

Electricity & Controls for **HVAC/R**



Stephen L. Herman
Bennie L. Sparkman

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6th
Edition



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**Electricity and Controls for HVAC/R,
6th Edition****Stephen L. Herman, Bennie L. Sparkman**

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PREFACE

Electricity and Controls for HVAC/R is written with the assumption that the student has no prior knowledge of electricity or control systems. Basic electrical theory is presented in a practical, straightforward manner. Mathematical explanations are used only when necessary to explain certain concepts of electricity. Each unit starts with the objectives of the unit and ends with a summary of important facts.

The text begins with the study of **basic electrical theory** and progresses to **series circuits, parallel circuits, alternating current, inductive circuits, and capacitive circuits**. The text also includes information on different types of three-phase services found in industrial and commercial locations as well as single-phase residential services. Individual devices and components common to the air conditioning, heating, and refrigeration field are presented in a practical manner. Devices are explained from a standpoint of how they operate and how they are used. The text contains testing procedures for many of the devices covered. The practical presentation of these devices makes this text a *must-have* reference book for the service technician working in the field.

Electricity and Controls for HVAC/R, sixth edition, includes information on isolation transformers, autotransformers, and current transformers. The three major types of three-phase motors—squirrel cage induction, wound rotor, and synchronous—are also covered. Coverage of single-phase motors includes: split-phase motors, resistance-start induction-run motors, capacitor-start induction-run motors, and permanent-split capacitor motors. Shaded-pole induction motors and multispeed motors are also covered. The sixth edition also provides information on variable-frequency drives.

Control circuits are developed using the components in the text. The text assumes that the student

has no prior knowledge of control systems. **Operation of the manufacturer's control schematics is explained to aid the student in understanding how a control system operates and how to troubleshoot the system.**

Electricity and Controls for HVAC/R, sixth edition, includes information on **household and commercial icemaker controls**. These circuits are explained in a step-by-step procedure to ensure that students have a thorough working knowledge of these units.

Solid-state devices common to the HVAC/R field are covered in a straightforward manner. The devices covered are: **diode, transistor, SCR, diac, triac, and operational amplifier**. The last section of the text covers **programmable logic controllers**, which are becoming more and more common in the field.

NEW FOR THE SIXTH EDITION

The unit on atomic structure has been rewritten to reflect the most accepted theories concerning the structure of atoms. Many of the illustrations have been updated to help students gain a better understanding of the principles involved concerning the subject matter. The unit devoted to troubleshooting has been expanded to include an example of a step-by-step procedure for determining the problems with a central air conditioning system.

FEATURES OF THIS BOOK

Electricity and Controls for HVAC/R, sixth edition, contains many features to help enhance learning for the student:

- A special section covering **Safety** rules at the front of the book reminds students to follow correct procedures and take the necessary precautions when working around electricity.

- **Step-by-Step Procedures** are integrated throughout the text where applicable, and provide students with a thorough working knowledge of the HVAC systems.
- **Troubleshooting Questions** present situations in which students must develop critical-thinking and problem-solving skills to prepare them for the field.
- **Review Questions** and **Practice Problems** are included at the end of each unit to allow students to evaluate their comprehension of the material and apply what they have learned from the information presented in the unit.
- **An extensive art program** includes schematics, line drawings, and up-to-date photos that help to reinforce the information presented in the text.

SUPPLEMENT TO THIS BOOK

Also available to the instructor is the *Instructor Resource to Accompany Electricity & Controls for HVAC/R*, sixth edition. Thoroughly updated to reflect changes to the sixth-edition book, the *Instructor's Resource* contains:

- Instructors Guide with answers to the text's Review Questions
- PowerPoint presentations
- Test bank

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SECTION 1

Basic Electricity

A SPECIAL NOTE ON SAFETY

The purpose of this textbook is to provide the air conditioning and refrigeration technician with knowledge of electricity. Electricity is an extremely powerful force and should never be treated in a careless manner. The air conditioning and refrigeration technician commonly works with voltages ranging from 24 volts to 480 volts. One mistake can lead to serious injury or death.

Never work on an energized circuit if it is possible to disconnect the power. When possible, use a three-step check to make certain that the power is turned off. The three-step check is as follows:

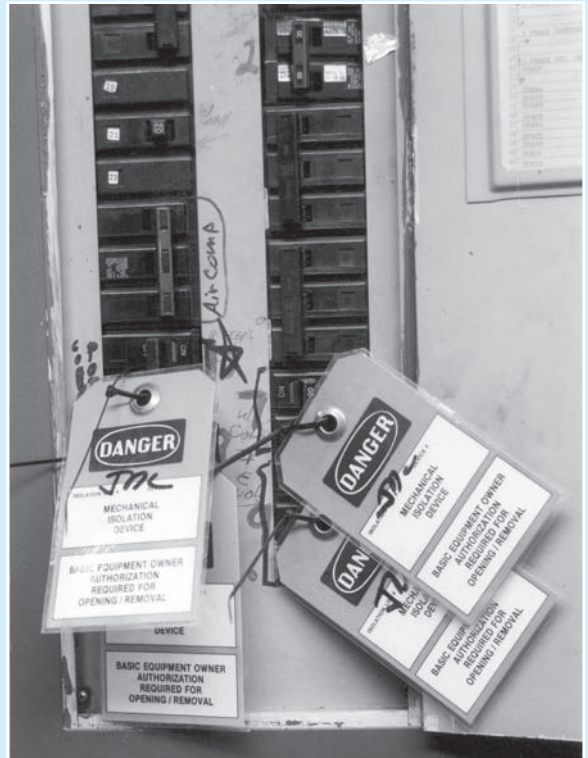
1. Test the meter on a known live circuit to make sure the meter is operating.
2. Test the circuit that is to be de-energized with the meter.
3. Test the meter on the known live circuit again to make certain that the meter is still operating.

Install a warning tag at the point of disconnection to warn people not to restore power to the circuit, as shown in Figure SF-1.

GENERAL SAFETY RULES

Think

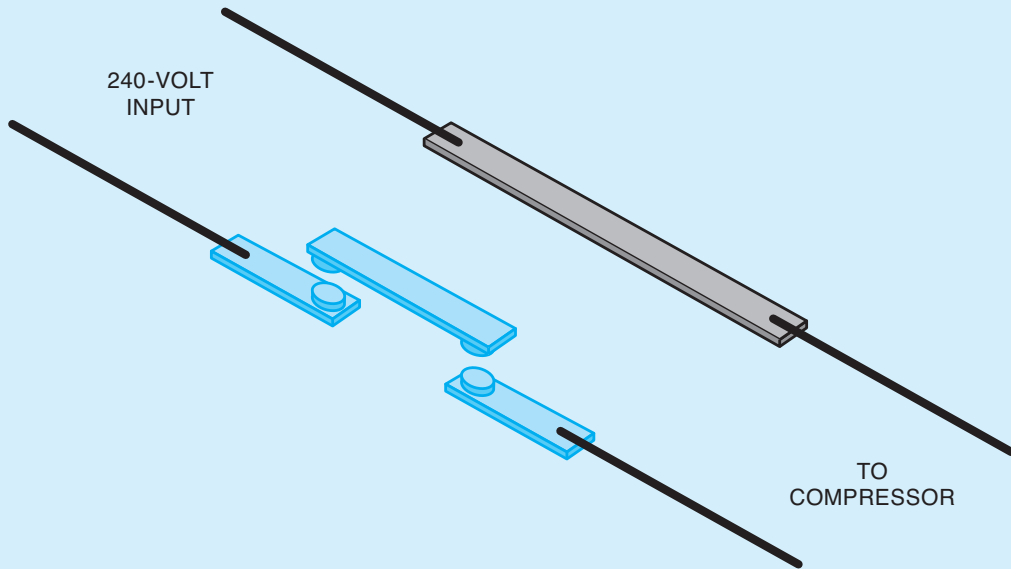
Of all the rules concerning safety, this one is probably the most important: No amount of safeguarding or “idiot-proofing” a piece of equipment can protect a person as well as the person’s taking time to think before acting. Many technicians have been killed by supposedly “dead” circuits. Do not depend on circuit breakers, fuses, or someone else to open a circuit. Test it yourself before you touch it. If you are working on high-voltage equipment, use insulated gloves and meter probes designed to be used on the voltage being tested. Your life is your own, so *think* before you touch something that can take it away.



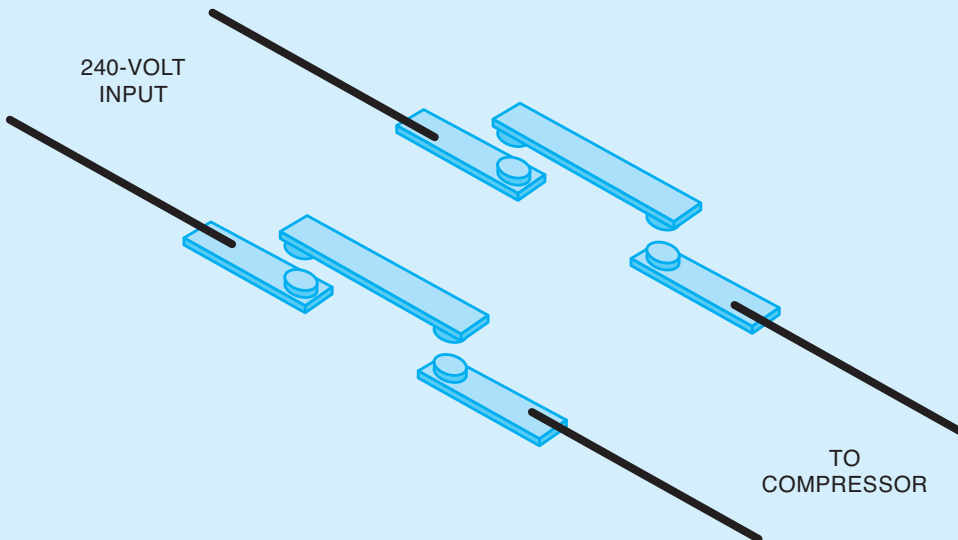
► **Figure SF-1**

Warning tags warn people that the circuit should not be turned back on. (Source: Delmar/Cengage Learning)

Certain pieces of equipment can be especially hazardous if you are not aware of them. Some central air conditioning units use a main contactor that has only one set of contacts to disconnect a 240-volt circuit, as shown in Figure SF-2. The contactor operates on the principle that a complete circuit must exist for current to flow. If one line is broken or open, no current can flow to the compressor. The hazard lies in the fact that one of the 240-volt lines is still supplying power to the unit. If a technician should touch the unbroken line and ground, a 120-volt circuit is completed through his body. Other contactors employ two load contacts to break the circuit to the compressor, as shown in Figure SF-3. This type of contactor is much safer and can prevent a serious injury.



► **Figure SF-2**
Some main contactors use one set of load contacts to break a 240-volt connection to the compressor.
(Source: Delmar/Cengage Learning)



► **Figure SF-3**
Contactors that employ two load contacts to break both sides of the 240-volt line are much safer and can prevent a serious injury. (Source: Delmar/Cengage Learning)

Avoid Horseplay

Jokes and horseplay have a time and place, but the time and place are not when someone is working on an electric circuit or a piece of moving machinery. Do not be the cause of someone's being injured or killed, and do not let someone else be the cause of you being injured or killed.

Do Not Work Alone

Work with someone else, especially when working in a hazardous location or on a live circuit. Have someone with you to turn off the power or give artificial respiration or cardiopulmonary resuscitation (CPR). One of the effects of electrical shock is that it causes breathing difficulties and can cause the heart to go into fibrillation.

Work with One Hand When Possible

The worst case for electrical shock is when the current path is from one hand to the other. This path causes the current to pass directly through the heart. A person can survive a severe shock between the hand and one foot that would otherwise cause death if the current path were from one hand to the other.

Learn First Aid

Anyone working on electrical equipment should make an effort to learn first aid. Knowing first aid is especially important for anyone who must work with voltages above 50 volts. A knowledge of first aid and especially CPR may save your life or someone else's.

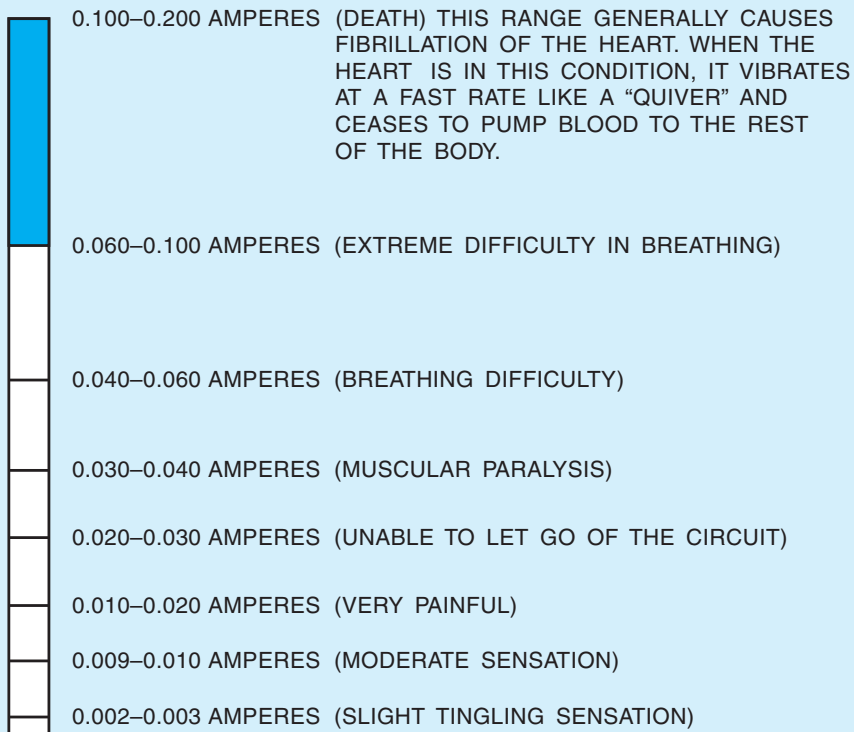
Effects of Electric Current on the Body

Most people have heard that it is not the voltage that kills but the current. Although this is a true statement, do not be misled into thinking voltage cannot harm you. Voltage is the force that pushes the current through the circuit. Voltage can be compared to the pressure that pushes water through a pipe. The more pressure available, the greater the volume of

water flowing through a pipe. Students often ask how much current will flow through the body at a particular voltage. There is no easy answer to this question. The amount of current that can flow at a particular voltage is determined by the resistance of the current path. Different people have different resistances. A body will have less resistance on a hot day when sweating because salt water is a very good conductor. What you ate and drank for lunch can have an effect on your body resistance. The length of the current path can affect the resistance. Is the current path between two hands or from one hand to one foot? All of these factors affect body resistance.

The chart in Figure SF-4 illustrates the effects of different amounts of current on the body. This chart is general and shows the effects on most people. Some people may have less tolerance to electricity, and others may have greater tolerance.

A current of 2 to 3 milliamperes will generally cause a slight tingling sensation. The tingling sensation will increase as current increases and becomes very noticeable at about 10 milliamperes. The tingling sensation is very painful at about 20 milliamperes. Currents between 20 and 30 milliamperes generally cause a person to seize the line and become unable to let go of the circuit. Currents between 30 and 40 milliamperes cause muscular paralysis, and currents between 40 and 60 milliamperes cause breathing difficulty. By the time the current increases to about 100 milliamperes, breathing is extremely difficult. Currents from 100 to 200 milliamperes generally cause death because the heart usually goes into fibrillation. Fibrillation is a condition in which the heart begins to "quiver" and the pumping action stops. Currents above 200 milliamperes generally cause the heart to squeeze shut. When the current is removed the heart will typically return to a normal pumping action. This is the principle of operation of a defibrillator. It is often said that 120 volts is the most dangerous voltage to work with. The reason is that 120 volts generally cause a current flow between 100 and 200 milliamperes through the bodies of most people. Large amounts of current can cause severe electrical burns. Electrical burns are usually very serious because the burn occurs on the inside of the body. The exterior of the body may not look seriously burned, but the inside may be severely burned.



► **Figure SF-4**
The effects of electric current on the body. (Source: Delmar/Cengage Learning)

UNIT 1



Atomic Structure

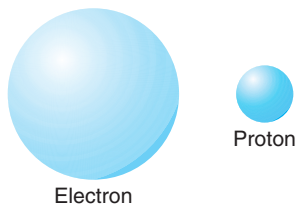
OBJECTIVES

After studying this unit the student should be able to:

- » Discuss basic atomic theory
- » Name the principal parts of an atom
- » Discuss the law of charges
- » Define electricity
- » Discuss the differences between conductors and insulators

To understand electricity, one should start with the study of atoms. The **atom** is the basic building block of the universe. All matter is composed of atoms. An atom is the smallest part of any element. Atoms are composed of three principal parts, the electron, the proton, and the neutron. Electrons exhibit a negative charge, protons exhibit a positive charge, and neutrons have no charge. Some theories suggest that neutrons are composed of both a proton and an electron. The positive charge of the proton and the negative charge of the electron cancel each other.

Protons and neutrons are extremely massive particles as compared to the electron. It is believed that the electron is approximately three times larger than a proton, but the proton weighs approximately 1840 times more than an electron, as shown in Figure 1–1. It is like comparing a piece of lead shot to a soap bubble.



► **Figure 1-1**
The electron is three times larger than the proton, but the proton weighs 1840 times more than the electron.
(Source: Delmar/Cengage Learning)

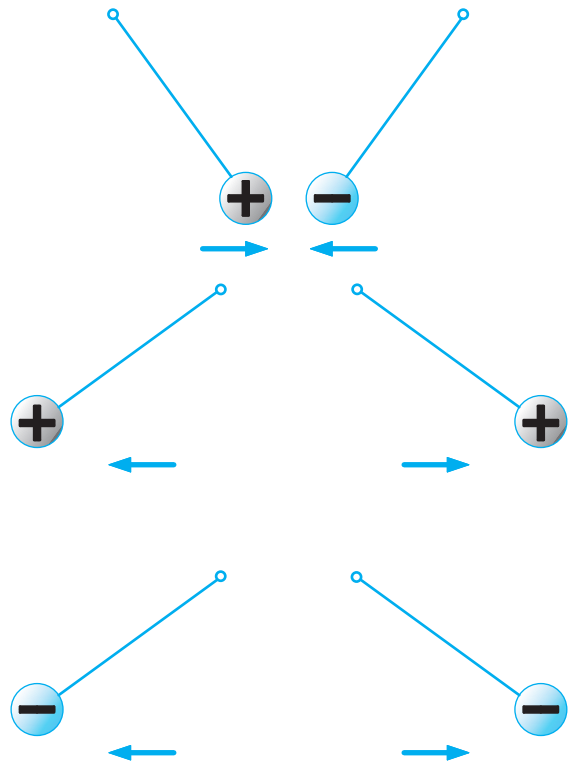
THE LAW OF CHARGES

One of the basic laws of physics concerning atoms is the **law of charges**. This law states that opposite charges attract each other and like charges repel each other. If charged particles were suspended from a string, a positively charged particle and negatively charged particle would attract each other, but two positively charged particles or two negatively charged particles would repel each other, as shown in Figure 1-2. Since **electrons** are negatively charged particles and **protons** are positively charged particles, they are attracted to each other.

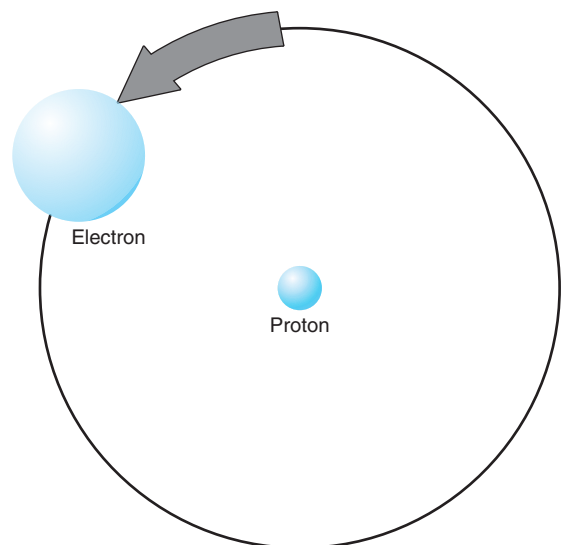
STRUCTURE OF THE ATOM

The **nucleus** or center of the atom is composed of protons and **neutrons**. Electrons orbit the exterior of the atom in specific orbits or shells. The smallest of all atoms is hydrogen. Hydrogen does not contain a neutron in its nucleus. The hydrogen atom contains one proton and one electron, as shown in Figure 1-3. The smallest atom that contains both protons and neutrons in the nucleus is helium, shown in Figure 1-4. Helium contains two protons, two neutrons, and two electrons.

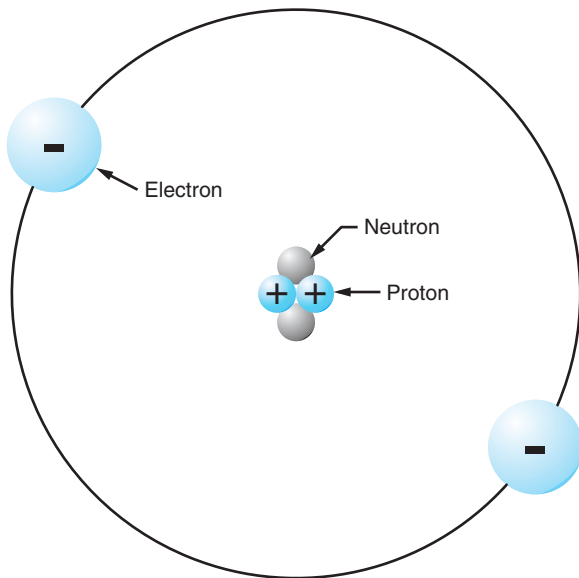
In 1808 a scientist named John Dalton proposed that all matter was composed of atoms. Although the assumptions that Dalton used to prove his theory were later found to be factually incorrect, the idea that all matter is composed of atoms was adopted by most of the scientific world. Then in 1897 J. J. 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,



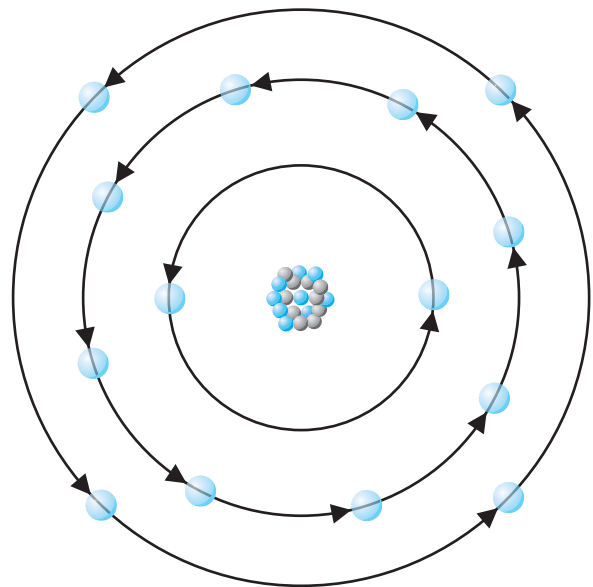
► **Figure 1-2**
The law of charges states that opposite charges attract and like charges repel. (Source: Delmar/Cengage Learning)



► **Figure 1-3**
An atom of hydrogen contains one proton and one electron. (Source: Delmar/Cengage Learning)



► **Figure 1-4**
A helium atom contains both protons and neutrons in the nucleus. (Source: Delmar/Cengage Learning)



► **Figure 1-5**
Electrons exist in allowed orbits or shells. (Source: Delmar/Cengage Learning)

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, similar to the way that planets orbit the sun, as shown in Figure 1-5. 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.

Atoms have a set number of electrons that can be contained in one orbit or shell, as shown in Figure 1-6. The number of electrons that can be contained in any one shell is determined 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.

$$2 \times (1)^2$$

$$2 \times 1 = 2$$

The second orbit can hold no more than eight electrons.

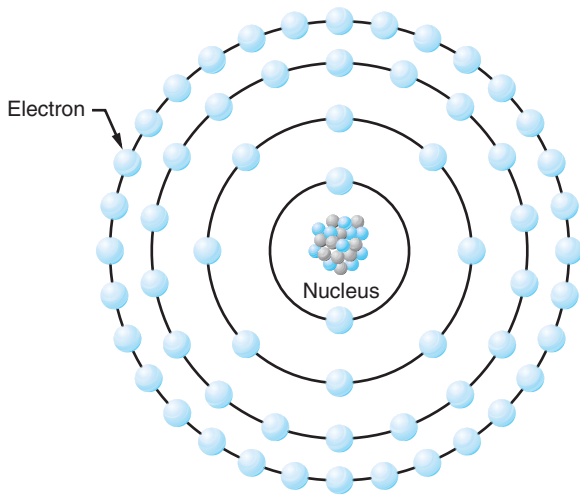
$$2 \times (2)^2$$

$$2 \times 4 = 8$$

The third orbit can contain no more than 18 electrons.

$$2 \times (3)^2$$

$$2 \times 9 = 18$$



► **Figure 1-6**
There is a maximum number of electrons that can be contained in one orbit or shell. (Source: Delmar/Cengage Learning)

The fourth and fifth orbits cannot hold more than 32 electrons. Thirty-two is the maximum number of electrons that can be contained in any orbit.

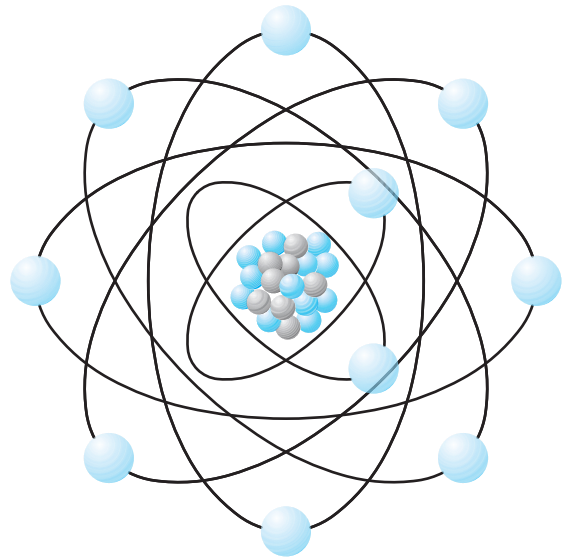
$$2 \times (4)^2$$

$$2 \times 16 = 32$$

Although atoms are often drawn flat, as illustrated in Figure 1-6, the electrons orbit around the nucleus in a circular fashion, as shown in Figure 1-7. The electrons travel at such a high rate of speed that they form a shell around the nucleus. It would be similar to a golf ball being surrounded by a tennis ball that is surrounded by a basketball. For this reason, electron orbits are often referred to as *shells*.

VALENCE ELECTRONS

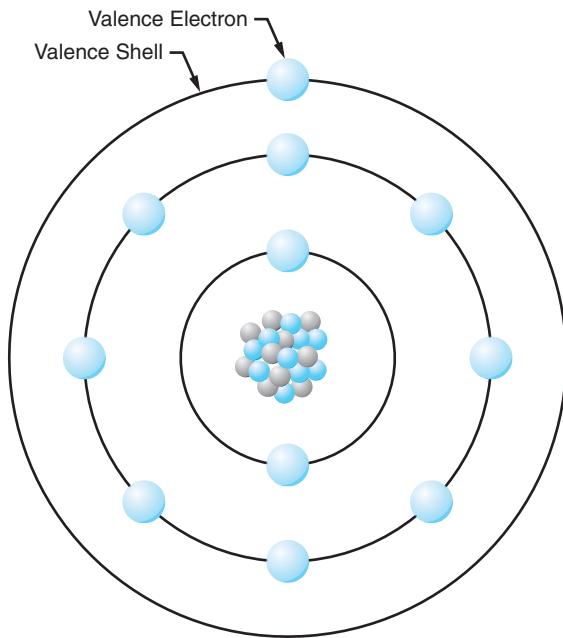
The outermost shell of an atom is known as the **valence shell**. Any electrons located in the outer shell of an atom are known as **valence electrons**, as shown in Figure 1-8. The valence shell of an atom cannot hold more than eight electrons. It is the valence electrons that are of primary concern in the study of **electricity**, because it is these



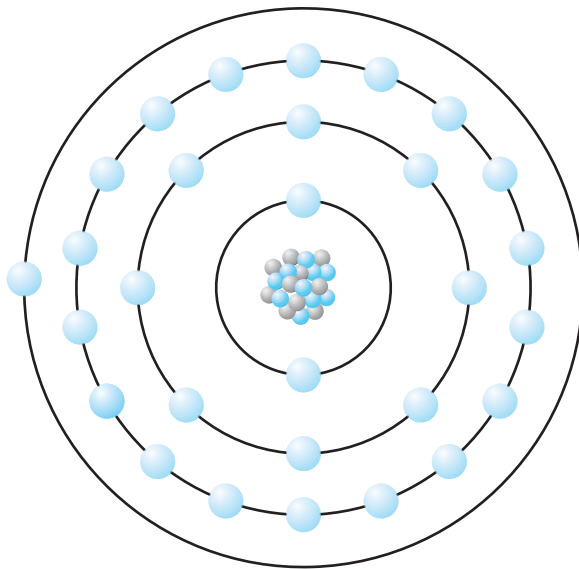
► **Figure 1-7**
Electrons orbit the nucleus in a circular manner. (Source: Delmar/Cengage Learning)

electrons that explain much of electrical theory. A **conductor**, for instance, is made from a material that contains one or two valence electrons. Atoms with one or two valence electrons are unstable and will give up these electrons easily. Conductors are materials that permit electrons to flow through them easily. Silver, copper, and gold 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. An atom of copper is shown in Figure 1-9. Although it is known that atoms containing few valence electrons are the best conductors, it is not known why some of these materials are better conductors than others. Copper, gold, platinum, and silver all contain only one valence electron. Silver, however will conduct electricity more readily than any of the others. Aluminum, which contains three valence electrons, is a better conductor of electricity than platinum, which contains only one valence electron.

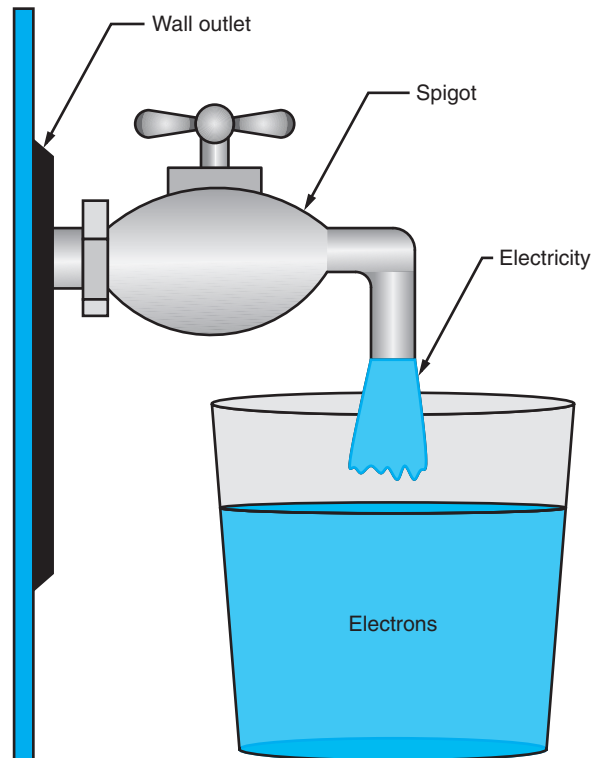
Electricity is composed of electrons. If it were possible to connect a spigot to a wall outlet and catch electricity in a glass, the glass would be full of electrons, as shown in Figure 1-10. Electric current is the flow of electrons, which means that



► **Figure 1-8**
Valence electrons are located in the outermost orbit of an atom. (Source: Delmar/Cengage Learning)



► **Figure 1-9**
Copper atom. (Source: Delmar/Cengage Learning)



► **Figure 1-10**
Electricity is composed of electrons. (Source: Delmar/Cengage Learning)

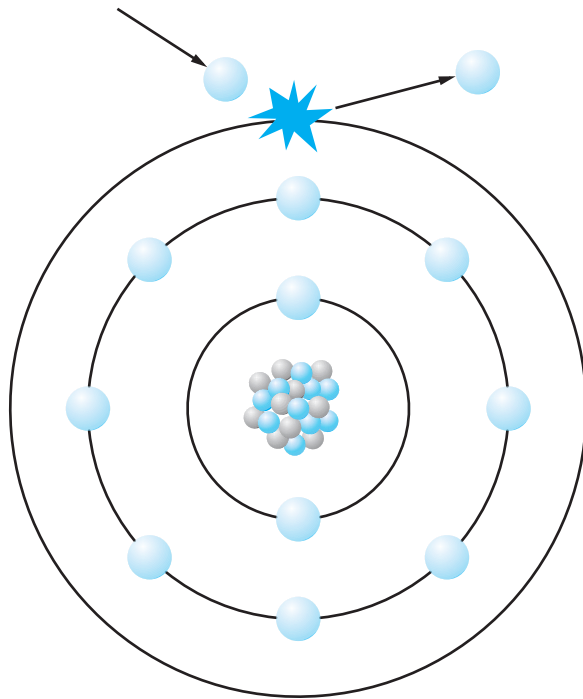
the electrons must be moving to produce current. It is the movement of the electrons that produces electrical energy. There are several theories concerning how electrons are made to flow through a conductor. One theory is generally referred to as the *bump theory*. It states that current flow is produced when an electron from one atom knocks electrons of another atom out of orbit, as shown in Figure 1-11. The striking electron gives its energy to the electron being struck. The striking electron settles into orbit around the nucleus, and the electron that was struck moves off to strike another electron. This action can often be seen in the game of pool. The moving cue ball gives it energy to the ball being struck, as shown in Figure 1-12. The stationary ball then moves off with most of the energy of the cue ball, and the cue ball stops moving. Although most of the energy

was transferred to the stationary ball, some energy was dissipated as heat caused by the impact of the cue ball striking the stationary ball.

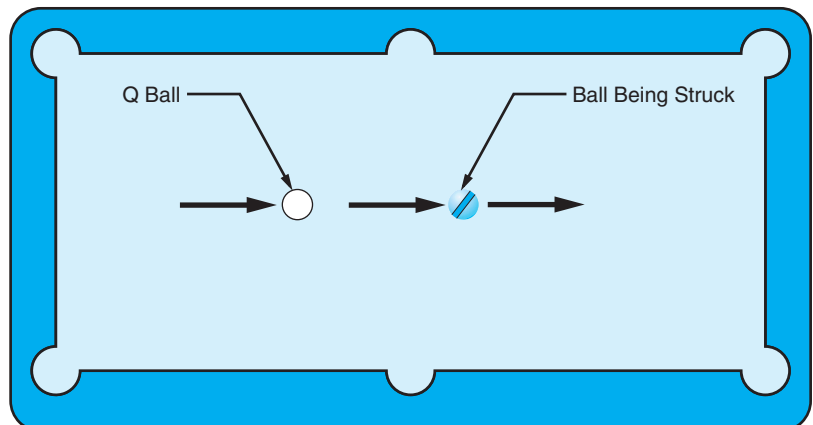
Other theories deal with the fact that all electric power sources produce a positive and negative

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, as shown in Figure 1–13. 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 terminal, as shown in Figure 1–14. The greater the difference in the number of electrons between the negative and positive terminals, the greater the force of repulsion and attraction.

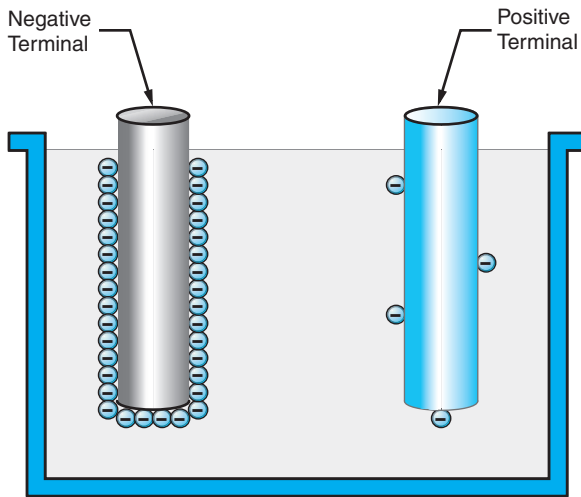
Most of the world's electric power is produced by rotating machines called alternators. Alternators work on the principle of cutting magnetic lines of flux with a conductor. One of the basic principles of electricity is that anytime a conductor cuts magnetic lines of flux, a voltage is induced into the conductor. Another common source of electricity is batteries. Batteries produce electricity by chemical action. Other methods include solar cells, thermocouples, and piezoelectric devices. Solar cells produce electricity when they receive photons of light that cause electrons to move. Thermocouples produce electricity by heating the junction of two different types of metal, and the piezoelectric effect produces current flow from pressure.



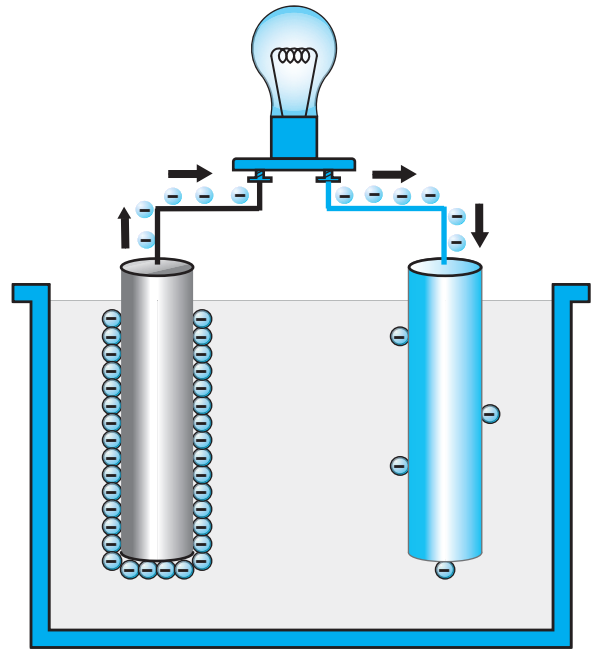
► **Figure 1-11**
One electron knocks another electron out of orbit. (Source: Delmar/Cengage Learning)



► **Figure 1-12**
The cue ball gives its energy to the ball it strikes. (Source: Delmar/Cengage Learning)



► **Figure 1-13**
The negative terminal of a power source has an excess of electrons, and the positive terminal has a lack of electrons. (Source: Delmar/Cengage Learning)

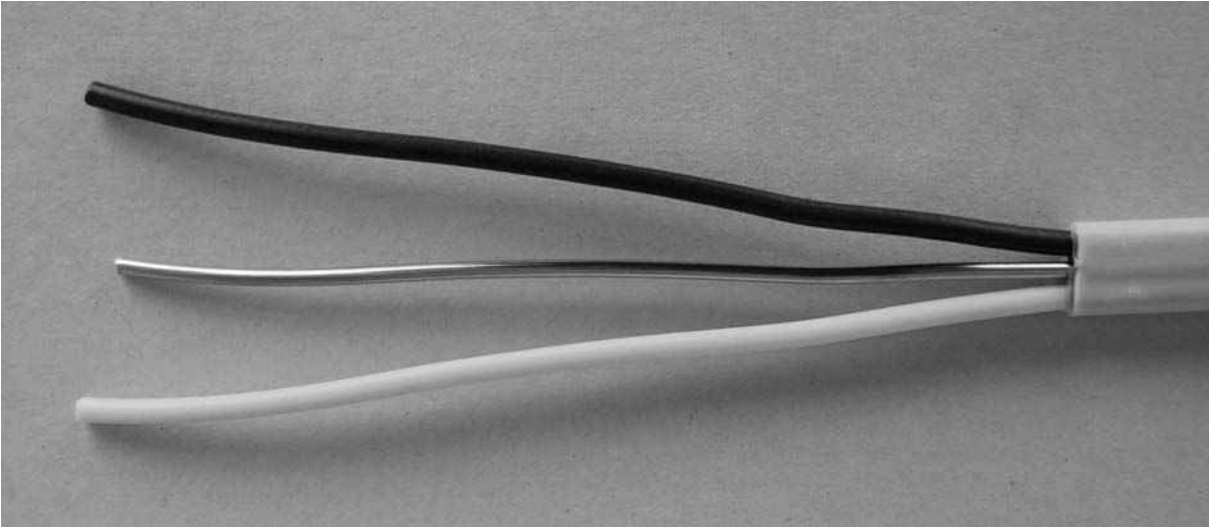


► **Figure 1-14**
Electrons flow from the negative terminal, through the load, to the positive terminal of the power source. (Source: Delmar/Cengage Learning)

INSULATORS

Insulators are materials that do not permit electrons to flow through them easily. The atoms of an insulator generally contain seven or eight valence electrons. When an atom contains seven or eight valence electrons, they are tightly held by the atom and not easily given up. Insulator materials are generally made from compounds instead of a pure element. The molecules of the compounds are extremely stable and do not break

their bond easily. Some examples of insulators are wood, ceramic, mica, rubber, and thermoplastic. Insulator materials are generally rated by voltage. The voltage rating indicates the amount of voltage they can withstand without breaking down. A very common electric cable used in residential wiring is the nonmetallic two-conductor cable with ground, shown in Figure 1-15. This cable is generally referred to as NM or Romex. The insulation around the conductors has a voltage rating of 600 volts.



► **Figure 1-15**
Two conductor cables with ground are commonly used in residential wiring. (Source: Delmar/Cengage Learning)

SUMMARY

- The three major parts of an atom are the electron, proton, and neutron.
- Electrons have a negative charge, protons have a positive charge, and neutrons have no charge.
- The nucleus of the atom contains protons and neutrons.
- An electron is about three times larger than a proton, but the proton weighs about 1840 times more than an electron.
- The law of charges states that opposite charges attract and like charges repel.
- Electrons exist in allowed orbits around the nucleus of the atom.
- Neutral atoms contain the same number of electrons and protons.
- Valence electrons are the electrons located in the outermost orbit of an atom.
- The best conductors of electricity generally contain one or two valence electrons.
- Insulators are materials that do not conduct electricity easily.
- Insulator materials are rated by voltage.

