE-INDUCTIVE-CAPACITIVE PARALLEL CIRCUITS



$E_T = E_R = E_L = E_C$

$E_T = I_T \times Z$

$E_T = \dfrac{VA}{I_T}$

$E_T = \sqrt{VA \times Z}$

$Z = \dfrac{1}{\sqrt{\left(\dfrac{1}{R}\right)^2 + \left(\dfrac{1}{X_L} - \dfrac{1}{X_C}\right)^2}}$

$Z = \dfrac{VA}{I_T^2}$

$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$

$I_T = \dfrac{VA}{E_T}$

$I_T = \sqrt{\dfrac{VA}{Z}}$

$Z = \dfrac{E_T}{I_T}$

$Z = \dfrac{E_T^2}{VA}$

$Z = R \times PF$

$I_T = \dfrac{E_T}{Z}$

$I_T = \dfrac{I_R}{PF}$

$VA = E_T \times I_T$

$PF = \dfrac{Z}{R}$

$PF = \text{Cos} \angle\theta$

$E_L = E_T = E_R = E_C$

$VA = I_T^2 \times Z$

$PF = \dfrac{P}{VA}$

$E_L = I_L \times X_L$

$E_L = \sqrt{VARs_L \times X_L}$

$VA = \dfrac{E_T^2}{Z}$

$PF = \dfrac{I_R}{I_T}$

$E_L = \dfrac{VARs_L}{I_L}$

$L = \dfrac{X_L}{2\pi F}$

$VA = \sqrt{P^2 + (VARs_L - VARs_C)^2}$

$X_L = \dfrac{E_L}{I_L}$

$X_L = 2\pi FL$

$VARs_L = \dfrac{E_L^2}{X_L}$

$VA = \dfrac{P}{PF}$

$I_L = \dfrac{VARs_L}{E_L}$

$X_L = \dfrac{E_L^2}{VARs_L}$

$VARs_L = I_L^2 \times X_L$

$I_L = \dfrac{E_L}{X_L}$

$I_L = \sqrt{\dfrac{VARs_L}{X_L}}$

$X_L = \dfrac{VARs_L}{I_L^2}$

$VARs_L = E_L \times I_L$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

RESISTIVE-INDUCTIVE-CAPACITIVE PARALLEL CIRCUITS (CONTINUED)

$E_R = I_R \times R$ $\quad I_R = \sqrt{I_T^2 - (I_L - I_C)^2}$ $\quad I_R = I_T \times PF$

$E_R = \sqrt{P \times R}$ $\quad I_R = \dfrac{E_R}{R}$ $\quad R = \dfrac{E_R}{I_R}$ $\quad R = \dfrac{1}{\sqrt{\left(\dfrac{1}{Z}\right)^2 - \left(\dfrac{1}{X_L} - \dfrac{1}{X_C}\right)^2}}$

$E_R = \dfrac{P}{I_R}$ $\quad I_R = \dfrac{P}{E_R}$

$E_R = E_T = E_L = E_C$ $\quad I_R = \sqrt{\dfrac{P}{R}}$ $\quad R = \dfrac{P}{I_R^2}$ $\quad R = \dfrac{Z}{PF}$ $\quad R = \dfrac{E_R^2}{P}$

$P = \sqrt{VA^2 - (VARs_L - VARs_C)^2}$ $\quad P = E_R \times I_R$ $\quad P = I_R^2 \times R$

$E_C = \dfrac{VARs_C}{I_C}$ $\quad P = VA \times PF$ $\quad P = \dfrac{E_R^2}{R}$ $\quad X_C = \dfrac{1}{2\pi FC}$

$E_C = I_C \times X_C$ $\quad I_C = \dfrac{E_C}{X_C}$ $\quad X_C = \dfrac{E_C}{I_C}$ $\quad VARs_C = E_C \times I_C$

$E_C = E_T = E_R = E_L$ $\quad I_C = \dfrac{VARs_C}{E_C}$ $\quad X_C = \dfrac{E_C^2}{VARs_C}$ $\quad VARs_C = I_C^2 \times X_C$

$E_C = \sqrt{VARs_C \times X_C}$ $\quad I_C = \sqrt{\dfrac{VARs_C}{X_C}}$ $\quad X_C = \dfrac{VARs_C}{I_C^2}$ $\quad VARs_C = \dfrac{E_C^2}{X_C}$

TRANSFORMERS

$\dfrac{E_P}{E_S} = \dfrac{N_P}{N_S}$ $\quad \dfrac{E_P}{E_S} = \dfrac{I_S}{I_P}$ $\quad \dfrac{N_P}{N_S} = \dfrac{I_S}{I_P}$ $\quad Z_P = Z_S \left(\dfrac{N_P}{N_S}\right)^2$ $\quad Z_S = Z_P \left(\dfrac{N_P}{N_S}\right)^2$

E_P — voltage of the primary

E_S — voltage of the secondary

I_P — current of the primary

I_S — current of the secondary

N_P — number of turns of the primary

N_S — number of turns of the secondary

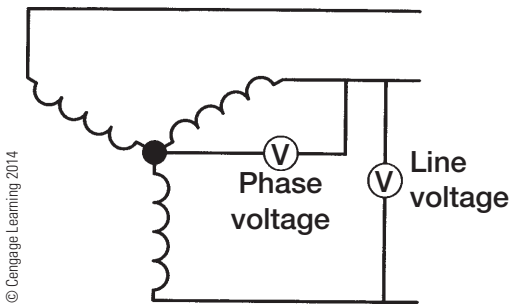
Z_P — impedance of the primary

Z_S — impedance of the secondary

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

THREE-PHASE CONNECTIONS

WYE CONNECTION



© Cengage Learning 2014

In a *wye* connection, the line current and phase current are the same.

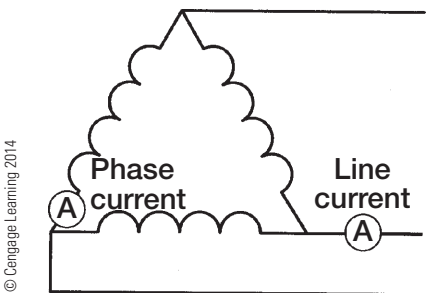
$$I_{(LINE)} = I_{(PHASE)}$$

In a *wye* connection, the line voltage is higher than the phase voltage by a factor of the square root of 3.

$$E_{(LINE)} = E_{(PHASE)} \times \sqrt{3}$$

$$E_{(PHASE)} = \frac{E_{(LINE)}}{\sqrt{3}}$$

DELTA CONNECTION



© Cengage Learning 2014

In a *delta*-connected system, the line voltage and phase voltage are the same.

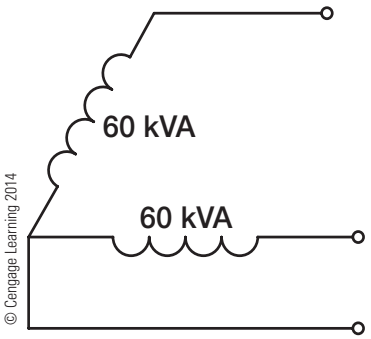
$$E_{(LINE)} = E_{(PHASE)}$$

In a *delta*-connected system the line current is higher than the phase current by a factor of the square root of 3.

$$I_{(LINE)} = I_{(PHASE)} \times \sqrt{3}$$

$$I_{(PHASE)} = \frac{I_{(LINE)}}{\sqrt{3}}$$

OPEN DELTA CONNECTION



© Cengage Learning 2014

Open delta connections provide 86.6% of the sum of the power rating of the two transformers. Example: The two transformers shown are rated at 60 kVA each.

The total power rating for this connection would be

$$60 + 60 = 120 \text{ kVA}$$

$$120 \text{ kVA} \times 0.866 = 103.92 \text{ kVA}$$

All values of voltage and current are computed in the same manner as for a closed delta connection.

APPARENT AND TRUE POWER

$$VA = \sqrt{3} \times E_{(LINE)} \times I_{(LINE)}$$

$$VA = 3 \times E_{(PHASE)} \times I_{(PHASE)}$$

$$P = \sqrt{3} \times E_{(LINE)} \times I_{(LINE)} \times PF$$

$$P = 3 \times E_{(PHASE)} \times I_{(PHASE)} \times PF$$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

APPENDIX D

Greek Alphabet

Name of Letter	Upper Case	Lower Case	Designates
Alpha	Α	α	Angles
Beta	Β	β	Angles; flux density
Gamma	Γ	γ	Conductivity
Delta	Δ	δ	Change of a quantity
Epsilon	Ε	ε	Base of natural logarithms
Zeta	Ζ	ζ	Impedance; coefficients; coordinates
Eta	Η	η	Hysteresis coefficient; efficiency
Theta	Θ	θ	Phase angle
Iota	Ι	ι	
Kappa	Κ	κ	Dielectric constant; coefficient of coupling; susceptibility
Lambda	Λ	λ	Wavelength
Mu	Μ	μ	Permeability; the prefix micro-, amplification factor
Nu	Ν	ν	Change of a quantity
Xi	Ξ	ξ	
Omicron	Ο	ο	
Pi	Π	π	3.1416
Rho	Ρ	ρ	Resistivity
Sigma	Σ	σ	
Tau	Τ	τ	Time constant; time phase displacement
Upsilon	Υ	υ	
Phi	Φ	ϕ	Angles; magnetic flow
Chi	Χ	χ	
Psi	Ψ	ψ	Dielectric flux; phase difference
Omega	Ω	ω	Resistivity

© Cengage Learning 2014

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

APPENDIX E

Answers to Practice Problems

UNIT 2 OHM'S LAW

1. 6.25 A $I = \sqrt{\frac{P}{R}}$ $I = \sqrt{\frac{1500}{38.4}}$
2. 240 V $E = 6.25 \times 38.4$
3. 0.8 A (100/120)
4. 960 Ω $R = \frac{E^2}{P}$
5. 4.332 A (300 × 4 = 1200) (1200/277)
6. 12 V (1500 × 0.008)
7. 45 mA
8. 450 μA
9. 61,594.203 A (850,000,000/13,800)
10. 2.542 kV

UNIT 2 RESISTORS

1st Band	2nd Band	3rd Band	4th Band	Value	% Tol.
Red	Yellow	Brown	Silver	240 Ω	10
Blue	Gray	Red	Gold	6800 Ω	5
Orange	Orange	Orange	Gold	33k Ω	5
Brown	Red	Black	Red	12 Ω	2
Brown	Green	Silver	Silver	0.15 Ω	10
Brown	Gray	Green	Silver	1.8 MΩ	10
Brown	Black	Yellow	None	100 kΩ	20
Brown	Black	Orange	Gold	10 kΩ	5
Violet	Green	Black	Red	75 Ω	2
Yellow	Violet	Red	None	4.7 kΩ	20
Gray	Red	Green	Red	8.2 MΩ	2
Green	Blue	Gold	Red	5.6 Ω	2

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 5 SERIES CIRCUITS

PRACTICE PROBLEM 1

E_T 116.624 V	E_1 15.882 V	E_2 13.299 V	E_3 27.698 V	E_4 **38** V	E_5 21.714 V
I_T 0.0391 A	R_1 406.189 Ω	R_2 340.128 Ω	R_3 708.394 Ω	R_4 971.083 Ω	R_5 555.334 Ω
R_T 2,982.712 Ω	P_1 **0.621** W	P_2 **0.52** W	P_3 **1.083** W	P_4 1.487 W	P_5 **.849** W
P_T **4.56** W					

PRACTICE PROBLEM 2

E_T 50 V	E_1 **6** V	E_2 16.5 V	E_3 11 V	E_4 9 V	E_5 7.5 V
I_T .005 A	R_1 1.2kΩ	R_2 **3.3 k**Ω	R_3 **2.2 k**Ω	R_4 **1.8 k**Ω	R_5 **1.5 k**Ω
R_T **10 k**Ω	P_1 0.03 W	P_2 0.0825 W	P_3 0.055 W	P_4 0.045 W	P_5 0.0375 W
P_T 0.25 W					

PRACTICE PROBLEM 3

E_T **340** V	E_1 **44** V	E_2 **94** V	E_3 60 V	E_4 **40** V	E_5 **102** V
I_T 0.002 A	R_1 22 kΩ	R_2 47 kΩ	R_3 30 kΩ	R_4 20 kΩ	R_5 51 kΩ
R_T 170 kΩ	P_1 0.088 W	P_2 0.188 W	P_3 **0.12** W	P_4 0.08 W	P_5 0.204 W
P_T 0.68 W					

PRACTICE PROBLEM 4

E_T **36** V	E_1 7.398 V	E_2 8.13 V	E_3 4.553 V	E_4 6.992 V	E_5 8.943 V
I_T 0.0813 A	R_1 **91** Ω	R_2 **100** Ω	R_3 **56** Ω	R_4 **86** Ω	R_5 **110** Ω
R_T 443 Ω	P_1 0.601 W	P_2 0.661 W	P_3 0.37 W	P_4 0.568 W	P_5 0.727 W
P_T 2.927 W					

PRACTICE PROBLEM 5

E_T 70.058 V	E_1 3.41 V	E_2 **4.65 V**	E_3 4.185 V	E_4 6.645 V	E_5 51.161 V
I_T **0.0155 A**	R_1 **220 Ω**	R_2 300 Ω	R_3 **270 Ω**	R_4 428.72 Ω	R_5 3300.728 Ω
R_T 4519.875 Ω	P_1 0.0529 W	P_2 0.0721 W	P_3 0.0649 W	P_4 **0.103 W**	P_5 **0.793 W**
P_T 1.086 W					

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 6 PARALLEL CIRCUITS

PRACTICE PROBLEM 1

E_T 119.524 V	I_1 **0.176** A	I_2 0.147 A	I_3 **0.255** A	I_4 **0.364** A
R_T 126.883 Ω	R_1 679.114 Ω	R_2 813.088 Ω	R_3 468.722 Ω	R_4 328.363 Ω
P_T 110.44 W	P_1 21.036 W	P_2 **17.57** W	P_3 30.479 W	P_4 43.507 W
I_T **0.942** A	$I_{2,3,4}$ 0.766 A	$I_{3,4}$ 0.619 A		

PRACTICE PROBLEM 2

E_T 277.154 V	I_1 2.31 mA	I_2 1.39 mA	I_3 1.54 mA	I_4 1.15 mA
R_T 43,373.494 Ω	R_1 **120 kΩ**	R_2 **200 kΩ**	R_3 **180 kΩ**	R_4 **240 kΩ**
P_T **1.771** W	P_1 0.64 W	P_2 0.385 W	P_3 0.427 W	P_4 0.319 W
I_T 6.39 mA	$I_{2,3,4}$ 4.08 mA	$I_{3,4}$ 2.69 mA		

PRACTICE PROBLEM 3

E_T 47.994 V	I_1 3 A	I_2 4.799 A	I_3 **3.2** A	I_4 2.34 A
R_T **3.582** Ω	R_1 **16** Ω	R_2 **10** Ω	R_3 14.998 Ω	R_4 **20** Ω
P_T 642.88 W	P_1 143.982 W	P_2 230.323 W	P_3 153.581 W	P_4 112.306 W
I_T 13.395 A	$I_{2,3,4}$ 10.339 A	$I_{3,4}$ 5.54 A		

PRACTICE PROBLEM 4

E_T 240.98 V	I_1 2.92 mA	I_2 3.24 mA	I_3 4.29 mA	I_4 3.86 mA
R_T 16,851.748 Ω	R_1 82,527.397 Ω	R_2 74,376.543 Ω	R_3 56,172.494 Ω	R_4 62,430.052 Ω
P_T 3.446 W	P_1 **0.704** W	P_2 **0.78** W	P_3 **1.031** W	P_4 **0.931** W
I_T **0.0143** A	$I_{2,3,4}$ 11.39 mA	$I_{3,4}$ 8.15 mA		

PRACTICE PROBLEM 5

E_T 36 V	I_1 0.03 A	I_2 0.0225 A	I_3 **0.015 A**	I_4 0.018 A
R_T 421.053 **Ω**	R_1 **1200 Ω**	R_2 **1600 Ω**	R_3 2400 **Ω**	R_4 **2000 Ω**
P_T 3.078 W	P_1 1.08 W	P_2 0.81 W	P_3 0.54 W	P_4 0.648 W
I_T 0.0855 A	$I_{2,3,4}$ 0.0555 A	$I_{3,4}$ **0.033 A**		

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

PRACTICE PROBLEM 6

E_T 17.82 V	I_1 0.509 mA	I_2 0.414 mA	I_3 0.178 mA	I_4 0.318 mA
R_T 12,549.51 Ω	R_1 **35 kΩ**	R_2 **43 kΩ**	R_3 **100 kΩ**	R_4 **56 kΩ**
P_T 0.0253 W	P_1 9.073 mW	P_2 7.377 mW	P_3 3.176 mW	P_4 5.671 mW
I_T 0.00142 A	$I_{2,3,4}$ 0.91 mA	$I_{3,4}$ 0.496 mA		

PRACTICE PROBLEM 7

E_T 120.019 V	I_1 **2.5 A**	I_2 2.083 A	I_3 4.167 A	I_4 **3.75 A**
R_T 9.602 Ω	R_1 48.008 Ω	R_2 57.618 Ω	R_3 28.802 Ω	R_4 32.005 Ω
P_T 1500.236 W	P_1 300.048 W	P_2 **250 W**	P_3 500.119 W	P_4 450.071 W
I_T **12.5 A**	$I_{2,3,4}$ 10 A	$I_{3,4}$ **7.917 A**		

PRACTICE PROBLEM 8

E_T 240 V	I_1 **10 A**	I_2 5 A	I_3 **4 A**	I_4 **2 A**
R_T 11.429 Ω	R_1 24 Ω	R_2 **48** Ω	R_3 60 Ω	R_4 120 Ω
P_T 5040 W	P_1 2400 W	P_2 1200 W	P_3 960 W	P_4 480 W
I_T 21 A	$I_{2,3,4}$ **11 A**	$I_{3,4}$ 6 A		

PRACTICE PROBLEM 9

E_T 70.28 V	I_1 **0.0318 A**	I_2 0.0212 A	I_3 **0.0389 A**	I_4 **0.0437 A**
R_T 518.289 Ω	R_1 2210.063 Ω	R_2 3315.094 Ω	R_3 1806.684 Ω	R_4 1608.24 Ω
P_T **9.53 W**	P_1 2.235 W	P_2 1.49 W	P_3 2.734 W	P_4 3.071 W
I_T 0.1356 A	$I_{2,3,4}$ **0.1038 A**	$I_{3,4}$ 0.0826 A		

PRACTICE PROBLEM 10

E_T **480 V**	I_1 **63 A**	I_2 **84 A**	I_3 **16 A**	I_4 **22 A**
R_T 2.595 Ω	R_1 7.619 Ω	R_2 5.714 Ω	R_3 30 Ω	R_4 21.818 Ω
P_T 88.8 kW	P_1 30.24 kW	P_2 40.32 kW	P_3 7.71 kW	P_4 10.56 kW
I_T 185 A	$I_{2,3,4}$ 122 A	$I_{3,4}$ 38 A		