KEY TERMS

atom
conductor
electricity
electron

insulator
law of charges
neutron
nucleus

proton
valence electrons
valence shell

REVIEW QUESTIONS

1. What are the three subatomic parts of an atom, and what charge does each carry?
2. How many times larger is an electron than a proton?
3. The weight of a proton is how many times heavier than that of an electron?
4. State the law of charges.
5. What scientist presented the most accepted theory concerning the behavior of atoms?
6. Materials that make the best conductors generally contain how many valence electrons?
7. What are valence electrons?
8. What is the maximum number of electrons that can exist in the valence orbit?
9. How is most of the electric power in the world produced?
10. Insulator materials are generally rated by the amount of _____ they can withstand without breaking down.

UNIT 2



Electrical Quantities and Ohm's Law

OBJECTIVES

After studying this unit the student should be able to:

- » Define a coulomb
- » Define an ampere
- » Define voltage
- » Discuss resistance
- » Define a watt
- » Use Ohm's law to solve electrical problems

Electricity has a standard set of values. Before you can work with electricity, you must have a knowledge of these values and how to use them. Because 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 or foot. Imagine what a house would look like that was constructed by two carpenters who used different lengths of measure for an inch or foot. The same holds true for people who work with electricity. A volt, ampere, or ohm is the same for everyone who uses them.

COULOMB

A **coulomb** is a quantity measurement of electrons. One coulomb contains 6.25×10^{18} electrons. The number shown in Figure 2-1 is the number of

6,250,000,000,000,000,000

► **Figure 2-1**
The number of electrons in a coulomb. (Source: Delmar/Cengage Learning)

electrons in one coulomb. Because the coulomb is a unit of measurement, it is similar to a quart, gallon, or liter. It takes a certain amount of liquid to equal a quart, just as it takes a certain amount of electrons to equal a coulomb.

AMPERE

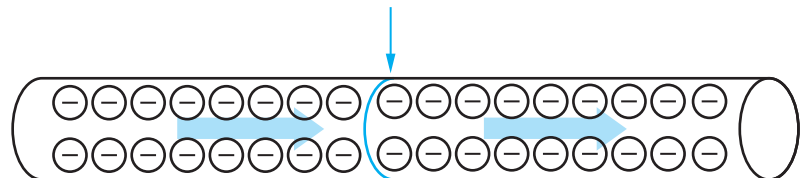
The **ampere**, or amp, is defined as one coulomb per second. Notice that the definition of an amp involves a quantity measurement (the coulomb) combined with a time measurement (the second). One amp of current flows through a conductor when one coulomb flows past a point on one second, Figure 2-2. Amperage 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 2-3. If one coulomb were to flow past a point in a half

second, there would be 2 amperes of current flow. If one coulomb were to flow past a point in two seconds there would be a half amp of flow. Current is normally measured in amperes, milliamperes, and microamperes. A milliamp is one-thousandth of an amp (0.001). A microamp is one-millionth of an amp (0.000,001).

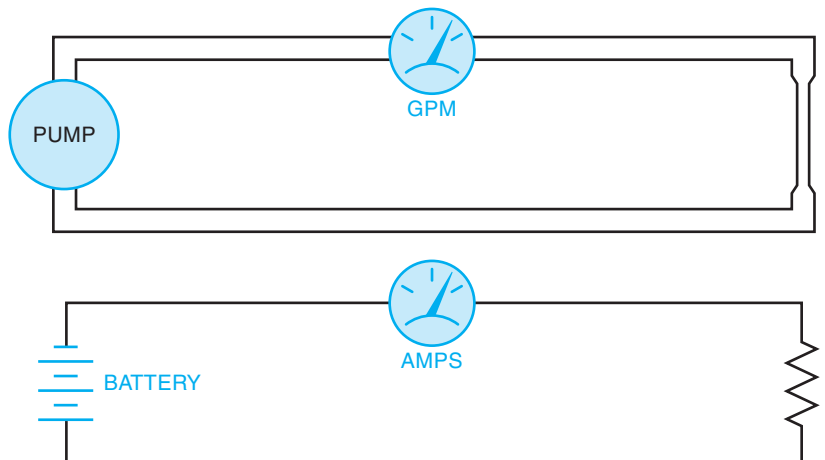
VOLT

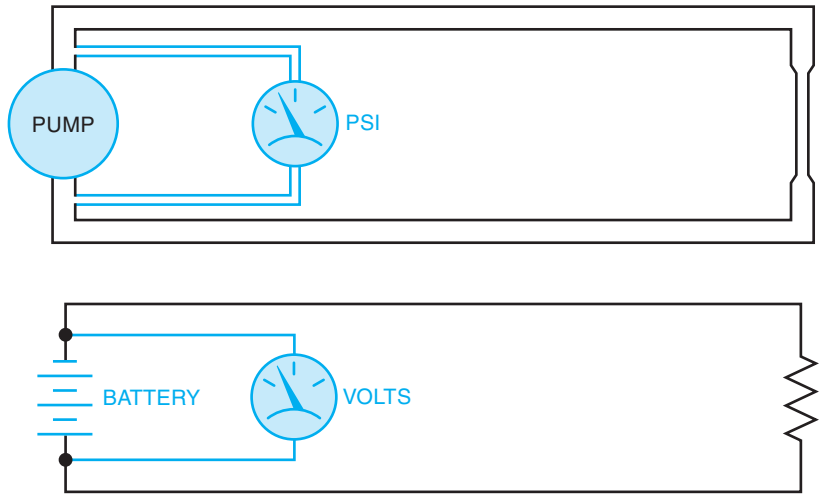
Voltage is actually defined as **electromotive force**, or EMF. It is the force that pushes the electrons through a wire and is often referred to as **electrical pressure**. One should remember that voltage cannot flow. To say that voltage flows is like saying that pressure flows through a pipe. Pressure 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. The 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 2-4.

► **Figure 2-2**
One coulomb flowing past a point in one second. (Source: Delmar/Cengage Learning)



► **Figure 2-3**
Water flow is similar to current flow. (Source: Delmar/Cengage Learning)





► **Figure 2-4**
The pressure in a water system is comparable to the voltage in an electric circuit. (Source: Delmar/Cengage Learning)

OHM

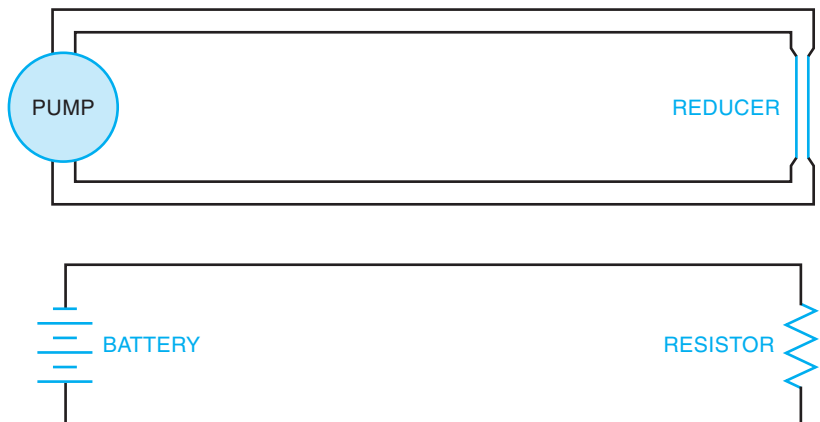
The **ohm** is the measure of the **resistance** to the flow of current. The voltage of the circuit must overcome the resistance before it can cause electrons to flow through it. Without resistance, every electrical circuit would be a short circuit. All electrical loads, such as heating elements, lamps, motors, transformers, and so forth, are measured in ohms. In a water system, a reducer would be used to control the flow of water. In an electrical circuit, a resistor can be used to control the flow of electrons. Figure 2-5 illustrates this concept.

There are electrical quantities other than resistance that are also measured in ohms. Inductive reactance and capacitive reactance are current-limiting forces that exist in alternating current circuits and

will be discussed later in the text. Another term used to describe a current-limiting force is impedance. **Impedance** is a combination of all current limiting forces in a circuit and can include resistance, inductive reactance, and capacitive reactance. Because resistance is only one of the current-limiting forces found in alternating current circuits, impedance is the quantity generally used to describe the current-limiting force in an alternating current circuit. Impedance will be discussed in more detail later in the text.

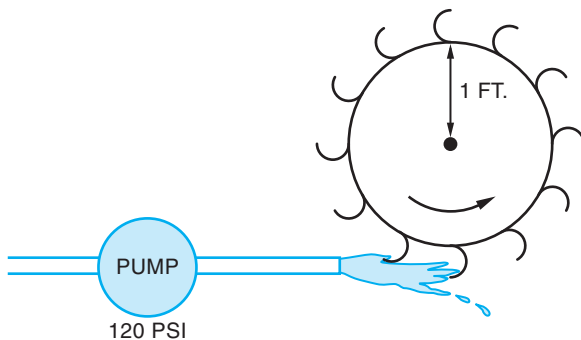
WATT

Wattage is a measure of the amount of power that is being used in the circuit. It is proportional to the amount of voltage and the amount of current flow.



► **Figure 2-5**
A reducer reduces the flow of water through a water system just as a resistor reduces the flow of electrons in an electric circuit. (Source: Delmar/Cengage Learning)

To understand watts, return to the example of the water system. Assume that a water pump has a pressure of 120 psi (pounds per square inch) and causes a flow rate of one gallon per second. Now assume that this water is used to drive a waterwheel as shown in Figure 2-6. Notice that the waterwheel has a radius of 1 ft from the center shaft to the rim of the wheel. Since water weighs 8.34 pounds per gallon, and is being forced against the wheel at a pressure of 120 psi, the wheel could develop a torque of 1000.8 foot pounds ($120 \times 8.34 \times 1 = 1000.8$). If the pressure is increased to 240 psi, but the water flow remains constant, the force against the wheel will double ($240 \times 8.34 \times 1 = 2001.6$). If the pressure remains at 120 psi, but the water flow is increased to two gallons per second, the force against the wheel will again double ($120 \times 16.68 \times 1 = 2001.6$). Notice that the amount of power developed by the waterwheel is determined by both the amount of pressure driving the water and the amount of flow.



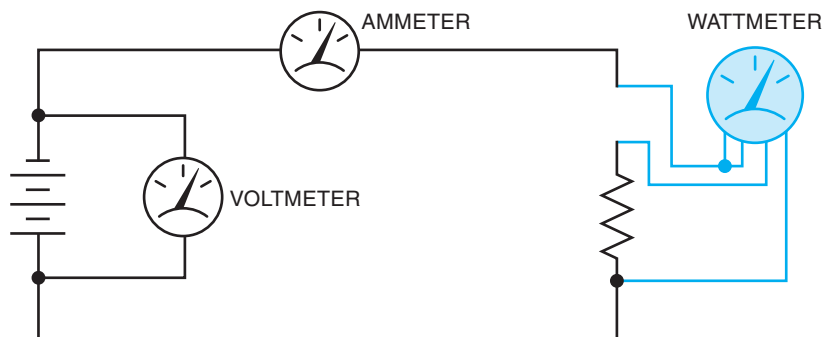
► **Figure 2-6**
Pump used to drive a waterwheel. (Source: Delmar/Cengage Learning)

The power of an electrical circuit is very similar. Figure 2-7 shows a resistor connected to a circuit with a voltage of 120 volts and a current flow of 1 amp. The resistor shown represents an electric heating element. When 120 volts forces a current of 1 amp through it, the heating element will produce 120 watts of heat ($120 \times 1 = 120$ watts). If the voltage is increased to 240 volts, but the current remains constant, the element will produce 240 watts of heat ($240 \times 1 = 240$ watts). If the voltage remains at 120 volts, but the current is increased to 2 amps, the heating element will again produce 240 watts ($120 \times 2 = 240$). Notice that the amount of power used by the heating element is determined by the amount of current flow and the voltage driving it.

A good rule to remember concerning watts, or **true power**, is that before watts can exist in an electric circuit, electrical energy must be converted or changed into some other form. When current flows through a resistor, the resistor becomes hot and dissipates heat. Heat is a form of energy. The wattmeter connected in the circuit shown in Figure 2-7 measures the amount of electrical energy that is being converted into heat energy. If the resistor shown in Figure 2-7 were replaced with an electric motor the wattmeter would measure the amount of electrical energy that was converted into mechanical energy.

OHM'S LAW

Ohm's law is named for the German scientist George S. Ohm. Ohm 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 1 volt to push 1 amp through 1 ohm*.



► **Figure 2-7**
The amount of voltage and current determine the power. (Source: Delmar/Cengage Learning)

Figure 2–8 shows three basic Ohm's law formulas. In these formulas, E stands for electromotive force and is used to represent the voltage. The I stands for the intensity of the current and is used to represent the amount of current flow or amps. The letter R stands for resistance and is used to represent the ohms.

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 ohms and a current flow through it of 2 amps. The voltage connected to this circuit is 100 volts ($2 \text{ amps} \times 50 \text{ ohms} = 100 \text{ volts}$). The second formula indicates that if the voltage and resistance of the circuit are known, the amount of current flow can be found. Assume a 120-volt circuit is connected to a resistance of 30 ohms. The amount of current that will flow in the circuit is 4 amps ($120 \text{ volts} / 30 \text{ ohms} = 4 \text{ amps}$). The third formula states that if the voltage and current flow in a circuit are known, the resistance can be found. Assume a circuit has a voltage of 240 volts and a current flow of 10 amps. The resistance in the circuit is 24 ohms ($240 \text{ volts} / 10 \text{ amps} = 24 \text{ ohms}$).

Figure 2–9 shows a simple chart that can be a great help when trying to remember the Ohm's law formula. To use the chart, cover the quantity 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 IR . Therefore, $E = I \times R$. If the current is to be found, cover the I on the chart. The chart now shows E/R . Therefore, $I = E/R$. If the resistance of a circuit is to be found, cover the R on the chart. The chart now shows E/I . Therefore, $R = E/I$.

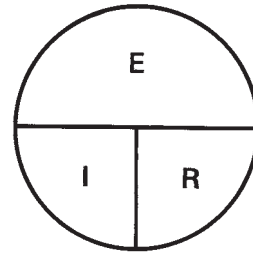
A larger chart that shows the formulas needed to find watts as well as the voltage, amperage, and resistance is shown in Figure 2–10. Because watt is the unit of electric power, the letter P is used to represent watts. The chart is divided into four quadrants. Each quadrant contains three formulas that can be used to find the electrical quantity represented in that quadrant.

EXAMPLE 1: An electric heating element is connected to 120 volts and has a resistance of 18 ohms. What is the power consumption of this element?

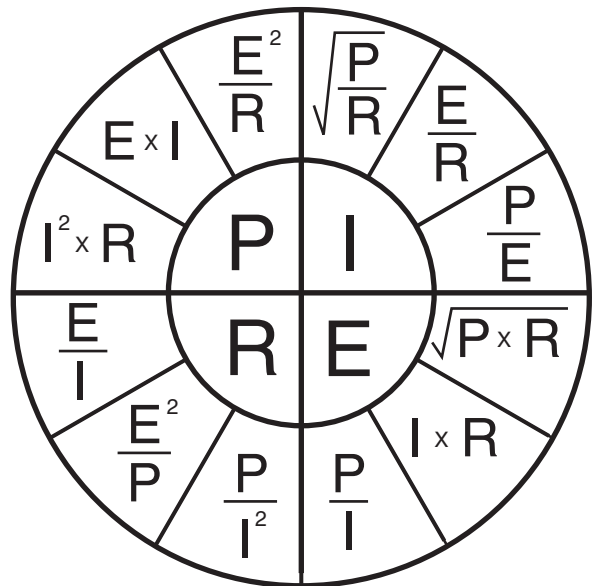
SOLUTION: The electrical quantity to be determined is power, or watts. The known electrical values are voltage and resistance. Using the formula chart in

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

► **Figure 2–8**
Three Ohm's law formulas. (Source: Delmar/Cengage Learning)



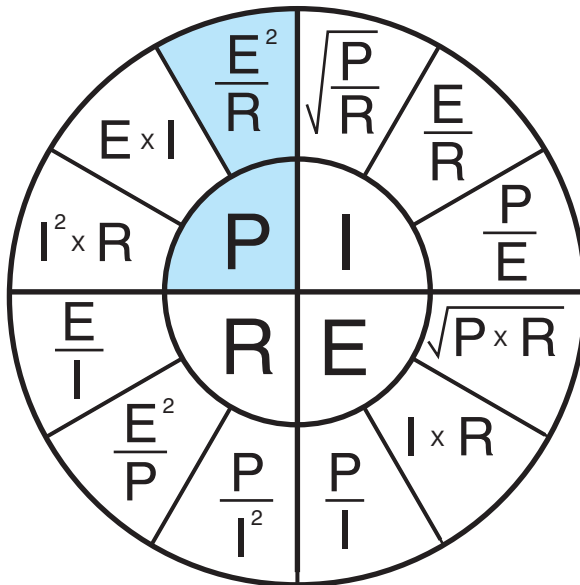
► **Figure 2–9**
Ohm's law formula chart. (Source: Delmar/Cengage Learning)



► **Figure 2–10**
Ohm's law chart. (Source: Delmar/Cengage Learning)

Figure 2–10, choose the formula for finding power that includes the two known electrical quantities. The formulas for determining power are located in the first quadrant of the chart. The formula that contains the known values of voltage and resistance is $P = E^2/R$, as shown in Figure 2–11.

$$\begin{aligned} P &= \frac{E^2}{R} \\ P &= \frac{120 \times 120}{18} \\ P &= 800 \text{ watts} \end{aligned}$$



► **Figure 2-11**
Power can be determined when the voltage and resistance are known. (Source: Delmar/Cengage Learning)

EXAMPLE 2: A 240-volt electric furnace has a power rating of 15,000 watts, or 15 kW. How much current will this furnace draw when in operation?

SOLUTION: The quantity you are looking for is current or amps, represented by the letter I .

Formulas for determining current are located in the second quadrant of the formula chart shown in Figure 2-10. The two known quantities are power (watts) and voltage. The correct formula is $I = P/E$, as shown in Figure 2-12.

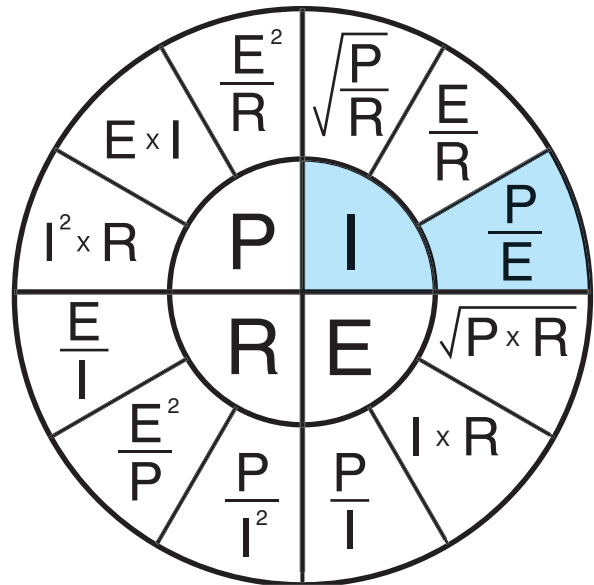
$$I = \frac{P}{E}$$

$$I = \frac{15,000}{240}$$

$$I = 62.5 \text{ amperes}$$

METRIC PREFIXES

Metric prefixes are used in the electrical field just as they are in most other scientific fields. In the English system of measure, different divisions are used for different measurements. A yard, for example, can be divided into 3 feet. A foot is generally divided into 12 inches, and an inch is often divided into sixteenths. In the metric system, ten or a multiple of ten is always the dividing factor. A kilometer can be



► **Figure 2-12**
Current can be determined when the power and voltage are known. (Source: Delmar/Cengage Learning)

kilo	1000
hecto	100
deka	10
Base unit	1
deci	$\frac{1}{10}$ or 0.1
centi	$\frac{1}{100}$ or 0.01
milli	$\frac{1}{1000}$ or 0.001

► **Figure 2-13**
Standard metric prefixes. (Source: Delmar/Cengage Learning)

divided into 10 hectometers. A hectometer can be divided into 10 dekameters, and a dekameter can be divided into 10 meters. A chart listing standard metric prefixes is shown in Figure 2-13.

In the electrical field, a different type of metric notation called *engineering notation* is used instead of the standard metric prefixes. Engineering notation is in steps of one thousand instead of ten. A chart

listing common engineering notation prefixes and their symbols is shown in Figure 2–14. Starting with the base unit or one, the first engineering unit greater than one is kilo, or one thousand. The next engineering unit greater than kilo is Mega, or one million. A million is one thousand times larger than a thousand. The first engineering unit less than the base unit is milli, or one one thousandth. The next

engineering unit less than milli is micro, or one one-millionth. A millionth is one thousand times smaller than a thousandth.

These prefixes are used to simplify standard electrical measurements. Five billion watts can be written as 5,000,000,000 W or as 5 GW. Twenty-five microamperes can be written as 0.000,025 A or as 25 μA .

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

► **Figure 2–14**
Standard prefixes used in engineering notation. (Source: Delmar/Cengage Learning)

SUMMARY

- ⌚ A coulomb is a quantity measurement of electrons that is equal to 6.25×10^{18} electrons.
- ⌚ An ampere is the amount of current that flows through a circuit.
- ⌚ An ampere is defined as one coulomb per second.
- ⌚ Voltage is the force that pushes the electrons through a circuit.
- ⌚ Voltage is defined as electromotive force (EMF).
- ⌚ Voltage is sometimes referred to as electrical pressure.
- ⌚ Resistance to the flow of electricity is measured in ohms.
- ⌚ Wattage is a measurement of electric power.
- ⌚ Before an electric circuit can have true power, or watts, electrical energy must be converted into some other form of energy.
- ⌚ Ohm's law can be used to mathematically find electrical values when at least two of these values are known.

KEY TERMS

ampere
coulomb
electrical pressure
electromotive force

impedance
ohm
Ohm's law
resistance

true power
voltage
wattage

REVIEW QUESTIONS

1. What is a coulomb?
2. What is the definition of an amp?
3. Define the term *voltage*.
4. Define the term *ohm*.
5. Define the term *watt*.
6. An electric heating element has a resistance of 16 ohms and is connected to a voltage of 120 volts. How much current (amps) will flow in the circuit?
7. How many watts of heat are being produced by the heating element in question 6?
8. A 240-volt circuit has a current flow of 20 amps. How much resistance (ohms) is connected in the circuit?
9. An electric motor has an apparent resistance of 15 ohms. If a current of 8 amps is flowing through the motor, what is the connected voltage?
10. A 240-volt air conditioning compressor has an apparent resistance of 8 ohms. How much current (amps) will flow in the circuit?
11. How much power (watts) is being used by the compressor in question 10?



- 12.** A 5,000-watt electric heating unit is connected to a 240-volt line. What is the current flow (amps) in the circuit?
- 13.** If the voltage in question 12 is reduced to 120 volts, how much current (amps) would be needed to produce the same amount of power?
- 14.** Is it less expensive to operate the electric heating unit in question 12 on 240 volts or on 120 volts? Explain your answer.

UNIT 3



Measuring Instruments

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation and connection of a voltmeter
- Measure voltage using a multirange voltmeter
- Discuss the operation of an ammeter
- Describe different types of ammeters
- Measure current with an ammeter

Anyone who wants to work in the air conditioning and refrigeration field must become proficient with the common instruments used to measure electrical quantities. These instruments are the **voltmeter**, **ammeter**, and **ohmmeter**. In the air-conditioning and refrigeration field, the technician works almost exclusively with alternating current. For this reason, the meters covered in this unit are intended to be used in an alternating current system.

VOLTMETER

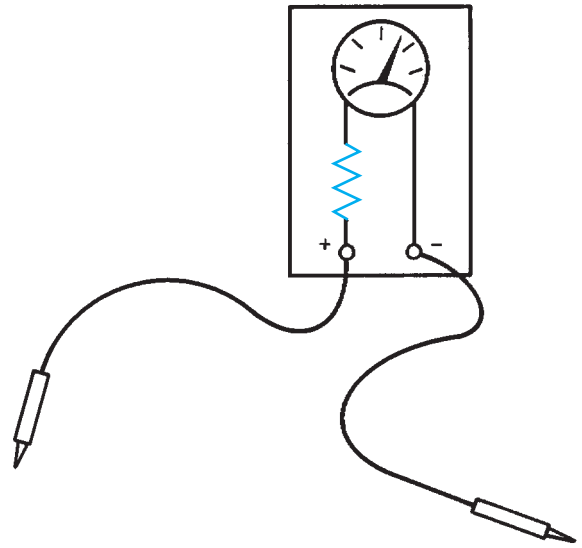
The voltmeter is designed to be connected directly across the source of power. Figure 3–1 shows a voltmeter being used to test the voltage of a panel box. Notice that the leads of the meter are connected directly across the source of voltage. The reason a voltmeter can be connected directly across the power



► **Figure 3-1**
Voltmeter being used to test the voltage of a panel.
(Source: Delmar/Cengage Learning)

line is because it has a very high resistance connected in series with the meter movement, Figure 3-2. A common resistance for a voltmeter is about 20,000 ohms per volt for DC and 5,000 ohms per volt AC. Assume the voltmeter shown in Figure 3-2 is an AC meter and has a full-scale range of 300 volts. The resistor connected in series with the meter would, therefore, have a resistance of 1,500,000 ohms ($300 \text{ volts} \times 5,000 \text{ ohms per volt} = 1,500,000 \text{ ohms}$).

Most voltmeters are **multiranged**, 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 volts full-scale, 12 volts full-scale, 30 volts full-scale, 60 volts full-scale, 120 volts full-scale, 300 volts full-scale, and 600 volts full-scale.



► **Figure 3-2**
A voltmeter has high resistance connected in series with the meter movement. (Source: Delmar/Cengage Learning)

The reason for making a meter with this number of scales is to make the meter as versatile as possible. If it is necessary to check for a voltage of 480 volts, the meter can be set on the 600-volt range. If it becomes necessary to check a control voltage of 24 volts, however, it would be very difficult to do on the 600-volt range. If the meter is set on the 30-volt range, however, it becomes a simple matter to test for a voltage of 24 volts. The meter shown in Figure 3-3 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, Figure 3-4. Notice that when the higher voltage settings are selected, more resistance is inserted in the circuit.

Another type of voltmeter that is gaining popularity is the **digital meter**. A digital meter displays the voltage in digits instead of using a meter movement, Figure 3-5. Digital meters have several advantages over voltmeters that use a meter movement (commonly called **analog meters**). The greatest advantage is that the **input impedance**, or resistance, is higher. Analog meters commonly

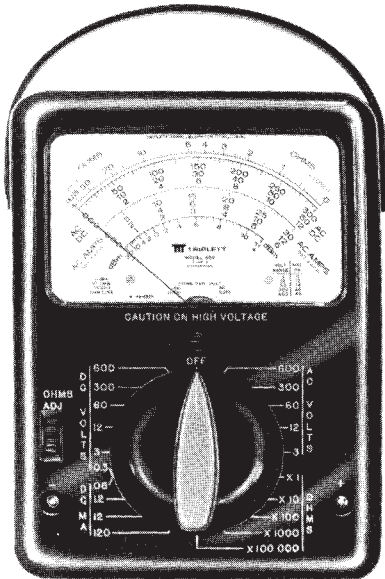
have a resistance of about 5,000 ohms per volt. This means that on a 3-volt full-scale range, the meter movement has a resistance of 15,000 ohms connected in series with it ($3 \times 5,000 = 15,000$). On the 600-volt full-scale range, the meter movement has a resistance of 3,000,000 ohms connected in series with it ($600 \times 5,000 = 3,000,000$). Digital meters commonly have an input impedance of

10,000,000 ohms (10 megohms), regardless of the range they are set on. The advantage of this high input impedance is that it does not interfere with a low-power circuit. The advantage of this may not be too clear at first, because most technicians are used to working with circuits that have more than enough power to operate the meter. However, many of the newer controls are electronic; these circuits may be greatly altered if tested with a low impedance meter.

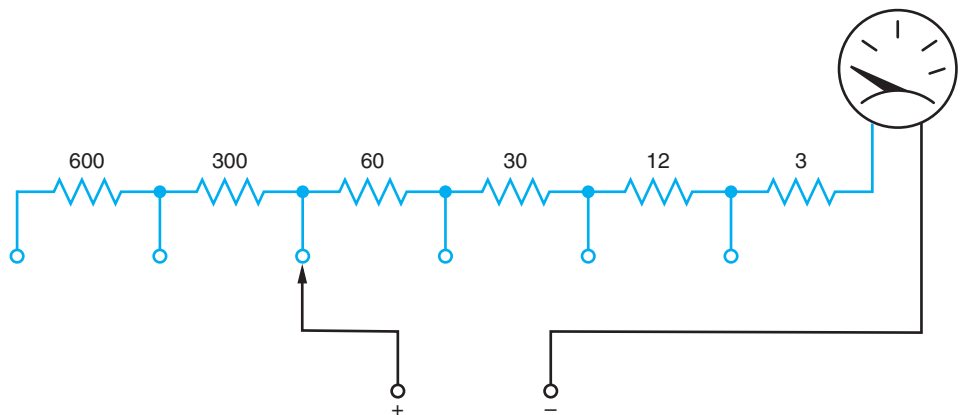
For example, assume an electronic control is operated on 5 volts, and has a total current capacity of 100 microamps (.000100 amps). Now assume that a 5,000-ohm-per-volt meter is set on the 12-volt scale and is to be used to check the control circuit. The voltmeter has a resistance of $5,000 \times 12 = 60,000$ ohms. If this meter is used to test the circuit, the meter will have a current draw of 83.3 microamps ($5 \text{ volts} / 60,000 \text{ ohms} = .0000833 \text{ amps}$). Because the control circuit only has a total current capacity of 100 microamps, the meter is using most of the current to operate. The circuit has been changed to such a degree that it can no longer operate.

If the digital meter is used to test this same circuit, it will have a current draw of 0.5 microamp ($5 \text{ volts} / 10,000,000 = .00000005 \text{ amp}$). The circuit will be able to furnish the 0.5 microamp needed to operate the meter without a problem or altering the circuit.

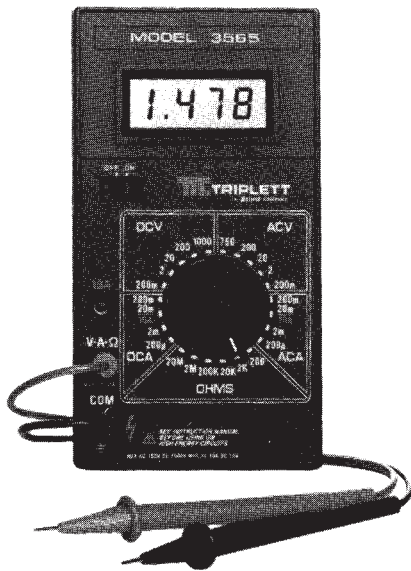
Another advantage of the digital meter is that it is generally easier for an inexperienced person to learn to read. Analog meters can be used for about



► **Figure 3-3**
Multimeter with an analog scale. (Courtesy of Triplett Corp.).



► **Figure 3-4**
A multirange voltmeter.
(Source: Delmar/Cengage Learning)



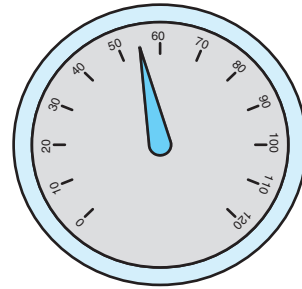
► **Figure 3-5**
Digital multimeter. (Courtesy of Triplet Corp.).

99% of the measurements that must be taken, but it generally takes some time and practice to read them properly.

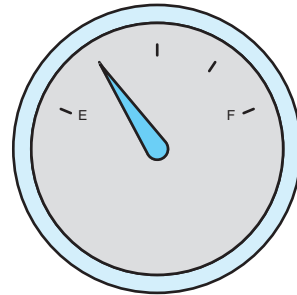
Learning to read the scale of a multimeter takes time and practice. Most people use meters everyday without thinking about it. A very common type of meter used daily by most people is shown in Figure 3-6. The meter illustrated is a speedometer similar to those seen in an automobile. This meter is designed to measure speed. It is calibrated in miles per hour (mph). The speedometer shown has a full-scale value of 80 mph. If the pointer is positioned as shown in Figure 3-6, most people would know instantly that the speed of the automobile is 55 mph.

Figure 3-7 illustrates another common meter used by most people. This meter is used to measure the amount of fuel in the tank of an 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 now indicating that there are a total of 5 gallons of fuel remaining in the tank.

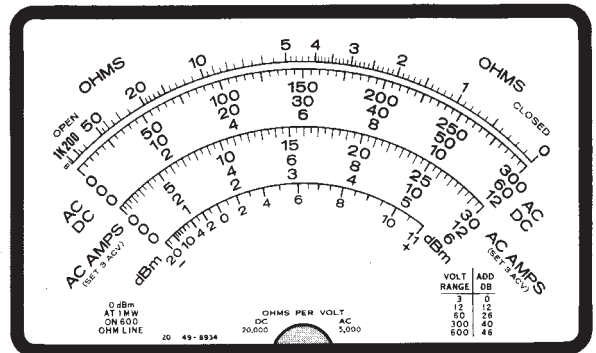
Learning to read the scale of a multimeter is similar to learning to read a speedometer or fuel



► **Figure 3-6**
Speedometer. (Source: Delmar/Cengage Learning)



► **Figure 3-7**
Fuel gauge. (Source: Delmar/Cengage Learning)



► **Figure 3-8**
Multimeter face. (Source: Delmar/Cengage Learning)

gauge. The meter scale shown in Figure 3-8 has several scales used to measure different values and quantities. The very top of the scale is used to measure resistance or ohms. Notice that the scale begins at the left-hand side with infinity, and zero

can be found at the far right-hand side. Ohmmeters will be covered later in this unit. The second scale is labeled AC-DC and is used to measure voltage. Notice this scale has three different full-scale values. The top scale is 0 to 300, the second scale is 0 to 60, and the third scale is 0 to 12. The scale used is determined by the setting of the range control switch. The third set of scales is labeled AC AMPS. 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 seldom if ever used by the technician in the field.

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. Because these numbers are in multiples of 10, it is an easy matter 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 volts full-scale, the 300-volt scale would be used, and the reading divided by 100. The reading can be divided by 100 by moving the decimal point 2 places to the left. In Figure 3-9, the meter is indicating a voltage of 2.5 volts if the selector switch is set for 3 volts full-scale. The pointer is indicating a value of 250. Moving the decimal point 2 places to the left will give a reading of 2.5 volts. If the selector switch is set for a full-scale value of 30 volts, the meter shown in Figure 3-9 would be indicating a value of 25 volts. 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 volts. The meter shown in Figure 3-10 is indicating a voltage of 440 volts. Since the full-scale value of the meter is set for 600 volts, use the 60-volt range and multiply the reading on the meter by 10. This can be done by moving the decimal point one place to the right. The pointer in Figure 3-10 is indicating a value of 44. If this value is multiplied by 10, the correct voltage reading becomes 440 volts.

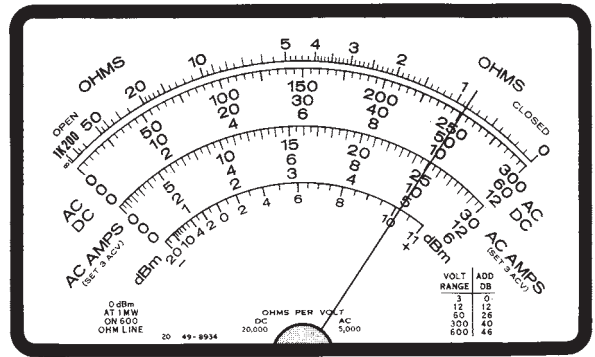


Figure 3-9
Reading an analog multimeter. (Source: Delmar/Cengage Learning)

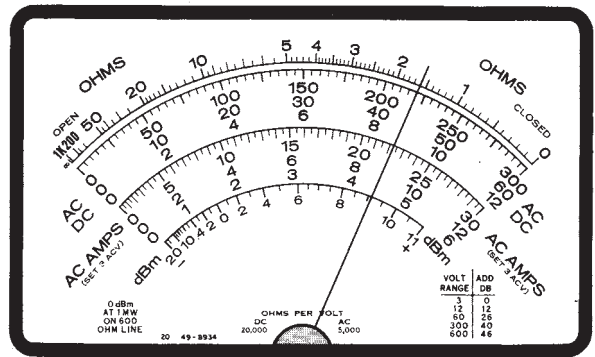


Figure 3-10
Reading an analog multimeter. (Source: Delmar/Cengage Learning)

There are three distinct steps that should be followed when reading a meter. Following the steps is especially important for someone who has not had a great deal of experience reading a multimeter. These steps are:

1. **Determine what the meter indicates.** Is the meter set to read a value of DC voltage, DC current, AC voltage, AC current, ohms? It is impossible to read a meter if you do not know what the meter is measuring.
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 readings when the meter is set to indicate a value of 600 volts full-scale and when it is set for 30 volts full-scale.

If you are not sure of the voltage value being tested, always set the meter on its highest range and then reduce the range until the indicator moves up scale to a value that can be easily read. A meter can never be damaged by placing it on a high range setting and then reducing it, but it can be damaged by placing it on a low range setting and then connecting it to a high voltage.

Another consideration is the position of the indicator. Analog meters are more accurate at the upper end of the scale than at the lower end. If possible, adjust the range setting so that the indicator is more than halfway up the 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 hatch marks on the meter face for the range the selector switch is set for. If the meter in Figure 3-8 is set for a value of 300 volts full-scale, each hatch mark has a value of 5 volts. If the full-scale value of the meter is 60 volts, however, each hatch mark has a value of 1 volt.

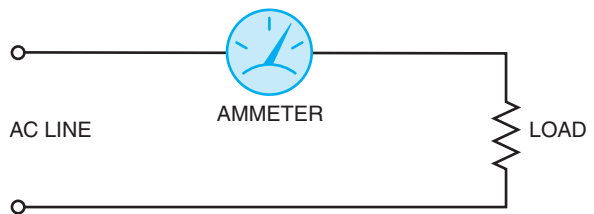
When reading a meter, always look straight at the indicator. Viewing the indicator from the side causes a parallax view and the reading will not be accurate. It is the same effect as produced when trying to determine the speed of an automobile by looking at the speedometer from the passenger seat. The only way to accurately determine the speed is to view the speedometer straight on, not from the side. Some meters have a mirror section on the meter face. This permits the person using the meter to line up the indication with the reflection behind it to ensure an accurate reading.

AMMETER

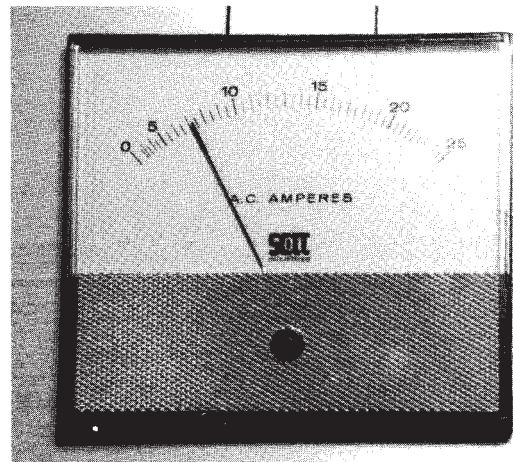
There are several different types of ammeters used to measure electric current. Clamp-on types are generally used in the field for troubleshooting, and inline

ammeters are panel mounted. The inline ammeter, unlike the voltmeter, is a very-low-impedance device. Inline ammeters must be connected in series with the load to permit the load to limit the current flow, Figure 3-11.

An ammeter has a typical impedance of less than .1 ohm. 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 an impedance of .1 ohm is connected across a 240-volt AC line. The current flow in this circuit would be 2,400 amps ($240/.1 = 2,400$). The blinding flash of light would be followed by the destruction of the ammeter. Ammeters that are connected directly into the circuit as shown in Figure 3-11 are referred to as **inline** ammeters. Figure 3-12 shows an inline ammeter.



► **Figure 3-11**
An ammeter must be connected in series with the load.
(Source: Delmar/Cengage Learning)



► **Figure 3-12**
AC inline ammeter. (Source: Delmar/Cengage Learning)

Notice that the meter in Figure 3–12 has several ranges. AC ammeters use a **current transformer** to provide multiscale capability. The primary of the transformer is connected in series with the load, and the ammeter is connected to the secondary of the transformer. Figure 3–13 illustrates this type of connection. 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.

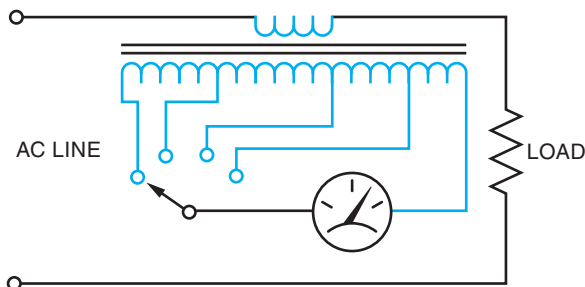
When a large amount of AC current must be measured, a current transformer is connected in to the power line. The ammeter is then connected to the secondary of the transformer. The AC ammeters are designed to indicate a current of 5 amps, and the current transformer determines the value of line current that must flow to produce a current of 5 amps on the secondary of the transformer. The incoming line may be looped around the opening in the transformer several times to produce the proper turns ratio between the primary and the secondary windings. Figure 3–14 shows a transformer of this type. This type of connection is often used for panel meters mounted on large commercial units.