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 7 COMBINATION CIRCUITS

PRACTICE PROBLEM 1

A–B	55.636	A–C	93.497	A–D	73.262
B–C	81.497	B–D	93.497	C–D	66.225

PRACTICE PROBLEM 2

A–B	767.742	A–C	1535.484	A–D	838.71
B–C	1187.097	B–D	1535.484	C–D	1470.968

PRACTICE PROBLEM 3

A–B	390,539.568	A–C	648,381.295	A–D	640,287.77
B–C	447,194.245	B–D	648,381.295	C–D	547,661.871

PRACTICE PROBLEM 4

A–B	31,109.434	A–C	55,449.057	A–D	58,090.566
B–C	36,022.642	B–D	55,449.057	C–D	62,264.151

PRACTICE PROBLEM 5

E_T **36** V	E_1 16.68 V	E_2 19.315 V	E_3 19.315 V
I_T 0.695 A	I_1 0.695 A	I_2 0.284 A	I_3 0.411 A
R_T 51.791 Ω	R_1 **24** Ω	R_2 **68** Ω	R_3 **47** Ω
P_T 25.02 W	P_1 11.593 W	P_2 5.485 W	P_3 7.938 W

PRACTICE PROBLEM 6

E_T 47.895 V	E_1 24.72 V	E_2 23.173 V	E_3 23.173 V
I_T 2.06 mA	I_1 2.06 mA	I_2 0.772 mA	I_3 1.29 mA
R_T **23,250** Ω	R_1 **12,000** Ω	R_2 30,000 Ω	R_3 **18,000** Ω
P_T 0.0987 W	P_1 0.0509 W	P_2 **0.0179** W	P_3 0.03 W

PRACTICE PROBLEM 7

E_T 24.006 V	E_1 9.441 V	E_2 14.58 V	E_3 14.736 V	E_4 9.271 V
I_T 0.0629 A	I_1 0.0286 A	I_2 0.0286 A	I_3 0.0343 A	I_4 0.0343 A
R_T 381.653 Ω	R_1 330.105 Ω	R_2 509.79 Ω	R_3 **430** Ω	R_4 270.288 Ω
P_T **1.510** W	P_1 **0.270** W	P_2 **0.417** W	P_3 0.505 W	P_4 **0.318** W

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

PRACTICE PROBLEM 8

E_T 120.062 V	E_1 68.64 V	E_2 51.58 V	E_3 80 V	E_4 40 V
I_T **0.00829** A	I_1 0.00429 A	I_2 0.00429 A	I_3 0.004 A	I_4 0.004 A
R_T 14,482.759 Ω	R_1 **16 kΩ**	R_2 **12 kΩ**	R_3 **20 kΩ**	R_4 **10 kΩ**
P_T 0.995 W	P_1 0.294 W	P_2 0.221 W	P_3 0.343 W	P_4 0.172 W

PRACTICE PROBLEM 9

E_T 207.869 V	E_1 155.366 V	E_2 155.366 V	E_3 52.503 V	E_4 75.682 V	E_5 132.187 V
I_T **0.351** A	I_1 0.0973 A	I_2 0.0779 A	I_3 0.175 A	I_4 0.176 A	I_5 0.0695 A
R_T 592.219 Ω	R_1 1596.773 Ω	R_2 1994.429 Ω	R_3 300.017 Ω	R_4 430.011 Ω	R_5 1901.971 Ω
P_T 72.962 W	P_1 **15.123** W	P_2 **12.099** W	P_3 **9.188** W	P_4 **13.32** W	P_5 **8.712** W
E_6 132.187	I_6 0.11 A	R_6 1201.7 Ω	P_6 **14.52** W		

PRACTICE PROBLEM 10

E_T **208** V	E_1 48 V	E_2 64 V	E_3 38.4 V	E_4 57.6 V	E_5 96 V
I_T 0.64 A	I_1 0.64 A	I_2 0.64 A	I_3 0.32 A	I_4 0.32 A	I_5 0.32 A
R_T 325 Ω	R_1 **75** Ω	R_2 **100** Ω	R_3 **120** Ω	R_4 **180** Ω	R_5 **300** Ω
P_T 133.12 W	P_1 30.72 W	P_2 40.96 W	P_3 12.288 W	P_4 18.432 W	P_5 30.72 W

UNIT 10 ALTERNATING CURRENT LOADS

INDUCTANCE (H)	FREQUENCY (Hz)	INDUCTIVE REACTANCE (Ω)
1.2	60	452.4 Ω
0.085	400	213.628 Ω
0.75	1000	4712.389 Ω
0.65	600	2450.442 Ω
3.6	30	678.584 Ω
2.62	25	411.459 Ω
0.5	60	188.5 Ω
0.85	1200	6408.849 Ω
1.6	20	201.062 Ω
0.45	400	1130.973 Ω
4.8	80	2412.743 Ω
0.0065	1000	40.841 Ω

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

UNIT 11 CAPACITIVE CIRCUITS

CAPACITANCE	CAPACITIVE REACTANCE (Ω)	FREQUENCY
38 μF	69.803 Ω	60 Hz
5.049 μF	78.8 Ω	400 Hz
250 pF	4.5 k Ω	141.47 Hz
234 μF	0.068 Ω	10 k Hz
13.263 μF	240 Ω	50 Hz
10 μF	36.8 Ω	432.486 Hz
560 nF	0.142 Ω	2 MHz
176.84	15 k Ω	60 Hz
75 μF	560 Ω	3.789 Hz
470 pF	1.693 k Ω	200 kHz
58.513 nF	6.8 k Ω	400 Hz
34 μF	450 Ω	10.402 Hz

UNIT 12 THREE-PHASE CIRCUITS

PRACTICE PROBLEM 1

$E_{P(Alt.)}$	138.57 V	$E_{P(Line)}$	240 V
$I_{P(Alt.)}$	34.64 A	$I_{P(Line)}$	20 A
$E_{L(Alt.)}$	**240** V	$E_{L(Line)}$	240 V
$I_{L(Alt.)}$	34.64 A	$I_{L(Line)}$	34.64 A
P	14,399.6 W	$Z_{(Phase)}$	**12 Ω**

PRACTICE PROBLEM 2

$E_{P(Alt.)}$	4160 V	$E_{P(Line)}$	2401.85 V
$I_{P(Alt.)}$	23.11 A	$I_{P(Line)}$	40.03 A
$E_{L(Alt.)}$	**4160** V	$E_{L(Line)}$	4160 V
$I_{L(Alt.)}$	40.03 A	$I_{L(Line)}$	40.03 A
P	288,420.95 W	$Z_{(Phase)}$	**60 Ω**

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

PRACTICE PROBLEM 3

$E_{P(Alt.)}$	323.33 V	$E_{P(Line\ 1)}$	323.33 V	$E_{P(Line\ 2)}$	560 V
$I_{P(Alt.)}$	185.91 A	$I_{P(Line\ 1)}$	64.67 A	$I_{P(Line\ 2)}$	70 A
$E_{L(Alt.)}$	**560** V	$E_{L(Line\ 1)}$	560 V	$E_{L(Line\ 2)}$	560 V
$I_{L(Alt.)}$	185.91 A	$I_{L(Line\ 1)}$	64.67 A	$I_{L(Line\ 2)}$	121.24 A
P	180,317.83 W	$Z_{(Phase\ 1)}$	**5 Ω**	$Z_{(Phase\ 2)}$	**8 Ω**

UNIT 13 TRANSFORMERS

1.

E_P 120 V	E_S 24 V
I_P 1.6 A	I_S 8 A
N_P 300	N_S 60
Ratio 5:1	$Z = 3\ \Omega$

2.

E_P 240 V	E_S 320 V
I_P 0.853 A	I_S 0.643 A
N_P 210	N_S 280
Ratio 1:1.333	$Z = 500\ \Omega$

3.

E_P 64 V	E_S 160 V
I_P 33.333 A	I_S 13.333 A
N_P 32	N_S 80
Ratio 1:2.5	$Z = 12\ \Omega$

4.

E_P 48 V	E_S 240 V
I_P 3.333 A	I_S 0.667 A
N_P 220	N_S 1100
Ratio 1:5	$Z = 360\ \Omega$

5.

E_P 35.848 V	E_S 182 V
I_P 16.5 A	I_S 3.25 A
N_P 87	N_S 450
Ratio 1:5.077	$Z = 56\ \Omega$

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

6.

E_P 480 V	E_S 916.346 V
I_P 1.458 A	I_S 0.764 A
N_P 275	N_S 525
Ratio 1:1.909	Z = 1.2 Ω

7.

E_P 208 V	E_{S1} 320 V	E_{S2} 120 V	E_{S3} 24 V
I_P 11.93 A	I_{S1} 0.0267 A	I_{S2} 20 A	I_{S3} 3 A
N_P 800	N_{S1} 1231	N_{S2} 462	N_{S3} 92
	Ratio 1 1:1.54	Ratio 2 1.73:1	Ratio 3 1:8.67
	R_1 = 12 kΩ	R_2 6 Ω	R_3 8 Ω

8.

E_P 277 V	E_{S1} 480 V	E_{S2} 208 V	E_{S3} 120 V
I_P 8.93 A	I_{S1} 2.4 A	I_{S2} 3.47 A	I_{S3} 5 A
N_P 350	N_{S1} 606	N_{S2} 263	N_{S3} 152
	Ratio 1 1:1.73	Ratio 2 1.33:1	Ratio 3 2.31:1
	R_1 = 200 Ω	R_2 60 Ω	R_3 24 Ω

UNIT 14 THREE-PHASE TRANSFORMERS

1.