The type of ammeter used in the field by most air conditioning service technicians is the **clamp-on** type of ammeter similar to the one shown in Figure 3–15. To use this meter, the jaw of the meter is clamped around one of the conductors supplying power to the load. Figure 3–16 shows this connection. Notice that the meter is clamped around only one of the power 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.

This type of meter also uses a current transformer to operate the meter. 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 of the magnetic field and its frequency determine the amount of voltage induced in the current transformer. Since 60 Hz is a standard frequency throughout the country, the amount of induced voltage is proportional to the strength of the magnetic field.

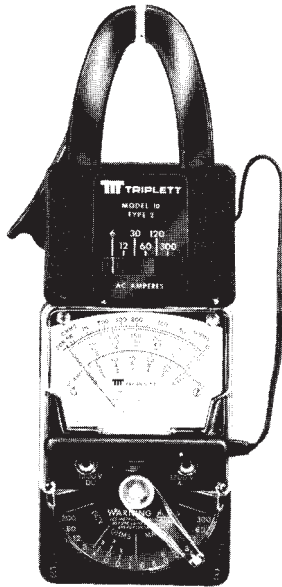
The clamp-on type of ammeter can have different range settings by changing the **turns ratio** of the secondary of the transformer just as the inline ammeter does in Figure 3–13. The primary of the current transformer is the conductor the ammeter is connected around. If the ammeter is connected around one wire as shown in Figure 3–16, the



► **Figure 3–13**
A current transformer provides different scales.
(Source: Delmar/Cengage Learning)

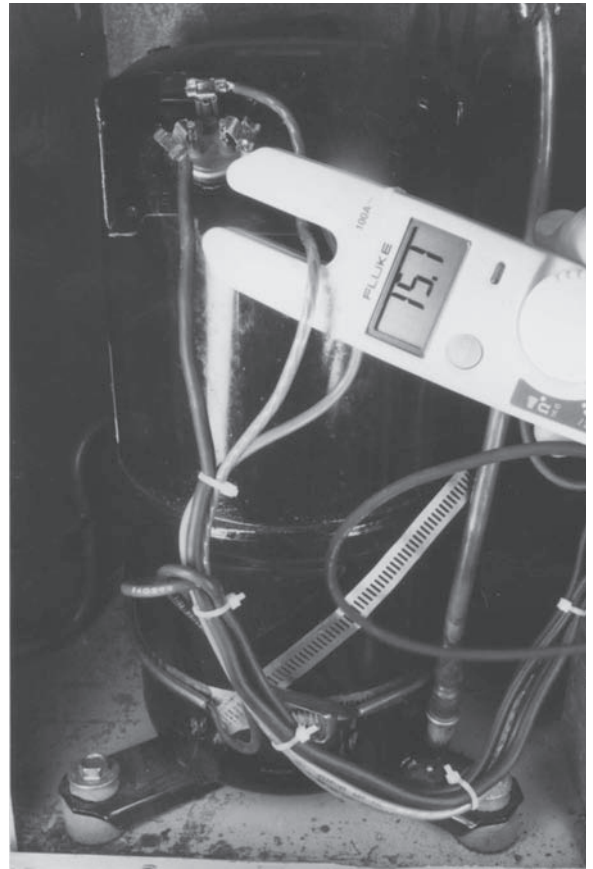


► **Figure 3–14**
Current transformer used to meter large AC currents.
(Source: Delmar/Cengage Learning)

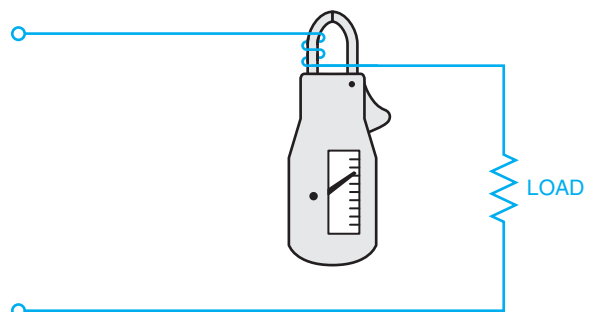


► **Figure 3-15**
Multirange and clamp-on ammeter combination.
(Courtesy of Triplett Corp.).

primary has one turn of wire as compared to the number of turns of wire in the secondary. If two turns of wire are wrapped around the jaw of the ammeter, the primary winding now contains two turns instead of one, and the turns ratio of the transformer is changed, Figure 3-17. 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. For example, assume two turns of wire have been wrapped around the ammeter jaw, and the meter indicates a current of 3 amps. The actual current in this circuit is 1.5 amps ($3 \div 2 = 1.5$). The ability to change the turns ratio of a clamp-on ammeter can be very useful for measuring low currents such as those found in a control circuit. Changing the turns ratio of the transformer is not limited to wrapping two turns of wire around the jaw of the ammeter. Any number of turns of wire can be wrapped around the jaw of the ammeter and the reading will be divided by that number. If three turns of wire are wrapped around the jaw of the meter, the reading will be divided by three.



► **Figure 3-16**
Clamp-on ammeter used to measure the running current of a compressor. (Source: Delmar/Cengage Learning)



► **Figure 3-17**
Two turns of wire change the turns ratio of the transformer. (Source: Delmar/Cengage Learning)



► **Figure 3-18**
Scale divider used with clamp-on ammeter. The ammeter indicates a value of 3.25 amperes. If the scale divider has a ratio of 10:1, the actual current is 0.325 amps.
(Source: Delmar/Cengage Learning)

A very handy device can be made by wrapping 10 turns of wire around some core of nonmagnetic material, such as a thin piece of plastic pipe. Because the device is intended to be used for low current readings, the wire size does not have to be large. A #20 or #18 American Wire Gauge (AWG) wire is large enough. Plastic tape is used to secure the turns of wire to the core material, and two alligator clips are connected to the ends of the wire. This device is shown in Figure 3-18. To use this device, break connection in the circuit to be tested, and insert the 10 turns of wire using the alligator clips. The jaw of the ammeter is placed around the plastic core. The primary of the transformer now contains 10 turns of wire, and the scale factor can now be divided by a factor of 10. The correct ammeter reading is found by moving the decimal point one place to the left. If the ammeter has a low scale of 6 amps full-scale, it can now be used to measure .6 amps full-scale. This can be a real advantage when it is necessary to measure control currents that may not be greater than .2 amps under normal operating conditions.

Some clamp-on ammeters use a digital read-out instead of a meter movement. A digital type meter is shown in Figure 3-19. The digital ammeters are



► **Figure 3-19**
Digital clamp-on ammeter. (Courtesy of Simpson Electric Co.).

generally better for measuring low current values, but the 10 turn scale divider can be used with these ammeters also. Just remember to divide the reading shown by a factor of 10. The clamp-on ammeters discussed in this unit are intended to be used for measuring AC currents only, and will not operate if connected to a DC line. There are clamp-on type ammeters, however, that can be used to measure DC current.

Many clamp-on ammeters are designed to measure AC volts and ohms as well as AC current. This makes the meter a more versatile instrument. When voltage or resistance is to be measured, a set of leads is attached to the meter.

OHMMETER

The ohmmeter is used to measure resistance. The common **volt-ohm-milliammeter (VOM)** contains an ohmmeter. The ohmmeter must provide its own power supply to measure resistance. This is done with batteries located inside the instrument. When resistance is to be measured, the meter must

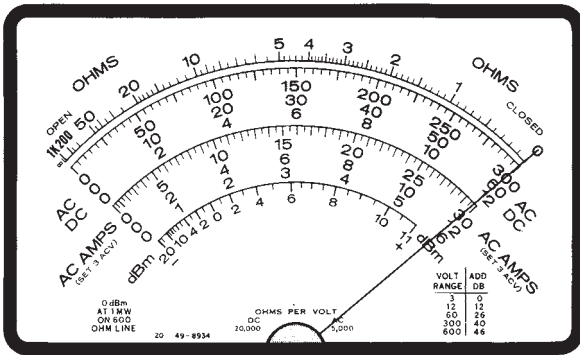


Figure 3-20
The ohmmeter must be set at zero. (Source: Delmar/Cengage Learning)

first be zeroed. Zeroing is done with the ohms adjust control located on the front of the meter. To zero the meter, connect the leads together and adjust the ohms adjust knob until the meter indicates 0 at the far right end of the scale, Figure 3-20. When the leads are separated, the meter will again indicate infinity resistance at the far left side of the meter scale. When the leads are connected across a resistance, the meter will again indicate up scale. Figure 3-21 shows a meter indicating a resistance of 25 ohms, assuming the range setting is $R \times 10$.

Ohmmeters can have different range settings such as $R \times 1$, $R \times 100$, $R \times 1,000$, or $R \times 10,000$. On the $R \times 1$ setting, the resistance is measured straight off the resistance scale located at the top of the meter. If the range is set for $R \times 1,000$, however, the reading must be multiplied by 1,000. The ohmmeter reading shown in Figure 3-21 would be indicating a resistance of 2,500 ohms if the range had been set for $R \times 1,000$. Notice that the ohmmeter scale is read backward from the other scales. Zero

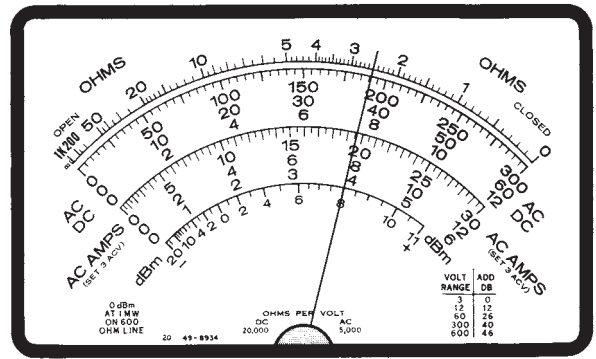


Figure 3-21
Read the ohmmeter from right to left. (Source: Delmar/Cengage Learning)

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.

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 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 (.200 K), it means $.2 \times 1,000$, or 200 ohms. If the meter indicates (1.65 M), it means $1.65 \times 1,000,000$, or 1,650,000 ohms.

The ohmmeter must never be connected to a circuit with power on. Because the ohmmeter uses its own internal power supply, it has a very low operating voltage. If a meter is connected to power when it is set in the ohms position, it will probably damage or destroy the meter.

SUMMARY

- ▶ A voltmeter is a high resistance device and is designed to be connected directly to the power line.
- ▶ The resistance of an analog voltmeter, a voltmeter with a scale and moving pointer, changes with the setting of the meter.
- ▶ An analog voltmeter typically has a resistance of 5,000 ohms per volt on the AC setting and 20,000 ohms per volt on the DC setting.
- ▶ Digital voltmeters generally have a resistance of 10 million ohms on all range settings.

- Ⓢ The three basic steps to reading an analog meter are:
 - A. Determine what the meter indicates.
 - B. Determine the full-scale value of the meter.
 - C. Read the meter.
- Ⓢ Ammeters are low resistance devices and must be connected in series with the load.
- Ⓢ AC ammeters generally use a current transformer to change scale values.
- Ⓢ Current transformers designed to measure large amounts of current have a standard output current of 5 amps.
- Ⓢ Most clamp-on ammeters can measure values of AC current only because they depend on magnetic induction to operate.
- Ⓢ The range setting of clamp-on ammeters can be changed by wrapping more turns of wire around the meter jaw.
- Ⓢ Ohmmeters are used to measure the resistance of a circuit.
- Ⓢ Ohmmeters should never be connected to a circuit that has power applied to it.
- Ⓢ Ohmmeters must have their own source of power to operate.

KEY TERMS

ammeter
analog meter
clamp-on
current transformer

digital meter
inline
input impedance
multiranged

ohmmeter
turns ratio
voltmeter
volt-ohm-milliammeter (VOM)

REVIEW QUESTIONS

1. What type of meter has a high resistance connected in series with the meter movement?
2. How is a voltmeter connected into the circuit?
3. If a voltmeter has a resistance of 5,000 ohms per volt, what is the resistance of the meter when it is set on the 300-volt range?
4. What is the advantage of using a voltmeter that has a high impedance as opposed to a low-impedance meter?
5. What is an analog meter?
6. Why must an ammeter be connected in series with the load?
7. What device is used to change the scale values of an AC ammeter?
8. What is meant by the term *inline* ammeter?
9. A clamp-on ammeter has three turns of wire wrapped around the movable jaw. If the meter is indicating a current of 15 amps, how much current is actually flowing in the circuit?
10. List the three steps for reading a meter.
11. What type of meter contains its own internal power supply?
12. What precaution must be taken when using an ohmmeter?

UNIT 4



Electrical Circuits

OBJECTIVES

After studying this unit the student should be able to:

- Define a series circuit
- Find Ohm's law values for series circuits
- Define a parallel circuit
- Find Ohm's law values for parallel circuits
- Discuss combination circuits
- Find Ohm's law values for combination circuits

Electrical circuits can be divided into three basic types. These are **series**, **parallel**, and **combination**. The simplest of these circuits is the series circuit shown in Figure 4-1. A series circuit is characterized by the fact that it has only one path for current flow. If it is assumed that current must flow from point A to point B in the circuit shown in Figure 4-1, it will flow through each of the resistors. Therefore, *the current flow in a series circuit must be the same at any point in the circuit*. Another rule of series circuits states that *the sum of the voltage drops around the circuit must equal the applied voltage*. A third rule of series circuits states that *the total resistance is equal to the sum of the individual resistors*.

The circuit shown in Figure 4-2 shows the values of **current flow**, **voltage drop**, and resistance for each of the resistors. Notice that the total resistance of the circuit can be found by adding the

Figure 4-1
Series circuit. (Source: Delmar/
Cengage Learning)

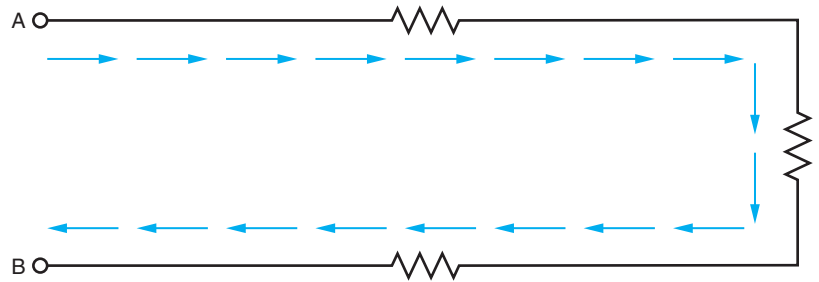
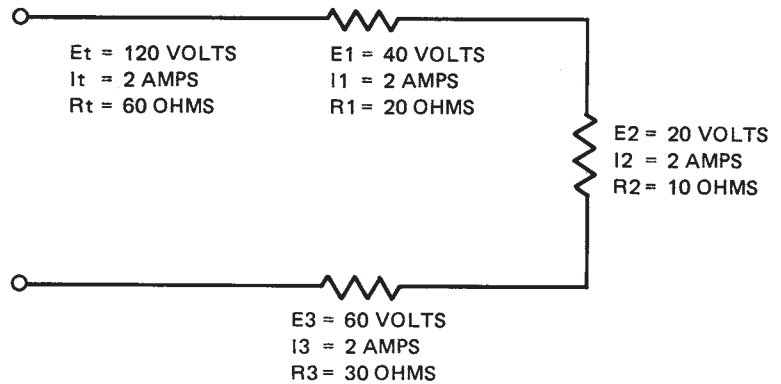


Figure 4-2
Series circuit. (Source: Delmar/
Cengage Learning)



values of each of the individual resistors ($20 + 10 + 30 = 60 \text{ ohms}$). The amount of current flow in the circuit can be found by using Ohm's law.

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

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

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

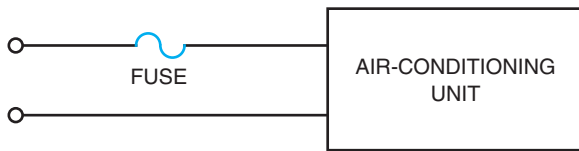
There is a current flow in the circuit of 2 amps. Notice that the same current flows through each of the resistors. The voltage drop across each resistor can be found using Ohm's law ($E = I \times R$). The voltage dropped across resistor R1 is $2 \times 20 = 40 \text{ volts}$. This means that it takes a voltage of 40 volts to push 2 amps of current through 20 ohms of resistance. If a voltmeter is connected across resistor R1, it would indicate a voltage drop of 40 volts. The voltage drop of resistor R2 can be found the same way ($E = I \times R$), ($2 \times 10 = 20$). The voltage dropped across resistor R2 is 20 volts. The third resistor has a voltage drop of $2 \times 30 = 60 \text{ volts}$. Notice that if the voltage drops are added together,

they will equal the voltage applied to the circuit ($40 + 20 + 60 = 120$).

Because a series circuit has only one path for current flow, if any point in the circuit should become open, current flow throughout the entire circuit will stop. Some strings of Christmas tree lights are wired in series. If any bulb in the string burns out, all of the lights will go out. When the defective bulb is replaced, all of the lights will operate. Because of this characteristic of series circuits, fuses and circuit breakers are connected in series with what they are intended to protect. Figure 4-3 shows a fuse used to protect an air conditioning unit. If the fuse should open, current flow to the entire circuit will stop.

PARALLEL CIRCUITS

Parallel circuits are characterized by the fact that they have more than one path for current flow. The circuit shown in Figure 4-4 illustrates multiple paths of a parallel circuit. If the current in this



► **Figure 4-3**
Fuses are connected in series. (Source: Delmar/Cengage Learning)

circuit is assumed to flow from point A to point B, there are three separate paths through which it can flow. Current can flow from point A, through resistor R1 to point B, or it can flow from point A through resistor R2 to point B, or from point A through resistor R3 to point B. Because current can flow through each of these resistors, the total current flow in the circuit is the sum of these individual currents. A rule for parallel circuits states that *the total current in a parallel circuit is the sum of the currents through the individual paths* ($I_t = I_1 + I_2 + I_3$). Notice in Figure 4-4 that each of the resistors is connected directly across the incoming power line. Therefore, *all the components in a parallel circuit have the same voltage drop*.

Each time a new component is added to a parallel circuit, a new path for current flow is created. Because there is less opposition to current flow each time a component is added, the total resistance of the circuit is decreased. The total resistance of a parallel circuit can be found using either of three formulas. The first of these formulas is:

$$R_t = \frac{R_1 \times R_2}{R_1 + R_2}$$

The second formula is:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}$$

or

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}$$

The third formula is:

$$R_t = \frac{R}{N}$$

The third formula can be used only when all resistors connected in parallel are the same value. Assume that four resistors with a value of 100 ohms each are connected in parallel. The total resistance would be 25 ohms. To use this formula, divide the resistance of one resistor by the total number of resistors.

$$R_t = \frac{R}{N}$$

$$R_t = \frac{100}{4}$$

$$R_t = 25 \Omega$$

Figure 4-5 shows a parallel circuit containing three resistors with the values of 15, 10, and 30 ohms. The total resistance of the circuit can be found by using either of the two formulas.

$$R_t = \frac{15 \times 10}{15 + 10} = \frac{150}{25} = 6$$

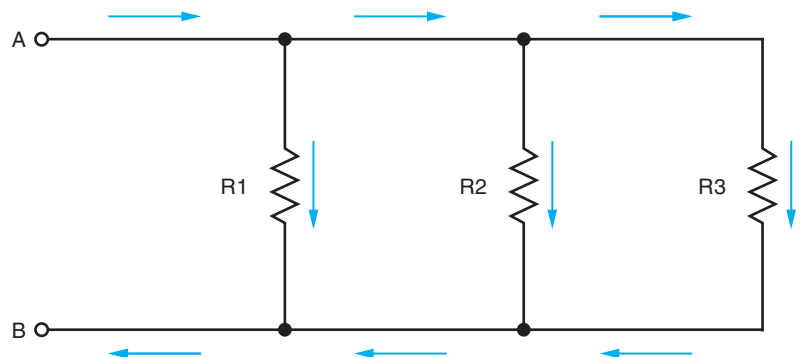
Notice that in this formula only two of the resistors can be found at a time. It is now necessary to use the total resistance of the first two resistors and use that value for R1 in the formula. Resistor R3 is used in the R2 position in the formula.

$$R_t = \frac{6 \times 30}{6 + 30}$$

$$R_t = \frac{180}{36}$$

$$R_t = 5 \text{ ohms}$$

The total resistance of this parallel circuit is 5 ohms. The second formula can be used to find the total



► **Figure 4-4**
Parallel circuits have more than one path for current flow.
(Source: Delmar/Cengage Learning)

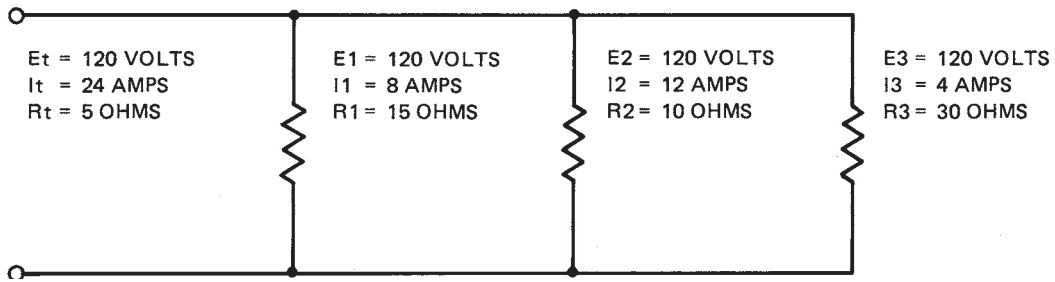


Figure 4-5
Three parallel resistors. (Source: Delmar/Cengage Learning)

resistance by plugging the values of resistance into the formula. With these values, it becomes a matter of adding fractions. When fractions are to be added, the first thing that must be done is to find some number all the denominators will divide into. This is called finding a **common denominator**. For this problem, 30 will be the common denominator.

$$\begin{aligned}\frac{1}{R_t} &= \frac{1}{15} + \frac{1}{10} + \frac{1}{30} \\ \frac{1}{R_t} &= \frac{2}{30} + \frac{3}{30} + \frac{1}{30} \\ \frac{1}{R_t} &= \frac{6}{30} \\ \frac{R_t}{1} &= \frac{30}{6} \\ R_t &= 5 \text{ ohms}\end{aligned}$$

Notice that the two formulas give the same answer.

Another method of finding the total resistance in a parallel circuit is to find the **reciprocal** of each individual resistor. A third rule for parallel circuits states that *total resistance is the reciprocal of the sum of the reciprocals of the individual resistors*. The problem can, therefore, be solved by finding the reciprocal of each individual resistor, adding them together, and finding the reciprocal of the sum. (The reciprocal of any number can be found by dividing that number into 1.) The problem can be solved as follows:

$$\begin{aligned}\frac{1}{R_t} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \\ \frac{1}{R_t} &= \frac{1}{15} + \frac{1}{10} + \frac{1}{30} \\ \frac{1}{R_t} &= .0667 + .1 + .0333 \\ \frac{1}{R_t} &= .2 \\ R_t &= 5 \text{ ohms}\end{aligned}$$

If 120 volts is applied to the circuit, the values of voltage and current for the entire circuit can be found. Because each of the resistors is connected directly across the power line, each resistor will have the same voltage drop of 120 volts. The current flow through resistor R1 can be found using Ohm's law.

$$\begin{aligned}I &= \frac{E}{R} \\ I &= \frac{120}{15} \\ I &= 8 \text{ amps}\end{aligned}$$

The current flow through resistor R2 is (120/10 = 12 amps). The current flow through resistor R3 is (120/30 = 4 amps). The total current flow in the circuit can be found by using the formula

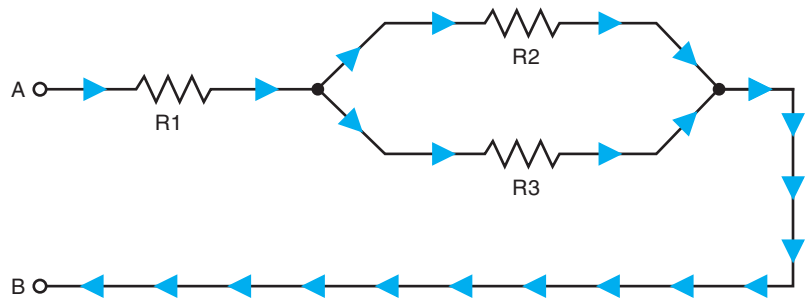
$$\begin{aligned}I_t &= \frac{E_t}{R_t} \\ I_t &= 120/5 \\ I_t &= 24 \text{ amps}\end{aligned}$$

Notice that the total current can also be found by adding the currents flowing through the individual resistors (8 + 12 + 4 = 24 amps).

Most circuits are connected in parallel. The lights and outlets in a house are connected in parallel. Because all of the lights and outlets are connected in parallel, each light has an applied voltage of 120 volts, and each outlet can supply 120 volts to whatever is connected to it. If the lights in a house were wired in series, all of the lights would have to be turned on before any of them would burn.

COMBINATION CIRCUITS

A combination circuit contains both series and parallel connections within the same circuit. In



► **Figure 4-6**
Combination circuit. (Source: Delmar/
Cengage Learning)

Figure 4-6, resistor R1 is connected in series with resistors R2 and R3. Resistors R2 and R3 are connected in parallel with each other. If it is assumed that current flows from point A to point B, all of the current will have to flow through resistor R1. At the junction of resistors R2 and R3, however, the current divides and flows through separate paths. The amount of current that flows through each resistor is determined by its resistance. Notice that all of the circuit current must flow through R1. Because there is only one current path through R1, it is connected in series with the rest of the circuit. When the current reaches the junction of resistors R2 and R3, there is more than one path for current flow. These resistors are, therefore, connected in parallel.

Values will now be added to the example circuit shown in Figure 4-6. It will be assumed that resistor R1 has a value of 75 ohms; resistor R2 has a value of 100 ohms; and resistor R3 has a value of 125 ohms. It will also be assumed that a voltage of 24 volts is connected to the circuit, Figure 4-7. To find the missing values in this circuit, it is first necessary to determine the total resistance. The first step in

determining the total resistance is to calculate the resistance of the parallel block formed by resistors R2 and R3. This value will become RC (resistance of the combination).

$$R_c = \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_c = \frac{1}{\frac{1}{100} + \frac{1}{125}}$$

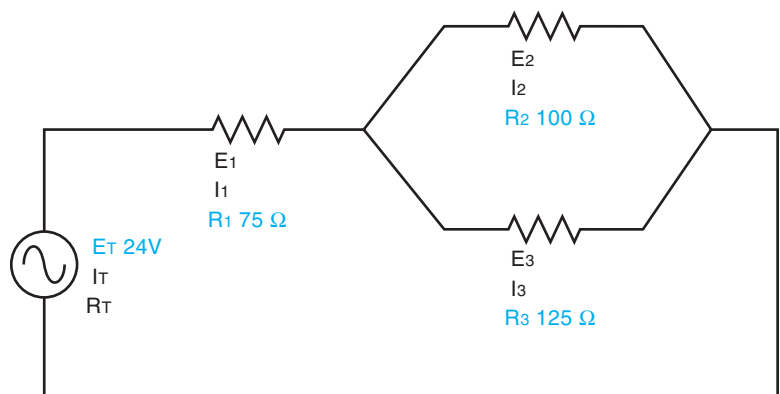
$$R_c = \frac{1}{0.01} \times 0.008$$

$$R_c = \frac{1}{0.018}$$

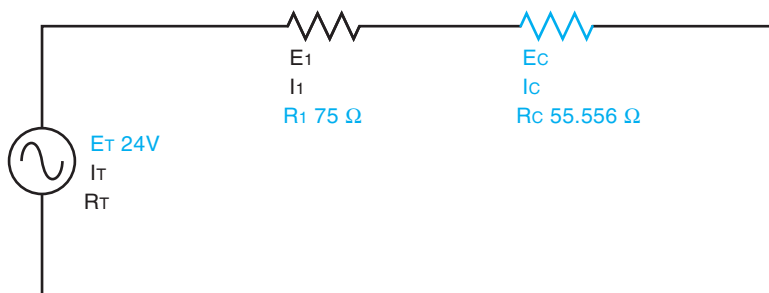
$$R_c = 55.556 \, \Omega$$

Now that the combined resistance of resistors R2 and R3 is known, this value can be treated as one single resistor. The circuit will now be redrawn as shown in Figure 4-8. The circuit is now a simple series circuit containing resistors R1 and RC.

The total circuit resistance of the circuit can be determined by adding the values of resistors R1 and RC.



► **Figure 4-7**
Adding circuit values. (Source: Delmar/
Cengage Learning)



► **Figure 4-8**
Resistors R2 and R3 become RC.
(Source: Delmar/Cengage Learning)

$$R_t = R_1 + R_C$$

$$R_t = 75 + 55.556$$

$$R_t = 130.556 \Omega$$

Because the applied or total circuit voltage is known and the total resistance is known, the total circuit current can be determined using Ohm's law.

$$I_t = \frac{E_t}{R_t}$$

$$I_t = \frac{24}{130.556}$$

$$I_t = 0.184 \text{ amps}$$

In a series circuit the current is the same at any point in the circuit. The voltage drop across resistors R1 and RC can now be determined.

$$E_1 = I_1 \times R_1$$

$$E_1 = 0.184 \times 75$$

$$E_1 = 13.8 \text{ volts}$$

$$E_C = I_C \times R_C$$

$$E_C = 0.184 \times 55.556$$

$$E_C = 10.2 \text{ volts}$$

The computed circuit values are shown in Figure 4-9.

Resistor RC in reality is the combined values of resistors R2 and R3. The values that apply to resistor RC, therefore, apply to the parallel block formed by resistors R2 and R3. In a parallel circuit, the voltage is the same across each branch. Therefore, the voltage dropped across resistor RC is dropped across both R2 and R3. Now that the voltage drop across each is known, the current flow through each can be determined using Ohm's law.

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{10.2}{100}$$

$$I_2 = 0.102 \text{ amps}$$

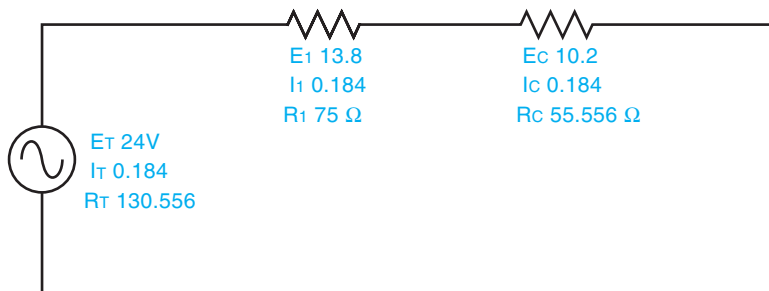
$$I_2 = \frac{E_3}{R_3}$$

$$I_2 = \frac{10.2}{125}$$

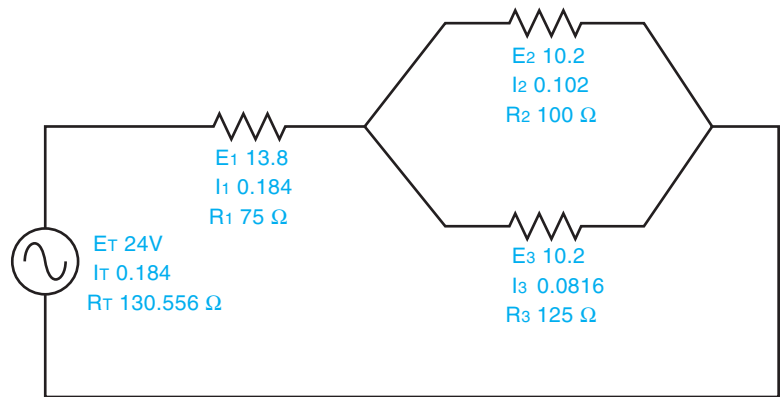
$$I_2 = 0.0816 \text{ amps}$$

The circuit with all calculated values is shown in Figure 4-10.

Another example of a combination circuit is shown in Figure 4-11. In this circuit, resistors R1 and R2 are connected in series with each other and resistors R3 and R4 are connected in series with each other. Resistors R1 and R2 are connected in

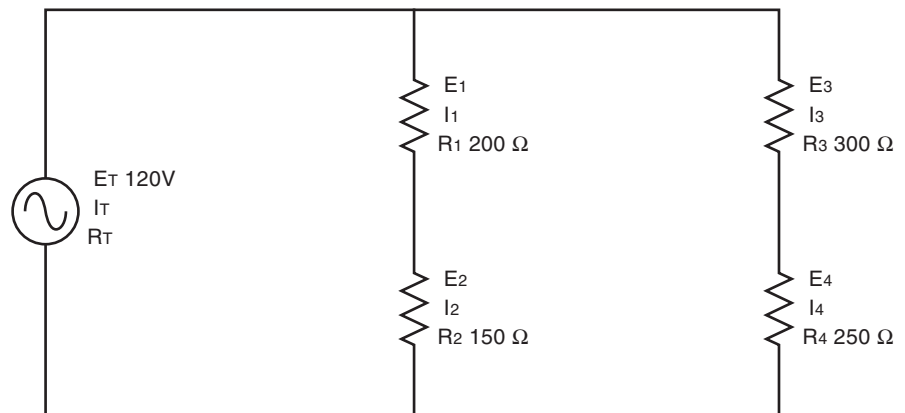


► **Figure 4-9**
Circuit values for the series circuit are determined. (Source: Delmar/Cengage Learning)



► **Figure 4-10**
Circuit with all computed values.

(Source: Delmar/Cengage Learning)



► **Figure 4-11**
Example combination
circuit 2. (Source: Delmar/
Cengage Learning)

parallel with resistors R3 and R4. It is assumed that resistor R1 has a value of 200 ohms, resistor R2 has a value of 150 ohms, resistor R3 has a value of 300 ohms, and resistor R4 has a value of 250 ohms. It is also assumed that 120 volts is applied to the circuit.

The first step in solving this circuit is to compute the total circuit resistance. This can be done by computing the total resistance of the branch containing resistors R1 and R2 and the branch containing resistors R3 and R4. Resistors R1 and R2 are connected in series. The total resistance of this branch can be computed by adding the values of resistors R1 and R2. This value will be RC1 (resistance of combination 1).

$$\begin{aligned} RC1 &= R1 + R2 \\ RC1 &= 200 + 150 \\ RC1 &= 350 \Omega \end{aligned}$$

The resistance of the second branch can be computed by adding the values of R3 and R4. This resistance value will be RC2 (resistance of combination 2).

$$\begin{aligned} RC2 &= R3 + R4 \\ RC2 &= 300 + 250 \\ RC2 &= 550 \Omega \end{aligned}$$

The circuit can now be reduced to a simple parallel circuit containing a 300-ohm and a 550-ohm resistor, Figure 4-12. The total resistance can now be computed using one of the parallel resistance formulas.

$$\begin{aligned} Rt &= \frac{Rc1 \times Rc2}{Rc1 + Rc2} \\ Rt &= \frac{350 \times 550}{350 + 550} \\ Rt &= \frac{192,500}{900} \\ Rt &= 213.889 \Omega \end{aligned}$$

Figure 4-12
Reducing the circuit to a simple parallel circuit.
(Source: Delmar/Cengage Learning)

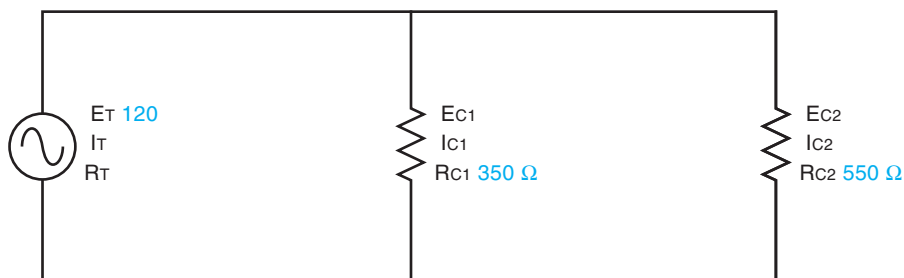
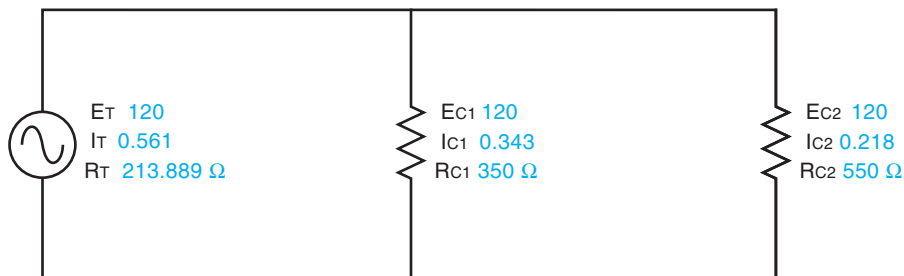


Figure 4-13
The values for the parallel circuit have been determined. (Source: Delmar/Cengage Learning)



The total current can now be computed using Ohm's law.

$$I_t = \frac{E_t}{R_t}$$

$$I_t = \frac{120}{213.889}$$

$$I_t = 0.561 \text{ amps}$$

Because resistors RC1 and RC2 are connected in parallel, the voltage across each is the same as the applied voltage of the circuit. The current through each branch can now be determined.

$$I_{C1} = \frac{120}{350}$$

$$I_{C1} = 0.343 \text{ amps}$$

$$I_{C2} = \frac{120}{550}$$

$$I_{C2} = 0.218 \text{ amps}$$

The complete values for the parallel circuit are shown in Figure 4-13.

The values of RC1 and RC2 can now be substituted in the original circuit. Resistor RC1 is a combination of resistors R1 and R2. The values of RC1 apply to the branch composed of R1 and R2. Resistors R1 and R2 are connected in series. In a series circuit, the current flow is the same

through any part of the circuit. Therefore, the current flowing through RC1 is the same current flowing through R1 and R2. Likewise, the current flowing through RC2 is the same current that flows through resistors R3 and R4, Figure 4-14. Now that the value of resistance and current are known for each of the resistors, the voltage drop across each can be computed.

$$E_1 = I_1 \times R_1$$

$$E_1 = 0.343 \times 200$$

$$E_1 = 68.6 \text{ V}$$

$$E_2 = I_2 \times R_2$$

$$E_2 = 0.343 \times 150$$

$$E_2 = 51.45 \text{ V}$$

$$E_3 = I_3 \times R_3$$

$$E_3 = 0.218 \times 300$$

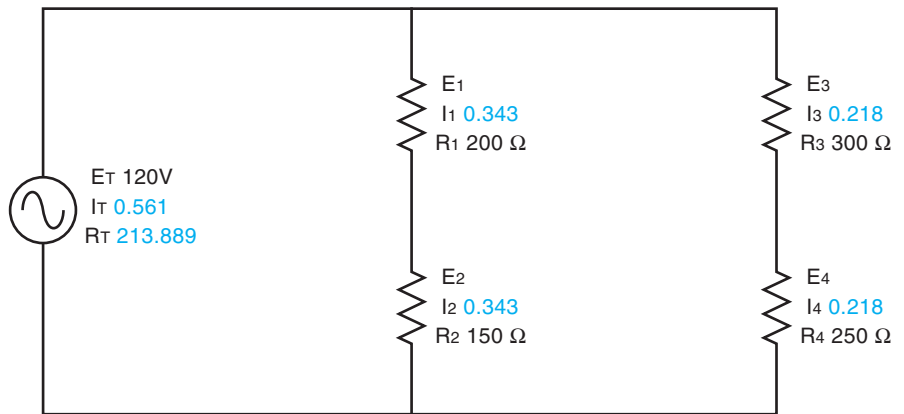
$$E_3 = 65.4 \text{ V}$$

$$E_4 = I_4 \times R_4$$

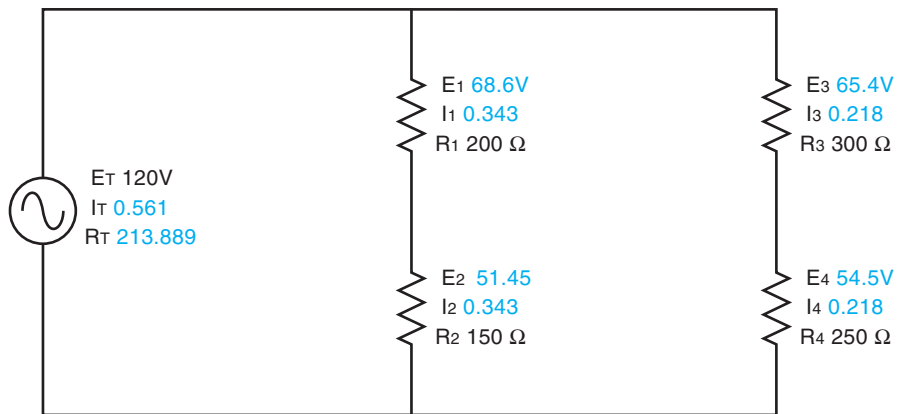
$$E_4 = 0.218 \times 250$$

$$E_4 = 54.5 \text{ V}$$

All values for the circuit are shown in Figure 4-15.



► **Figure 4-14**
Determining the current
flow through each
branch. (Source: Delmar/
Cengage Learning)



► **Figure 4-15**
All missing values have
been determined.
(Source: Delmar/Cengage Learning)

SUMMARY

- Three basic types of electric circuits are the series, parallel, and combination.
- Series circuits contain only one path for current flow.
- Three rules concerning the electrical values in a series circuit are:
 - A. The current flow is the same in all parts of a series circuit.
 - B. The sum of the voltage drops across each element is equal to the applied voltage.
 - C. The total resistance can be determined by adding the resistance of each element in the circuit.
- Parallel circuits contain more than one path for current flow.
- Three rules concerning the electrical values in a parallel circuit are:
 - A. The voltage is the same across all branches in a parallel circuit.
 - B. The total current can be found by adding the current flow through each branch of the circuit.

C. The total resistance can be found by adding the reciprocal of the resistance of each branch and then taking the reciprocal of that sum.

- Ⓢ Combination circuits contain both series and parallel branches.

KEY TERMS

combination
common denominator
current flow

parallel
reciprocal

series
voltage drop

REVIEW QUESTIONS

1. List the three basic types of electrical circuits.
2. What is the major characteristic of a series circuit?
3. List the three basic rules for series circuits.
4. What is the major characteristic of a parallel circuit?
5. List the three basic rules for the parallel circuit.
6. What type of circuit is used most often in industry and the home?
7. What type of circuit is used the least in industry and the home?
8. Three resistors valued at 300 ohms, 200 ohms, and 600 ohms are connected in series. What is their total resistance?
9. If the three resistors in question 8 are connected in parallel, what is their total resistance?
10. How are fuses and circuit breakers connected in a circuit and why are they connected this way?

PRACTICE PROBLEMS SET 1

1. Refer to the circuit shown in Figure 4–2. Find the missing values.

$E_T = 240$	E_1	E_2	E_3
I_T	I_1	I_2	I_3
R_T	$R_1 = 1,200\ \Omega$	$R_2 = 2,000\ \Omega$	$R_3 = 1,800\ \Omega$

2.

$E_T = 48$	E_1	E_2	$E_3 = 22.795$
I_T	I_1	I_2	I_3
$R_T = 990\ \Omega$	$R_1 = 220\ \Omega$	$R_2 = 300\ \Omega$	R_3

3.

$E_T = 120$	$E_1 = 24.75$	E_2	$E_3 = 59.4$
I_T	I_1	I_2	I_3
R_T	R_1	$R_2 = 2.2\ \text{k}\Omega$	R_3

4. Refer to the circuit shown in Figure 4–5. Find the missing values.

E_T	E_1	E_2	E_3
$I_T = 26$	I_1	I_2	I_3
R_T	$R_1 = 24\ \Omega$	$R_2 = 18\ \Omega$	$R_3 = 36\ \Omega$

5.

E_T	E_1	E_2	E_3
I_T	I_1	I_2	$I_3 = 1.5$
$R_T = 8\ \Omega$	$R_1 = 24\ \Omega$	$R_2 = 48\ \Omega$	R_3

6.

E_T	E_1	E_2	E_3
$I_T = 0.289$	$I_1 = 0.139$	$I_2 = 0.1$	I_3
R_T	$R_1 = 860\ \Omega$	$R_2 = 1,200\ \Omega$	$R_3 = 2,400\ \Omega$

7. Refer to the circuit shown in Figure 4–7. Find all missing values.

$E_T = 120$	E_1	E_2	E_3
I_T	I_1	I_2	I_3
R_T	$R_1 = 360\ \Omega$	$R_2 = 1,200\ \Omega$	$R_3 = 1,600\ \Omega$

8.

E_T	E_1	E_2	E_3
I_T	$I_1 = 0.080$	I_2	I_3
$R_T = 2,600\ \Omega$	R_1	$R_2 = 2,400\ \Omega$	$R_3 = 4,800\ \Omega$

9.

E_T	E_1	E_2	$E_3 = 114.18$
$I_T = 0.466$	I_1	I_2	I_3
R_T	$R_1 = 270\ \Omega$	$R_2 = 510\ \Omega$	$R_3 = 470\ \Omega$

10. Refer to the circuit shown in Figure 4-11. Find all missing values.

$E_T = 277$	E_1	E_2	E_3	E_4
I_T	I_1	I_2	I_3	I_4
R_T	$R_1 = 3,300\ \Omega$	$R_2 = 4,300\ \Omega$	$R_3 = 2,700\ \Omega$	$R_4 = 5,100\ \Omega$

11.

E_T	E_1	E_2	E_3	E_4
I_T	$I_1 = 0.06$	I_2	I_3	I_4
$R_T = 960\ \Omega$	R_1	$R_2 = 1,000\ \Omega$	$R_3 = 650\ \Omega$	$R_4 = 950\ \Omega$

12.

E_T	E_1	E_2	E_3	E_4
I_T	$I_1 = 0.0444$	I_2	$I_3 = 0.0369$	I_4
R_T	$R_1 = 3,000\ \Omega$	$R_2 = 2,400\ \Omega$	$R_3 = 1,800\ \Omega$	$R_4 = 4,700\ \Omega$

PRACTICE PROBLEMS SET 2

Ohm's Law

1. $E =$

$I = 10\text{ A}$

$R = 12\ \Omega$

2. $I =$

$E = 220\text{ V}$

$R = 10\ \Omega$

3. $R =$

$E = 120\text{ V}$

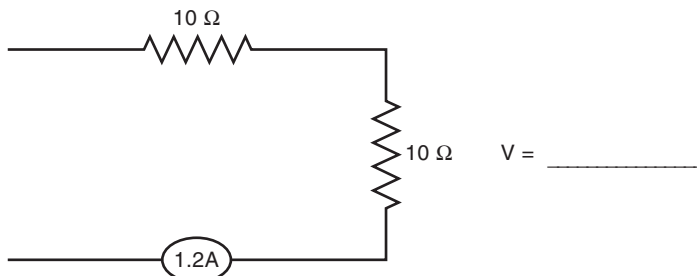
$I = 3\text{ A}$

4. $E =$

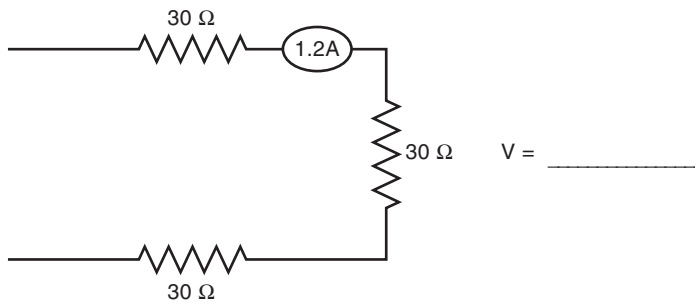
$I = 1\text{ A}$

$R = 240\ \Omega$

5.



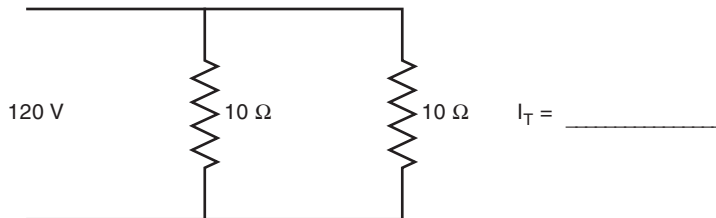
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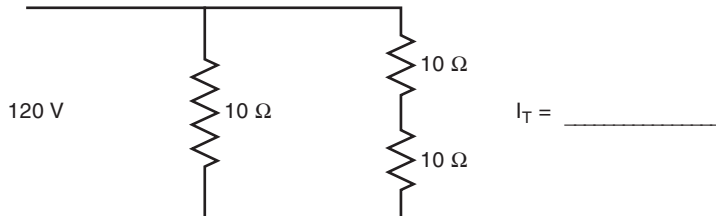
PRACTICE PROBLEMS SET 3

Ohm's Law

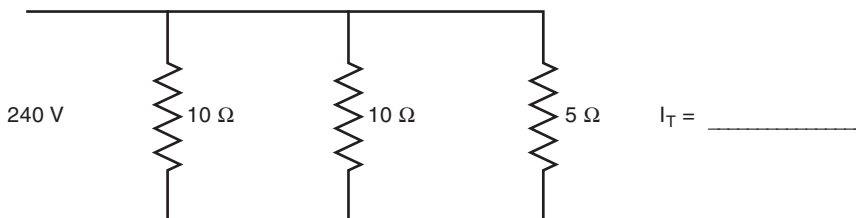
1.



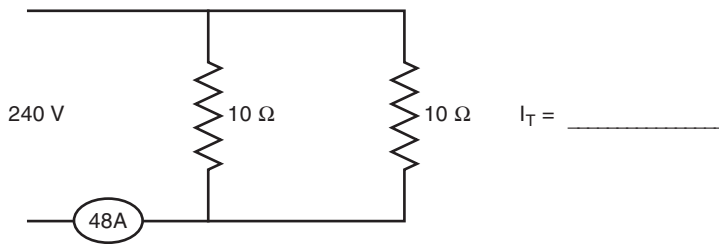
2.



3.



4.



PRACTICE PROBLEMS SET 4

Ohm's Law

1. $E =$

$$I = 1\text{ A}$$

$$R = 12\ \Omega$$

2. $I =$

$$E = 220\text{V}$$

$$R = 5\ \Omega$$

3. $R =$

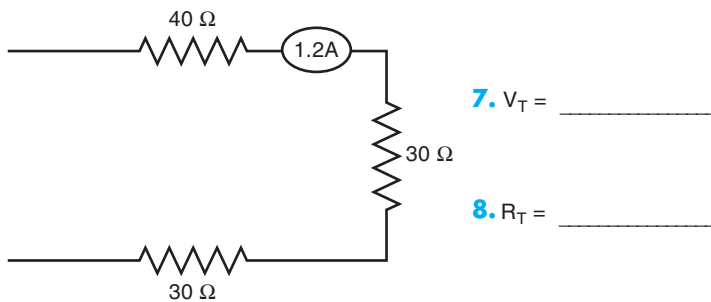
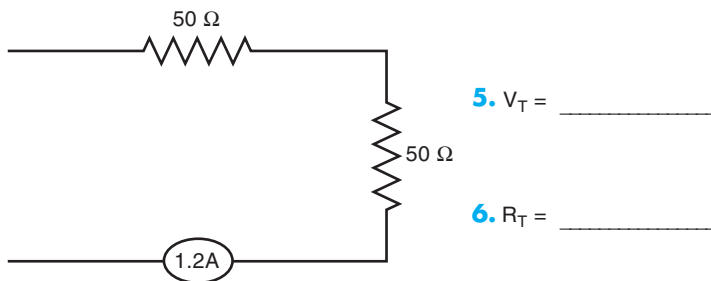
$$E = 120\text{V}$$

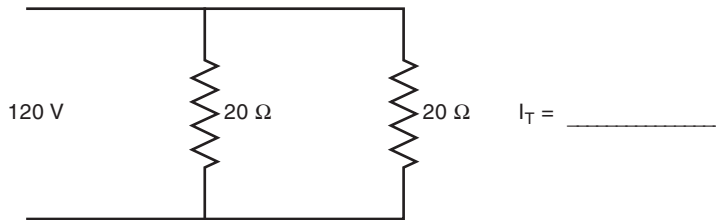
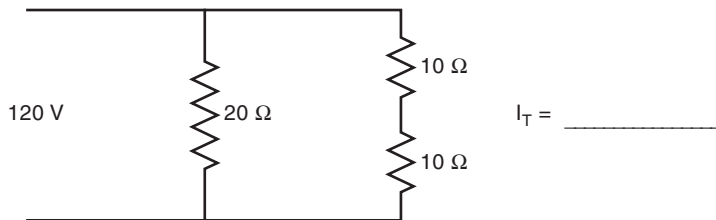
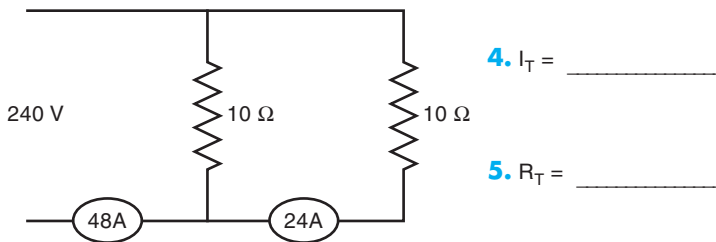
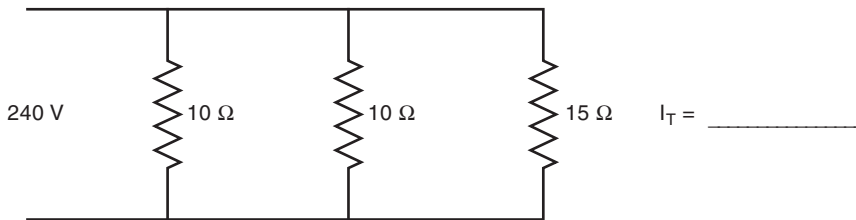
$$I = 5\text{ A}$$

4. $E =$

$$I = .5\text{ A}$$

$$R = 240\ \Omega$$



PRACTICE PROBLEMS SET 5**1.****2.****3.**

UNIT 5

Electrical Services

OBJECTIVES

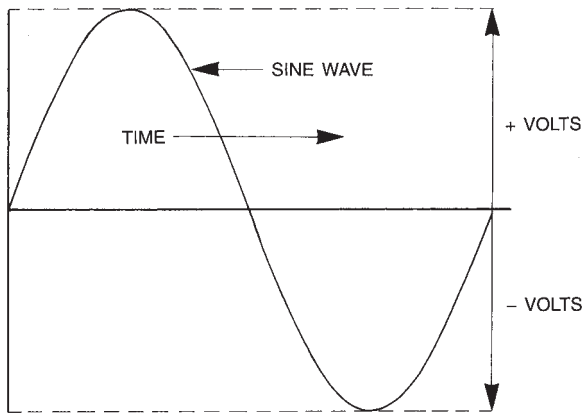
After studying this unit the student should be able to:

- Discuss alternating current
- Discuss three-phase power
- Find voltage and current values for a wye-connected three-phase service
- Find voltage and current values for a delta-connected three-phase service
- Discuss a high-leg three-phase connection
- Discuss an open-delta three-phase service
- Discuss a 120/240 volt single-phase service
- Describe different kinds of circuit-breakers
- Discuss fuses
- Be able to find standard fuse rating in accord with the *National Electrical Code*®
- Install a single-phase panel box

Air conditioning equipment must be connected to an electrical service. The type of air conditioning equipment used is generally determined by the type of electrical service available to operate it. The air conditioning technician must have knowledge of different types of electrical services.

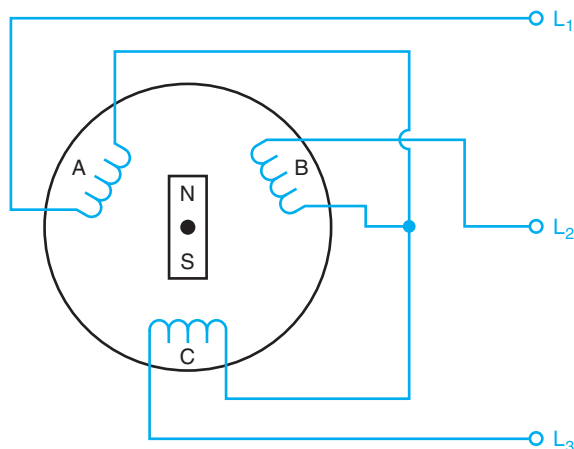
POWER GENERATION

In the United States and Canada, power is generated as a three-phase 60-hertz voltage. The term **hertz** means 60 cycles per second. This means that the voltage increases from zero to its maximum positive value, returns to zero, increases to its maximum negative value and returns to zero 60 times each second. Figure 5–1 shows one complete cycle of AC voltage.

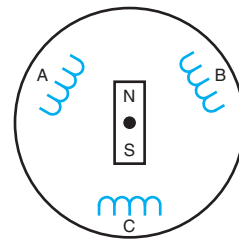


► **Figure 5-1**
AC sine wave. (Source: Delmar/Cengage Learning)

The term **three phase** means that there are three separate voltage waveforms produced by the **alternator**. An alternator is a generator that produces AC voltage. For the alternator to produce the three phases, the internal windings of the alternator—called the **stator**—are wound 120° apart. Figure 5-2 illustrates the windings of an alternator. The moving part of the alternator, called the **rotor**, is actually a large electromagnet. When the magnet is turned, the magnetic field cuts through the windings of the stator and induces a voltage into them. The amount of voltage induced is controlled by the strength of the magnetic field, and the frequency or hertz is controlled by the speed of the rotation of the magnet. Because the windings of the stator are



► **Figure 5-3**
Wye or star connection. (Source: Delmar/Cengage Learning)

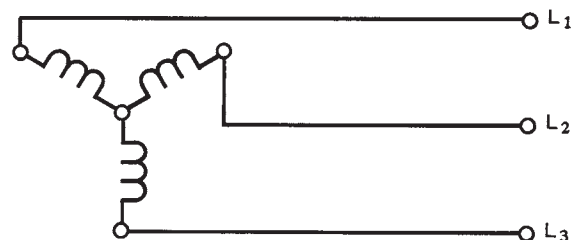


► **Figure 5-2**
The windings of an alternator are 120° apart.
(Source: Delmar/Cengage Learning)

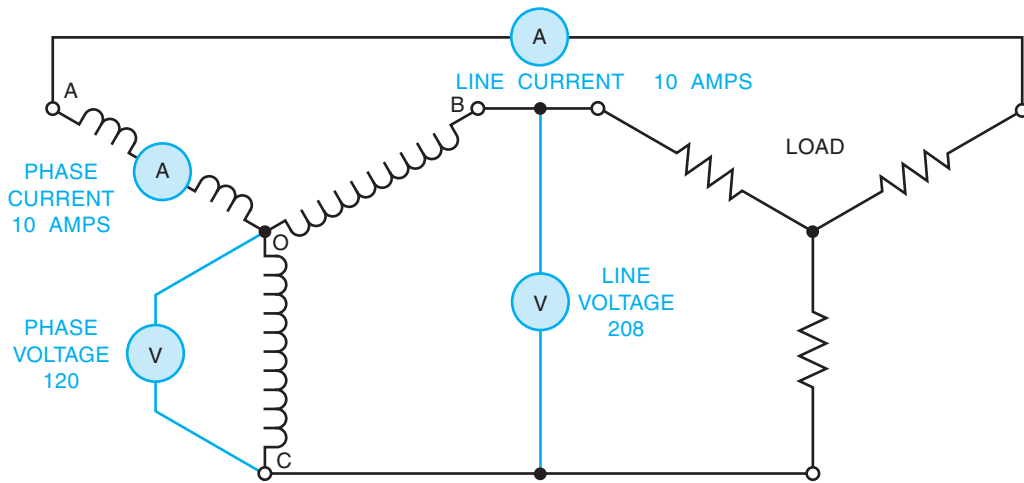
physically wound 120° apart, the three voltages are 120° out of phase with each other. The windings of the stator are connected to form one of the two basic three-phase connections. These connections are the **delta** and **wye**.

WYE CONNECTION

The wye connection is also referred to as the **star** connection. This connection is made by joining one end of each of the windings together as shown in Figure 5-3. The connection shown in Figure 5-4 is a wye connection that has been drawn schematically to make it easier to see and understand. Notice how one end of each of the windings is joined at the centerpoint. The wye connection can be used to provide an increase in the output or line voltage. The phase voltage is the voltage produced across one of the windings. The line voltage is the voltage produced across the output points of the connection. Figure 5-5 shows a wye connection connected to a three-phase load bank. Ammeters and voltmeters are used to illustrate the differences between phase values and line values. Notice that the phase value of voltage is measured from the output of the winding, at point C, to the centerpoint of the wye



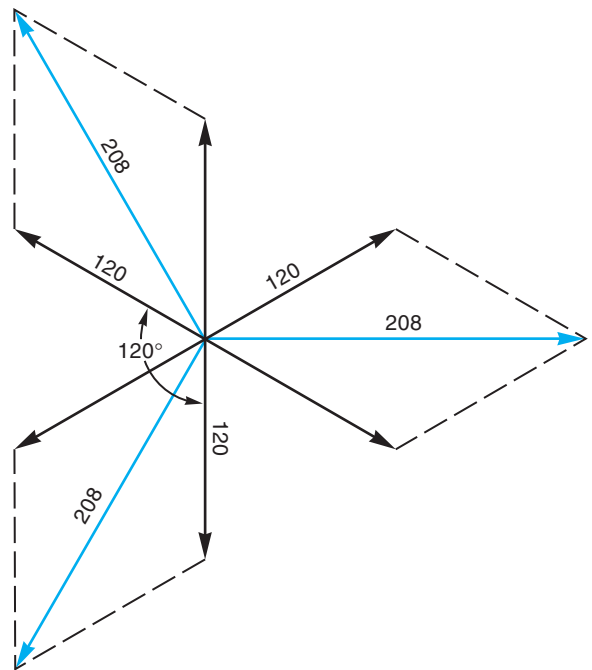
► **Figure 5-4**
Schematic of a wye connection. (Source: Delmar/Cengage Learning)



► **Figure 5-5**
Phase and line values of a wye connection. (Source: Delmar/Cengage Learning)

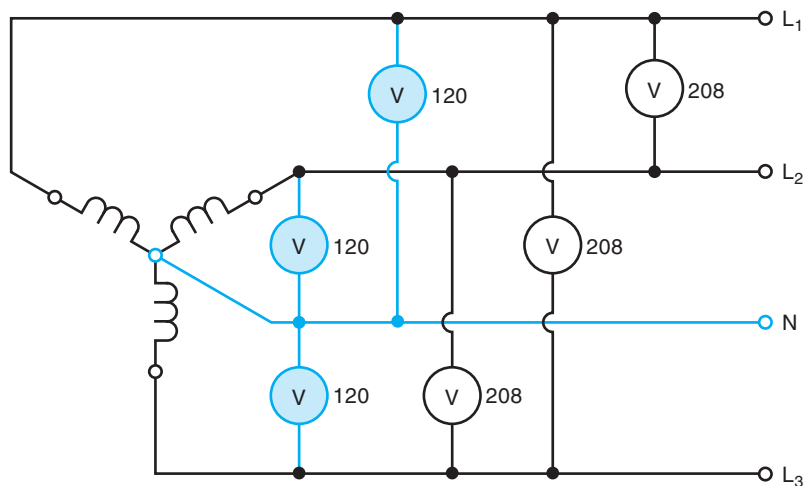
connection at the point labeled O. The line value is measured across two of the output points of the connection (B&C). The phase current meter is inserted in the winding of the alternator, and the line current meter is inserted in the output line. Notice also that the two ammeters are indicating the same value of current. *In a wye connection, phase current and line current are equal.* The voltages, however, are not. *The line voltage in a wye connection is 1.732 times greater than the phase voltage (1.732 is the square root of 3).* The reason for this voltage increase is that the voltages are 120° out of phase with each other. Figure 5-6 shows a diagram to illustrate this. Because the three voltages are out of phase with each other, they will be added. Vector addition must be used, however, because of the 120° phase shift. If three voltages are shown in a length that corresponds to 120 volts, and a resultant is drawn to the point of intersection, it will be found that the length of the resultant corresponds to 208 volts. The 120° phase shift between voltages is the reason the two 120-volt phases add to produce 208 volts instead of 240 volts.

Wye-connected systems often use a fourth conductor connected to the center of the connection. This conductor becomes the neutral, Figure 5-7. Notice in this connection that the voltage between any line and neutral is the phase voltage or 120 volts,

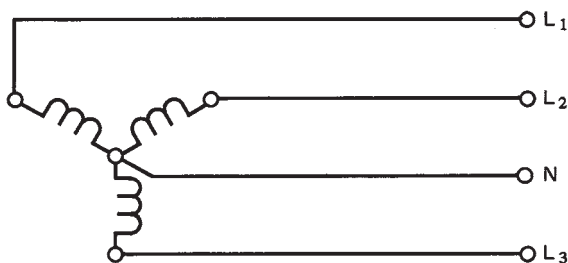


► **Figure 5-6**
Vector diagram of the phase and line values in a three-phase system. (Source: Delmar/Cengage Learning)

and the voltage between any two of the lines is 208 volts. The 208/120-volt three-phase connection is very common in industry and commercial buildings. Another very common three-phase



► **Figure 5-7**
Fourth wire connected for a neutral.
(Source: Delmar/Cengage Learning)

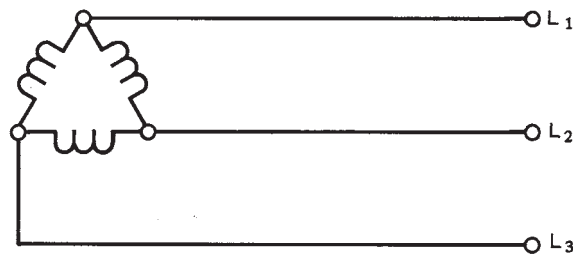


► **Figure 5-8**
A 480/277-volt connection. (Source: Delmar/Cengage Learning)

four-wire connection is shown in Figure 5-8. This is a 480/277-volt connection. Two hundred seventy-seven volts is often used in large stores and office buildings to operate the fluorescent lights while the 480-volt is used to operate large air conditioning systems. The 120-volt connections are provided by transformers that step down the 480 volts to 120 volts.

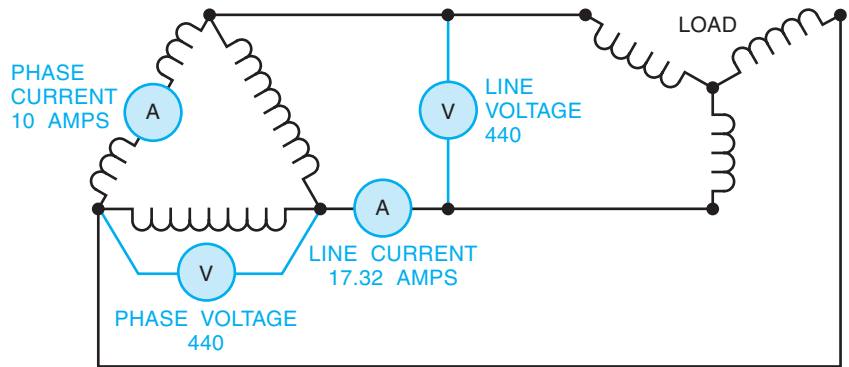
DELTA CONNECTION

The next connection to be covered is the delta. A schematic diagram of a delta connection is shown in Figure 5-9. This connection gets its name from the fact that it looks like the Greek letter delta (Δ).



► **Figure 5-9**
The delta connection. (Source: Delmar/Cengage Learning)

Figure 5-10 shows a delta system connected to a three-phase load bank. Ammeters and voltmeters are used to illustrate the differences in phase and line values of voltage and current. Notice that the values of phase voltage and line voltage are equal for the delta connection. One of the rules for three-phase systems states that *line voltage and phase voltage are equal in a delta connection*. The ammeters, however, are not equal. *In a delta connection, the line current is 1.732 times greater than the phase current*. This is the reason that the delta connection is so popular in industry. The current flow through the windings of a transformer are less than the line amps if the transformer bank is connected in delta.



► **Figure 5-10**
Voltage and current relationships in a delta connection.
(Source: Delmar/Cengage Learning)

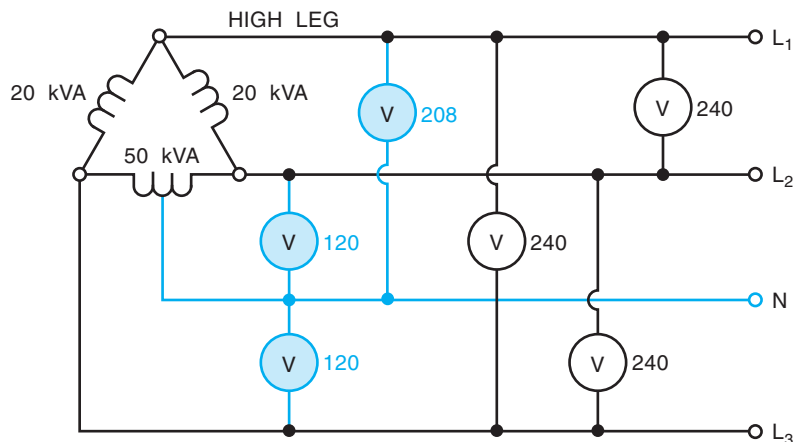
HIGH-LEG SYSTEM

Figure 5-11 illustrates another common type of transformer connection. This is a 240/120-volt system with a **high-leg**. Three transformers are connected to form a delta connection. One of the transformers is larger than the other two, however, and is center tapped. The large transformer must be able to supply power for both three-phase and single-phase loads. The other two transformers supply power for the three-phase loads only. If the phase voltage of the transformers is 240 volts, the voltage between any of the three lines is 240 volts. If the center-tap connection is used as a neutral conductor, however, the voltages between L2 and neutral, and L3 and neutral will be 120 volts. Therefore, L2,

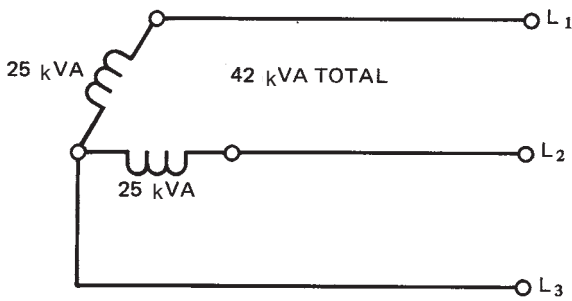
L3, and neutral are used to supply 240/120 volts for single-phase loads. Care must be taken not to connect a 120-volt device across L1 and neutral. Line L1 is known as a high leg and a voltage of about 208 volts exists between these two points.

OPEN-DELTA SYSTEM

Another type of three-phase service is known as the open delta. The **open-delta system** has the advantage of needing only two transformers to provide three-phase voltage. This connection is often used when the amount of three-phase power needed is low, or if the power needs are expected to increase in the future. The open-delta connection, however, does have some disadvantages. The total



► **Figure 5-11**
High-leg system. (Source: Delmar/Cengage Learning)

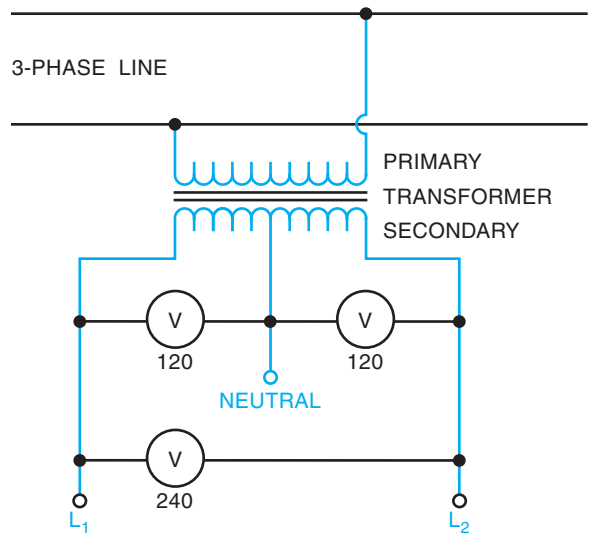


► **Figure 5-12**
Open-delta system. (Source: Delmar/Cengage Learning)

output power is only 84% of the combined rating of the transformers. If the two transformers shown in Figure 5-12 each have a power rating of 25 kVA (kilovolt amps), the total delivered power of this connection is only 42 kVA ($25 + 25 = 50$) ($50 \times 84\% = 42$). If at a later date the power requirements increase, a third transformer can be added to close the delta. The total output power of this connection is the combined rating of all three transformers. In this case it will be 75 kVA ($25 + 25 + 25 = 75$).

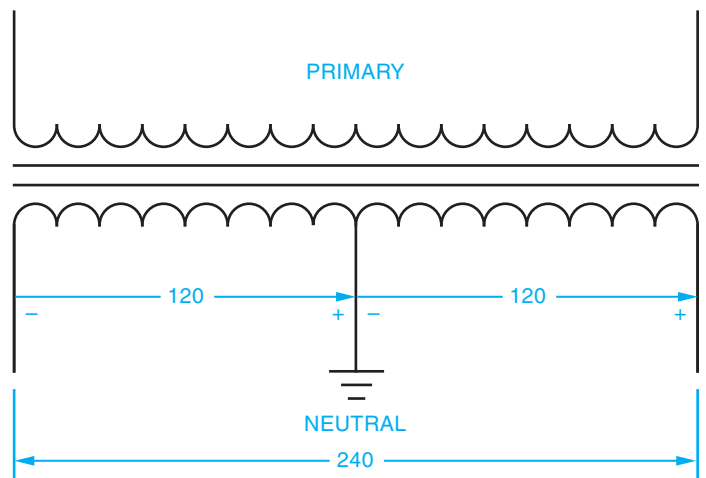
SINGLE-PHASE SERVICE

A **single-phase** 240/120-volt system can be obtained by connecting a single transformer to two lines of a three-phase system. The primary of the transformer shown in Figure 5-13 is connected to two of the three-phase lines of the power company.



► **Figure 5-13**
Single-phase transformer. (Source: Delmar/Cengage Learning)

The secondary voltage of the transformer is 240 volts. The secondary winding of the transformer is center tapped. The center tap is grounded and becomes the **neutral** conductor. If the voltage across the entire secondary is measured, it will be 240 volts. If the voltage between either of the secondary leads is measured to the center tap, it will be 120 volts. The reason this is true for single-phase and not three-phase is that the voltages of the single-phase system are in phase with each other, Figure 5-14. Because the transformer center tap

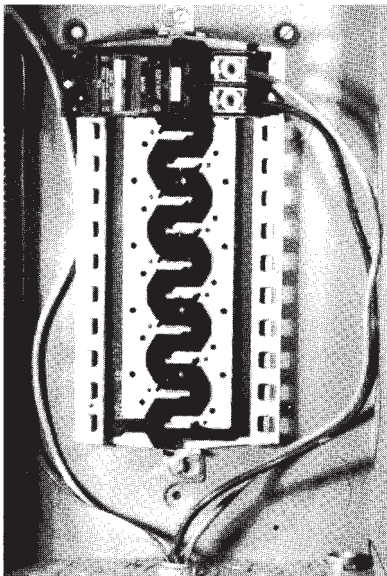


► **Figure 5-14**
The voltages across the winding of the secondary of the single-phase transformer are in phase with each other. (Source: Delmar/Cengage Learning)

is the neutral conductor, it will be 120 volts more positive than one side of the secondary winding and 120 volts more negative than the other side of the secondary winding at a particular point in time. Because these two vectors are in phase or are in the same direction, they will produce a total voltage of 240 volts.

PANEL BOX

Regardless of the type of service used, connection will be made at a **fuse** or **circuit-breaker** box. Figure 5-15 shows a 150-amp single-phase circuit-breaker panel. Circuit breakers are made in different sizes and types. Figure 5-16 shows three different types of circuit breakers. The **single-pole breaker** is used for connecting a 120-volt circuit, the **two-pole breaker** is used for connecting a 240-volt single-phase circuit, and the **three-pole breaker** is used for connecting a three-phase circuit. The three-pole breaker must be used with a three-phase circuit-breaker panel and cannot be used in a single-phase panel.



► **Figure 5-15**
150-amp single-phase panel. (Source: Delmar/Cengage Learning)



► **Figure 5-16**
Single-pole, double-pole, and three-pole circuit breakers. (Source: Delmar/Cengage Learning)

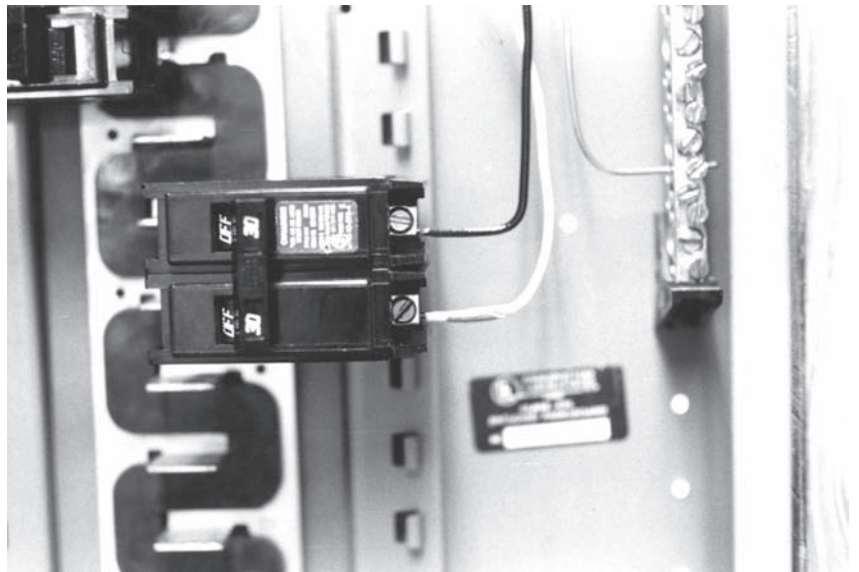
When a 120-volt connection is to be made, cable is brought into the panel. A **two-conductor romex** cable contains three wires—a black, white, and bare copper. The bare copper wire is the grounding wire or safety wire and is not considered a circuit conductor. Only the black and white wires are considered to be circuit conductors. The black wire is used as the “hot” conductor and the white wire is used as the neutral. Figure 5-17 shows a 120-volt single-phase circuit connected into the panel box. Notice that the black wire is connected to the circuit breaker, and the white wire is connected to the neutral bus. Notice also that the bare copper wire is connected to the neutral bus with the white wire.

When a 240-volt connection must be made, a two-pole circuit breaker is used. If the connection is to use only two-circuit conductors as shown in Figure 5-18, the black wire connects to one pole of the two-pole breaker. The *National Electrical Code*® does not permit a white wire to be used as a hot circuit conductor. For this reason the wire must be identified by wrapping a piece of colored tape around it. The tape can be any color except white, gray, or green. Black or red tape is generally used. The identified conductor is then connected to the other pole of the two-pole breaker. The bare copper wire is connected to the neutral bus.

If a 240-volt three-wire circuit is to be connected to the panel, a three-conductor cable is used. The three-conductor cable contains four wires—a black, red, white, and green. The green is the grounding or safety wire and is not considered a circuit conductor.



► **Figure 5-17**
120-volt single-phase
connection. (Source: Delmar/
Cengage Learning)



► **Figure 5-18**
240-volt single-phase two-wire
connection. (Source: Delmar/Cengage
Learning)

Figure 5-19 shows a 240-volt three-wire connection. The black and red wires are connected to the two poles of the circuit breaker. The white and green wires are connected to the neutral bus.

When a three-phase panel connection is made, a three-pole circuit breaker is used. There may or may

not be a neutral depending on the type of circuit. For example, a 208/120-volt connection would use a fourth wire connected to the neutral bus. A 440-volt straight, three-phase connection would use only three conductors connected to a three-pole breaker.



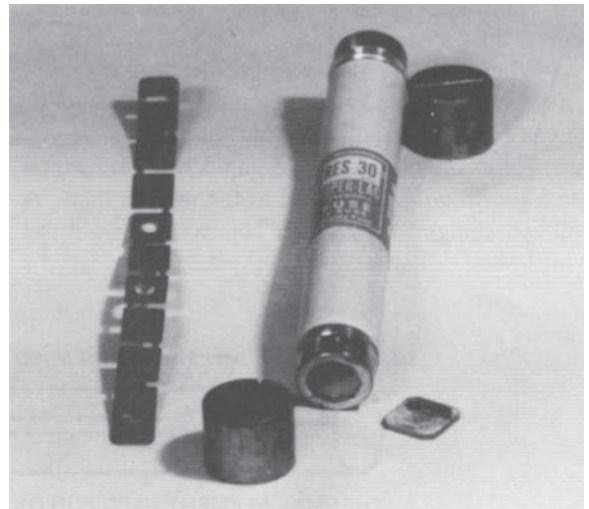
► **Figure 5-19**
240-volt single-phase three-
wire connection. (Source: Delmar/
Cengage Learning)

FUSES

Circuit breakers are not the only means used to provide circuit protection. Fuses are still used to a great extent. Fuses are rated in two ways—by voltage and current. The voltage rating of a fuse indicates the amount of voltage the fuse is designed to interrupt without arcing across. Although fuses can be obtained that have ratings of several thousand volts, the most common fuses used in the air conditioning field are 250 volt and 600 volt. The 600-volt fuse is longer to provide a greater distance between the two contact ends if the fuse link should blow. The extra length is needed at higher voltages to prevent **arc-over**.

Figure 5-20 shows a type of fuse that uses a replaceable link. When this fuse blows, the fuse cartridge can be taken apart and the fuse link replaced. This type of fuse is more expensive to purchase, but it could be a savings if the fuse has to be replaced frequently.

Fuses used for circuit protection are made in standard ampere ratings. Figure 5-21 shows these ratings as taken from the *National Electrical Code*®. Fuses for air conditioning and refrigeration equipment are normally sized at 175% of the rated full-load current of the motor. If this does not permit the motor to start, however, compressors can be fused



► **Figure 5-20**
Replaceable-link type of fuse. (Source: Delmar/Cengage Learning)

as much as 225% of their full-load running current. If the fuse size needed does not correspond with one of the standard fuse sizes, the next smaller size fuse will have to be used. For example, assume it has been determined that a fuse rating of 130 amps is needed. The standard ratings chart for fuses shown in Figure 5-21 does not list a 130 amp fuse. Therefore, the closest standard rating less than 130 amps

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 5-21

Standard fuse ratings. (Reprinted with permission from NFPA 70™, *National Electrical Code*®. Copyright 2008, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety. *National Electrical Code*® and *NEC*® are registered trademarks of the National Fire Protection Association, Inc., Quincy MA 02269).

is 125 amps. A 125-amp fuse will be used. Notice that fuses can be sized as much as 225% of the full-load current of the compressor. Fuses are sized this much above the running current of the motor to permit the fuse the ability to withstand the starting current of the motor. Fuses are designed to protect the circuit against short circuits; they are not used to protect the motor from overloads.

Overload protection for the motor is provided by the overload relay, which will be covered later, or by dual-element time delay fuses. Dual-element time delay fuses are designed to provide both types of protection. Figure 5-22 illustrates a dual-element time delay fuse. The fuse link is designed to open quickly in the event of a short circuit. Short circuit currents are generally several hundred times the rating

of the fuse. The fuse link is also designed to allow some amount of overload for a short period of time. This time delay permits the motor to start without opening the fuse link. The overload protection is provided by a solder link. The solder is intended to melt at a specific temperature and a spring is used to pull the link apart. Although the motor starting current is greater than the overload protection would permit, it takes time for the solder to melt, permitting the motor to start.