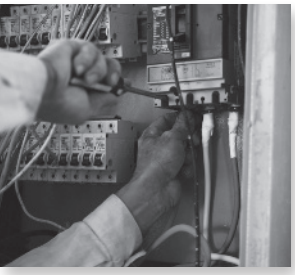
Primary	**Secondary**	**Load**
E_P 7205.1 V	E_P 440 V	E_P 254 V
I_P 2.6 A	I_P 41.9 A	I_P 72.6 A
E_L **4160** V	E_L **440** V	E_L 440 V
I_L 2.6 A	I_L 72.6 A	I_L 72.6 A
	RATIO: 16.4:1	Z = **3.5**

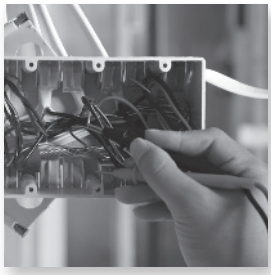
2.

Primary	**Secondary**	**Load**
E_P 41.57 V	E_P 20 V	E_P 138.6 V
I_P 1.15 A	I_P 240 A	I_P 34.65 A
E_L 7200 V	E_L 240 V	E_L 240 V
I_L 1.15 A	I_L 34.65 A	I_L 34.65 A
	RATIO: 17.32:1	Z = 4 Ω

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Glossary







alternating current current that reverses its direction of flow periodically. Reversals generally occur at regular intervals.

alternators machines for producing alternating current.

ammeter instrument used to measure the flow of current.

ammeter shunt a low value resistance designed to shunt most the current away from the meter movement.

amortisseur winding squirrel-cage winding on the rotor of a synchronous motor used for starting purposes only.

amp unit of measure for the rate of current flow.

ampere-turns basic unit for the measurement of magnetism (the product of turns of wire and current flow).

analog meters voltmeter that uses a meter movement to indicate the voltage value. Analog meters use a pointer and scale.

atom smallest part of an element that contains all the properties of that element.

atomic number the number of protons contained in the nucleus of an atom.

attraction the force that attracts one object to another.

autotransformers transformer that uses only one winding for both primary and secondary.

average the voltage produced by converting AC into DC.

Ayrton shunt a type of ammeter shunt.

bidirectional current that flows in more than one direction.

bridge circuit circuit that consists of four sections connected in series to form a closed loop.

BTU (British Thermal unit) English measure of thermal energy.

capacitive reactance (X_C) reactance caused by capacitance.

carbon film resistor resistors that employ a film of carbon as the resistive element.

center tap a connection in the center of a transformer winding that will provide one half of the rated voltage of the winding.

centrifugal switch switch used to disconnect the start winding when the motor reaches a predetermined speed.

chassis ground grounding a circuit to the case or chassis of a piece of equipment.

circuit branch a circuit that branches off the main circuit.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

circuit breakers device designed to open under an abnormal amount of current flow. The device is not damaged and may be used repeatedly. It is rated by voltage, current, and horsepower.
clamp-on ammeter an ammeter that does not have to be physically connected into the circuit.
combination circuit a circuit that contains both series and parallel elements.
compensating winding winding embedded in the main field poles of a DC machine. The compensating winding is used to help overcome armature reaction.
complete path a current path that exists from the most negative potential to the most positive potential.
composition carbon resistor resistors made with a carbon compound as the resistive material.
conductor device or material that permits current to flow through it easily.
consequent pole motors that changed the number of stator poles in order to change speed.
consequent-pole motor motors that change speed by changing the number of stator poles.
conventional current flow theory considers current to flow from the most positive source to the most negative source.
coulomb quantity of electrons equal to 6.25×10^{18}.
current limiters fuses that permit the current to rise to only a certain level before opening.
current relay relay that is operated by a predetermined amount of current flow. Current relays are often used as one type of starting relay for air conditioning and refrigeration equipment.
current transformer electrical device that changes one value of AC voltage into another value of AC voltage.
cycle one complete AC waveform.
d'Arsonval movement meter movement using a permanent magnet and a coil of wire; this is the basic meter movement used in many analog-type voltmeters, ammeters, and ohmmeters.
delta a three-phase connection formed by connecting the start end of a phase winding to the finish end of another.
delta connection circuit formed by connecting three electrical devices in series to form a closed loop. It is used most often in three-phase connections.
demagnetized removing magnetism from object.
dielectric constant a measurement of the characteristics of different types of dielectric material.
dielectric electrical insulator.
dielectric stress stress placed on the molecular structure of the dielectric.
direct current current that does not reverse its direction of flow.
direction of rotation direction the magnetic field rotates.
distribution transformer transformer used to provide power to businesses or homes.
duplex receptacles two outlets on the same strap.
earth ground grounding a circuit directly to the earth via a grounding rod.
eddy current circular induced current contrary to the main currents. Eddy currents are a source of heat and power loss in magnetically operated devices.
effective value of AC voltage that will produce as much power when connected across a resistor as a like amount of DC voltage.
electrolyte chemical compound capable of conducting electric current by being broken down into ions. Electrolytes can be acids or alkalines.
electromagnetic magnetism produced by electricity
electromagnets magnets that depend on electricity.
electromotive force voltage; electrical pressure.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

electron one of the three major parts of an atom. The electron carries a negative charge.
electron spin patterns the patterns that electrons spin.
electron theory the theory states that current flows from the most negative potential to the most positive potential.
electrostatic charge charge caused by the accumulation of electrons on one plate and the lack of electrons on the other.
element (1) One of the basic building blocks of nature. An atom is the smallest part of an element. (2) One part of a group of devices.
excitation current direct current used to produce electromagnetism in the fields of a DC motor or generator or in the rotor of an alternator or synchronous motor.
exponential curve a natural curve.
farad basic unit of capacitance.
fixed resistors resistors with one ohmic value that cannot be changed.
flux magnetic lines of force.
frequency number of complete cycles of AC voltage that occur in 1 second.
fuses device used to protect a circuit or electrical device from excessive current. Fuses operate by melting a metal link when the current becomes excessive.
galvanometers meter movement requiring microamperes to cause a full-scale deflection. Many galvanometers utilize a zero center, which permits them to measure both positive and negative values.
ground point point where a circuit is connected to ground.
grounding conductor the conductor used to ground a piece of equipment.
henry (H) basic unit of inductance.
hertz (Hz) international unit of frequency.
high leg one leg of a transformer that has a higher voltage to ground than the other two.
HIPOT a device used to test the dielectric strength.
Holtz motor a type of single phase synchronous motor.
horsepower measure of power for electrical and mechanical devices.
hysteresis loss power loss in a conductive material due to molecular friction. Hysteresis loss is proportional to frequency.
impedance total opposition to current flow in an electrical circuit.
in phase state at which the voltage and current rise and fall at the same rate and in the same time.
induced voltage voltage that is induced.
inductive reactance (X_L) current-limiting property of an inductor in an alternating-current circuit.
insulators materials used to electrically isolate two conductive surfaces.
isolation transformers transformer whose secondary winding is electrically isolated from its primary winding.
joule basic unit of electrical energy. A joule is the amount of power used when 1 amp flows through 1 ohm for 1 second. A joule is equal to 1 watt/second.
leakage current the amount of current that passes through the dielectric.
left-hand generator rule a rule to determine polarity in a generator.
left-hand rule rule for determining the polarity of a magnet.
Lenz's Law a law concerning induced voltage.
line voltage voltage measured between the lines.
linear wave a waveform in which the voltage increases and decreases at a constant rate with respect to time.
lines of flux lines of magnetism.
load the amount of power a power source must provide.
lodestones natural magnets.
magnetic coupling the amount of magnetic flux produced by one object that influences another.
magnetic domains magnetic regions inside a magnet.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

magnetic induction voltage will be induced in a conductor when it cuts magnetic lines of force.
magnetomotive force (mmf) magnetic force produced by current flowing through a conductor or coil.
matter a physical substance.
meggers common name for megohmmeters.
metal film resistors resistors that employ a thin metal coating as the resistive element.
metal glaze resistor resistors that combine carbon and glass as the resistive element.
molecules the smallest part of a compound.
moving coil meter A moving coil meter is a d'Arsonval type movement.
multirange ammeters ammeters that contain more than one range.
multirange voltmeters voltmeters that contain more than one range of voltages.
multispeed motors motor that can be operated at more than one speed.
multiturn variable resistors resisters that operate by moving the wiper arm with a screw of some number of turns.
neutral conductor grounded conductor.
neutron one of the principal parts of an atom. The neutron has no charge and is part of the nucleus.
node a point at which connections are joined.
Nonpolarized capacitors capacitors that are not polarity sensitive.
nucleus the center of an atom composed of protons and neutrons.
ohm unit of measure for electrical resistance.
Ohm's Law law to measure electrical resistance.
Ohm's Law the basis of almost all the physical laws concerning electricity.
ohmmeter device used to measure resistance.
open delta a three-phase transformer connection requiring only two transformers.
oscillators device used to change DC voltage into AC voltage.
oscilloscope voltmeter that displays a waveform of voltage in proportion to its amplitude with respect to time.
out of phase condition in which two components do not reach their positive or negative peaks at the same time.
parallel block components connected in parallel.
parallel circuits circuit that contains more than one path for current flow.
peak highest value obtained by the wave.
percent slip rotor frequency of the current inducted in the rotor.
permanent magnets magnets that require no force to maintain their magnetic properties.
permeability measurement of a material's ability to conduct magnetic lines of flux. The standard is air, which has a permeability of 1.
phase rotation meter a device for determining the direction of field rotation.
phase voltage voltage measured across a single winding.
phasing checking a delta connection for proper connection.
photons particles of light.
photovoltaic material or device that produces a voltage in the presence of light.
piezo producing electricity by placing certain materials under pressure.
plates thin pieces of metal.
Polarized capacitors capacitors that are polarity sensitive.
positive/negative one polarity of a voltage, current, or charge.
pot/rheostat variable resistor.
potentiometer variable resistor with a sliding contact that is used as a voltage divider.
power the amount of electrical energy converted into some other form.
primary voltaic cell that cannot be recharged.
primary winding winding of a transformer to which power is applied.
product over sum method one method of determining total resistance connected in parallel.
proton one of the three major parts of an atom. The proton has a positive charge.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

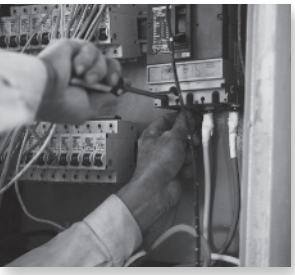
pull-out torque the amount of torque necessary for the magnetic attraction between the rotor and stator magnetic fields to pull apart.
reactance opposition to current flow in an AC circuit offered by pure inductance or pure capacitance.
reactive power (VARs) the amount of power required to operate reactive components such as inductors and capacitors.
receptacles outlets for electrical power.
reciprocal formula one of the methods of determining total resistance connected in parallel.
redraw draw the circuit in its simpler form.
reduce to make smaller.
reluctance resistance to magnetism.
repulsion the force that repels one object from another.
residual magnetism amount of magnetism left in an object after the magnetizing force has been removed.
resistance opposition to current flow in an AC or DC circuit.
resistive loads loads that are comprised of resistive elements.
ripple pulses of direct current.
RMS value of AC voltage that will produce as much power when connected across a resistor as a like amount of DC voltage.
rotating magnetic field a magnetic field that rotates.
rotating transformers Nicola Tesla patented induction motors as rotating transformers.
rotor frequency frequency of the current inducted in the rotor.
run winding the winding in a single phase motor that remains energized after the motor has started.
saturation maximum amount of magnetic flux a material can hold.
secondary voltaic cell that can be recharged.
secondary winding winding of a transformer to which the load is connected.
Seebeck effect producing a voltage by heating the junction of two dissimilar metals.
semiconductors material that contains four valence electrons and is used in the production of solid-state devices.
series circuit circuit that contains only one path for current flow.
series resistance in a series circuit the total resistance is the sum of all circuit resistances.
shaded-pole induction motor a type of single phase motor.
shading coil a shorted loop around part of a pole piece.
short circuit electrical circuit that contains no resistance to limit the flow of current.
simple parallel circuit a circuit that contains only elements connected in parallel.
sine wave a waveform in which the voltage value increases and decreases in accord with the sine of the angel of rotation.
single phasing caused by the loss of one phase in a three-phase system.
speed rate of cutting action.
split-phase motors type of single-phase motor that uses resistance or capacitance to cause a shift in the phase of the current in the run winding and the current in the start winding. The three primary types of split-phase motors are: resistance-start induction-run, capacitor-start induction-run, and permanent split-capacitor motor.
squirrel-cage motor a type of rotor used in induction motors.
stab-locks a type of connection to outlets and switches.
star connection *see* wye connection.
start winding a single phase motor winding used to produce a rotating magnetic field.
static stationary or not moving.
step-down transformer transformer that produces a lower voltage at its secondary than is applied to its primary.
step-up transformer transformer that produces a higher voltage at its secondary than is applied to its primary.
strength of magnetic field flux density of the magnetic field.

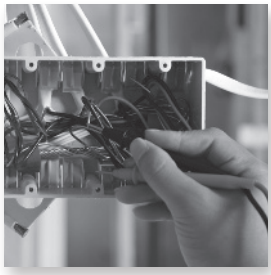
Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

synchronous a type of three-phase motor.
synchronous motors a type of fractional horsepower single phase motor.
synchronous speed speed of the rotating magnetic field of an AC induction motor.
thermal circuit breakers circuit breakers that are sensitive to heat.
three-phase transformer three separate transformers wound on a common core.
time-delay fuses fuses that provide some amount of time delay before opening.
tolerance the upper and lower resistive limits.
torque turning force developed by a motor.
transformer bank single-phase transformers connected in a three-phase configuration.
transformer electrical device that changes one value of AC voltage into another value of AC voltage.
transient currents from other power sources.
triangle wave a linear wave form.
true power the amount of electrical energy converted into some other form.
turns of wire the number of turns of wire.
turns ratio the ratio of the number of primary turns of wire as compared to the number of secondary turns.
two-phase a power system that produces two voltages that are 90 degrees out of phase with each other.
unbalanced a three-phase load that has unequal current flow through the phases.
unidirectional current that flows in one direction only.
universal motor a type of single phase motor that can operate on AC or DC power.
valence electrons electrons located in the outer orbit of an atom.
variable resistor resistor whose resistance value can be varied between its minimum and maximum values.
volt the unit of measure for potential.
voltage divider a circuit that provides different voltage drops across electrical components.
voltage drop amount of voltage required to cause an amount of current to flow through a certain resistance.
voltaic cells device that converts chemical energy into electrical energy.
voltmeter instrument used to measure a level of voltage.
volts-per-turn ratio the ratio of the voltage to the number of turns of wire.
Warren motor a type of single phase synchronous motor.
watt measure of the amount of electrical energy converted into some other form.
wattmeter measures the true power in a circuit.
weber (Wb) measure of magnetic lines of flux in the meter-kilogram-second (MKS) system (1 weber = 100 million [1×10^8] lines of flux).
Wheatstone bridge a device for measuring resistance.
wire wound resistors resistors that use resistive wire as the resistive element.
wound-rotor motor three-phase motor containing a rotor with windings and sliprings. This rotor permits control of rotor current by connecting external resistance in series with the rotor winding.
wye a three-phase connection formed by connecting one end of each phase together to form a center point.
wye connection connection of three components made in such a manner that one end of each component is connected. This connection is generally used to connect devices to a three-phase power system.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Index







A

AC. *See* Alternating current (AC)
Air core inductors, 104–105
Air core magnets, 106
Alnico 5, 89
Alternating current (AC)
  advantages of, 240–241
  direct current vs., 241
  explanation of, 1
  power in circuit, 257
Alternating current (AC) circuits
  capacitance in, 291
  loads for, 255–256
  power in, 257
Alternating current (AC) loads
  capacitive, 270–296
  computing induced voltage and, 259–260
  explanation of, 255–256
  inductance and, 257–259
  inductive circuit power and, 265–266
  inductive reactance and, 260–263
  reactive power and, 266–267
  resistive, 256
  voltage in inductive circuit and, 263–265
Alternating current (AC) waveforms
  average values and, 250–253
  sine, 244–249
  square, 241–243
  triangle, 243
Alternating current ammeters, 202–203
Alternating current electrolytic capacitors, 286–287
Alternating current formulas, 582–594
Alternating current transformers (CTs), 202–203
Alternators, 62
Aluminum bus, 384
Aluminum conductors, 384
American wire gauge table, 577
Ammeters
  alternating current, 202–203
  clamp-on, 206–209
  DC-AC clamp-on, 209–211
  explanation of, 198
  in-line, 198, 199
  multirange, 201
Ammeter shunts, 198–201
Amortisseur winding, 486
Amp, 22–23
Ampere ratings, 385, 386
Ampere-turns, 91
Analog meters, 192–193
Analog ohmmeters, 215
Analog voltmeters, 193, 194
Angle of declination, 85
Apparent and true power, 594
Arc-fault circuit interrupters (AFCIs), 441–446

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Arc-fault detection, 443–445
Arc-faults, 441–445
Atomic number, 4
Atoms
  explanation of, 3–6
  nucleus of, 4, 6–7
  structure of, 8
Attenuated probes, 229–230
Attraction, 2, 15
Autotransformers, 340–342
Auxiliary contacts, 527, 528
Average values
  explanation of, 250–251, 583
  method to determine, 252–253
Ayrton shunt, 201, 202

B

Barium titanate, 75
Base unit, 42
Batteries
  connections for, 70
  explanation of, 63
  marine, 68–69
  primary cells and, 63–67
  secondary cells and, 67–70
Bidirectional current, 1
Bohr, Niels, 8
Branch circuits
  conductor size and, 385
  connected to panel, 376–381
Bridge circuits, 222–224
British thermal unit (BTU), 35
Bump theory, 12

C

Cables
  four-conductor, 401
  nonmetallic, 399
  three-conductor, 400–401
  two-conductor, 399–400
Cadmium-plated copper bus, 384
Capacitance
  in alternating current circuits, 291
  of capacitors, 271, 278
  factors that determine, 273–274
  farad as unit of, 278–279
Capacitive circuits
  power in, 294–296
  voltage and current relationships in, 293–294
Capacitive loads
  dielectric constants and, 277–278
  dielectric stress and, 274–277
  explanation of, 270
Capacitive reactance
  explanation of, 291–292
  method to compute, 290, 292–293
Capacitors
  AC electrolytic, 286–287
  alternating current and, 291, 293–294
  applications for, 282
  charge and discharge of, 280–282
  connected in parallel, 280
  dielectric constants and, 277–278
  dry-type electrolytic, 287
  electrostatic change and, 273–277
  function of, 271–273, 275
  method to test, 288–290
  nonpolarized, 282–284
  polarized, 284–286
  ratings of, 278–280
  variable, 288
Capacitor-start capacitor-run motors
  explanation of, 503–505
  operation of, 509–511
Carbon film resistors, 47
Carbon-zinc cell, 63, 64, 66
Center tap, 361
Centrifugal switch, 497–499
Ceramic magnets, 89
CGS system of measurement, 108
Changing peak values, 583
Changing RMS values, 583
Charged materials, 2
Chassis ground, 135
Chimes, 449–452
Circuit branch, 141