FUSED DISCONNECTS

Fused disconnects provide both a disconnect switch and fuse holders. Figure 5-23 shows a fused disconnect used for three-phase circuits. Fused disconnects,

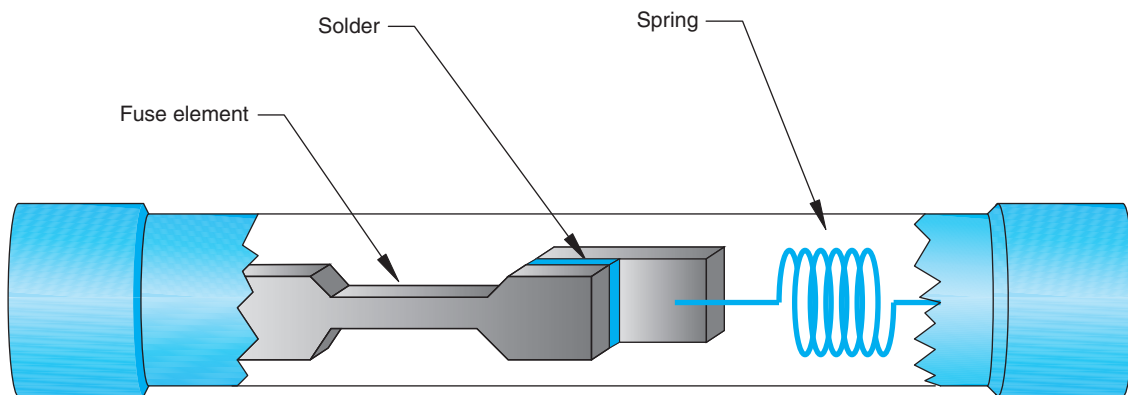
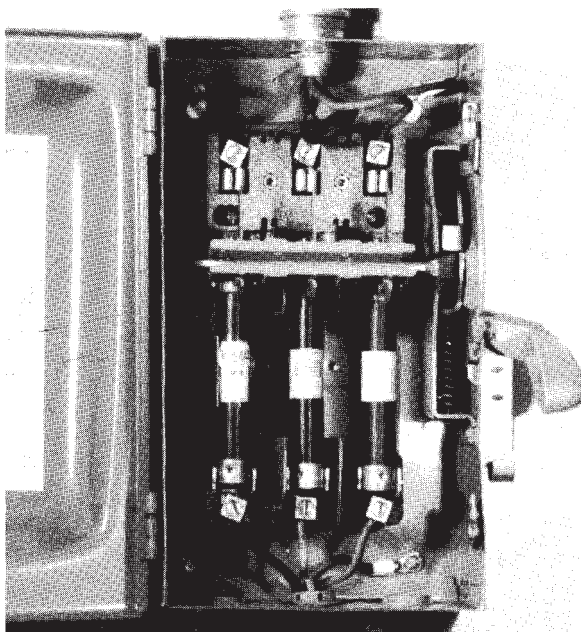


Figure 5-22

Dual-element time-delay fuse. (Source: Delmar/Cengage Learning)



► **Figure 5-23**
Three-phase fused disconnect. (Source: Delmar/Cengage Learning)

like fuses, have standard ratings. The standard sizes for fused disconnects are shown in Figure 5-24. The rating of the disconnect indicates the maximum size of fuse that can be used in that enclosure. For example, assume the 125-fuse discussed earlier in this unit is to be mounted in a disconnect. Because the fuse size is greater than 100 amps, it cannot be mounted in a 100-amp enclosure. The next standard size enclosure is 200 amps. The 125-amp fuses will have to be mounted in a 200-amp disconnect.

When servicing equipment, it is often necessary to turn off the power to the equipment. When this is

STANDARD DISCONNECT SIZES

30 amp
60 amp
100 amp
200 amp
400 amp
600 amp
1,000 amp
1,200 amp
1,600 amp
2,000 amp
3,000 amp
4,000 amp
5,000 amp
6,000 amp

► **Figure 5-24**
Standard disconnect sizes. (Source: Delmar/Cengage Learning)

necessary, certain precautions should be taken by the service technician. Remember that your life is your own and do not trust someone else not to turn the circuit back on while it is being serviced. Most industries provide a tag that is hung on the disconnect while it is being serviced. A paper tag, however, cannot stop someone from turning the power back on. For this reason, a small padlock should be used to lock the disconnect in the off position. If a lock is not available, the fuses should be removed with fuse pullers. There is no such thing as being too safe when working with high-voltage electricity.

SUMMARY

- The electric power in the United States and Canada is generated as three phase with a frequency of 60 Hz.
- The voltages of a three-phase system are 120° out of phase with each other.
- The two basic types of three-phase connections are the wye and delta.
- In a wye-connected system, the line voltage is greater than the phase voltage by a factor of the $\sqrt{3}$ (1.732).

- ▶ In a wye-connected system, the line current and phase current are equal.
- ▶ In a delta-connected system, the line voltage and phase voltage are equal.
- ▶ In a delta-connected system, the line current is greater than the phase current by a factor of $\sqrt{3}$.
- ▶ Some delta-connected systems can produce a high-leg that has one phase with a voltage that is 1.732 times greater than the other two-phase voltages.
- ▶ Open-delta systems use only two transformers.
- ▶ In an open-delta system, the total kVA capacity is only about 84% of the combined kVA capacity of the two transformers.
- ▶ Single-phase services produce voltages that are 180° out of phase with each other.
- ▶ Single-phase services generally provide a 120/240-volt connection by grounding the center tap of a transformer secondary and using it as a neutral conductor.
- ▶ A single-pole circuit breaker is used to provide power to a 230-volt circuit.
- ▶ A two-pole circuit breaker is used to provide power to a 240-volt circuit.
- ▶ A three-pole circuit breaker is used to provide power to a three-phase circuit.
- ▶ Fuses are sometimes used instead of circuit breakers.
- ▶ Section 240.6 of the *National Electrical Code*® lists standard sizes of fuses and circuit breakers.

KEY TERMS

alternator
arc-over
circuit breaker
delta
fuse
hertz
high-leg

neutral
open-delta system
rotor
single-phase
single-pole breaker
star
stator

three phase
three-pole breaker
two-conductor
romex
two-pole breaker
wye

REVIEW QUESTIONS

1. What is an alternator?
2. What controls the output voltage of an alternator?
3. What controls the frequency of the alternator?
4. How many degrees out of phase with each other are the voltages of a three-phase system?
5. What are the two major types of three-phase connections?
6. List the rules concerning line and phase values of current and voltage in a wye connection.



7. List the rules concerning line and phase values of current and voltage in a delta connection.
8. In a high-leg delta-connected system, what is the voltage between the high leg and neutral?
9. What type of three-phase transformer connection uses only two transformers?
10. How many degrees out of phase are the voltages of a single-phase system?
11. A two-conductor romex cable contains three wires. Which wire is not counted and why.
12. What type of circuit breaker is used to make a 240-volt connection?
13. Where does the grounding conductor connect in a panel?
14. In what two electrical units are fuses rated?
15. It has been calculated that a 290-amp fuse is needed to protect the circuit supplying an air conditioning compressor. What standard rating of fuse should be used?
16. What size fuse disconnect will be used for the fuse in question 15?
17. What is a dual-element fuse?

UNIT 6



Wire Size and Voltage Drop

OBJECTIVES

After studying this unit the student should be able to:

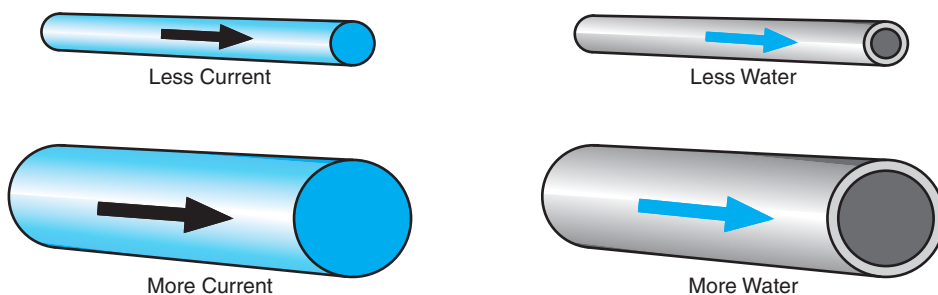
- ▶ List factors that determine wire resistance
- ▶ Determine the resistance of a piece of wire
- ▶ Use the *National Electrical Code*® to determine wire size
- ▶ Test an installation of excessive voltage drop on the conductors

When installing air conditioning equipment it is important to use the proper size wire. If wire is used that is larger than needed, it is an unnecessary expense. If wire is used that is too small, it will cause excessive voltage drop and damage the equipment.

WIRE RESISTANCE

Most people think of wire as having zero resistance. In fact, many electrical calculations are made that assume the resistance of the wire is so little that it is negligible. In actual practice, however, all wire has resistance. There are four factors that determine the resistance of a piece of wire. The factors are:

1. The diameter of the wire.
2. The material the wire is made of.
3. The length of the wire.
4. The temperature of the wire.



► **Figure 6-1**
Larger wire
can carry more
current. (Source:
Delmar/Cengage
Learning)

AREA

The cross-sectional area of wire is measured in **circular mils**. The circular mil area of a wire can be found by finding the diameter of the wire in thousandths of an inch (1 mil = $\frac{1}{1,000}$ inch) and squaring that number. (Squaring a number means to multiply that number by itself.) For example, assume a piece of wire is measured with a micrometer and is found to have a diameter of 8 thousandths of an inch (.008). The circular mil area of the wire is 64 ($8 \times 8 = 64$). Notice that 64 is written as a whole number, not a decimal number. A wire that has a diameter of .064 inch has a circular mil area of 4096 ($64 \times 64 = 4,096$).

The circular mil area of stranded wire is determined by finding the area of one of the strands and then multiplying by the number of strands. For example, assume that a wire has 24 strands of wire that are .012 inches in diameter. The area of one wire is 144 CM (circular mils). The entire conductor has a circular mil area of 3,456 CM ($144 \times 24 = 3,456$). Large wire is generally stranded to make it easier to bend.

The larger the diameter of a wire, the less resistance it will have and the more current it can carry, Figure 6-1. Current flowing through a wire is very similar to water flowing through a pipe. A large wire can carry more current at a specific voltage than a small wire. A large pipe can carry more water at a specific pressure than a small pipe.

MATERIAL

A standard measurement used for finding the resistance of wire is the **mil-foot**. A mil-foot of wire

is a piece of wire one circular mil in diameter and one foot long. If the resistance of a mil-foot of different types of wire is found, a mathematical formula can be used to determine the resistance of different types, sizes, and lengths of wire. This formula is:

$$R = K \times L/CM$$

Where: K = the ohms per mil-foot of the wire.
 L = the length of the wire in feet.
 CM = the circular mil area of the wire.

The table in Figure 6-2 gives the resistance of different types of wire in ohms per mil-foot. Using the table shown in Figure 6-3, the diameter and circular mil area for different sizes of wire can be found.

K = OHMS RESISTANCE PER MIL-FOOT (AT 70°F)	
Aluminum	17
Brass	42
Cadmium Bronze	12
Copper	10.4
Copperclad Aluminum (20% Cu)	15.2
Copperweld	26-34
Iron	60
Nichrome	600
Silver	9.6
Steel	75
Tungsten	33

► **Figure 6-2**
Larger wire can carry more current. (Source: Delmar/
Cengage Learning)

American Wire Gauge Table												
B & S Gauge No.	Diam. in Mils	Area in Circular Mils	Ohms per 1000 Ft. (ohms per 100 meters)					Pounds per 1000 Ft. (kg per 100 meters)				
			Copper *		Copper *		Aluminum		Copper	Aluminum		
			68°F	(20°C)	167°F	(75°C)	68°F	(20°C)				
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)	0.191	(0.062)	0.256	(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	(0.129)	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)	4.80	(0.71)
14	64	4,107	2.525	(0.828)	3.07	(1.01)	4.14	(1.36)	12.4	(1.84)	3.80	(0.56)
15	57	3,257	3.184	(1.044)	3.98	(1.27)	5.22	(1.71)	9.86	(1.47)	3.00	(0.45)
16	51	2,583	4.016	(1.317)	4.88	(1.60)	6.59	(2.16)	7.82	(1.16)	2.40	(0.36)
17	45.3	2,048	5.06	(1.66)	6.16	(2.02)	8.31	(2.72)	6.20	(0.922)	1.90	(0.28)
18	40.3	1,624	6.39	(2.09)	7.77	(2.55)	10.5	(3.44)	4.92	(0.713)	1.50	(0.22)
19	35.9	1,288	8.05	(2.64)	9.79	(3.21)	13.2	(4.33)	3.90	(0.580)	1.20	(0.18)
20	32	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	(0.11)
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	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	25	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	2.5											
43	-											
44	1.97											

* Resistance figures are given for standard annealed copper. For hard-drawn copper add 2%

Figure 6-3
American Wire Gauge table. (Source: Delmar/Cengage Learning)

PROBLEM 1: What is the resistance of a piece of #18 AWG (American Wire Gauge) copper wire 400 feet long?

SOLUTION: First, state the formula to be used.

$$R = \frac{K \times L}{CM}$$

Second, substitute known numeric values in the formula. The value of K can be found in the table shown in Figure 6–2. The K value for copper is 10.4. The CM area of #18 AWG wire can be found from the chart in Figure 6–3. The circular mil area of #18 AWG wire is 1624 CM. If these values are substituted in the formula for letters, the formula will be:

$$R = \frac{10.4 \times 400}{1624}$$

$$R = \frac{4160}{1624}$$

$$R = 2.56 \text{ ohms}$$

PROBLEM 2: What is the resistance of a piece of #12 AWG aluminum wire 250 feet long?

SOLUTION:

$$R = \frac{K \times L}{CM}$$

$$R = \frac{17 \times 250}{6530}$$

$$R = \frac{4250}{6530}$$

$$R = .6508 \text{ ohms}$$

TEMPERATURE

The resistance of a piece of wire is also affected by **temperature**. As the temperature increases, the resistance of wire increases also. Notice that the charts in Figures 6–2 and Figure 6–3 state the resistance of wire at a specific temperature. Most wire tables will provide some means for determining the resistance of wire as temperature increases. Figure 6–4 shows Table 310.16 of the *National Electrical Code*®. Notice that at the bottom of the table ampacity correction factors are given.

INSULATION

The type of **insulation** around the wire also partly determines the amount of current the wire is permitted to carry. Some types of insulation can withstand more heat than others, and are, therefore, permitted to carry more current. For example, in Table 310.16, the type of wire insulation is listed at the top of each column. Notice the different temperature ratings for the types of insulation listed. Also notice the amount of current a wire is permitted to carry for different types of insulation. Find a #2 AWG conductor on the far left-hand side of the wire table. Notice the different amounts of current this conductor is permitted to carry with different types of insulation.

VOLTAGE RATING

Wire also has a **voltage rating**. The voltage rating of wire has nothing to do with the type of material the wire is made of or its diameter. The voltage rating is determined by the type of insulation. Most wire used in industry has a voltage rating of 600 volts. The amount of voltage the insulation can effectively hold off is determined by the material the insulation is made of and its thickness.

SIZING CONDUCTORS FOR HERMETICALLY SEALED COMPRESSORS

Requirements for the installation of hermetically sealed compressors are covered in Article 440 of the *National Electrical Code*®. Note that this section covers hermetically sealed units only and does not apply to separate motor and compressor units. NEC® Section 440.6(A) states that the rated-load current marked on the nameplate of the equipment is to be used in determining the rating or ampacity of the disconnecting means, branch circuit conductors, controller, fuses or circuit breakers, ground fault protection equipment, and overload protection. If the rated-load current is not shown on the equipment nameplate, the rated load current shown on the compressor is to be used. Note the difference

Table 310.16 Allowable Ampacities of Insulated Conductors Rated 0 Through 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)

Size AWG or kcmil	Temperature Rating of Conductor (See Table 310.13.)						Size AWG or kcmil
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	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	
COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM				
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14*	20	20	25	—	—	—	—
12*	25	25	30	20	20	25	12*
10*	30	35	40	25	30	35	10*
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	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	190	230	255	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	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	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	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000

CORRECTION FACTORS							
Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below.						Ambient Temp. (°F)
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	—	0.58	0.71	132–140
61–70	—	0.33	0.58	—	0.33	0.58	141–158
71–80	—	—	0.41	—	—	0.41	159–176

* See 240.4(D).

Figure 6-4

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between the equipment nameplate and compressor nameplate. The equipment nameplate is generally shown on the unit itself, Figure 6–5. The compressor nameplate is located on the compressor.

NEC® Section 440.6(A) Ex. 1 states that where so marked, the branch circuit selection current shall be used instead of the rated load current to determine the rating or ampacity of the disconnecting

MODEL NO. CA24S-4 SERIAL NO. A 25067JFC

FOR OUTDOOR USE

SPEC. CODE [] STAMPING NO. 312300028

MIN. AMPACITY CIRCUIT A 20 MAX. FUSE SIZE CIRCUIT A 30 AMP

PSI TEST PRESSURE H.S. 300 L.S. 150

ELECTRICAL RATING VOLTS A.C. PH. HZ. R.L.A. L.R.A.

COMP. 230 1 60 13.8 65

INDOOR FAN MOTOR 230 1 60 1.3

OUTDOOR FAN MOTOR 230 1 60 1.3

MIN. OPERATING VOLTAGE 197 REFRIGERANT 22 FACTORY CHARGED 64 OZ.

MIN. CLEARANCE TO COMBUSTIBLE MATERIAL WITH OR WITHOUT ELECTRICAL STRIP HEATERS: CABINET 0 IN

PLENUM AND DUCT FOR 6 FEET FROM PLENUM 1 IN

FOR USE WITH ELECTRIC HEATERS LISTED BELOW

EL5-2 EL10-2

IF NO HEATER IS INSTALLED MARK HERE

NOTE: WHEN HEATERS ARE INSTALLED RATING PLATE FOR ELECTRIC HEATERS MUST BE INSTALLED BELOW

3227983

► **Figure 6-5**
Equipment nameplate. (Source: Delmar/Cengage Learning)

means, branch circuit conductors, controller, short circuit protective device, and ground fault protective device. *NEC® Section 440.32* states that for a single motor compressor, the branch circuit conductors shall have an ampacity not less than 125% of either the motor compressor rated load current or the branch circuit selection current, whichever is greater. As a general rule the branch circuit selection current will be greater than the compressor rated load amps because the selection current includes any indoor and/or outdoor fans.

Termination Temperature

Another factor that must be taken into consideration is the temperature rating of different terminations. The termination is the point of attachment for conductors such as circuit breakers, disconnects, switches, and so forth. *NEC® Section 110.14(C)* basically states that the temperature rating of the termination cannot be exceeded. Although a wire with a higher temperature rating may be used, the ampacity of the wire must be selected on the basis of the lowest temperature rating in the circuit. Type THHN insulation has a temperature rating of 90°C, but assume

that it is connected to a device with a temperature rating of 75°C. The ampacity of the wire would have to be selected on the basis of 75°C, not 90°C.

Occasionally the temperature rating of a device will be listed on the device or in the manufacturer's literature, but as a general rule it is not known. For this reason, the *National Electrical Code®* states that conductors for circuits rated at 100 amperes or less will be selected from the 60°C column, and conductors rated over 100 amperes are to be selected from the 75°C column. An exception to this is if the insulation type is rated less than 75°C as is the case with type TW and UF. If either of these two types of insulation are employed, the ampere rating of the conductor must be determined from the 60°C column regardless of the circuit current.

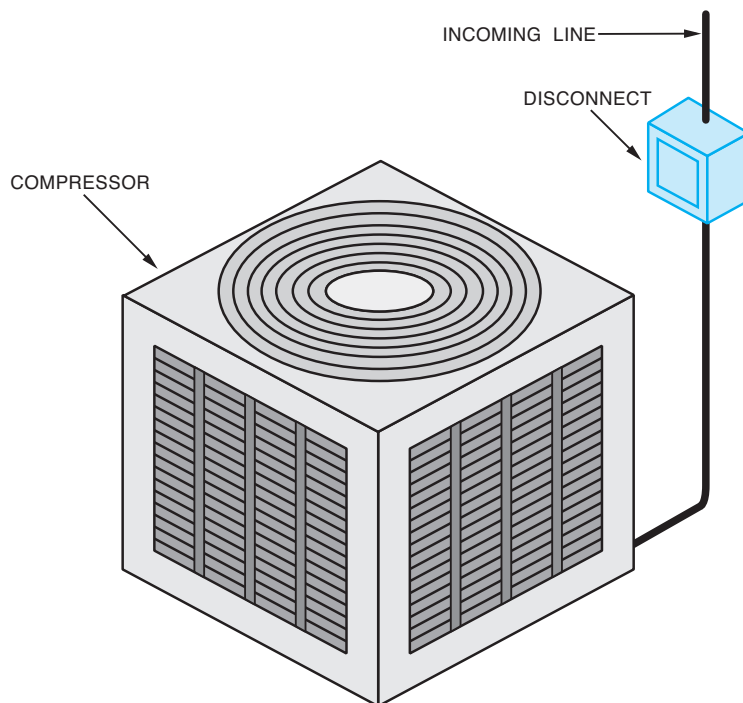
EXAMPLE

Assume that an equipment nameplate lists the rated load amps (RLA) of the compressor at 14.8 amps and the circuit selection current at 22 amps. To determine the correct conductor size for this unit, multiply the larger of the two rating by 125%.

$$22 \times 1.25 = 27.5 \text{ amps}$$

The next step is to determine the conductor size from *NEC® Table 310.16*. It will be assumed that copper conductors with type THWN insulation will be used for this installation. Although THWN insulation is located in the 75°C column, the conductor size will be selected from the 60°C column because the total circuit current is less than 100 amperes. *Table 310.16* indicates a #10 AWG conductor is the closest size without going under 27.5 amperes. A #10 AWG conductor will be used for this installation.

The *National Electrical Code®* also requires that a disconnecting means be located within sight from and readily accessible to the air conditioning or refrigeration equipment, Figure 6–6. The *NEC®* does permit the disconnect to be installed on or within the equipment provided it is not installed on a panel that is designed to allow access to the equipment. The disconnect may be located away from the air conditioning or refrigeration equipment provided there is a working clearance of at least 30 inches to allow service accessibility. This is to enable the service technician to disconnect power from the unit without having to enter the building to find the main



► **Figure 6-6**
A disconnecting means must be located in sight of the compressor. (Source: Delmar/Cengage Learning)

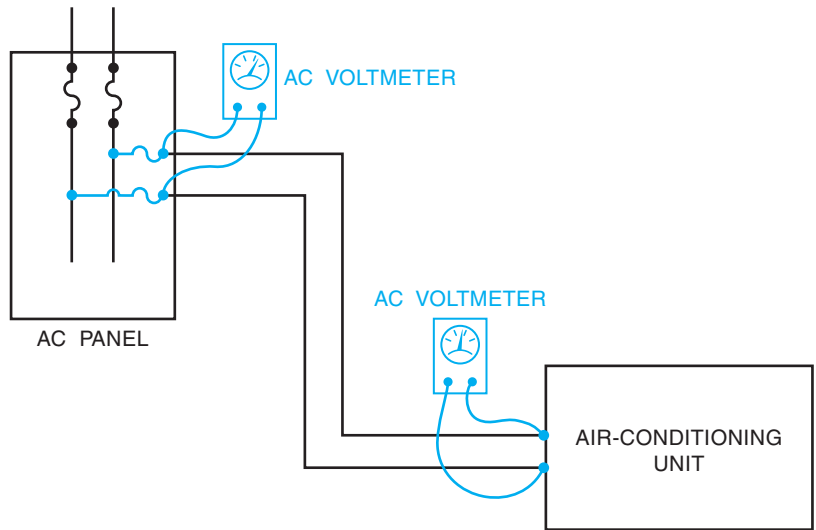
power panel. A typical disconnect used for air conditioning service is shown in Figure 6-7.

TESTING FOR EXCESSIVE VOLTAGE DROP

Testing a unit for excessive voltage can be done with a voltmeter. First, test the voltage at the panel with the unit turned off. Assume this voltage to be 240 volts. Next, start the air conditioning unit and again check the voltage at the panel. If the voltage remains unchanged, it is an indication that there is no voltage drop at the panel and that all connections for the part of the circuit are good. If there is excessive voltage drop at the panel, it is an indication of bad connections, or the service entrance is too small for the load. For this example, assume the voltage remains at 240 volts when the unit is turned on. Next, check the voltage at the unit, Figure 6-8. If there is a significant voltage drop at the unit, it indicates that the wire size is too small and that too much voltage is being used to push current through the wire. This problem can be corrected by connecting larger wires from the panel to the unit.



► **Figure 6-7**
Disconnect switch used for air conditioning equipment. (Source: Delmar/Cengage Learning)



► **Figure 6-8**
Testing for voltage drop.
(Source: Delmar/Cengage Learning)

SUMMARY

- ⌚ The resistance of wire is determined by four factors:
 - A. The diameter of the wire.
 - B. The material the wire is made of.
 - C. The length of the wire.
 - D. The temperature of the wire.
- ⌚ The cross-sectional area of wire is measured in circular mils.
- ⌚ Circular mil area is found by squaring the diameter of the wire.
- ⌚ The standard measurement for wire resistance in the English system is the mil-foot.
- ⌚ Different types of materials have different resistances per mil-foot.
- ⌚ The wire tables in the *National Electrical Code*® are often used to determine the size wire needed for a particular installation.
- ⌚ The voltage rating of wire is determined by the type of insulation.
- ⌚ Excessive voltage drop can be determined by measuring the voltage at the source and at the load when the unit is in operation.

KEY TERMS

AWG (American Wire Gauge)
circular mils

insulation
mil-foot
temperature

termination
temperature
voltage rating

REVIEW QUESTIONS

1. Name four factors that determine the resistance of wire.
2. A wire has a diameter of .057 inches. What is its circular mil area?
3. What is a mil-foot of wire?
4. When the temperature of wire increases, does its resistance increase or decrease?
5. What determines the voltage rating of wire?
6. What two factors determine the amount of voltage rating a certain type of insulation will have?
7. How much resistance does 75 feet of #24 AWG wire have?
8. If a current of 4 amps flows through the wire in question 7, how much voltage will be dropped by the wire?

UNIT 7



Inductance

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the voltage and current relationship in an AC circuit containing pure resistance and pure inductance
- Discuss the properties of an inductive circuit
- Calculate values of inductive reactance
- Calculate values of impedance in circuit containing resistance and inductance
- Discuss true power, apparent power, and reactive power
- Discuss the power factor of an alternating-current circuit

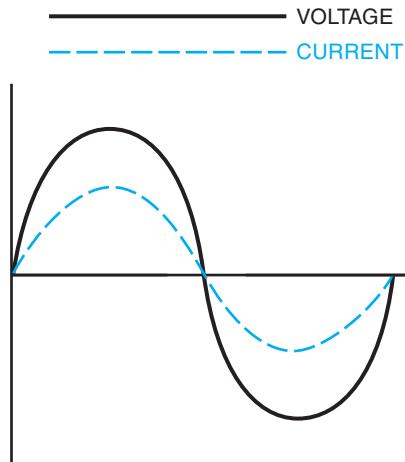
Alternating-current circuits contain three basic types of loads. These are (1) resistive, (2) inductive, and (3) capacitive.

RESISTIVE CIRCUITS

The simplest of the AC loads is a circuit that contains only pure resistance, Figure 7-1. In a **pure-resistive circuit**, the voltage and current are **in phase** with each other, Figure 7-2. Voltage and current are in phase when they cross the zero line at the same point, and have their peak positive and negative values at the same time. A pure-resistive circuit is very similar to a direct-current circuit in the respect that true power or watts is equal to the voltage times the current. Examples of pure-resistive circuits are the heating elements of an electric range, an electric hot-water heater, and the resistive elements of an electric furnace.



► **Figure 7-1**
Pure-resistive circuit. (Source: Delmar/Cengage Learning)

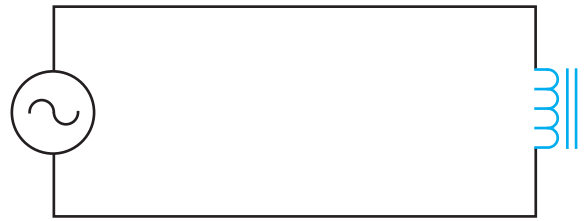


► **Figure 7-2**
Current and voltage are in phase. (Source: Delmar/Cengage Learning)

INDUCTIVE CIRCUITS

An inductive circuit contains an inductor or coil as the load instead of a resistor, Figure 7-3. The two most common types of inductive circuits are motors and transformers. Inductors are measured in units called the **henry**. The unit of inductance is named in honor of Joseph Henry, a physicist who studied electricity. The electrical symbol for inductance is L .

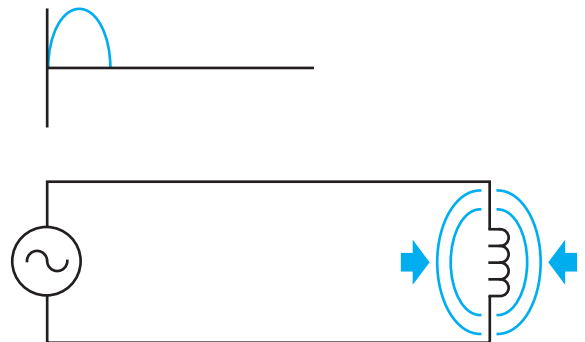
Inductors differ from resistors in several ways. One way is that the current of an inductor is not limited by the resistance of the coil. When an inductor is connected into an AC circuit and the voltage begins to rise from zero toward its peak value, a **magnetic field** is created around the coil, Figure 7-4. As the expanding magnetic field cuts through the wires of the coil, a voltage is induced in the coil. *The voltage induced in a coil is always opposed*



► **Figure 7-3**
A pure inductive circuit. (Source: Delmar/Cengage Learning)

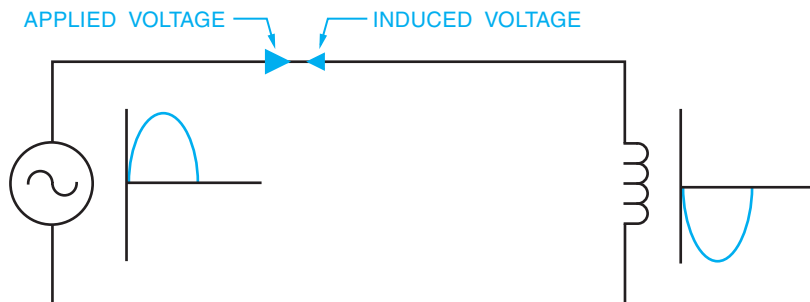


► **Figure 7-4**
Magnetic field expands. (Source: Delmar/Cengage Learning)



► **Figure 7-5**
Magnetic field collapses. (Source: Delmar/Cengage Learning)

to the voltage that creates it. As the applied voltage begins to drop from its peak value back toward zero, the magnetic field around the inductor begins to collapse, Figure 7-5. Notice that the induced voltage is opposite in polarity to the applied voltage. An induced voltage is 180° out of phase with the applied voltage, Figure 7-6.



► **Figure 7-6**
The induced voltage is opposed to the applied voltage. (Source: Delmar/Cengage Learning)

Because the induced voltage is opposed to the applied voltage, it will limit current flow through the circuit just as resistance will. Although the induced voltage of a coil will limit the current flow “like” resistance, it is not resistance and cannot be treated as resistance. The unit of measure used to describe the current-limiting effect of an induced voltage is **reactance** and is given the electrical symbol X . Because this reactance is caused by an inductance, it is called **inductive reactance** and is given the electrical symbol X_L (pronounced X sub L). Inductive reactance is measured in ohms just as resistance is.

The inductive reactance of a coil is determined by two factors. These are:

1. The inductance of the coil.
2. The frequency of the applied voltage.

If these factors are known, a formula can be used to find the inductive reactance of the coil. This formula is:

$$X_L = 2 \times \pi \times F \times L$$

X_L = inductive reactance

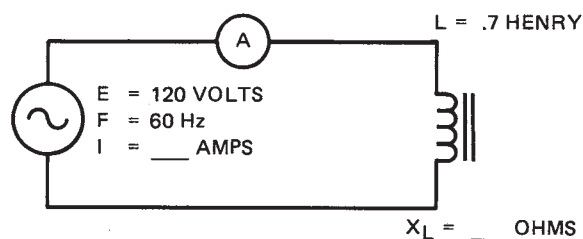
π = the Greek letter Pi, which has a value of 3.1416

F = the frequency of the AC voltage

L = the inductance of the coil in henrys

EXAMPLE

In the circuit shown in Figure 7-7, a coil has an inductance of .7 henrys, and is connected to a 120-volt, 60-Hz line. Find the current flow in the circuit.



► **Figure 7-7**
Current flow is limited by inductive reactance. (Source: Delmar/Cengage Learning)

To solve the problem, the first step is to find the amount of inductive reactance in the circuit.

$$X_L = 2 \times \pi \times F \times L$$

$$X = 2 \times 3.1416 \times 60 \times .7$$

$$X_L = 263.9 \text{ ohms}$$

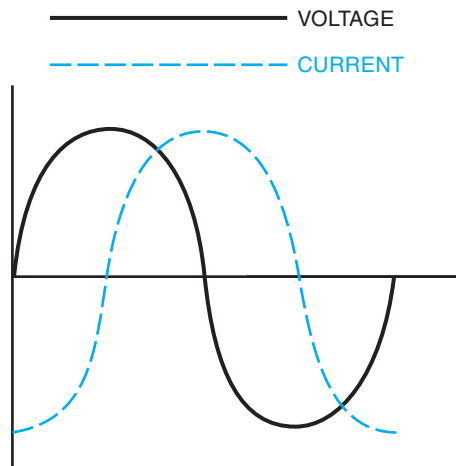
Now that the inductive reactance of the coil is known, the current flow in the circuit can be calculated. If the value of inductive reactance is used like resistance, the formula to find current in a pure-inductive circuit is $I = E/X_L$.

$$I = \frac{120}{263.9}$$

$$I = .455 \text{ amps}$$

VOLTAGE AND CURRENT RELATIONS

As stated previously, the voltage and current in a pure-resistive circuit are in phase with each other. In a **pure-inductive circuit**, however, the current lags behind the voltage by 90°, Figure 7-8.



► **Figure 7-8**
Current lags voltage by 90° in a pure inductive circuit.
(Source: Delmar/Cengage Learning)

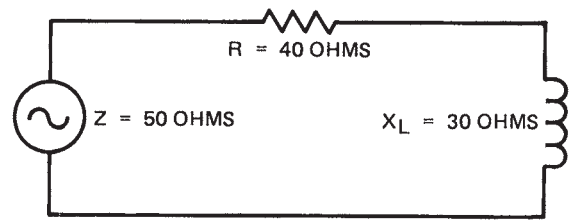
In this type of circuit there is no true power or watts. In a resistive circuit, the resistor limits the current flow by converting the energy of the moving electrons into heat. This conversion of one form of energy into another represents a true power loss. In an inductive circuit, the energy of the moving electrons is stored in the magnetic field created around the inductor. When the magnetic field collapses, this energy is given back into the circuit. Notice that the resistor used the electrical energy by converting it into heat, but the inductor stored the energy and then returned it to the circuit.

IMPEDANCE

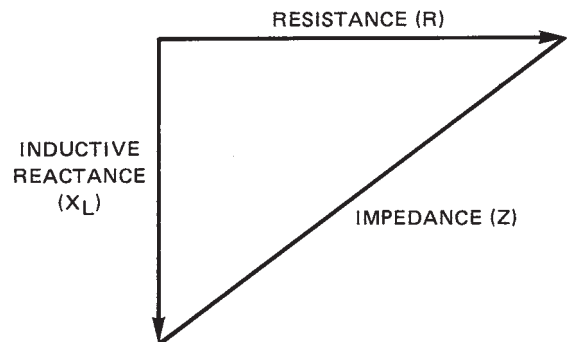
In an alternating-current circuit that contains only resistance, the current is limited by the value of the resistor only. In this type of circuit the current flow can be calculated using the Ohm's law formula $I = E/R$.

In an AC circuit that contains only inductance, the current is limited only by the value of inductive reactance. In this type of circuit, the current flow can be calculated using the formula $I = E/X_L$.

In a circuit like the one shown in Figure 7-9, there are elements of both resistance and inductive reactance contained in the same circuit. In this type of circuit, it cannot be said that the current is



► **Figure 7-9**
A series circuit containing resistance and inductance.
(Source: Delmar/Cengage Learning)



► **Figure 7-10**
Impedance is the sum of resistance and inductive reactance. (Source: Delmar/Cengage Learning)

limited by resistance, because there is also inductive reactance. It can also not be said that the current is limited by inductive reactance because of the resistance. Alternating-current circuits use a different value to represent the total amount of opposition to current flow in the circuit regardless of what type of components are found in the circuit. This value is known as **impedance** and is given the symbol Z .

The resistor and inductor in Figure 7-9 are connected in series. Because these two components are connected in series, they will be added. They cannot be added in the normal way, however, because the inductance is not in phase with the resistance. Because inductive reactance is 90° out of phase with resistance, the total amount of opposition to current flow will be the value of the hypotenuse of the right triangle formed by the resistance and inductive reactance, Figure 7-10. To find the total value of impedance in this circuit, the formula $Z = \sqrt{R^2 + X_L^2}$ can be

used. If the resistor has a value of 40 ohms and the inductor has an inductive reactance of 30 ohms, the impedance will be:

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{40^2 + 30}$$

$$Z = \sqrt{1600 + 90}$$

$$Z = \sqrt{2500}$$

$$Z = 50 \text{ ohms}$$

APPARENT POWER

In a direct-current circuit, the true power or watts is always equal to the voltage multiplied by the current because the current and voltage are never out of phase with each other. This also is true for an AC circuit that contains only pure resistance because the voltage and current are in phase.

In a circuit that contains pure inductance, however, there is no true power or watts. In this type of circuit, the voltage multiplied by the current equals a value known as **VARs**, which stands for **Volt-Amps Reactive**. VARs is often referred to as wattless power.

The **apparent power** or **volt-amps** of an AC circuit is the applied voltage multiplied by the current flow in the circuit. The amount of apparent power as compared to the true power or VARs is determined by the elements of the circuit itself. In the circuit shown in Figure 7-11, the amount of true

power is 400 watts. The amount of reactive power is 300 VARs. The apparent power is 500 volt-amps. Notice that the apparent power is found by adding the watts and VARs together in the same manner that the resistance and inductive reactance were added to find the total value of impedance. Volt-amps can be calculated by the formula:

$$\text{Volt-amps} = \sqrt{W^2 + \text{VARs}^2}$$

POWER FACTOR

The **power factor** of an alternating-current circuit is a ratio of the apparent power compared to the true power. Power factor is important because utility companies charge industries large penalties for a poor power factor. The power factor of the circuit shown in Figure 7-11 can be found by:

$$PF = \frac{W}{VA}$$

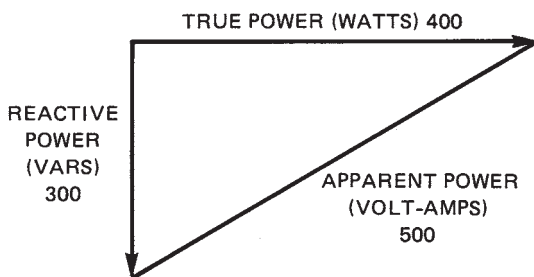
$$PF = \frac{400}{500}$$

$$PF = .8$$

$$PF = 80\%$$

Notice in this circuit, the power factor is 80%. This means 80% of the load is resistive and 20% is reactive. If the load is pure resistive, the power factor will be 100% or **unity**.

Utility companies become very concerned about power factor because they must furnish the amount of current needed to produce the volt-amp value. The company, however, is charged by the amount of true power or watts used. In this instance, if the applied voltage is 120 volts, the utility company must supply 4.16 amps to operate the load (500 volt-amps/120 volts = 4.16 amps). The actual amount of current being used to operate the load, however, is 3.33 amps (400 watts/120 volts = 3.33 amps). Because the air conditioning load is often the major part of the electrical power consumed by an industry or office building, power factor can become an important consideration to the service technician.



► **Figure 7-11**
Volt-amps is the vector sum of watts and VARs.
(Source: Delmar/Cengage Learning)

SUMMARY

- ▶ In 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° .
- ▶ Inductive reactance (X_L) is the current-limiting property of inductance.
- ▶ Inductive reactance is actually a counter voltage, which opposes the applied or line voltage.
- ▶ Inductive reactance is proportional to two factors:
 - A. The inductance of the coil.
 - B. The frequency of the applied voltage.
- ▶ Inductive reactance is measured in ohms like resistance.
- ▶ Impedance (Z) is a measurement of the total current limiting effect in an alternating-current circuit.
- ▶ Impedance is a combination of all current limiting properties of an AC circuit and is measured in ohms.
- ▶ True power is measured in watts.
- ▶ Watts is a measurement of the amount of electrical energy converted to some other form such as heat or mechanical.
- ▶ VARs is a measure of the amount of power in a pure inductive circuit sometimes referred to as wattless power.
- ▶ Apparent power or volt amperes (VA) is a combination of true power or watts and VARs.
- ▶ In an AC circuit, apparent power is determined by multiplying the applied voltage by the circuit current.
- ▶ Power factor (PF) is a comparison of the amount of true power with the apparent power in an alternating-current circuit.
- ▶ Power factor is measured in a percent.