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Circuit breakers
duplex and half-size, 382–384
function of, 115, 373
magnetic, 373–376
single-pole, 435
thermal, 373, 374, 376
Circuits. *See also specific types of circuits*
alternating current, 255–256
basic information about, 26–30
branch, 376–381, 385
bridge, 222–224
closed, 26, 28
combination, 164–184
connecting, 376–381, 529–532
grounded, 27, 29–30
inductive, 263–266
open, 27
parallel, 140–158
series, 115–136
short, 27, 28, 44
three-phase, 300–316
three-way switch, 414–416
Clamp-on ammeters
DC-AC, 209–211
digital, 210
explanation of, 206–209
Clamp-on ground resistance test, 392–395
Closed circuits, 26, 28
Code letters, 475–476
Coercive force, 107–108
Coils
as air core magnet, 106
inductance of, 104–106
in schematic diagrams, 525
Color bands, for resistors, 48–52
Combination circuits
explanation of, 164, 165
methods to simplify, 166–184
method to solve for, 165–166
parallel circuit rules to solve for, 166
series circuit rules to solve for, 166
Compensating winding, 519
Complete path, 26
Composition carbon resistors, 45
Conductors. *See also* Switch connections
explanation of, 10
grounding, 408–409
magnetic fields and, 91–93
neutral, 29–30, 337–339, 387, 388, 416, 418, 420, 421, 427
size of, 385–387, 552, 553, 566
Consequent pole single-phase motors, 480–482, 515
Conventional current flow theory, 24–25
Coulombs, 22, 23
Coulomb's Law of electrostatic charges, 7, 22
Current
alternating, 240–253 (*See also* Alternating current (AC))
direct, 1, 241
excitation, 324
explanation of, 23
leakage, 272, 273
locked-rotor, 556–558
speed of, 25–26
transient, 387
Current adds, 141
Current limiters, 373
Current relays, 501–502
Current transformers, 203–205
Cycle, 244

D

Dalton, John, 8
d'Arsonval movement, 192, 193
DC-AC clamp-on ammeters, 209–211
DC circuits, 37
Delta connections
example of, 310–315
explanation of, 305–307, 350, 594
three-phase circuits and, 305–307
Demagnetizing, 109–111
Diagrams. *See* Schematic diagrams; Wiring diagrams
Dielectric, 235, 271, 274, 275
Dielectric constants, 277–278
Dielectric stress, 274–277

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Digital clamp-on ammeters, 210
Digital meters, 214–218
Digital multimeters, 216–218
Digital ohmmeters, 214–216
Dimmers. *See* Light dimmers
Direct current (DC)
  alternative current vs., 241
  explanation of, 1
Direct current motors, 241
Direction of rotation. *See* Rotation direction
Distribution transformers, 337–339
Double circuit breakers, 382
Double-pole, half-size circuit breakers, 382
Double-pole circuit breakers, 377
Double-squirrel-cage rotors, 476–477
Double-throw, 410
Dry-type electrolytic capacitors, 287
Dual-voltage split-phase motors, 505–507
Dual-voltage three-phase motors
  explanation of, 461
  high-voltage connections for, 461, 462
  low-voltage connections for, 462–464
  voltage and current relationships for, 464–466
DuFay, Charles, 2
Duplex circuit breakers, 382–384
Duplex receptacles, 401–402
Dynamic wattmeters. *See* Wattmeters
Dynes, 109

E

Earth, as magnet, 85, 86
Earth ground, 134–135
Eddy current loss, 105
Edison, Thomas, 241
Effective value, 249
Electric, 2
Electrical quantities
  amp, 22–23
  BTU, 35
  coulomb, 22
  horsepower, 34–35
  joule, 35
  ohm, 31–32
  volt, 30–31
  watt, 33–34
Electrical services
  circuit breakers and, 373–376, 382–384 (*See also* Circuit breakers)
  conductor size and, 385–387
  connecting branch circuits to panel in, 376–381
  fuses and, 372–373
  grounding in, 387–395
  single-phase, 371–372
  three-phase, 367–371
Electricity
  historical background of, 2–3
  impulse of, 25–27
  sources of, 1
Electricity sources. *See also* Batteries
  piezoelectricity as, 75–76
  primary cells as, 63–67
  secondary cells as, 67–70
  solar cells as, 71–72
  thermocouples as, 72–75
Electrolytes, 63
Electrolytic capacitors
  alternating current, 286–287
  direct current, 285
  dry-type, 287
  explanation of, 284–286
  wet-type, 285, 286
Electromagnetic force, 7
Electromagnetic induction, 62
Electromagnets, 91, 92
Electromotive force (EMF), 30, 31
Electronic wattmeters, 222
Electrons
  explanation of, 3–6
  flow of, 12–15
  orbit of, 8–10
  valence, 10–13, 15
Electron spin patterns, 86–87
Electron theory, 23
Electron theory of magnetism, 86–88
Electrostatic charge, 275–277
Elektron, 2

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Elements, 3, 5
Engineering notation, 41–42
English system of measure, 108
Excitation current, 324
Exponential curve, 103–104
Exponential rate, 280

F

Farad, 278–279
Faraday, Michael, 278
Field discharge resistors, 487
Field effect transistors (FETs), 217
Fixed resistors, 45, 52–53
Fleming's left-hand generator rule, 94–96
Flux, 89, 90
Flux density, 108
Formulas
  alternating current, 582–594
  capacitance, 290
  capacitance reactance, 292
  delta connection current, 307
  flux density, 108
  inductance of coil, 105–106
  instantaneous value, 245
  parallel resistance, 143–148
  reciprocal, 146–148
  resistive load power, 308
  RMS or peak value, 249
  series circuit, 123
  torque, 470, 475
  transformer, 320–321, 593
Four-conductor cables, 401
Four-way switches
  explanation of, 423–425
  method to connect, 425–430
Franklin, Benjamin, 3
Frequency, 227–229, 244
Full-load current, 546–548
Fuses, 115, 372–373

G

Galvanometers, 192, 223
Gauss, 108
General wiring practices. *See* Wiring practices
Generators, Hall, 209–211
Geographic poles, 85
Giga, 42
Gilbert, William, 2
Gilberts, 108
Gluon, 7
Greek alphabet, 595
Ground, used as reference, 134–136
Grounded circuits, 27, 29–30
Grounded conductor, 29–30
Ground fault, 436–437
Ground fault circuit interrupters (GFCIs), 434–440
Ground fault receptacles, 438–441
Grounding
  clamp-on ground resistance test for, 392–395
  explanation of, 387–388
  tests for, 388–390
  three-point fall-of-potential test for, 392
  Wenner four-point test for, 390–393
Grounding conductors, 408–409
Ground point, 134–135

H

Half-size circuit breakers, 382–384
Hall, Edward H., 209
Hall effect, 209
Hall generator, 209–211
Heat, 32
Helium, 5, 7
Henry (H), 104
Hermetically sealed motors, 498–502, 510
Hertz (Hz), 244
High leg, 361
High-leg voltage, 369–371
HIPOT, 290
Holtz motors, 518–519
Horsepower (hp), 34–35
Hot conductor, 27, 29
Hot wire relay connection, 499, 500
Hot-wire relays, 498–499
Hydrogen, 68
Hydrogen atom, 5, 18
Hysteresis loss, 105

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

I

Impedance, 32
Induced voltage
  explanation of, 97–98, 101, 258, 259, 264
  method to compute, 259–260
Inductance (L)
  in alternating current circuits, 257–259
  explanation of, 104–106
Induction motors. *See* Single-phase motors; Three-phase motors
Inductive circuits, power in, 265–266
Inductive reactance, 260–263
Inductors
  air core, 104–105
  iron core, 105
  Lenz's Law and, 98–99
  rise time of current in, 101–102
  schematic symbols for, 263
In phase, 256
Instantaneous and maximum values formulas, 582
Instantaneous value formula, 245
Instantaneous voltage values, 245
Insulators, 15–17
Iron core inductors, 105
Isolation transformers
  calculating values for, 325–330, 334–337
  construction of, 322, 323
  distribution, 337–339
  excitation current of, 324
  explanation of, 321–322
  with multiple secondaries, 334–337
  multiple-tapped windings for, 331–333
  mutual induction and, 324–325
  turns ratio and values for, 327–330

J

Joule, 35

K

Kilo, 42

L

Law of charges, 6–7
Lead-acid secondary cells, 67–68
Leakage current, 272, 273
Left-hand generator rule (Fleming), 94–96
Left-hand rule, 109, 110
Lenz, Heinrich, 98
Lenz's Law, 98–100
Light dimmers, 445–448
Light dimmer switch control circuits, 447
Lightning
  explanation of, 79
  protection against, 80–81
Lightning arrestors, 80–81
Lightning rods, 80, 81
Linear waves, 243
Line voltage
  in delta connection, 305, 306
  explanation of, 302, 303
Lithium-ion cells, 67, 69–70
Load contacts, 527
Loading effect, 217
Loads
  capacitive, 270–296
  explanation of, 26, 142
  resistive, 256
  single-phase, 359
  three-phase, 362–363
  unbalanced, 350–351
Locked-rotor current, 556–558
Lodestones, 85
Low-impedance voltage testers, 218–220

M

Magnetic circuit breakers, 373–376
Magnetic coupling, 348
Magnetic devices, 111–112
Magnetic domains, 87
Magnetic fields
  explanation of, 86, 92, 93, 96
  moving, 96