KEY TERMS

apparent power
henry
impedance
inductive reactance
in phase

magnetic field
power factor
pure-inductive circuit
pure-resistive circuit
reactance

unity
VARs (Volt-Amps Reactive)
volt-amps

REVIEW QUESTIONS

1. Name the three basic types of alternating-current loads.
2. What type of load always has its voltage and current in phase with each other?



3. In a pure-inductive circuit, how many degrees out of phase is the current with the voltage?
4. Does the current lead or lag the voltage in question 3?
5. What electrical value is used to measure inductance?
6. What is inductive reactance?
7. What electrical value is used to measure the total opposition to current flow in an AC circuit?
8. What is power factor?

UNIT 8



Capacitance

OBJECTIVES

After studying this unit the student should be able to:

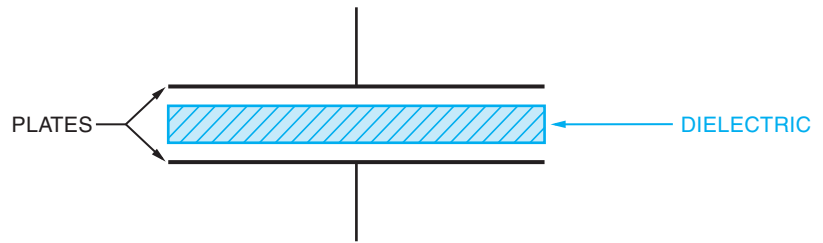
- Discuss the operating theory of a capacitor
- List the factors that determine the amount of capacitance a capacitor will have
- Discuss the voltage and current relationship in an AC circuit containing pure capacitance
- Discuss the voltage and current relationship in an AC circuit containing resistance and capacitance
- Compute values of capacitive reactance
- Compute values of impedance for circuits that contain both resistance and capacitive reactance
- Discuss power factor correction
- Compute the amount of capacitance needed to correct the power factor of a motor
- Discuss different types of capacitors and methods for testing

The third type of alternating-current load to be discussed is **capacitance**. A capacitor can be made by separating two metal plates with an insulating material, Figure 8–1. The insulating material used to isolate the plates from each other is called the **dielectric**. There are three factors that determine how much capacitance a capacitor will have. These are:

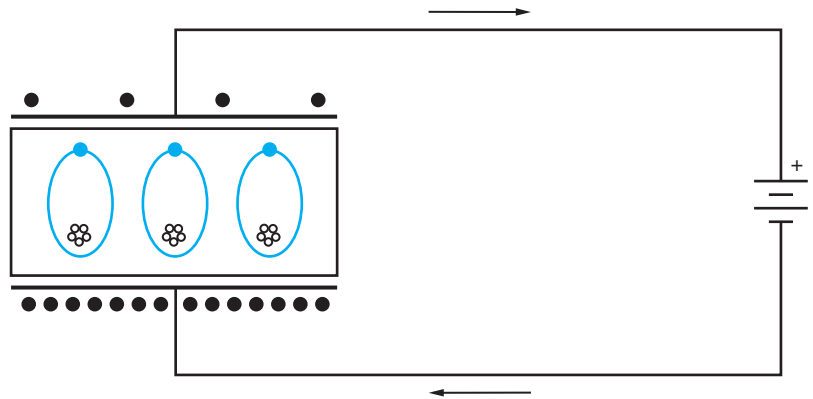
1. The surface area of the plates.
2. The distance between the plates.
3. The type of dielectric material used between the plates.

CHARGING A CAPACITOR

In Figure 8–2, the terminals of a capacitor have been connected to a battery. Electrons are negative particles. Therefore, the positive terminal of



► **Figure 8-1**
A capacitor is made with two metal plates separated by a dielectric.
(Source: Delmar/Cengage Learning)



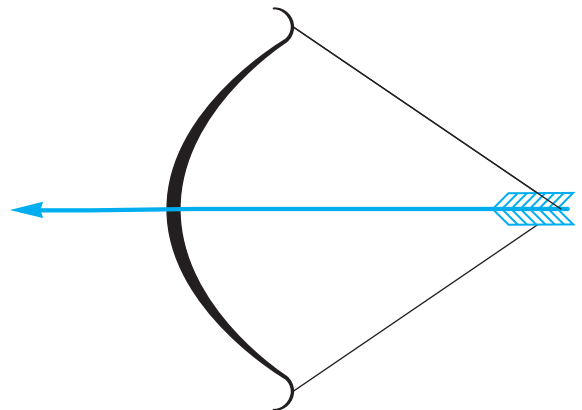
► **Figure 8-2**
An electrostatic charge is stored in the atoms of the dielectric. (Source: Delmar/Cengage Learning)

the battery attracts electrons from one plate of the capacitor. The negative terminal of the battery will cause electrons to flow to the other capacitor plate. This flow of current will continue until the voltage across the capacitor plates is equal to the battery voltage. If the battery is disconnected, the capacitor will be left in a charged state. **CAUTION: It is the habit of some people to charge a capacitor to a high voltage and then hand the capacitor 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 certain conditions, a capacitor can have enough power to cause a person's heart to go into fibrillation.**

ELECTROSTATIC CHARGE

Notice the illustration of the atoms in the dielectric material in Figure 8-2. When a capacitor has been charged, the negative electrons of the dielectric material are repelled from the negative plate of the capacitor and attracted to the positive plate. This

causes the electron orbit of the atoms in the dielectric to extend. This places the atoms of the dielectric material in tension. This is known as **dielectric stress**. Placing the atoms of the dielectric under stress has the same effect as drawing back a bow and arrow and holding it, Figure 8-3.



► **Figure 8-3**
Dielectric stress is similar to drawing back a bow and arrow, and holding it. (Source: Delmar/Cengage Learning)

The amount of dielectric stress is determined by the voltage between the plates. The greater the voltage, the greater the dielectric stress. If the voltage becomes too great, the dielectric will break down and destroy the capacitor. This is the reason capacitors have a voltage rating that must be followed.

The energy of a capacitor is stored in the dielectric and is known as 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 charged capacitor are shorted together, it has the same effect as releasing the drawn bow in Figure 8–3. The arrow will be propelled forward at great speed. The same is true for the electrons of the capacitor. When the electron orbits of the dielectric snap back, the electrons stored on the negative capacitor plate are propelled toward the positive plate at great speed.

CAPACITOR RATINGS

Capacitors are rated in units called the **farad**. The farad is actually such a large amount of capacitance it is not practical to use. For this reason a unit called the **micro-farad** is generally used. A micro-farad is one millionth of a farad. The Greek lowercase letter mu is used to symbolize micro, μ . The term micro-farad is indicated by combining mu and lowercase f, μf . Because the letter mu is not included on a standard typewriter, the term micro-farad is sometimes shown as uf or mf. All of these terms mean the same thing.

Another term used is the **pico-farad**. This term is used for extremely small capacitors found in electronics applications. A pico-farad is one millionth of a micro-farad and is generally shown as $\mu\mu\text{f}$ or pf.

When AC voltage is applied to a capacitor, Figure 8–4, the plates of the capacitor are alternately charged and discharged each time the current changes direction of flow. When a capacitor is charged, the voltage across its plates becomes the same as this applied voltage. As the voltage across the plates of a capacitor increases, it offers resistance to the flow of current. The applied voltage must continually overcome the voltage of the capacitor to produce current flow. The current in a **pure-capacitive circuit** is limited by the



► **Figure 8–4**

A pure capacitive circuit. (Source: Delmar/Cengage Learning)

voltage of the charged capacitor. Because current is limited by a counter voltage and not resistance, the counter voltage of the capacitor is referred to as reactance. Recall that the symbol for reactance is X . Because this reactance is caused by capacitance, it is called **capacitive reactance** and is symbolized by X_c (pronounced X sub c).

The amount of capacitive reactance in a circuit is determined by two factors. These are:

1. Frequency of the AC voltage.
2. The size of the capacitor.

If the frequency of the line and the capacitance rating of the capacitor are known, the capacitive reactance can be found using the following formula:

$$X_c = \frac{1}{2 \times \pi \times F \times C}$$

The value of capacitive reactance is measured in ohms. In the formula to find capacitive reactance:

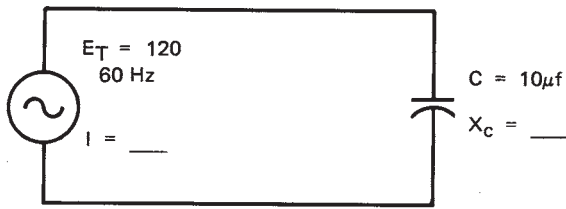
X_c = Capacitive Reactance

π = The Greek letter Pi, which has a value of 3.1416

F = Frequency in Hz

C = The value of capacitance in farads.

Because most capacitors are rated in micro-farads, be sure to write the capacitance value in farads. This can be done by dividing the micro-farad rating by 1,000,000, or moving the decimal point six places to the left. Example: to change a 50- μf capacitor to a value expressed in farads, move the decimal point after the 50 six places to the left. This capacitor has a value of .000050 farads.



► **Figure 8-5**
Capacitive reactance limits current flow. (Source: Delmar/
Cengage Learning)

EXAMPLE

Find the current flow in the circuit shown in Figure 8-5.

Solution: To find the current flowing in this circuit, the amount of capacitive reactance of the capacitor must first be found.

$$X_c = \frac{1}{2 \times \pi \times F \times C}$$

$$X_c = \frac{1}{2 \times 3.1416 \times 60 \times .000010}$$

$$X_c = \frac{1}{.0037699}$$

$$X_c = 265.2 \text{ ohms}$$

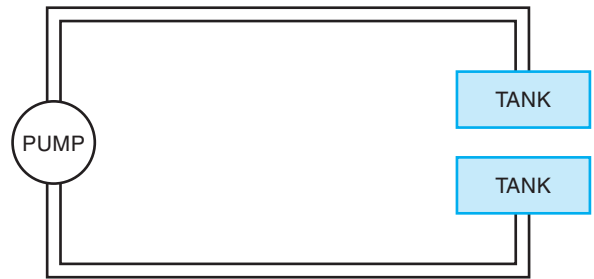
Now that the capacitive reactance of the circuit is known, the value of current can be found using the formula: $I = E/X_c$.

$$I = \frac{120}{265.2}$$

$$I = .452 \text{ amps}$$

CURRENT FLOW IN A CAPACITIVE CIRCUIT

Notice that a capacitor is constructed of two metal plates separated by an insulator. One of the metal plates is connected to one side of the circuit, and the other metal plate is connected to the other side of the circuit. Because there is an insulator separating the two plates, current cannot flow through a capacitor. When a capacitor is connected into a direct-current circuit, current will flow until the capacitor has been charged to the value of the applied voltage,



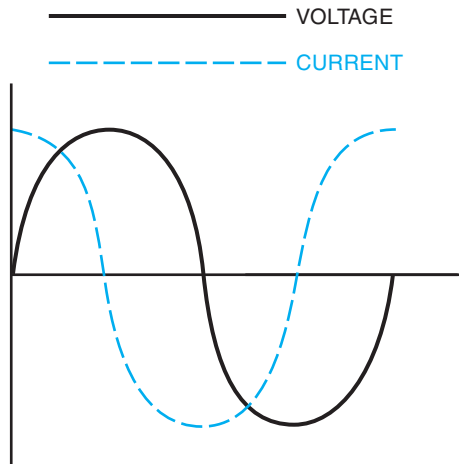
► **Figure 8-6**
Water flows in this system in a manner similar to the way current flows in a capacitive circuit. (Source: Delmar/
Cengage Learning)

and then stop. When a capacitor is connected into an alternating-current circuit, current will “appear” to flow through the capacitor. This is because the plates of the capacitor are alternately charged and discharged each time the current reverses direction. To understand this concept better, refer to the water circuit shown in Figure 8-6. In this illustration, a water pump is connected to two tanks. The pump is used to pump water back and forth between the two tanks. When one tank becomes full, the direction of the pump is reversed and water is pumped from the full tank back into the empty tank. Notice that there is no complete loop in this hydraulic circuit for water to flow from one side of the pump to the other, but water does flow because it is continuously pumped from one tank to the other.

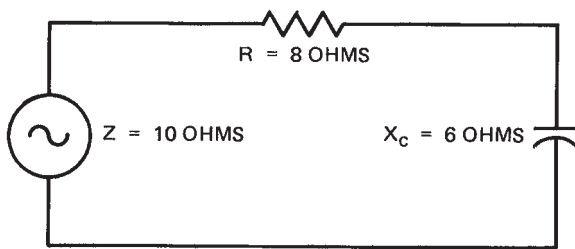
CURRENT AND VOLTAGE RELATIONSHIPS

In a pure-capacitive circuit, the voltage and current are out of phase with each other. Figure 8-7 shows that the current in a pure-capacitive circuit leads the voltage by 90° . Because the voltage and current are 90° out of phase with each other, there is no true power or watts consumed in a pure-capacitive circuit. The capacitor stores the energy in an electro-static field, and then returns it to the circuit at the end of each half cycle.

In the circuit shown in Figure 8-8, a resistor and capacitor are connected in series with each other. Since this circuit contains elements of both resistance and capacitive reactance, the current is limited by impedance. The impedance for a circuit



► **Figure 8-7**
Current leads voltage by 90° in a pure capacitive circuit. (Source: Delmar/Cengage Learning)

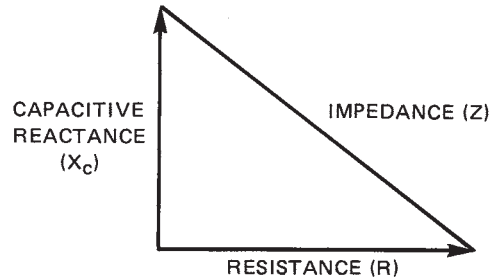


► **Figure 8-8**
Impedance must be used to determine the current flow in a circuit that contains resistance and capacitive reactance. (Source: Delmar/Cengage Learning)

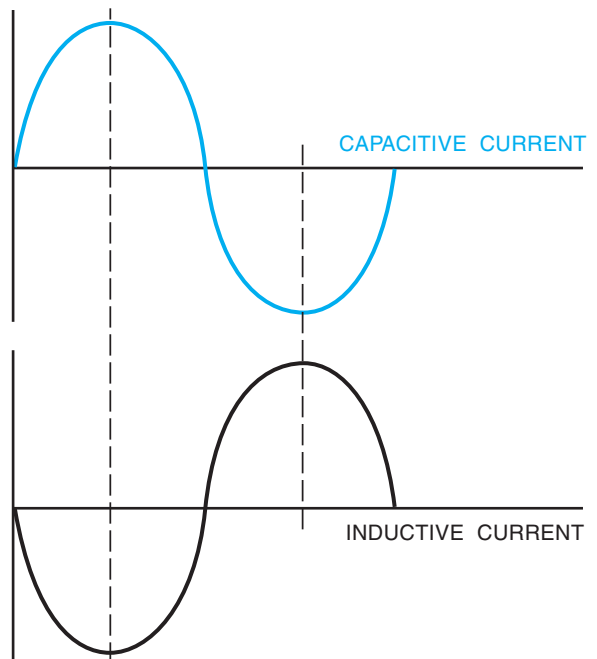
of this type can be found by using the formula $Z = \sqrt{R^2 + X_c^2}$. Notice this is the same basic formula as the one used to find the impedance of a circuit that contains both resistance and inductive reactance. The impedance of the circuit shown in Figure 8-8 can be found by the following:

$$\begin{aligned} Z &= \sqrt{R^2 + X_c^2} \\ Z &= \sqrt{8^2 + 6^2} \\ Z &= \sqrt{64 + 36} \\ Z &= \sqrt{100} \\ Z &= 10 \text{ ohms} \end{aligned}$$

Figure 8-9 shows a vector diagram of the circuit in Figure 8-8.



► **Figure 8-9**
Impedance is the vector sum of R and X_c .
(Source: Delmar/Cengage Learning)



► **Figure 8-10**
Capacitive and inductive current are 180° out of phase with each other. (Source: Delmar/Cengage Learning)

POWER FACTOR CORRECTION

Because the current flow in a capacitive circuit leads the voltage by 90° and the current in an inductive circuit lags the voltage by 90°, the current of a capacitive circuit is in direct opposition to the current of an inductive circuit. Figure 8-10 illustrates the currents of capacitive and inductive circuits

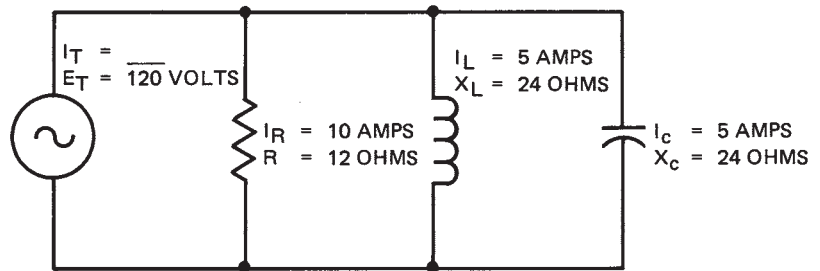


Figure 8-11
A parallel circuit has resistance, inductance, and capacitance.

(Source: Delmar/Cengage Learning)

as compared with each other. These two currents are 180° out of phase with each other. When the capacitive current is at its peak positive value, the inductive current is at its peak negative value. When the capacitive current is at its peak negative value, the inductive current is at its peak positive value. Because these two currents are in direct opposition, one can be used to cancel the other.

The circuit shown in Figure 8-11 shows a parallel circuit that contains a resistor, an inductor, and a capacitor. The applied voltage of the circuit is 120 volts at 60 Hz. Because this is a parallel circuit, the voltage applied to each component will be the same—120 volts. The resistor has a resistance of 12 ohms. This permits a current flow of 10 amps through the resistor ($120/12 = 10$). The inductor has an inductive reactance of 24 ohms. This permits a current flow through the inductor of 5 amps ($120/24 = 5$). The capacitor has a capacitive reactance of 24 ohms. This permits a current flow through the capacitor of 5 amps.

QUESTION

What is the total current flow in the circuit? In a parallel circuit, current is added. Therefore, it would appear that the current flow would be 20 amps ($10 + 5 + 5 = 20$). The currents of this circuit, however, are out of phase with each other. Figure 8-12 shows a vector diagram of this circuit. Notice that the 5 amps of capacitive current is 180° out of phase with the 5 amps of inductive current. These two currents will cancel each other. The AC alternator sees only the resistance in this circuit. The current is, therefore, the same as the current flow through the resistor, or 10 amps.

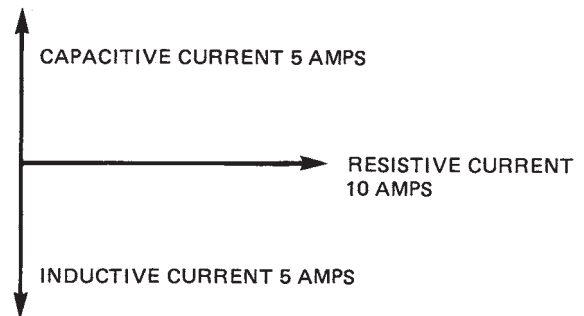


Figure 8-12
Capacitive current and inductive current are 180° out of phase with each other. (Source: Delmar/Cengage Learning)

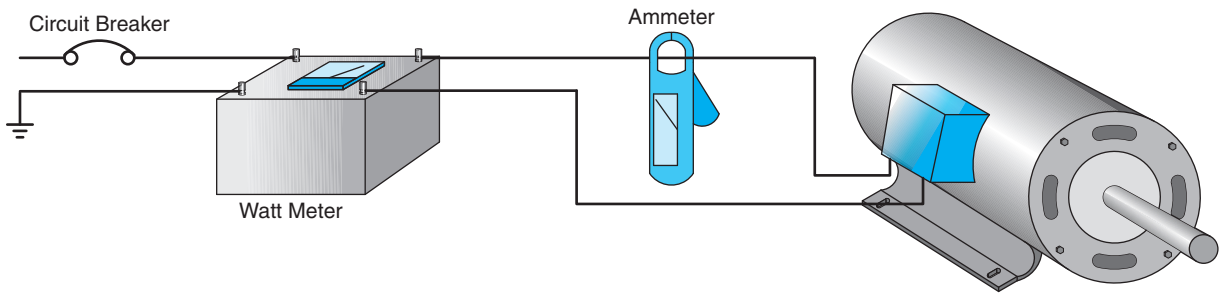
POWER FACTOR CORRECTION OF A MOTOR

In the circuit shown in Figure 8-13, an AC induction motor is connected to a 120-volt line. A wattmeter is used to measure the amount of true power in the circuit. For this example it will be assumed that the wattmeter has a reading of 720 watts. An ammeter has also been inserted in the circuit. Assume the ammeter has a reading of 10 amps. The apparent power or volt-amp value for this circuit is 1,200 VA ($120 \text{ volts} \times 10 \text{ amps} = 1,200 \text{ VA}$). The power factor of this circuit can now be computed using the formula ($PF = W/VA$).

$$PF = \frac{W}{VA}$$

$$PF = \frac{720}{1200}$$

$$PF = .6 \text{ or } 60\%$$



► **Figure 8-13**
Finding the power factor of a motor. (Source: Delmar/Cengage Learning)

If the power factor of this motor is to be corrected, it must be determined how much of this circuit is comprised of true power and how much is composed of reactive power. Because the true power (watts) and the apparent power (volt-amps) is known, the reactive power (VARs) can be found using the following formula:

$$\text{VARs} = \sqrt{\text{VA}^2 - \text{W}^2}$$

$$\text{VARs} = \sqrt{1200^2 - 720^2}$$

$$\text{VARs} = \sqrt{1,440,000 - 518,400^2}$$

$$\text{VARs} = \sqrt{921,600}$$

$$\text{VARs} = 960$$

Because a motor is an inductive device, the reactive power in this circuit can be canceled by an equal amount of capacitive VARs. If a capacitor of the correct value is connected in parallel with the motor, the power factor will be corrected. To find the correct value of capacitance, determine the amount of capacitance needed to produce a VAR reading of 960. The amount of capacitive reactance can be found using the formula:

$$X_C = \frac{E^2}{\text{VARs}}$$

$$X_C = \frac{120^2}{960}$$

$$X_C = 15 \text{ ohms}$$

The amount of capacitance needed to produce 15 ohms of capacitive reactance at 60 Hz can be calculated using the following formula:

$$C = \frac{1}{2 \times \pi \times F \times X_C}$$

$$C = \frac{1}{2 \times 3.1416 \times 60 \times 15}$$

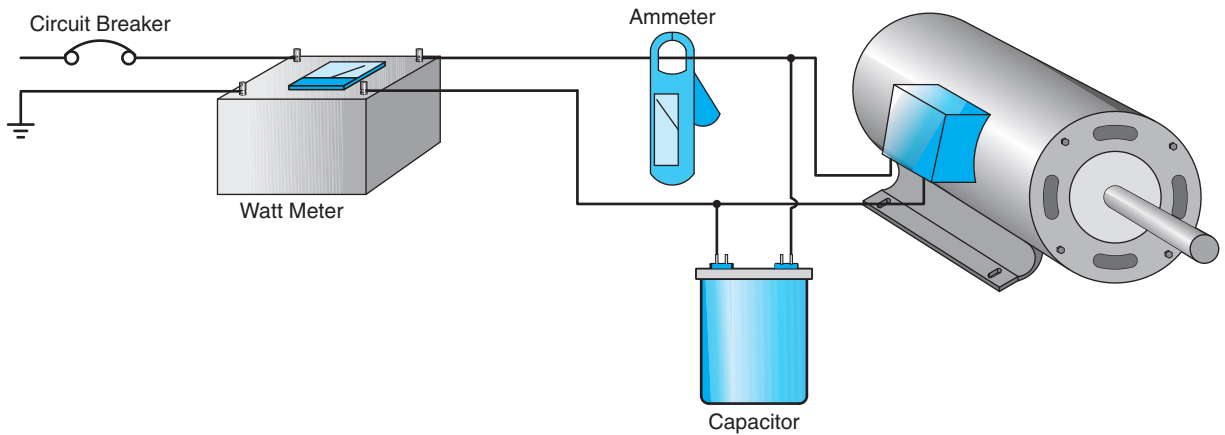
$$C = \frac{1}{5654.88}$$

$$C = .0001768 \text{ farads}$$

The answer for the value of C is in farads. To convert farads to micro-farads, multiply the answer by 1,000,000, or move the decimal point 6 places to the right. .0001768 farads becomes 176.8 μf . If a capacitor of this value is connected in parallel with the motor as shown in Figure 8-14, the power factor will be corrected.

CAPACITOR TYPES

The most common types of capacitors used in the air conditioning field fall into two categories. One kind is known as an oil-filled type. Figure 8-15 shows a photograph of this type of capacitor. The **oil-filled capacitor** is made with two metal foil plates separated by paper. The paper is soaked in a special dielectric oil. These capacitors are true AC capacitors and are generally used as the run capacitors on many single-phase air conditioning compressors. They are also used as the starting capacitors on some units. The important ratings on these capacitors are the micro-farad rating and the voltage rating. The voltage rating of a capacitor should never be exceeded. It is permissible to use a capacitor of higher voltage



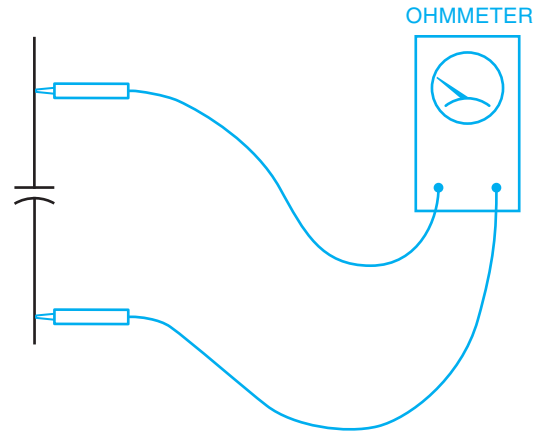
► **Figure 8-14**
A capacitor corrects the motor power factor. (Source: Delmar/Cengage Learning)



► **Figure 8-15**
Oil-filled capacitor. (Courtesy Westinghouse Electric Corp.)

rating, but never use a capacitor with less voltage rating.

The second type of capacitor frequently used in air conditioning systems is the **AC electrolytic capacitor**. The AC electrolytic capacitor is used as the starting capacitor on many small single-phase motors. This type of capacitor is designed to be used for a short period of time only. If an AC electrolytic capacitor were to be used in a continuous circuit such as the running capacitor of a compressor, it would fail in a short period of time. The advantage of the AC electrolytic capacitor is that a large amount of



► **Figure 8-16**
Testing a capacitor with an ohmmeter. (Source: Delmar/Cengage Learning)

capacitance can be housed in a small case size. This makes the AC electrolytic capacitor a good choice for starting circuits, because the capacitor is in the circuit for only a few seconds when the motor is started.

TESTING A CAPACITOR

Capacitors can be tested for a short with an ohmmeter. If an ohmmeter is connected across the terminals of a capacitor as shown in Figure 8-16, the meter should show a deflection up scale and then return to infinity ohms. The deflection up scale

indicates current flow to the capacitor when it is being charged by the ohmmeter battery. If the leads of the ohmmeter are reversed, the meter should deflect twice as far up scale and then return to infinity ohms.

The ohmmeter test basically indicates if the capacitor is shorted or not. A short indicates the dielectric has been punctured. This test will not indicate a broken plate, which would result in a lower capacitance value. Many digital meters contain a capacitance testing function, as shown in Figure 8-17. These meters actually measure the capacitance value, which can be compared to the rating marked on the capacitor.

Neither of these tests, however, can measure the dielectric strength. A capacitor may test OK with an ohmmeter or digital meter but break down when connected to line voltage. Ohmmeters and common digital meters do not supply enough voltage to test the dielectric at rated voltage. To test the dielectric strength, a dielectric test set should be used, as shown in Figure 8-18. The dielectric test set is sometimes referred to as a *hipot* because it provides a high potential or high voltage. The dielectric tester can provide rated voltage to the capacitor, and a microamperes meter measures any leakage current.



Figure 8-17
Digital meter capable of measuring capacitance.
(Source: Delmar/Cengage Learning)

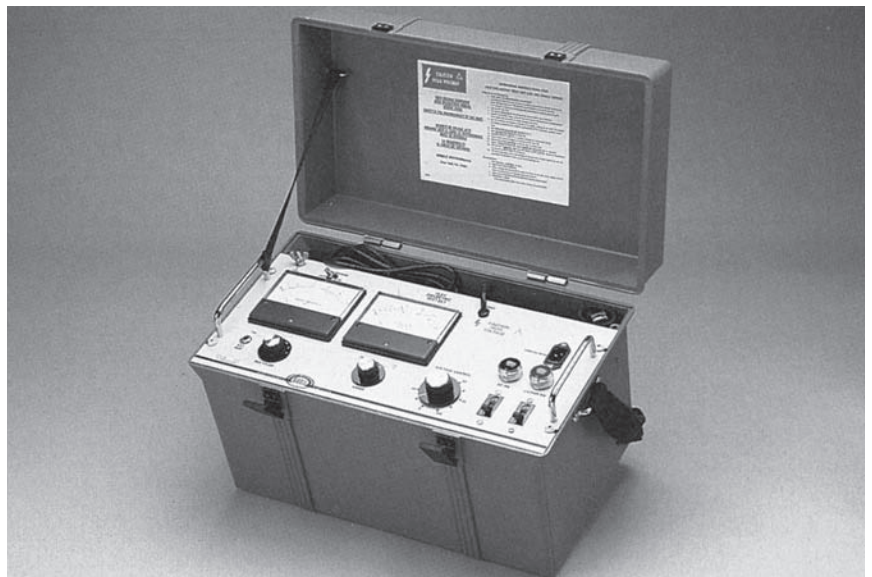


Figure 8-18
A dielectric test set. (Courtesy of
Megger®)

SUMMARY

- Ⓢ A capacitor can be constructed by separating two metal plates with an insulating material.
- Ⓢ The insulating material is called the dielectric.
- Ⓢ Three factors that determine the amount of capacitance a capacitor will have are
 - A. The surface area of the plates.
 - B. The distance between the plates.
 - C. The type of dielectric material used.
- Ⓢ Most of the energy of a capacitor is stored in an electrostatic charge.
- Ⓢ Capacitors can produce extremely high current for a short period of time.
- Ⓢ The basic unit of capacitance is the farad.
- Ⓢ Capacitance values are generally rated in micro-farads (μf), which are one-millionth of a farad.
- Ⓢ In an AC circuit containing pure capacitance, the current is limited by capacitive reactance.
- Ⓢ In a pure-capacitive circuit the current leads the voltage by 90 electrical degrees.
- Ⓢ Capacitors are often used to correct the power factor of a motor.

KEY TERMS

AC electrolytic capacitor
capacitance
capacitive reactance
dielectric

dielectric stress
electrostatic charge
farad
micro-farad

oil-filled capacitor
pico-farad
pure-capacitive circuit

REVIEW QUESTIONS

1. What three factors determine the capacitance of a capacitor?
2. What is the dielectric of a capacitor?
3. In what type of field is the energy of a capacitor stored?
4. In a pure-capacitive circuit, how many degrees are the current and voltage out of phase with each other?
5. Does a capacitive current lead the voltage or lag the voltage?
6. What limits the current in a pure capacitive circuit?
7. Name two common types of capacitors used in the air conditioning field.
8. What type of capacitor is generally used as the running capacitor on many air conditioning compressors?
9. What is the advantage of an AC electrolytic capacitor?
10. What is the disadvantage of an AC electrolytic capacitor?



SECTION 2

Control Circuits

UNIT 9



Schematics and Wiring Diagrams

OBJECTIVES

After studying this unit the student should be able to:

- Draw standard NEMA control symbols
- Define the meaning of a dashed line drawn between symbols
- Define a wiring diagram
- Define and read a schematic diagram

Schematics and **wiring diagrams** are the written language of control circuits. It will be impossible for a service technician to become proficient in trouble shooting electrical faults if he or she cannot read and interpret electrical diagrams. Learning to read electrical diagrams is not as difficult as many people first believe it to be. Once a few basic principles are understood, reading schematics and wiring diagrams will become no more difficult than reading a newspaper.

TWO-WIRE CIRCUITS

Control circuits are divided into two basic types, the two-wire and the three-wire. Figure 9–1 shows a simple **two-wire control circuit**. In this circuit, a simple switch is used to control the power applied to a small motor. If the switch is open, there is no

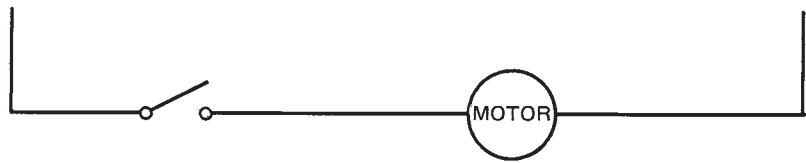
complete path for current flow, and the motor will not operate. If the switch is closed, power is supplied to the motor, and it then operates.

THREE-WIRE CIRCUITS

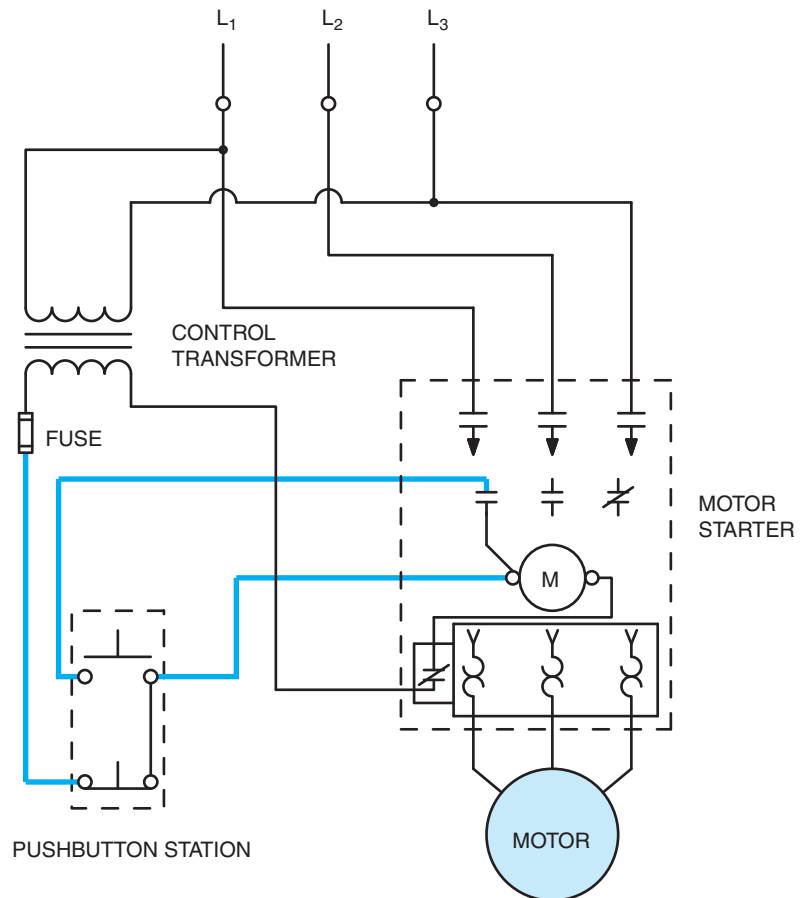
Three-wire control circuits are used because they are more flexible than two-wire circuits. Three-wire circuits are characterized by the fact that they

are operated by a magnetic relay or motor starter. These circuits are generally controlled by one or more pilot devices. Three-wire control circuits receive their name from the fact that three conductors or wires are required to make connection from a start-stop pushbutton station to a motor starter, Figure 9–2.

► **Figure 9–1**
Two-wire control circuit.
(Source: Delmar/Cengage Learning)



► **Figure 9–2**
Basic three-wire control circuit.
(Source: Delmar/Cengage Learning)



ELECTRICAL SYMBOLS

When a person first learns to read, he or she learns a set of symbols that are used to represent different sounds. This set of symbols is generally referred to as the alphabet. When learning to read electrical diagrams, it is necessary to learn the symbols used to represent different devices and components. The symbols shown below are commonly used on control schematics and wiring diagrams. These are not all the symbols used. Unfortunately, there is no set standard for the use of electrical symbols.

To better understand electrical symbols, it is helpful to understand some of the common terms used to describe these symbols. The terms **movable** and **stationary** contacts, for example, refer to electrical contacts located on different components. A simple switch contains both a movable and a stationary contact, Figure 9–3. Stationary contacts refer to contacts that cannot be moved or changed. Movable contacts can be moved from one position to another. The switch shown in Figure 9–3 can also be described as a **normally open** switch because:

1. The movable contact is shown not touching the stationary contact.
2. The movable contact is drawn *below* the stationary contact.

Control components are drawn in the position they should be in when the circuit is deenergized or turned off. Normally open means that there is no electrical connection or complete circuit made between the movable and stationary contacts of the switch.

The switch in Figure 9–3 can be described as a *single-pole single-throw* (SPST) switch. Single pole indicates that the switch contains only one movable contact. Single throw means that the movable contact will complete a circuit when *thrown* or moved in only one direction.

A normally closed single-pole single-throw switch is shown in Figure 9–4. The switch is **normally closed** because:

1. The movable contact is shown touching the stationary contact.
2. The movable contact is drawn above the stationary contact.

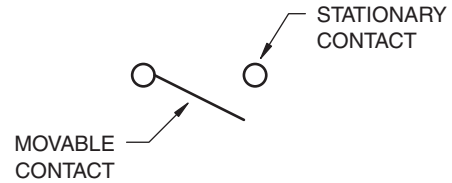


Figure 9–3
Normally open single-pole single-throw switch.
(Source: Delmar/Cengage Learning)

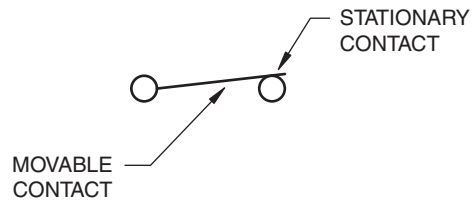
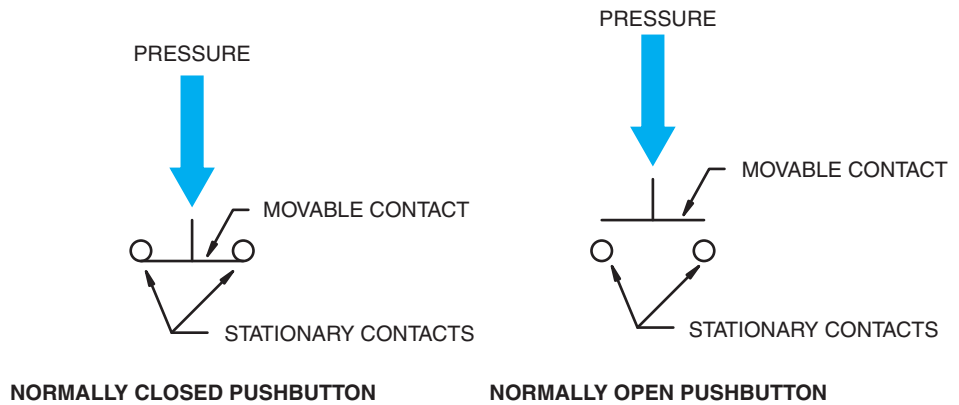


Figure 9–4
Normally closed single-pole single-throw switch.
(Source: Delmar/Cengage Learning)

When a component is normally closed it indicates that a complete circuit exists through the component.

Although these basic rules apply to switches, they do not necessarily apply to all control components. When possible, components are generally drawn to indicate how they function. Pushbuttons, for example, are drawn differently than switches. A normally closed pushbutton is drawn with the movable contact below instead of above the stationary contacts, Figure 9–5. It is drawn in this manner to illustrate that when pressure is applied to the spring-loaded stationary contact it will cause the movable contact to move downward, breaking the connection between the two stationary contacts. A normally open pushbutton symbol is drawn with the movable contact above instead of below the stationary contacts. Pressure forces the movable contact downward, bridging the gap between the two stationary contacts and completing a circuit.

► **Figure 9-5**
Common pushbutton
symbols. (Source: Delmar/
Cengage Learning)



Most of the following symbols are approved by the **National Electrical Manufacturers Association (NEMA)**:



1. Normally closed push button. Generally used to represent a stop button.



2. Normally open push button. Generally used to represent a start button.



3. Double-acting push button. Contains both normally closed and normally open contacts on one push button.



4. Double-acting push button drawn differently but meaning the same as number 3.



5. Double-acting push button. The dashed line indicates mechanical connection. This means that when one button is pushed, the other moves at the same time.



6. Single-pole single-throw switch (SPST).



7. Single-pole double-throw switch (SPDT). Notice this switch has only one pole, the switch arm, but it has two stationary contacts. In the diagram, the switch arm makes

contact with the upper stationary contact. When the switch is thrown, contact will be made between the switch arm and the lower stationary contact. The switch arm or pole of the switch is generally referred to as the common because it can make contact to either of the two stationary contacts.



8. Double-pole single-throw switch (DPST). Notice the dashed line, which indicates mechanical connection between the two switch arms.



9. Double-pole double-throw switch (DPDT).



10. Off-Automatic-Manual control switch. This switch is basically a single-pole double-throw that has a center off position.