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

polarity of, 93–95, 110
rotating, 456, 469, 470, 487, 488
strength of, 97
Magnetic induction, 91, 93–94
Magnetic lines of flux, 90, 93
Magnetic lines of force, 89–91
Magnetic materials, 89
Magnetic measurement, 108–109
Magnetic molecules, 87
Magnetic polarity, 109
Magnetism
amount of induced voltage and, 97–98
basic law, 90, 91
core material and, 106–108
demagnetizing and, 109–111
Earth and, 85, 86
electron theory of, 86–88
exponential curve and, 103–104
Fleming's left-hand generator rule and, 94–96
historical background of, 84–85
inductance and, 104–106
Lenz's Law and, 98–100
residual, 107–108
rise time of current in inductor and, 101–102
Magnetite, 84, 85
Magnetomotive force (mmf), 108
Magnets
air core, 106
ceramic, 89
Earth as, 85, 86
electomagnets, 91
permanent, 86
Main feeder calculations, 573, 574
Marine batteries, 68–69
Master chimes, 451, 452
Matter, 3
Maxwell, 108
Measurement instruments
alternating current ammeters, 202–203
ammeters, 198
ammeter shunts, 198–201
analog meters, 192–193
analog voltmeters, 193, 194
Ayrton shunt, 201, 202
bridge circuits, 222–224
clamp-on ammeters, 206–209
current transformers, 203–205
DC-AC clamp-on ammeters, 209–211
digital meters, 214–218
digital multimeters, 216–218
digital ohmmeters, 214–216
electronic wattmeters, 222
galvanometers, 23, 192
low-impedance voltage testers, 218–220
megohmmeters, 234–237
method to read meters, 195–196
multirange ammeters, 201
multirange voltmeters, 194, 195
ohmmeters, 211–214
oscilloscope, 224–234
recording meters, 222, 223
shunt-type ohmmeters, 214, 215
voltmeters, 196–198
wattmeters, 220–222
Mega, 42
Meggers®, 234–237
Megohmmeters, 234–237
Metal film resistors, 46–47
Metal glaze resistors, 47
Metal oxides, 17
Metal oxide semiconductor (MOS) devices, 17
Metric units, 41–42
Mica capacitors, 578–581
Micro, 42
Milli, 42
MKS (meter-kilogram-second) system, 109
Molecules
explanation of, 19
magnetic, 87
Motor installation
direct current motors and, 546, 547
locked-rotor current and, 556–558

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Motor installation (*Continued*)
main feeder calculations and, 573, 574
motor current determination and, 546–555
multiple motor calculations, 568–573
overload size and, 555–574
overview of, 545–546
short-circuit protection and, 559–567
single-phase motors and, 547, 548, 552, 553
termination temperature and, 552–555
three-phase motors and, 551–552
two-phase motors and, 549–551
Motors. *See specific types of motors*
Motor starter size, 561–567
Moving coil meter, 192
Multimeters, 195
Multiple motor calculations, 568–573
Multiple-tapped windings, transformer, 330–333
Multiplier band, 49, 52
Multirange ammeters, 201
Multirange voltmeters, 194, 195
Multispeed fan motors, 515–516
Multispeed motors, 515–516
Multiturn variable resistors, 56, 57
Mutual induction, 324–325

N

Nameplate current rating, 555, 564
Nameplates
motor, 478–480
overload size, 555
Nano, 42
National Electrical Code® (NEC)
aluminum conductors, 384
ampere conductors, 385
arc-fault circuit interrupters, 441
chimes, 449
grounded conductors, 401, 407
ground fault interrupters, 440
high leg identification, 361
motor current, 471, 546–549, 556–558, 560
NEMA design codes, 554
neutral conductors, 406, 407, 420
overload size, 555, 556, 565
personnel GFCI detectors, 434
protective devices, 433, 559, 560
switch leg, 409
termination temperature, 385, 553
National Electrical Manufacturers Association (NEMA)
design codes, 554, 561
locked-rotor current, 557, 558
motor starter sizes, 561, 562, 566
National Fire Protection Association (NFPA)
locked-rotor current, 556, 557
overload size, 556
short-circuit protection, 559, 560
Negative charge, 3, 8
Negative terminal, 15, 16
Neutral conductors, 29–30, 337–339, 416, 418, 420, 421, 427
Neutrons, 3–6
Nickel-cadmium (Ni-Cad) cells, 67, 69
Nickel-metal hydride (Ni-MH) cells, 67, 69
9-volt battery, 65
Node, 165
Nonelektriks, 2
Nonmetalic (NM) cables, 399
Nonpolarized capacitors, 282–284
N-type semiconductor material, 71
Nucleus, 4, 6

O

Ohm, 31–32
Ohm, Georg S., 31, 37
Ohmic value, 131
Ohmmeters
analog, 215
digital, 214–216
explanation of, 211–212
series, 212–214

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

shunt type, 214
testing transformers with, 342–343
tests of, 289–290
Ohm's Law
applications of, 118–122, 125, 131, 150, 153–158, 168, 171–173, 178, 199, 313, 329
explanation of, 37–41
Oil-filled capacitors, 282–283
Ω, 31
120-V appliance circuits, 381
120-V single-phase connections, 381
Open circuits, 27
Open delta transformer connections
delta-wye connection with neutral and, 363
explanation of, 258–259, 594
load conditions and, 362–363
single-phase loads and, 359–360
voltage values and, 360–461
Oscillators, 243
Oscilloscopes
attenuated probes for, 229–230
controls on, 230–232
explanation of, 224
frequency measurement and, 227–229
time base and, 227, 228
voltage range selection for, 225–227
waveforms displayed on, 232–234
Out of phase, 294
Overload relay, 527, 529
Overload size, 555–574
Oxygen atom, 18

P

Panels, circuit breaker, 383
Paper capacitors, 282–283
Parallel arc-faults, 442
Parallel block, 169, 172
Parallel capacitive circuits, 585
Parallel circuits. *See also* Combination circuits
explanation of, 140
resistance formulas for, 143–148
simple, 166–169
solving circuit values for, 148–158
total current, 140–141
total resistance, 141–143
voltage drop, 141
Parallel inductive circuits, 584
Parallel resistive circuits, 583
Peak-to-peak value, 247, 248
Peak value, 247–251, 512–513
Percent slip, 473–474
Permanent magnets, 86
Permanent split-capacitor motors. *See* Capacitor-start capacitor-run motors
Permeability, 106
Personnel GFCI detectors, 434–438
Phase rotation, 315–316
Phase rotation meter, 458–459
Phase voltage
in delta connection, 305, 306
explanation of, 302, 303
Phasing, 352
Photons, 71
Photovoltaic cells, 71, 72
Pico, 42
Piezo, 75
Piezoelectricity, 75–76
Pig tail, 404, 405, 410
Plates, 271, 272
Polarity
inducted voltage, 93–95
magnetic, 109
voltage, 134
Polarized capacitors. *See* Electrolytic capacitors
Positive charge, 3, 8
Positive terminal, 15, 16
Pot, 56
Potentiometer, 56–57
Power
in AC circuits, 257
apparent and true, 594
explanation of, 33
formulas to compute, 33–34
in inductive circuits, 265–266
measures to compute, 33–36

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Power (*Continued*)
in pure capacitive circuit, 294–296
reactive, 266–267
three-phase, 300–301, 308
transformer, 326
Power ratings, for resistors, 53–54
Primary cells, 63–67
Primary windings, 321, 330, 331, 333–335, 354
Probes, attenuated, 229–230
Product over sum method, 144–146
Protons, 3–6
P-type semiconductor material, 71
Pull-out torque, 488
Pure capacitive circuits, 585
Pure inductive circuits, 584–593
Pure resistive circuits, 583

Q

Quick-connects, 402

R

Reactance
explanation of, 260
inductive, 260–263
Reactive power, 266–267
Receptacles
connecting, 404, 405
duplex, 401–402
explanation of, 401–403
Reciprocal formula, 146–148
Recording meters, 222, 223
Rectifiers, 193, 194
Reduce, to a simpler circuit, 169
Reluctance, 106
Repulsion, 2, 15
Residual magnetism, 107–108
Resistance
of battery, 67, 68
explanation of, 26, 31, 43
in parallel circuits, 141–149
in series circuits, 117–118
standard values of, 52–53
Resistance adds, 118
Resistance-start induction-run motors
disconnecting start winding and, 497–498
explanation of, 496–497
hermetically sealed, 498–502
rotation direction and, 502–503
stator and rotor fields and, 502
Resistive-capacitive parallel circuits, 589–590
Resistive-capacitive series circuits, 588–589
Resistive-inductive-capacitive parallel circuits, 592–593
Resistive-inductive-capacitive series circuits, 590–592
Resistive-inductive parallel circuits, 587–588
Resistive-inductive series circuits, 586
Resistive loads
explanation of, 256
power of, 308
Resistors
carbon film, 47
color code for, 48–52
combination circuits and, 165
composition carbon, 45
of equal value, 143–146
explanation of, 31
fixed, 45, 52–53
metal film, 46–47
metal glaze, 47
power ratings of, 53–54
schematic symbols for, 58
uses of, 43–45
variable, 54–58
wire wound, 47–48
Rheostat, 56
Ripples, 251
RMS values, 248–249, 252
Rochelle salt, 75
Root-mean-square, 249
Rotating magnetic fields, 456, 469, 470, 487, 488
Rotating transformers, 456
Rotation direction

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

for resistance-start induction-run motors, 502–503
for split-phase motors, 508–509
for three-phase motors, 458–460
Rotor frequency, 474–475
Run capacitors, 284, 285
Run windings
for dual-voltage split-phase motors, 505–507
explanation of, 494–496