11. Normally open relay contact.



12. Normally closed relay contact.



13. Fuse



14. Fuse

	15. Transformer		31. Normally closed pressure switch
	16. Coil		32. Normally open pressure switch
	17. Coil (Generally used to represent the coil of a relay or motor starter in a control schematic.)		33. Normally closed temperature switch. (Normally closed thermostat)
	18. Pilot light or lamp		34. Normally open temperature switch.
	19. Lamp or light bulb		35. Normally closed flow switch. This symbol is used to represent both liquid- and air-sensing flow switches.
	20. Thermal heater element		36. Normally open flow switch.
	21. Thermal heater element. (Generally used to represent the overload heater element in a motor control circuit.)		37. Normally closed limit switch.
	22. Solenoid coil		38. Normally open limit switch.
	23. Fixed resistor		39. Normally closed ON-DELAY timer contact. Often shown on schematics as DOE, which stands for Delay On Energize.
	24. Variable resistor		40. Normally open ON-DELAY timer contact.
	25. Variable resistor		41. Normally closed OFF-DELAY timer contact. Often shown on schematics as DODE, which stands for Delay on De-Energize.
	26. Single-pole circuit breaker		42. Normally open OFF-DELAY timer contact
	27. Double-pole circuit breaker		43. Battery
	28. Capacitor		
	29. Normally closed float switch		
	30. Normally open float switch		



44. Electrical ground



45. Mechanical ground



46. Wires crossing without connection



47. Wires crossing without connection



48. Wires connecting. The dot in the center of the cross is known as a **node**. This is used to indicate connection.



49. Rotary switch



► **Figure 9-6**
Normally closed pressure switch. (Source: Delmar/Cengage Learning)



► **Figure 9-7**
Normally closed held-open pressure switch. (Source: Delmar/Cengage Learning)



► **Figure 9-8**
Normally open pressure switch. (Source: Delmar/Cengage Learning)



► **Figure 9-9**
Normally open held-closed pressure switch. (Source: Delmar/Cengage Learning)

The contact symbols shown are standard and relatively simple to understand. There can be instances, however, in which symbols can be used to show something that is not apparent. For example, the symbol for a normally closed pressure switch is shown in Figure 9-6. Notice that this symbol not only shows the movable arm making contact with the stationary contact, but it also shows the movable arm drawn above the stationary contact. In Figure 9-7, the contact arm is shown not making connection with the stationary contact. This symbol, however, is not a normally open contact symbol because the contact arm is drawn above the stationary contact. This symbol indicates a normally closed held-open pressure switch. This symbol is indicating that the switch is actually connected as a normally closed switch, but pressure is used to keep the contact open. If pressure decreases to a certain point, the switch contact will close.

Figure 9-8 shows a normally open pressure switch. Notice that the contact arm is drawn below the stationary contact. Figure 9-9 shows the same symbol except that the movable arm is making

connection with the stationary contact. This symbol represents a normally open held-closed pressure switch. This switch symbol indicates that the pressure switch is wired normally open, but pressure holds the contact closed. If the pressure decreases to a certain level, the switch will open and break connection to the rest of the circuit.

SCHEMATIC DIAGRAMS

Schematic diagrams show components in their electrical sequence without regard for physical location. Schematic diagrams are used to troubleshoot and install control circuits. Schematics are generally easier to read and understand than wiring diagrams.

WIRING DIAGRAMS

Wiring diagrams *show components mounted in their general location with connecting wires*. A wiring diagram is used to represent how the circuit generally appears. To help illustrate the differences between wiring diagrams and schematics, a basic control circuit will first be explained as a schematic and then shown as a wiring diagram.

READING SCHEMATIC DIAGRAMS

To read a schematic diagram, a few rules must first be learned. Commit the following rules to memory:

1. Reading a schematic diagram is similar to reading a book. It is read from left to right and from top to bottom.
2. Electrical symbols are always shown in their off or deenergized position.
3. Relay contact symbols are shown with the same numbers or letters that are used to designate the relay coil. All contact symbols that have the same number or letter as a coil are controlled by that coil regardless of where in the circuit they are located.
4. When a relay is energized, or turned on, all of its contacts change position. If a contact is shown as normally open, it will close when the coil is energized. If the contact is shown as normally closed, it will open when the coil is turned on.
5. There must be a complete circuit before current can flow through a component.

6. Components used to provide a function of stop are generally wired normally closed and connected in series. Figure 9–10 illustrates this concept. Both switches A and B are normally closed and connected in series. If either switch is opened, connection to the lamp will be broken and current will stop flowing in the circuit.

7. Components used to provide the function of start are generally wired normally open and connected in parallel. In Figure 9–11, switches A and B are normally open and connected in parallel with each other. If either switch is closed, a current path will be provided for the lamp and it will turn on.

DASHED LINES

Often the service technician must be able to determine what dashed lines indicate. Schematic diagrams often contain dashed lines.

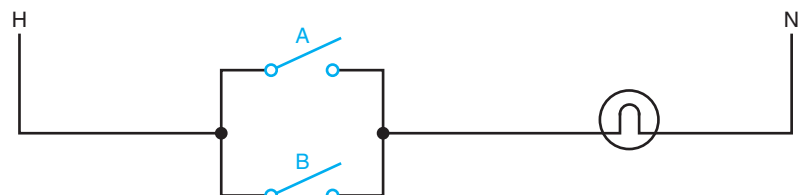
In the schematic diagram shown in Figure 9–12, dashed lines indicate several different conditions.

1. Mechanical connection between two components such as those shown in electrical symbols 5, 8, and 9. Each of these symbols show a dashed line connected between different components. The dashed line indicates that when one component is changed the other one is changed, at the same time. The double-acting push buttons illustrated in number 5 will both operate when one of them is pushed.

► **Figure 9–10**
Components used to perform the function of stop are normally closed and connected in series.
(Source: Delmar/Cengage Learning)



► **Figure 9–11**
Components used to perform the function of start are normally open and connected in parallel.
(Source: Delmar/Cengage Learning)





2. Field wired or installed components.
3. Components used only in special circumstances.
4. Factory wired or installed components.

At the top of the diagram, dashed lines indicate that only one set of the primary terminals is to be connected depending on the amount of input voltage. An input voltage of 480 volts, for example, would have one line connected to the H1 terminal and the other to the H4 terminal. An input voltage of 208 volts would have one line connected to the H1 terminal and the other connected to the H2 terminal.

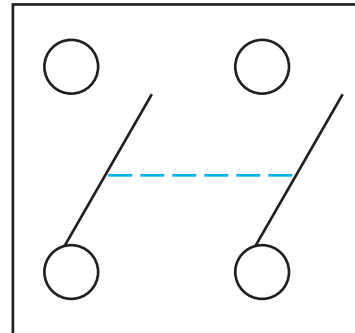
Another dashed line connected between two switches indicates that these two switches are mechanically connected. In reality, this would be a double-pole single-throw switch, Figure 9-13. The dashed line indicates that when one switch is opened or closed, the other one is opened or closed also.

Several components, such as 1M, 2M, and 3M are connected with dashed lines. The dashed lines in this instance indicates that these devices are field wired and not part of the assembled unit. Wiring to these devices is connected during the installation of the equipment. It should be noted that some diagrams will use dashed lines to indicate factory-installed wiring, and solid lines illustrate field-connected devices. There is no hard rule. It is generally necessary for the service person to determine the meaning of the lines on a particular schematic.

Another set of components shown in Figure 9-12 is surrounded by dashed lines. These dashed lines mark components that are used under special circumstances. Contactor coil, C2, and contact CR are installed only if the compressor motor utilizes part winding starting. If the motor does not employ part winding starting, these components will not be present.

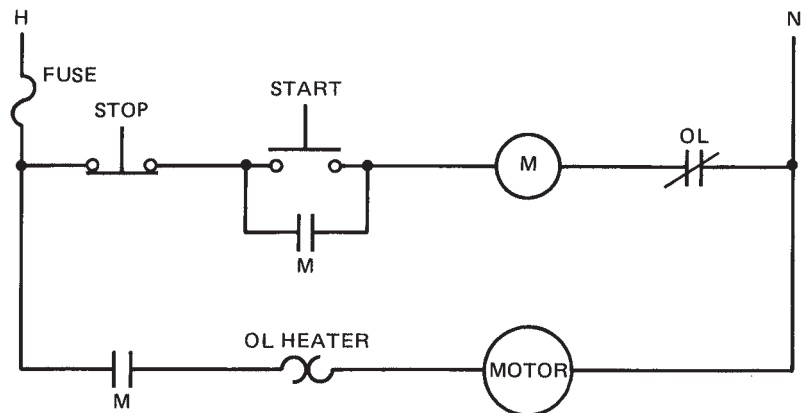
EXAMPLE

The first circuit to be discussed is a basic control circuit used throughout industry. Figure 9-14 shows a start-stop push button circuit. This schematic shows both the control circuit and the motor circuit. Schematic diagrams do not always show both control and motor connections. Many schematic diagrams show only the control circuit.



► **Figure 9-13**
Double-pole single-throw switch. (Source: Delmar/Cengage Learning)

► **Figure 9-14**
Start-stop pushbutton control circuit.
(Source: Delmar/Cengage Learning)



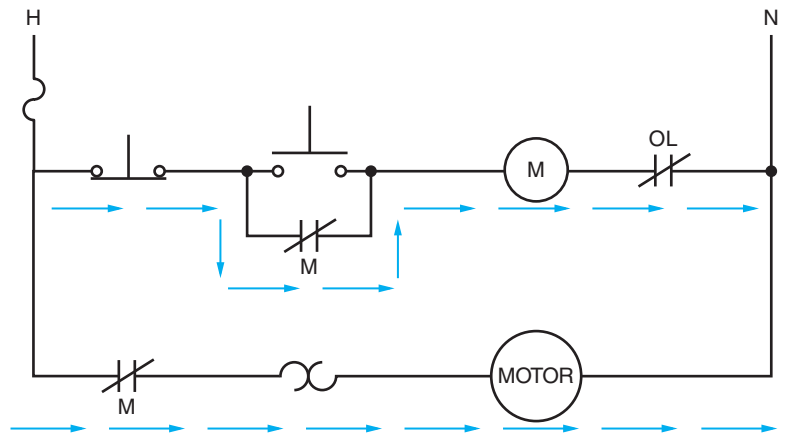
Notice in this schematic that there is no complete circuit to M motor starter coil because of the open start push button and open M auxiliary contacts. There is also no connection to the motor because of the open-M load contacts. The open-M contacts connected in parallel with the start button are small contacts intended to be used as part of the control circuit. This set of contacts is generally referred to as the holding, sealing, or maintaining contacts. These contacts are used to provide a continued circuit to the M coil when the start button is released.

The second set of M contacts is connected in series with the overload heater element and the motor, and are known as **load** contacts. These contacts are large and designed to carry the current needed to operate the load. Notice that these contacts are normally open and there is no current path to the motor.

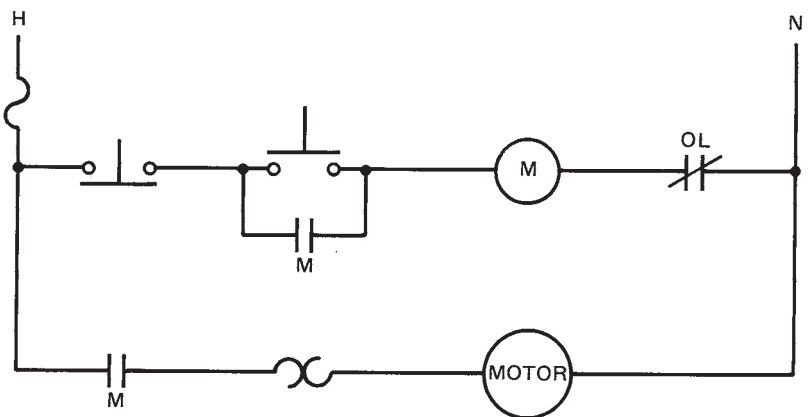
When the start button is pushed, a path for current flow is provided to the M-motor starter coil. When the M coil energizes, both M contacts close, Figure 9–15. The small auxiliary contact provides a continued current path to the motor starter coil when the start button is released and returns to its open position. The large M load contact closes and provides a complete circuit to the motor and the motor begins to run. The motor will continue to operate in this manner as long as the M coil remains energized.

If the stop button is pushed, Figure 9–16, the current path to the M coil is broken and the coil de-energizes. This causes both M contacts to return to their normally open position. When M holding contacts open, there is no longer a complete circuit provided to the coil when the stop button is returned to its normal position. The circuit remains in the off position until the start button is again pushed.

► **Figure 9–15**
Current path through the circuit.
(Source: Delmar/Cengage Learning)

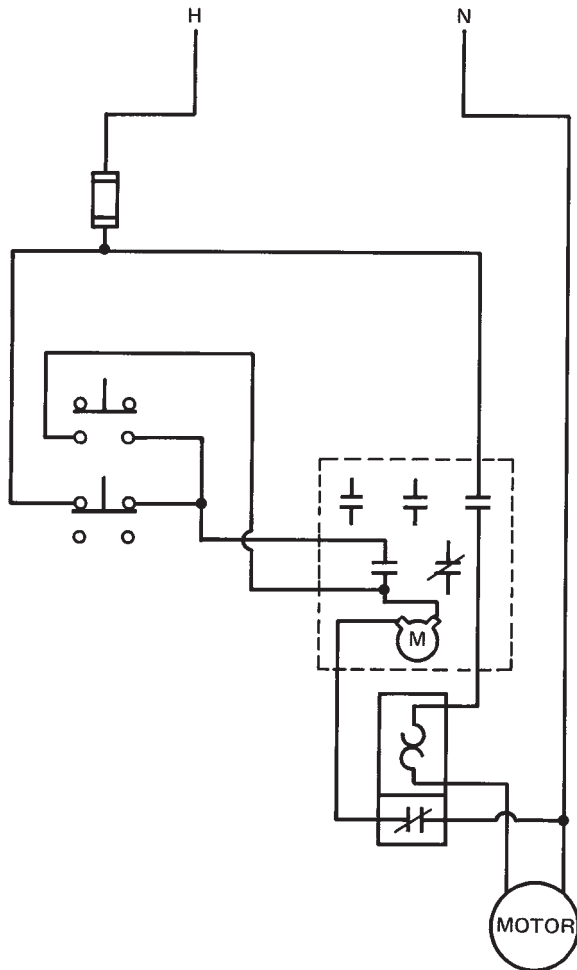


► **Figure 9–16**
The stop button breaks the circuit.
(Source: Delmar/Cengage Learning)



Notice that the overload contact is connected in series with the motor starter coil. If the overload contact should open, it has the same effect as pressing the stop button. The fuse is connected in series with both the control circuit and the motor. If the fuse should open, it has the effect of disconnecting power from the line.

A wiring diagram for the start-stop pushbutton circuit is shown in Figure 9-17. Although this diagram looks completely different, it is electrically the same as the schematic diagram. Notice the push button symbols indicate double-acting push buttons. The stop button, however, uses only the normally closed section and the start button uses only the



► **Figure 9-17**
Wiring diagram of start-stop pushbutton control circuit.
(Source: Delmar/Cengage Learning)

normally open section. The motor starter shows three load contacts and two auxiliary contacts. One auxiliary contact is open and one is closed. Notice that only the open contact has been used.

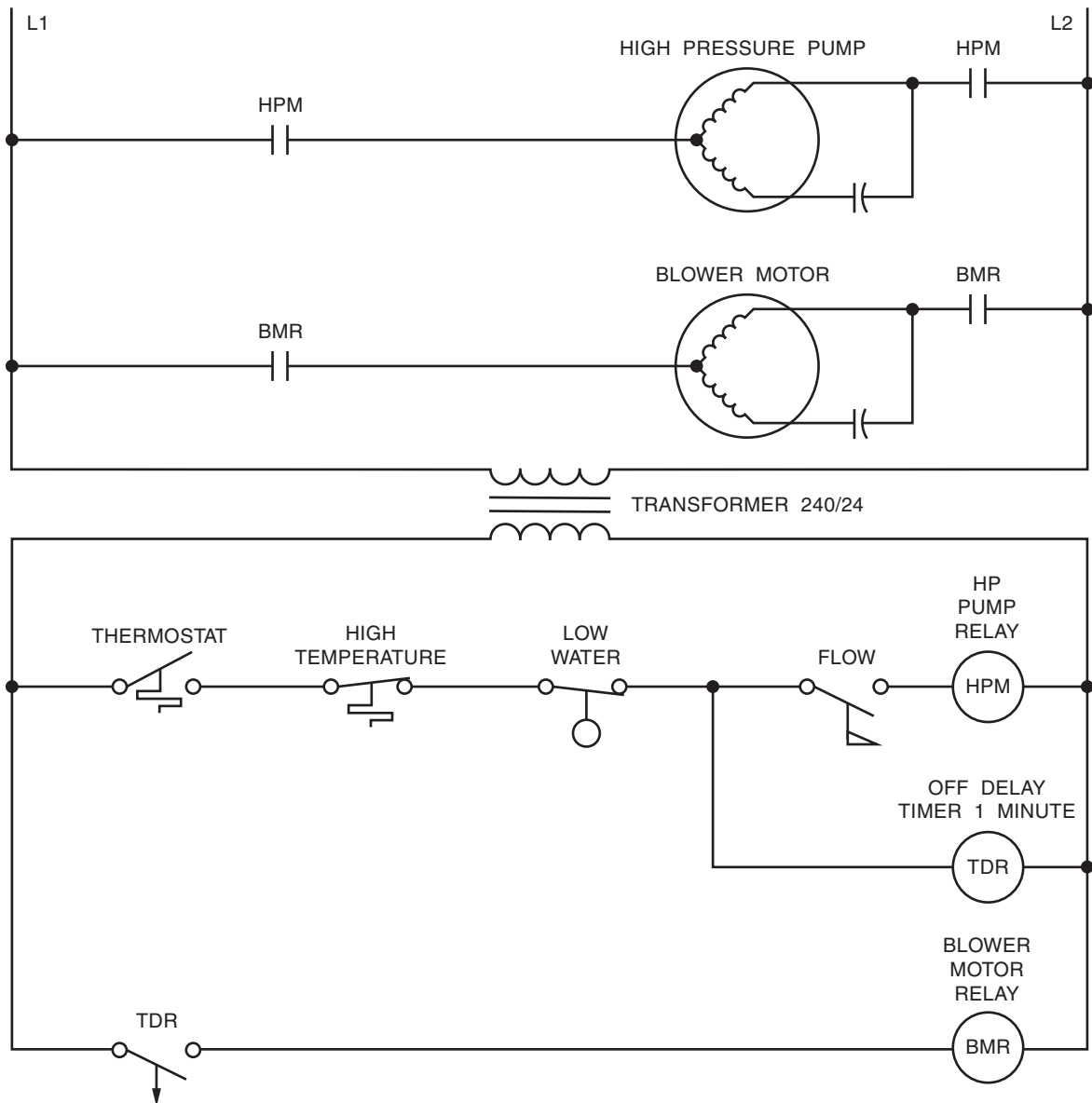
The overload unit shows two different sections. One section contains the thermal heater element connected in series with the motor, and the normally closed contact is connected in series with the coil of the M-motor starter.

EXAMPLE

The circuit shown in Figure 9-18 controls the operation of an oil-fired boiler. A high pressure pump motor is used to inject fuel oil into a combustion chamber where it is burned. A blower motor is used to supply combustion air to the chamber. The circuit will not permit fuel oil to be injected into the chamber unless the blower motor is operating. The circuit also permits the blower motor to continue operation for a period of one minute after the thermostat is satisfied. This permits any residual smoke or fumes to be removed from the combustion chamber.

The first step in understanding the operation of the circuit is to examine the components and determine what they control. The thermostat is a normally closed held open switch. It is normally closed because the movable contact is drawn above the stationary contact. The movable contact is not making connection to the stationary contact, however. This indicates that the contact is being held open. The thermal symbol indicates that the contact is controlled by temperature. The thermal symbol represents a bimetal helix. An increase in temperature causes the helix to expand and push upward on the contact. A decrease in temperature causes the helix to contract. If the helix contracts enough, the movable contact will make connection with the stationary contact and close the switch. This thermostat symbol indicates that an increase of temperature will open the switch and a decrease of temperature will close the switch. This is the normal operation of a heating thermostat.

The high temperature switch is a thermally activated switch also. The switch is shown normally closed. If the temperature should increase high enough, the switch will open and break connection to the high pressure pump motor relay and time delay relay.



► **Figure 9-18**
Boiler control circuit. (Source: Delmar/Cengage Learning)

The low water switch is a normally open held closed switch. The switch is normally open because the movable contact is drawn below the stationary contact. Because the movable contact is touching the station contact it is being held closed. This switch is drawn to indicate that a drop in liquid level will cause the switch contacts to open and break the circuit to the high pressure pump motor relay and time

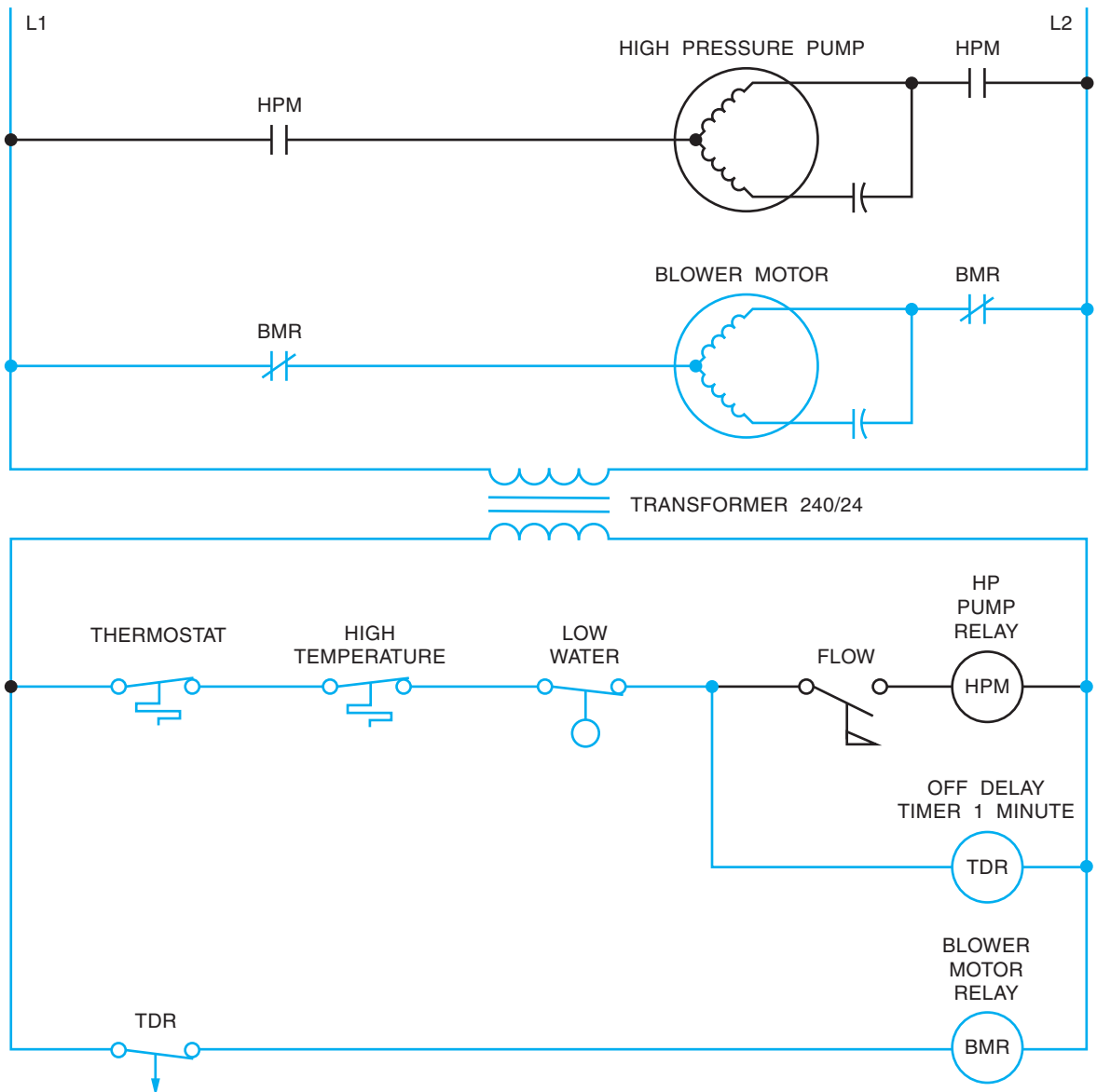
delay relay. One of the most dangerous conditions for a boiler is a low water level. If the water level should drop below a preset point, the switch will open.

The flow switch is normally open. A flow of air causes the switch contacts to close. The flow switch is used to insure that there is a flow of combustion air into the combustion chamber before fuel oil is injected into the chamber.

The time delay contact (TDR) is connected in series with the blower motor relay coil. The symbol indicates that the timer is an off delay timer. The arrow always points in the direction the contacts will move after the delay period. The arrow indicates that the contacts will delay reopening after they have changed position.

CIRCUIT OPERATION

When the thermostat contact closes, a circuit is completed through the closed high temperature switch, low water switch, and coil of the time delay relay. Since the timer is an off delay timer, TDR contacts close immediately and energize the blower motor relay, Figure 9–19. This causes the BMR

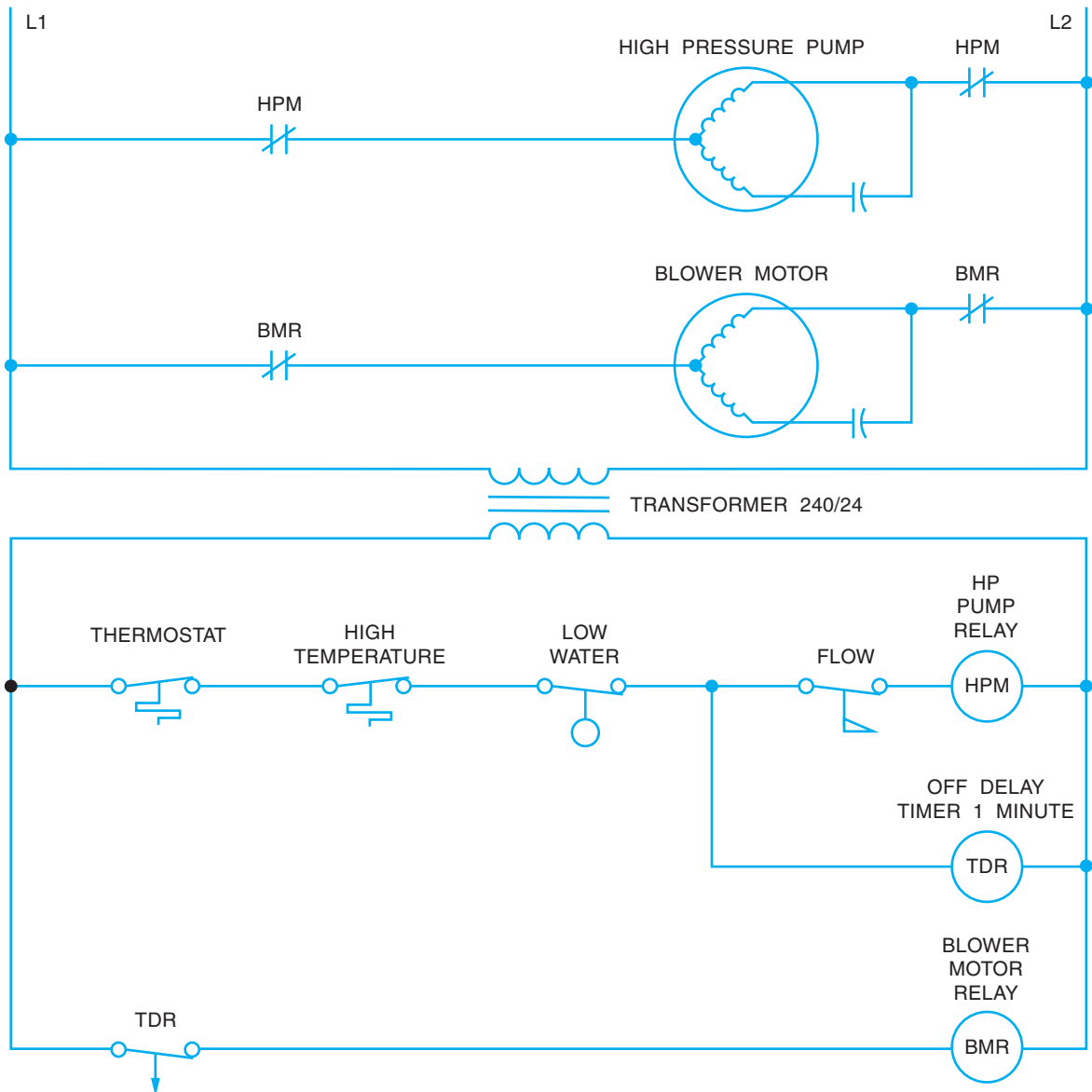


► **Figure 9–19**
The thermostat contacts close. (Source: Delmar/Cengage Learning)

contacts to close and connect the blower motor to the power line.

The air flow produced by the blower motor causes the flow switch to close and energize the coil of the high pressure pump motor relay, Figure 9–20. This causes the HPM contacts to close and connect the

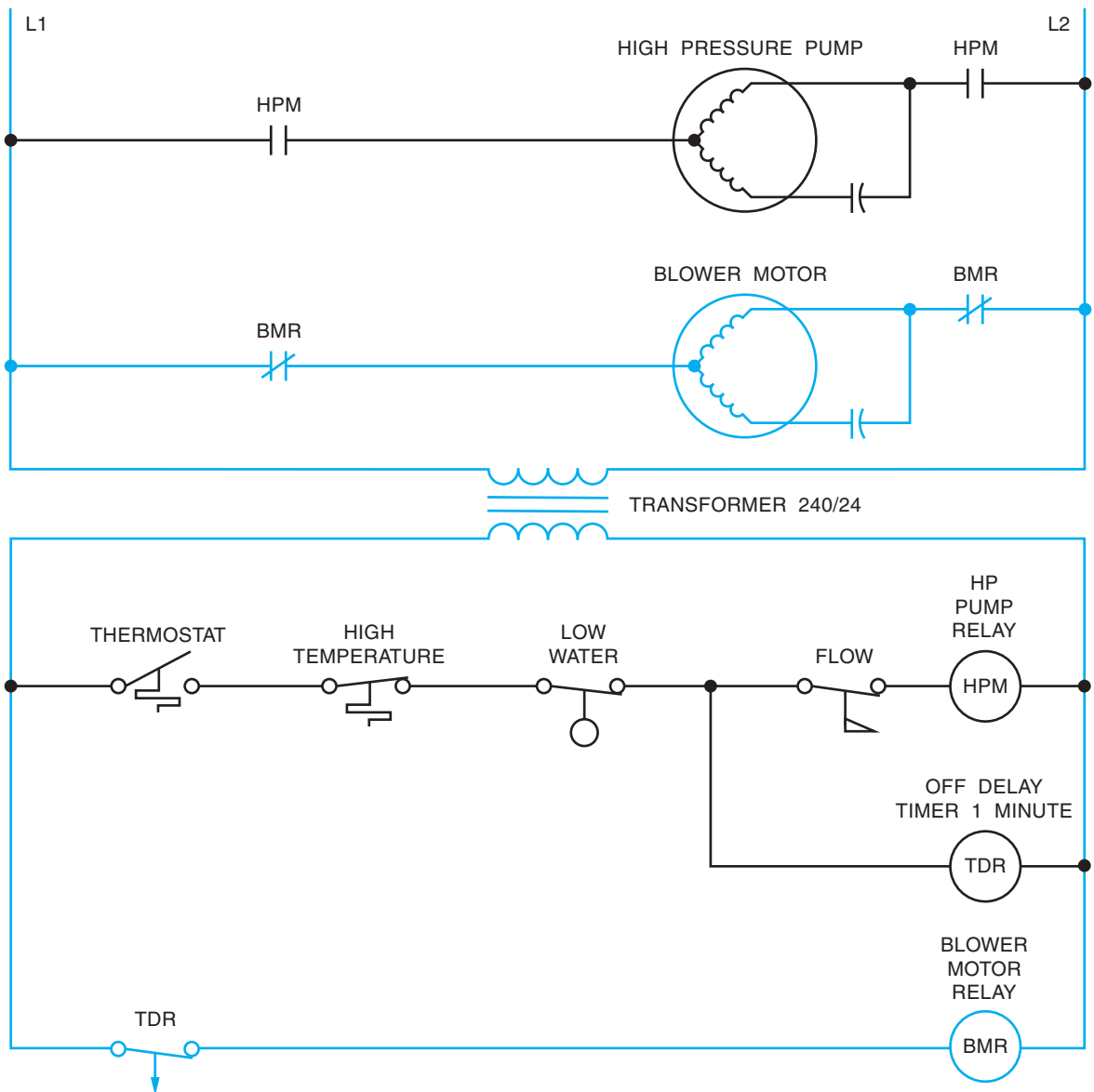
high pressure pump to the line. The circuit is now in full operation. The circuit will continue to operate in this manner until the thermostat contacts reopen, Figure 9–21. When the thermostat contacts reopen, power is disconnected from the high pressure pump motor relay and the time delay relay. Because the



► **Figure 9–20**
The circuit is in full operation. (Source: Delmar/Cengage Learning)

time delay relay is an off delay timer, it does not start timing until the coil is deenergized. The TDR contacts will remain closed for a period of 1 minute before reopening. This permits the blower motor to remove any smoke and fumes from the combustion

chamber. When the TDR contacts open, the circuit is back in its original state as shown in Figure 9–18. If the high temperature switch or low water switch should open, it would have the same effect as opening the thermostat.



► **Figure 9-21**
The thermostat contacts open. (Source: Delmar/Cengage Learning)

SUMMARY

- ▶ Schematics and wiring diagrams are the written language of control systems.
- ▶ Motor control symbols are generally drawn to pictorially represent their function.
- ▶ The way a motor control symbol is drawn indicates how it is to be connected in a circuit.
- ▶ Schematic diagrams show components in their electrical sequence without regard for physical location.
- ▶ Wiring diagrams show a pictorial representation of the circuit with connecting wires.
- ▶ Schematics and wiring diagrams always show the circuit in its deenergized or off position.

KEY TERMS

load
movable contact
National Electrical
Manufacturers
Association (NEMA)

node
normally closed
normally open
schematics
stationary contact

three-wire control circuits
two-wire control circuit
wiring diagrams

REVIEW QUESTIONS

1. What are the two basic types of motor controls?
2. Define a schematic diagram.
3. Define a wiring diagram.
4. Components used for the function of stop are generally wired _____ and connected in _____.
5. Components used for the function of start are generally wired _____ and connected in _____.
6. When reading a schematic diagram, are the components shown in their energized or deenergized position?
7. What does this symbol represent?



8. What does this symbol represent?



9. What does a dashed line drawn between components represent?



10. What is an auxiliary contact?
11. Make a schematic drawing of a cooling thermostat that turns on the coil of a contactor. Label the contactor CC, which stands for compressor contactor. Make sure that the circuit is drawn so that an increase in temperature will cause the contact to close.
12. Draw a schematic that controls the operation of a sump pump. A float switch is used to turn the pump on when the water rises to a high enough level. It is assumed that the float switch has contacts rated high enough to control the motor without the use of a relay.
13. Draw a schematic diagram for a low water level alarm. A float switch is used to detect the level of water in a tank. If it should fall below a predetermined level, a warning light will come on and an alarm will sound.
14. Draw a circuit for a low pressure cutoff switch. If the pressure falls below a certain level, it will cause a contactor coil to be disconnected. Label the contactor CC.
15. Add a thermal switch to the circuit in question 14. The switch is to be installed so that a rise in temperature will disconnect the contactor coil.

UNIT 10



Developing Wiring Diagrams

OBJECTIVES

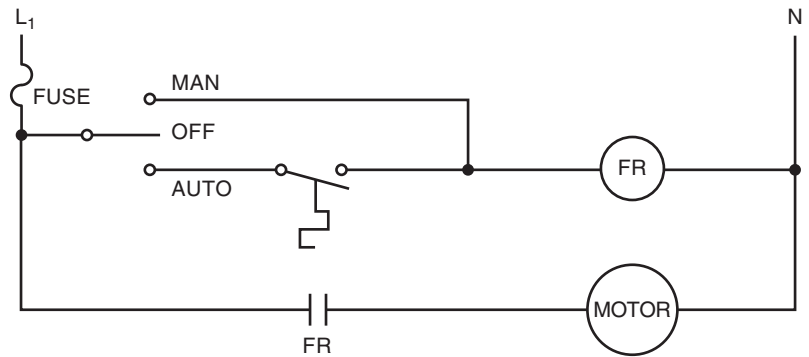
After studying this unit the student should be able to:

- ▶ Discuss the operation of an electric circuit by interpreting a schematic diagram
- ▶ Place wire numbers on a schematic diagram and develop a wiring diagram from the schematic

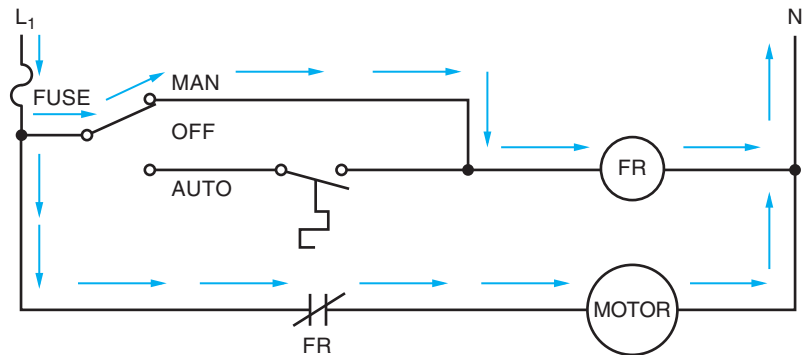
In this unit, two schematic diagrams are discussed, including their operation and development into wiring diagrams. Developing a wiring diagram from a schematic is the same basic procedure that is followed when installing a control system. Understanding this process is also a great advantage when troubleshooting existing circuits.

DEVELOPING CIRCUIT 1

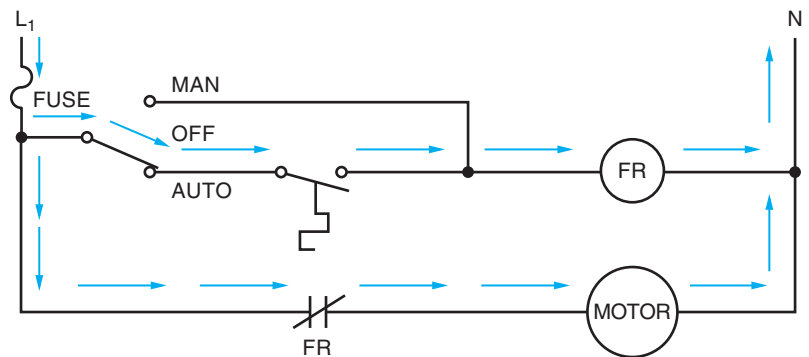
The first circuit discussed is shown in Figure 10–1. In this circuit, a fan motor is controlled by relay **FR (fan relay)**. The circuit is so designed that a switch can be used to turn the circuit completely off, operate the fan manually, or permit the fan to be operated by a thermostat. If the control switch is moved to the “MAN” position as shown in Figure 10–2, a complete circuit is provided to the



► **Figure 10-1**
Fan control circuit. (Source: Delmar/
Cengage Learning)



► **Figure 10-2**
Fan relay coil is energized by
control switch. (Source: Delmar/Cengage
Learning)



► **Figure 10-3**
Fan relay is controlled by the
thermostat. (Source: Delmar/Cengage
Learning)

fan relay coil. Then the relay energizes, FR contact closes and connects the motor to the line. This setting permits the fan to be operated at any time, regardless of the condition of the thermostat.

If the control switch is moved to the “AUTO” position as shown in Figure 10-3, the fan will be controlled by the action of the thermostat. When the temperature increases to a predetermined level, the thermostat contact will close. This completes a

circuit to FR coil. When FR coil energizes, the FR contact closes and connects the fan motor to the line. When the temperature decreases sufficiently, the thermostat contact opens and breaks the circuit to FR coil. When FR coil deenergizes, FR contact opens and disconnects the motor from the line.

This schematic will now be developed into a wiring diagram. To aid in the connection of this circuit, a simple numbering system will be used. To use

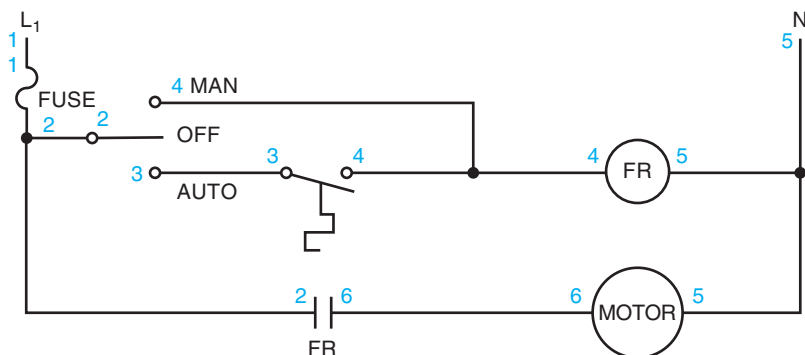


Figure 10-4
Schematic is numbered to aid in
connection of the circuit. (Source:
Delmar/Cengage Learning)

this numbering system, the following rules will be followed:

1. All components connected to the same line will receive the same number.
2. Any time a component is gone through, the number will change.
3. A set of numbers can be used only once.

Figure 10-4 shows the numbers placed on the schematic. Notice that a 1 is placed at the incoming power line and a 1 is also placed at one side of the fuse. Because the fuse is a component, the number must change on the other side of it. Therefore, the fuse has a 2 on the other side. There is also a 2 placed beside the common terminal of the OFF-MANUAL-AUTOMATIC switch, and a 2 placed beside one side of FR contact. Notice that all of these components have the same number because there is no break between them.

The AUTO side of the switch has been numbered 3, and one side of the thermostat has also been numbered 3. The other side of the thermostat is numbered 4, the MAN side of the switch is number 4, and one side of FR coil is numbered 4. The other side of the coil has been numbered 5, the neutral line is numbered 5, and one side of the motor is numbered 5. The other side of the motor is numbered 6, and the other side of FR contact is numbered 6.