S

Saturation, 107
Schematic diagrams
analyzing the circuit, 525–529
connecting the circuit, 529–532
connecting the wires, 536–542
converted to wiring diagrams, 529–532
example of, 524
explanation of, 523, 525
guidelines for viewing, 525
numbering the components, 532–536
Schematic symbols
for inductor, 263
list of basic, 526
magnetic circuit breaker, 375
for resistors, 58
thermo-magnetic circuit breaker, 376
three-phase synchronous motor, 489
Secondary cells, 67–70
Secondary windings, 321, 330, 332–337, 354
Seebeck effect, 72–73
Semiconductors
composition of, 71
explanation of, 17–18
Series arc-faults, 443
Series capacitive circuits, 585
Series circuits. *See also* Combination circuits
calculating values of, 118–132
explanation of, 115, 116
ground and, 134–136
power dissipation in, 123, 127–129
resistance in, 117–118
rules for, 120, 124, 127, 171–172
voltage divider for, 133–134
voltage drops in, 116–117
voltage polarity for, 134
Series inductive circuits, 584
Series ohmmeters, 212–214
Series resistive circuits, 583
Shaded-pole induction motors
explanation of, 511
operation of, 514, 515
shaded coil in, 511–513
speed in, 514
Shading coil, 511–513
Shell, 10
Short-circuit protective devices, 559–561
Short circuits, 27, 28, 44
Shunts
ammeter, 198–201
Ayrton, 201, 202
Shunt-type ohmmeters, 214, 215
Simple parallel circuits, 166–169
Sine waves, 244–247, 252
Sine wave values, 247–249
Single-phase circuit breakers, 377
Single-phase loads, 359–360
Single-phase motors
capacitor-start capacitor-run, 509–511
capacitor-start induction-run, 503–505
conductor size for, 552, 553
dual-voltage split-phase, 505–508
explanation of, 493, 494
motor current for, 546–548
multispeed, 515–516
resistance-start induction-run, 496–503
rotation direction for, 508–509
shaded-pole induction, 511–515
split-phase, 494–496
synchronous, 516–519
universal, 519
Single-phase services, 371–372

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Single-phase synchronous motors, 516–519
Single-phase voltage, 301
Single phasing, 478
Single-pole double-throw (SPDT) switch, 410
Single-pole switch connections, 406–410
Slow-blow fuses, 372
Solar cells, 71–72
Speakers, 111–112
Speed of current, 97
Split-phase motors
  capacitor-start capacitor-run, 509–511
  capacitor-start induction-run, 503–505
  classifications of, 494
  explanation of, 494
  resistance-start induction-run, 496–503
  rotation direction for, 508–509
  stator windings for, 494–496
  two-phase system for, 494
Square wave oscillator, 243
Square waves, 241–243
Squirrel-cage induction motors
  code letters for, 475–476
  consequent pole, 480–482
  double squirrel-cage rotor and, 476–477
  explanation of, 456, 467
  nameplate and, 478–480
  operation of, 467–469
  percent slip for, 473–474
  reduced voltage starting for, 475
  rotor frequency for, 474–475
  single phasing and, 478
  starting characteristics for, 471–473
  torque and, 470–471
Squirrel-cage rotors, 502, 514
Stab-locks, 402, 403
Star connection. *See* Wye connection
Starting relays, 498–502
Start windings
  disconnection of, 497–498
  for dual-voltage split-phase motors, 505–507
  explanation of, 494–496
Static, 76, 78
Static electricity
  explanation of, 76–78
  lightning and, 80–81
  in nature, 78–80
Step-up transformers, 327
Switch connections
  four-way, 423–430
  grounding conductors and, 408–409
  single-pole, 406–410
  three-way, 410–423
  types of, 406–407
Switch leg, 407, 409
Symbols. *See* Schematic symbols
Synchronous motors
  Holtz, 518–519
  single-phase, 516–519
  three-phase, 456, 485–489
  Warren, 517–518
Synchronous speed, 456–458, 496, 514

T

Table of elements, 3, 5
Tera, 42
Terminals
  positive and negative, 15, 16
  for variable resistors, 54–55
Termination temperature, 385, 552–555
Tesla, Nikola, 241
Thermal circuit breakers, 373, 374, 376
Thermocouples, 72–75
Thermo-magnetic circuit breakers, 376
Thermopile, 73, 74
Thompson, J. J., 8
Three-conductor cables, 400–401
Three-phase circuits
  calculations for, 308–315
  delta connection and, 305–307
  explanation of, 300–302
  phase rotation and, 315–316
  power in, 308
  three-pole circuit breakers to connect, 376
  wye connection and, 302–305

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Three-phase connections, 594
Three-phase four-wire connections, 278
Three-phase four-wire system, 368–370
Three-phase motors
  dual-voltage, 461–466
  full-load current for, 551–552
  horsepower rating of, 301
  rotating magnetic field and, 456
  rotation direction for, 458–460
  running current for, 546, 547, 549
  squirrel-cage induction, 467–482
  synchronous, 485–489
  synchronous speed and, 456–458
  types of, 456
  wound-rotor, 482–485
Three-phase power
  benefits of, 300–301
  explanation of, 308
Three-phase services, 367–371
Three-phase synchronous motors
  characteristics of, 485
  constant speed operation for, 487
  field discharge resistor for, 487
  power supply for, 489
  rotor construction for, 485
  schematic symbol for, 489
  starting up, 486–487
Three-phase three-wire connections, 377
Three-phase three-wire system, 368, 369, 379
Three-phase transformer banks, 349–351
Three-phase transformers
  calculations for, 353–358
  delta connections and, 352–353, 358–360
  delta-wye connections with neutral and, 363
  explanation of, 348, 439
  load conditions and, 362–363
  one line diagrams of, 351, 352
  single-phase loads and, 359–360
  voltage values and, 360–361
Three-point fall-of-potential test, 392
Three-pole circuit breakers, 376
Three-pole magnetic circuit breakers, 375
Three-way switch circuits, 414–416
Three-way switch connections
  with cable, 416–423
  construction of, 412–414
  explanation of, 410–412
Thunderclouds, 79
Time-delay fuses, 372
Tolerance, 46–47, 50
Tolerance band, 49
Toroid transformers, 204
Torque
  explanation of, 471, 475
  pull-out, 488
Transformer banks, three-phase, 349–351
Transformer formulas, 320–321, 593
Transformers
  alternating current, 202–203
  autotransformers, 340–342
  calculating values for, 325–330, 334–337
  classification of, 320
  construction of, 322, 323
  current, 203–205
  distribution, 337–339
  excitation current of, 324
  explanation of, 320
  function of, 240, 319
  isolation, 321–339 (*See also* Isolation transformers)
  maximum current for, 344
  with multiple secondaries, 334–337
  multiple-tapped windings for, 331–333
  mutural induction and, 324–325
  operating principles of, 323–324
  ratings for, 343
  step-up, 327
  tests for, 342–343
  three-phase, 348–363 (*See also* Three-phase transformers)
  toroid, 204
  turns ratio and values for, 327–330

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Transient currents, 387
Traveler conductors, 413–414
Triangle waves, 243
True power, 255
Tubular capacitors, 578–581
Turns of wire, 97
Turns ratio, 320, 327–330
Two-conductor cables, 399–400
240-V single-phase circuits, 377–379
240 V single-phase connections, 378
Two-phase motors, 546, 547, 549–551
Two-phase system, 494
Two-tone chimes, 449, 450
Type A rotors, 475, 476
Type B - E rotors, 476, 477
Type F - V rotors, 476, 477

U

Unbalanced loads, with three-phase transformers, 350–351
Ungrounded conductor, 27, 29
Unidirectional current, 1
Unit magnetic pole, 109
Universal motors, 519

V

Valence electrons, 10–13, 15
Variable capacitors, 288
Variable resistors, 54–58
VARs, 266–267
Volta, Alessandro, 63
Voltage
  explanation of, 30–31
  induced, 97–98, 101, 258, 263–265
  in pure capacitive circuit, 293–294
  three-phase transformer, 260–361
  of wye connection, 304–305
Voltage dividers, 44–45, 133–134
Voltage drop
  in parallel circuits, 141
  in series circuits, 116–117, 119–120
Voltage polarity, 134
Voltage testers, low-impedance, 218–220
Voltaic cells, 63
Voltmeters. *See also* Oscilloscopes
  analog, 193, 194
  method to read, 196–198
  multirange, 194, 195
Volts, 30–31
Volts-per-turn ratio, 324–325
VOM (volt-ohm-milliammeter), 211

W

Warren motors, 517–518
Watt, James, 33
Watt-hours, 66, 67
Wattmeters, 220–222
Watts, 33–34, 255, 257
Waveforms
  alternating current, 241–253
  interpretation of, 232–234
Weber (Wb), 97
Wenner four-point test, 390–392
Westinghouse, George, 241
Wet-type electrolytic capacitors, 285, 286
Wheatstone bridge, 222, 224
Wire wound resistors, 47–48
Wiring diagrams
  connecting the wires on, 536–542
  explanation of, 523, 525
  numbering the components on, 532–536
  schematic diagrams converted to, 529–532
Wiring practices
  arc-fault circuit interrupters and, 441–446
  cables and, 399–401
  chimes and, 449–452
  conducting receptacles and, 404, 405
  ground-fault receptacles and, 438–441
  light dimmers and, 445–449
  personnel GFCI detectors and, 434–438
  receptacles and, 401–403

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

switch connections and, 406–430
(*See also* Switch connections)
Wound-rotor induction motors
explanation of, 456, 482
operation of, 483–484
speed control for, 484–485
starting characteristics for, 484
Wye connections
delta, 363
examples of, 308–315
explanation of, 302–304, 350, 594
voltage relationships in, 304–305

X

Xenon, 276, 277

Y

Yukawa, Hideki, 7

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.

Copyright 2013 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part.