Notice that all the points that are electrically connected together have the same number. Notice also that no set of numbers was used more than once.

The components of the system are shown in Figure 10-5. Notice that numbers have been placed beside certain components. These numbers

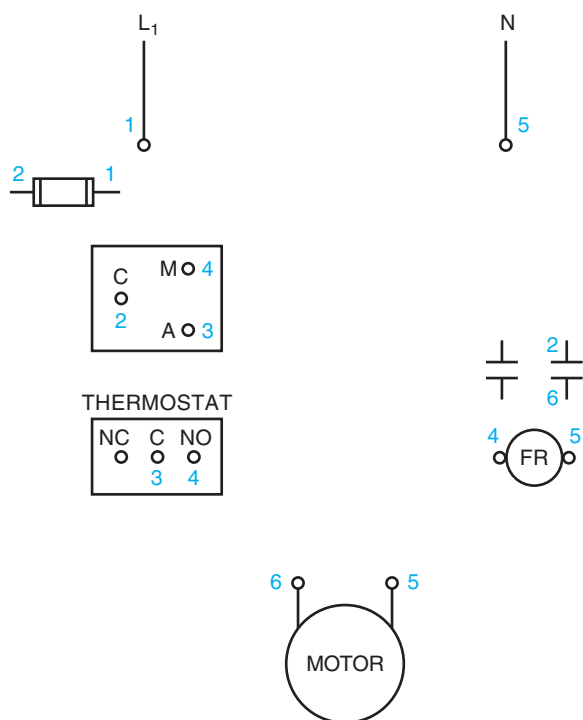


Figure 10-5
Circuit components are numbered with the same
numbers that appear on the schematic. (Source: Delmar/
Cengage Learning)

correspond to the numbers in the schematic. For example, the fuse in the schematic is shown with a 1 on one side and a 2 on the other side. The fuse in the wiring diagram is shown with a 1 on one side and a 2 on the other side. Notice the OFF-MANUAL-AUTOMATIC switch shown on the schematic. The common terminal is numbered 2, the

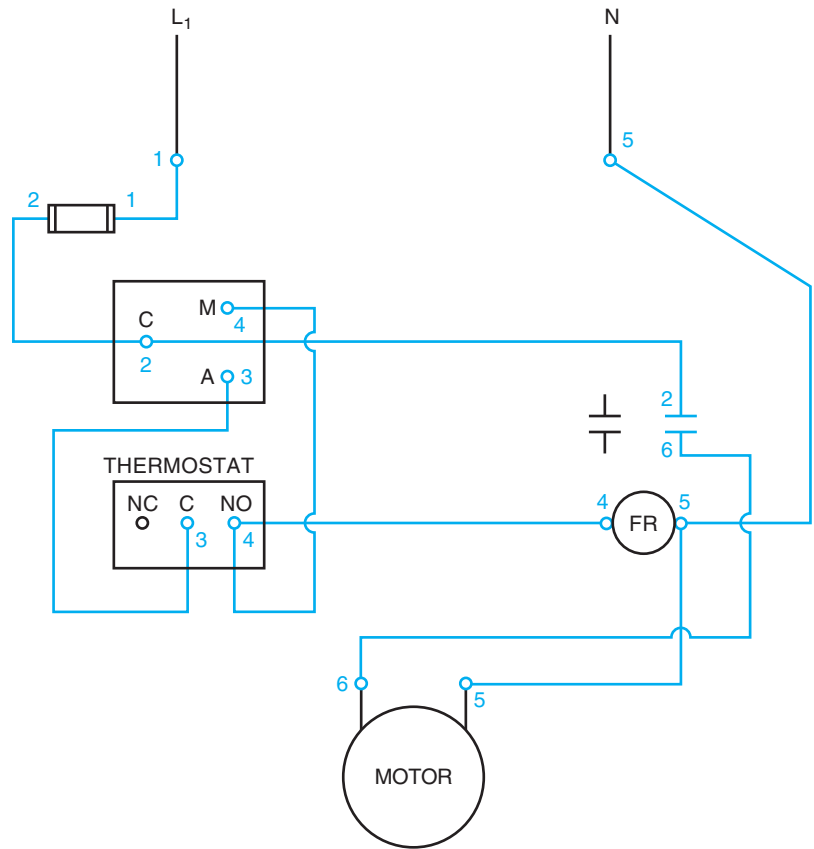


Figure 10-6
Like numbers are connected.
(Source: Delmar/Cengage Learning)

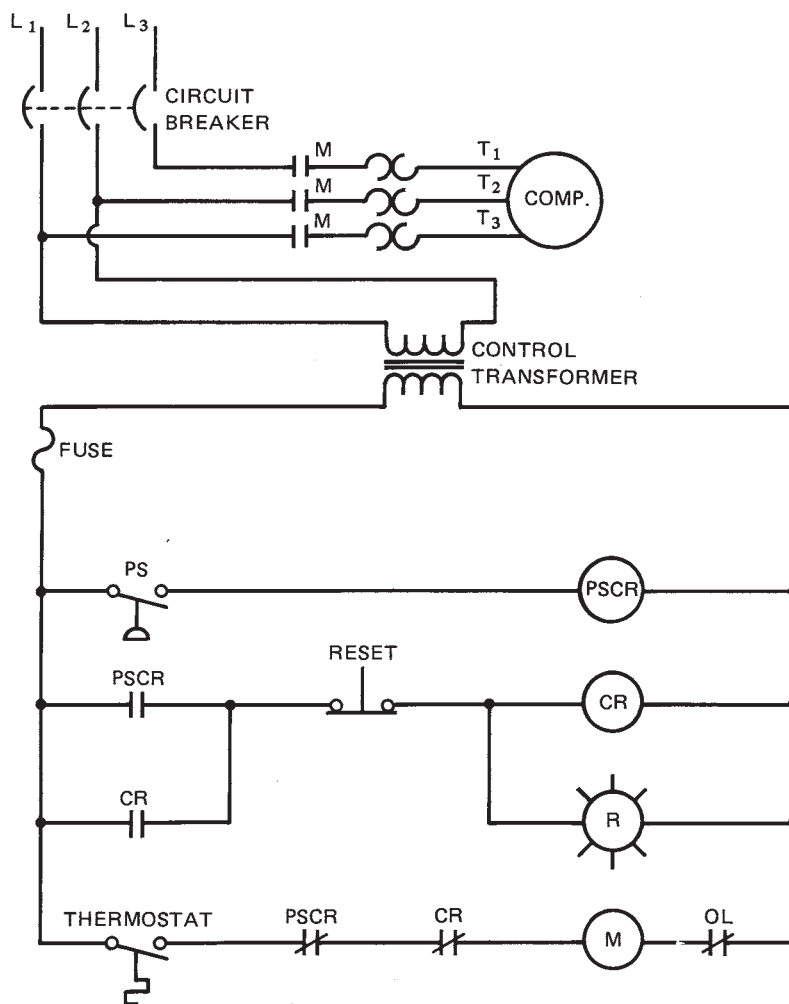
MAN terminal is numbered 4, and the AUTO terminal is numbered 3. Now notice the same switch on the wiring diagram. The common terminal is numbered 2, the MAN terminal is numbered 4, and the AUTO terminal is numbered 3. The thermostat in the schematic has been numbered 3 on one terminal and 4 on the other terminal. The thermostat shown in the wiring diagram has three terminals. One terminal is common, one terminal is marked NC, and the other terminal is marked NO. This is a common arrangement for many control components. This shows that the thermostat is a single-pole double-throw switch. Because the thermostat shown in the schematic is normally open, the 3 will be placed beside the common terminal, and the 4 will be placed beside the NO contact. Notice that one of the contacts on FR relay is numbered 2 on one side and 6 on the other side. FR coil is numbered

4 on one side and 5 on the other. One motor terminal is numbered 5 and the other is numbered 6.

Now that the component parts have been numbered with the same numbers as those used on the schematic, connection can be made easily and quickly. To connect the circuit, connect all the like numbers. For example, all the number 1s will connect together, all the number 2s will connect together, and so forth. The connected circuit is shown in Figure 10-6.

DEVELOPMENT OF CIRCUIT 2

The schematic diagram for circuit 2 is shown in Figure 10-7. Notice this schematic shows both the control circuit and the motor connection. This circuit is designed to turn off a compressor if the pressure in the system reaches a predetermined



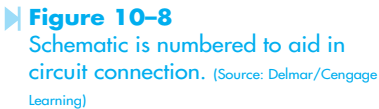
► **Figure 10-7**
High pressure locks
compressor off. (Source: Delmar/
Cengage Learning)

level. If the pressure becomes high enough to cause the pressure switch contacts to close, the compressor motor will not only be disconnected from the power line, but a warning light will also be turned on. Once the warning light has been turned on, the system must be manually reset by the service technician before the compressor can be restarted by the thermostat. The operation of the circuit is as follows:

When the thermostat contact closes, a circuit is completed to M motor starter coil. When M coil energizes, M contacts close and connect the compressor to the three-phase power line. When

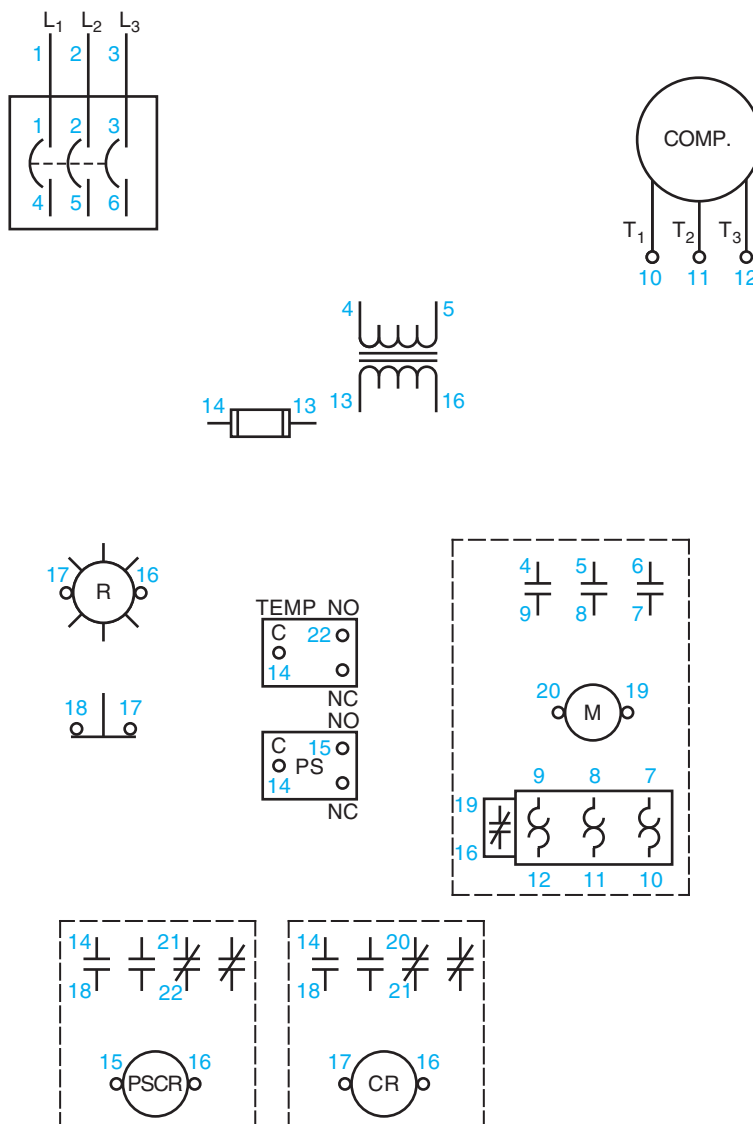
the temperature decreases, the thermostat contacts open and deenergize M coil. When M coil deenergizes, M contacts open and disconnect the compressor from the power line. Notice that in the normal action of this circuit, the compressor is controlled by the thermostat.

Now assume that the thermostat contacts are closed and that the compressor is connected to the power line. Also assume that the pressure in the system becomes too great and that the contacts of the pressure switch close. When the pressure switch contacts close, **PSCR (pressure switch control relay)** coil energizes. This causes both



thermostat if PSCR contact should reclose. Notice that the warning light is connected in parallel with the coil of CR relay. The warning light will be turned on as long as CR relay coil is turned on. As long as CR relay is energized, the compressor cannot be restarted by the thermostat.

Now assume that the pressure in the system has returned to normal and the problem that caused the excessive pressure has been corrected. When the pressure switch contact reopened, PSCR coil deenergized and reset both PSCR contacts to their normal position. When the service technician presses the reset button, CR coil deenergizes and both CR contacts return to their normal positions.



► **Figure 10-9**
Components are numbered the same in
the schematic. (Source: Delmar/Cengage Learning)

The circuit is now back in its original position and ready for normal operation.

This schematic diagram is now being developed into a wiring diagram. As before, the schematic is numbered in the same manner as the first example. The numbered schematic is shown in Figure 10-8. Notice that all components that are electrically tied together have the same number. Also notice that no number set has been used more than once.

The control components are shown in Figure 10-9. Notice that the numbers on the components correspond with like numbers on the schematic diagram. For example, on the schematic diagram the primary of the control transformer is numbered 4 and 5. The secondary leads are numbered 13 and 16. Notice the same is true on the wiring diagram. Note the number of each component on the schematic and then

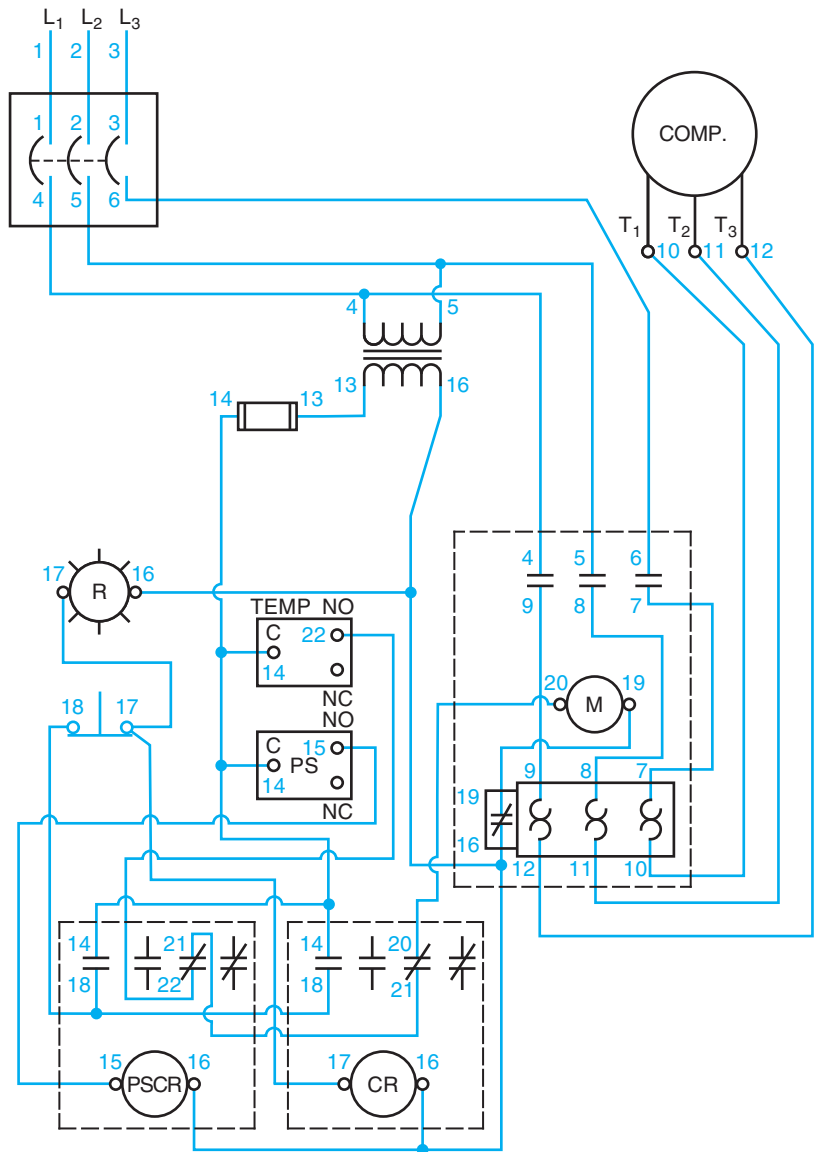


Figure 10-10
Connection is made by
connecting like numbers. (Source:
Delmar/Cengage Learning)

find the corresponding number beside the proper component used on the wiring diagram.

Once the components of the wiring diagram have been numbered with the same numbers as those on the schematic, the circuit can be connected by

connecting like numbers. The circuit connection is shown in Figure 10-10. Again, notice that the wiring diagram appears to be completely different from the schematic, but both are the same electrically.

SUMMARY

- ▶ Wiring diagrams are generally developed from a schematic diagram.
- ▶ All components in a schematic diagram are shown in their deenergized or off position.
- ▶ Wire numbers are often placed on schematic diagrams to aid in connecting a wiring diagram.
- ▶ Three basic rules for placing wire numbers on a schematic diagram are:
 - A. All components connected to the same line will receive the same number.
 - B. Any time a component is gone through, the number will change.
 - C. A set of numbers can be used only once.

KEY TERMS

FR (fan relay)

PSCR (pressure switch control relay)

REVIEW QUESTIONS

Refer to Figure 10–1 for the following questions.

1. Explain the action of the circuit if the thermostat should fail to operate.
2. Explain the action of the circuit if FR contacts should become shorted together.

Refer to Figure 10–7 for the following questions.

3. Explain the action of the circuit if the overload (OL) contact should open.
4. Explain the action of the circuit if the pressure switch contacts should become shorted.
5. Explain the action of the circuit if the CR coil should open.

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SECTION 3

Motors

UNIT 11



Split-Phase Motors

OBJECTIVES

After studying this unit the student should be able to:

- List the basic types of split-phase motors
- Discuss two-phase power
- Discuss the operation of a resistance-start induction run motor
- Discuss the operation of a capacitor-start induction run motor
- Discuss the operation of a permanent-split capacitor motor
- Reverse the direction of rotation of a split-phase motor
- Connect dual voltage motors for 120- or 240-volt operation
- Identify the terminal markings of an oil-filled capacitor and discuss the proper connection to a permanent split-capacitor motor

Because three-phase power is not available to small business and residential locations, the air conditioning equipment for these areas is powered by single-phase electric motors. The single-phase motors used in air conditioning systems are generally one of two types. These are the split-phase and the shaded-pole induction motor.

SPLIT-PHASE MOTORS

Split-phase motors fall into three general classifications. These are:

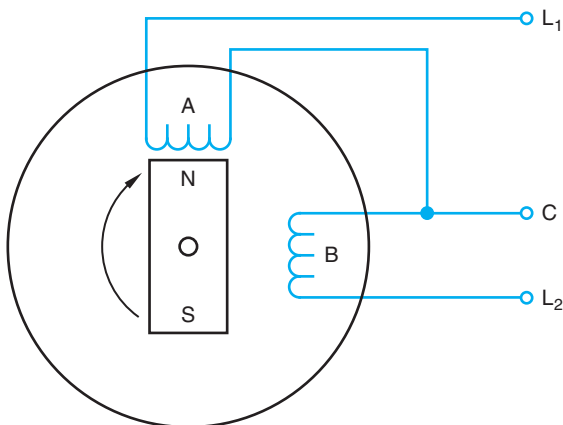
1. The **resistance-start induction-run motor**,
2. The **capacitor-start induction-run motor**,

3. The **permanent-split capacitor motor (PSC)**. It should be noted that although all permanent-split capacitor motors contain a run capacitor, some are equipped with a separate starting capacitor to improve starting torque. The motors with the separate starting capacitor are often referred to as **capacitor-start capacitor-run motors**.

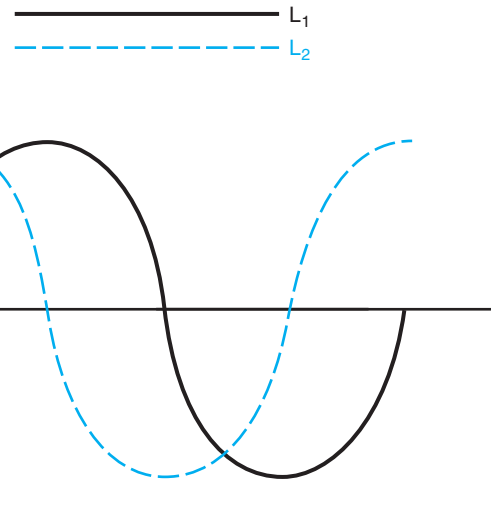
Although all of these motors have different operating characteristics, they are similar in construction. Split-phase motors get their name from the manner in which they operate. These motors operate on the principle of a *rotating magnetic field*. A rotating magnetic field, however, cannot be produced with only one phase. Split-phase motors literally split single-phase power in order to imitate a two-phase power system. A rotating magnetic field can be produced with two separate phases.

THE TWO-PHASE SYSTEM

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° out of phase with each other, Figure 11-1. The voltages of a two-phase system are, therefore, 90° out of phase with each other, Figure 11-2. The two out-of-phase voltages can be used to produce a rotating magnetic field. Because there have to



► **Figure 11-1**
Two-phase alternator. (Source: Delmar/Cengage Learning)



► **Figure 11-2**
Two-phase voltages are 90° out of phase with each other. (Source: Delmar/Cengage Learning)

be two voltages or currents out of phase with each other to produce a rotating magnetic field, single-phase motors use two separate windings and 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.

RESISTANCE-START INDUCTION-RUN AND CAPACITOR-START INDUCTION-RUN MOTORS

Resistance-start induction-run and capacitor-start induction-run motors are very similar in construction. The stator winding of both motors contains both a **start winding** and a **run winding**. The start winding is made of smaller wire and placed higher in the metal core material than the run winding, as shown in Figure 11-3. Since the start winding is made with smaller wire than the run winding, it will exhibit a higher resistance than the run winding. Placing the run winding deeper in the metal core material causes it to exhibit a greater amount of inductance than the start winding. Electrically, the winding appears similar to the circuit shown in Figure 11-4. The stator is constructed in this

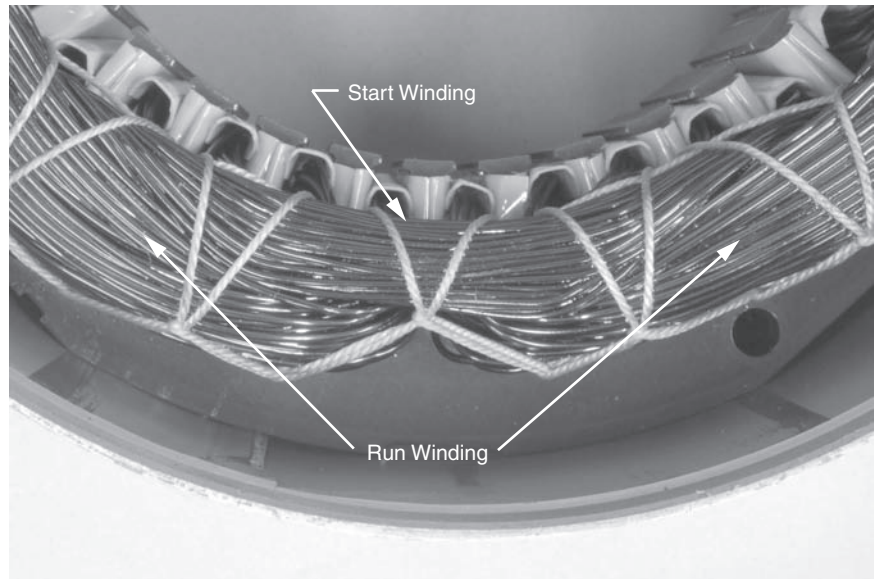


Figure 11-3
Stator winding of a
resistance-start induction-run
or capacitor-start induction-
run motor. (Source: Delmar/
Cengage Learning)

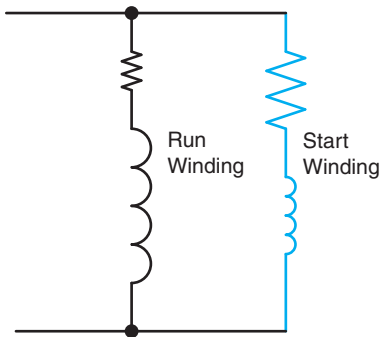
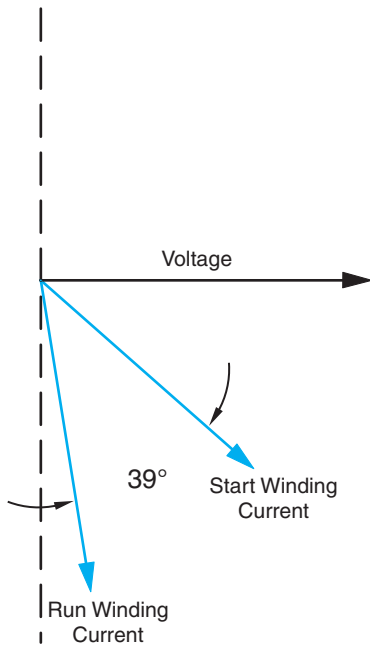


Figure 11-4
The run winding has more inductance and less
resistance than the start winding. The start winding
has more resistance and less inductance than the
run winding. (Source: Delmar/Cengage Learning)

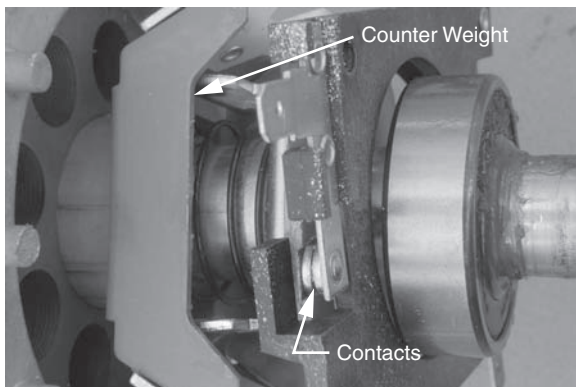
manner to produce a phase shift between the current flowing through the run winding and the current flowing through the start winding. Both the resistance-start and capacitor-start induction-run motors start rotation by producing a rotating magnetic field in the stator winding. Recall that a rotating magnetic field cannot be produced with a single phase.

Resistance-Start Induction-Run Motor

The rotating magnetic field of the resistance-start induction-run motor is produced by the out-of-phase currents in the run and start windings. Since the run winding appears more inductive and less resistive than the start winding, the current flow in the run winding will be close to 90 degrees out-of-phase with the applied voltage. The start winding appears more resistive and less inductive than the run winding, causing the start winding's current to be less out-of-phase with the applied voltage, as shown in Figure 11-5. The phase-angle difference between current in the run winding and current in the start winding of a resistance-start induction-run motor is generally 35 to 40 degrees. This is enough phase-angle difference to produce a weak rotating field, and consequently a weak torque, to start the motor. Once the motor reaches about 75% of its rated speed, the start winding is disconnected from the circuit and the motor continues to operate on the run winding. In nonhermetically sealed motors, the start winding is generally disconnected with a centrifugal switch. A centrifugal switch is shown in Figure 11-6. The contacts of the centrifugal switch are connected in series with the start winding, as

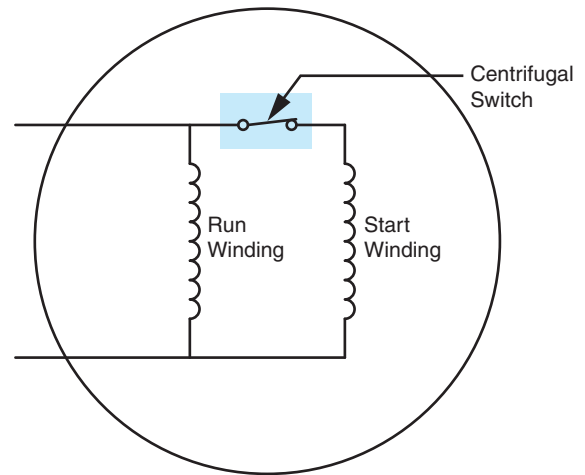


► **Figure 11-5**
The run winding current and start winding current of a resistance-start induction-run motor will generally be between 35 and 40 degrees out-of-phase with each other.
(Source: Delmar/Cengage Learning)

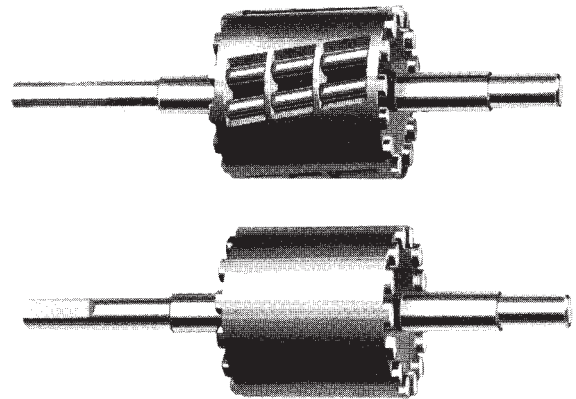


► **Figure 11-6**
A centrifugal switch is used to disconnect the start windings when the motor reaches about 75% of rated speed.
(Source: Delmar/Cengage Learning)

shown in Figure 11-7. When the motor is at rest or not running, the contacts of the centrifugal switch are closed and provide a circuit to the start winding. When the motor is started and reaches about 75% of its rated speed, a counterweight on the centrifugal switch moves outward because of centrifugal force,



► **Figure 11-7**
The centrifugal switch contacts are connected in series with the start winding. (Source: Delmar/Cengage Learning)

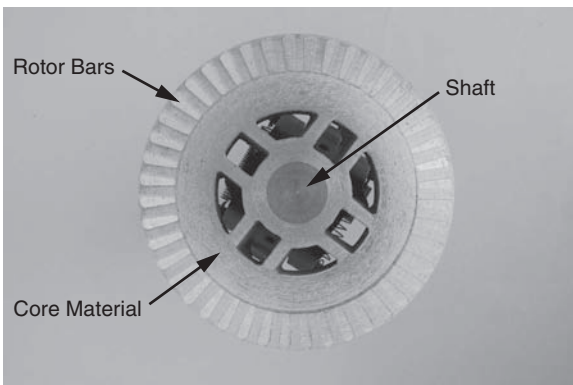


► **Figure 11-8**
Squirrel cage rotor. (Courtesy of Bodine Electric Co.).

causing the contacts to open and disconnect the start winding from power. The motor continues to operate on the run winding.

When the start winding is disconnected from the circuit, a rotating magnetic field is no longer produced in the stator. This type of motor continues to operate because of current induced in the squirrel cage windings in the rotor. Squirrel cage rotors are so named because they contain bars inside the rotor that would resemble a squirrel cage if the laminations were removed, as shown in Figure 11-8.

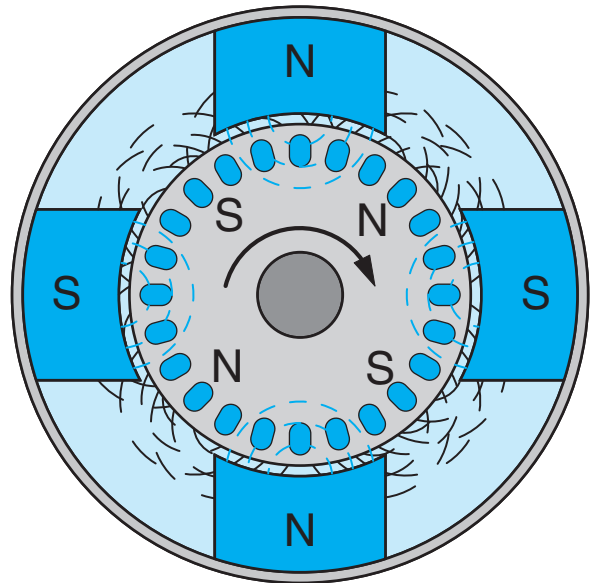
A squirrel cage is a device that is often placed inside the cage of small pets such as hamsters to permit them to exercise by running inside the squirrel cage. A squirrel cage rotor that has been cut in half clearly shows the bars and motor shaft, as shown in Figure 11–9. The bars of the turning squirrel cage rotor winding cut through lines of magnetic flux, causing an induced voltage in the rotor. Since the rotor bars are shorted together at each end, current flow through the rotor bars produces a magnetic field in the rotor. Alternate magnetic fields are produced in the rotor, causing the motor to continue operating, as shown in Figure 11–10. This is the same principle that permits a three-phase motor to continue operating if one phase is lost and the motor is connected to single-phase power. The main difference is that the split-phase motor is designed to operate in this condition and the three-phase motor is not. Resistance-start and capacitor-start induction-run motors are rugged and will provide years of service with little maintenance. Their operating characteristics, however, are not as desirable as those of other types of single-phase motors. Due to the way they operate, they have a low power factor. They will draw almost as much current when the motor is running at no load as they will when the motor is running at full load. Typically, if the motor has a full-load current draw of 8 amperes, the no-load current may be 6.5 to 7 amperes.



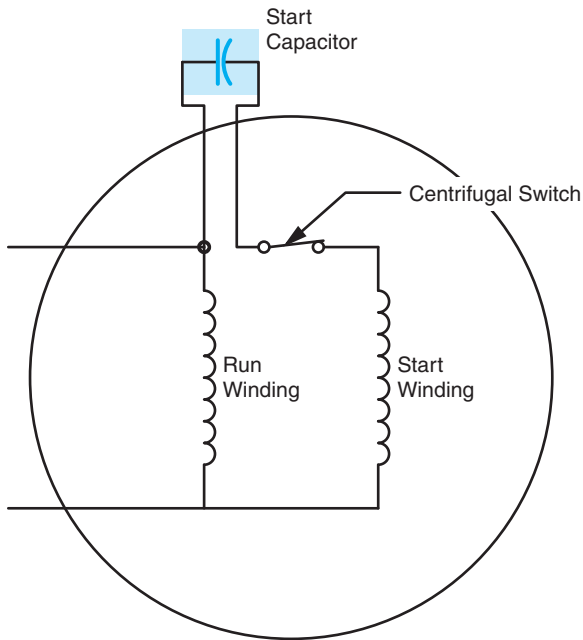
► **Figure 11–9**
Bars and shaft of a squirrel cage rotor. (Source: Delmar/Cengage Learning)

Capacitor-Start Induction-Run Motors

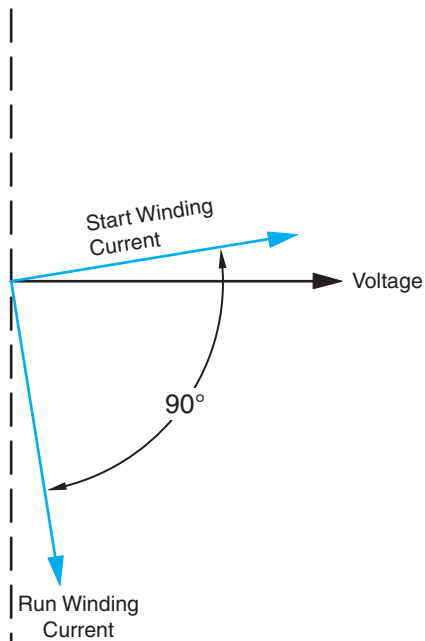
Capacitor-start induction-run motors are very similar to resistance-start induction-run motors. The design of the stator winding is basically the same. The main difference is that a capacitor is connected in series with the start winding, as shown in Figure 11–11. Inductive loads cause the current to lag the applied voltage. Capacitors, however, cause the current to lead the applied voltage. If the starting capacitor is sized correctly, the start winding current will lead the applied voltage by an amount that will result in a 90-degree phase shift between the run winding current and the start winding current, producing an increase in the amount of starting torque, as shown in Figure 11–12. If the capacitance of the start capacitor is too great, it will cause the start winding current to shift more than 90 degrees out-of-phase with the run winding current and starting torque will be reduced. When replacing the start capacitor for this type



► **Figure 11–10**
The rotor continues to turn because of magnetic fields produced by the current induced in the rotor of the motor. (Source: Delmar/Cengage Learning)



► **Figure 11-11**
A capacitor is connected in series with the start winding. (Source: Delmar/Cengage Learning)



► **Figure 11-12**
The capacitor causes a 90-degree phase shift between run winding current and start winding current. (Source: Delmar/Cengage Learning)



► **Figure 11-13**
A capacitor-start induction-run motor. (Source: Delmar/Cengage Learning)



► **Figure 11-14**
Typical starting capacitor. (Source: Delmar/Cengage Learning)

of motor, the micro-farad rating recommended by the manufacturer should be followed. It is permissible to use a capacitor with a higher voltage rating, but never install a capacitor with a lower voltage rating. A capacitor-start induction-run motor is shown in Figure 11-13. A typical starting capacitor is shown in Figure 11-14.

TESTING THE STATOR WINDING

The stator winding of a single-phase motor is generally tested with an ohmmeter. The ohmmeter test can be used to determine if a winding is open or grounded. Many single-phase motors have one

lead of the run and start windings connected as shown in Figure 11–15. To test the windings for an open, connect one ohmmeter lead to the common motor terminal, and the other meter lead to the run winding. The ohmmeter should indicate continuity through the winding. The resistance of the run winding of a single-phase motor can vary greatly from one motor to another. The winding resistance of a single-speed motor may be only one or two ohms, while the resistance of a multi-speed fan motor may be 10 to 15 ohms.

To test the start winding for an open, connect the ohmmeter leads to the common terminal and the S terminal. The start winding should indicate continuity, and should have a higher resistance than the run winding. This difference of resistance may not be great, but the start winding should have a higher resistance than the run winding.

To test the stator winding for a ground, connect one of the ohmmeter leads to the case of the motor, Figure 11–16. Alternately check each motor terminal with the other ohmmeter lead. The ohmmeter should indicate no continuity between either winding and the case of the motor.

A shorted start winding can sometimes be detected by the fact that the motor will not start, but will run if the shaft is turned by hand. The motor will produce a humming sound but will not turn when power is first applied to it. The shaft can be turned in either direction by hand and the motor will continue to run in that direction.

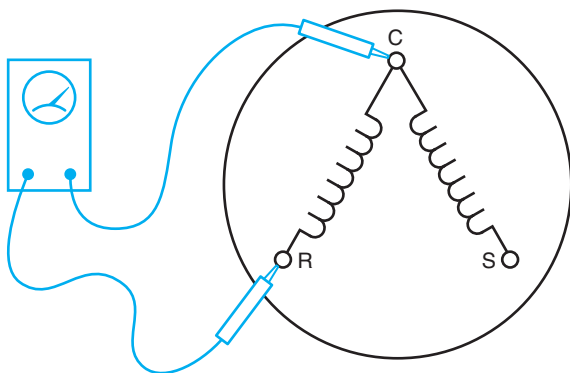


Figure 11–15
Testing the split-phase motor for an open winding.
(Source: Delmar/Cengage Learning)

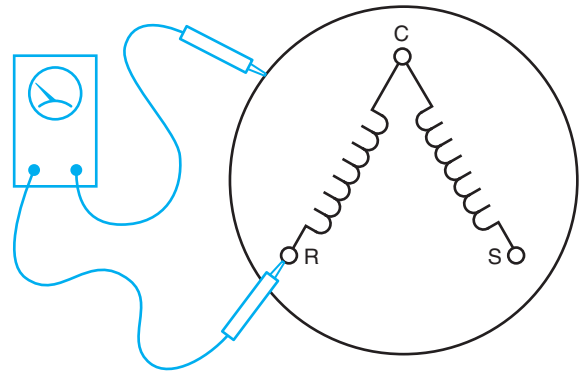


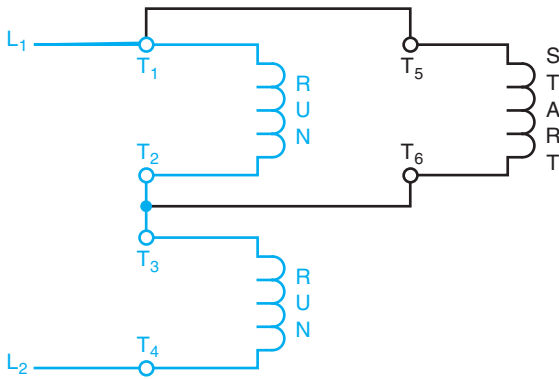
Figure 11–16
Testing a split-phase motor for a grounded winding.
(Source: Delmar/Cengage Learning)

REVERSING DIRECTION OF ROTATION

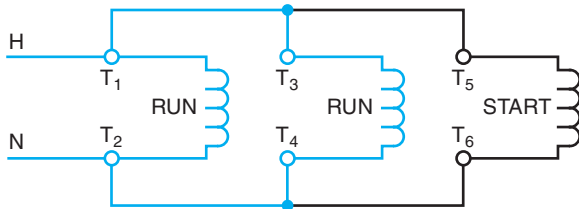
The direction of rotation of a split-phase motor can be reversed by changing the start winding leads or the run winding leads, but not both. The rotation is generally reversed by changing the start winding leads with respect to the run winding. Some motor manufacturers bring both start winding leads to the outside of the motor. This permits the service technician to decide the direction of rotation the motor is to turn when it is installed on the unit.

DUAL-VOLTAGE MOTORS

Single-phase motors can also be constructed to operate on two separate voltages. These motors are designed to be connected to 120 or 240 volts. A common connection for this type of motor contains two run windings and one start winding, Figure 11–17. The run windings are labeled T1–T2, and T3–T4. The start winding is labeled T5 and T6. In the circuit shown in Figure 11–17, the windings have been connected for operation on a 240-volt line. Each winding is rated at 120 volts. The two run windings are connected in series, which causes each to have a voltage drop of 120 volts when connected to 240 volts. Notice that the start winding has been connected in parallel with one of the run windings. This causes the start winding to have an



► **Figure 11-17**
The run windings are connected in series for a high-voltage connection. (Source: Delmar/Cengage Learning)

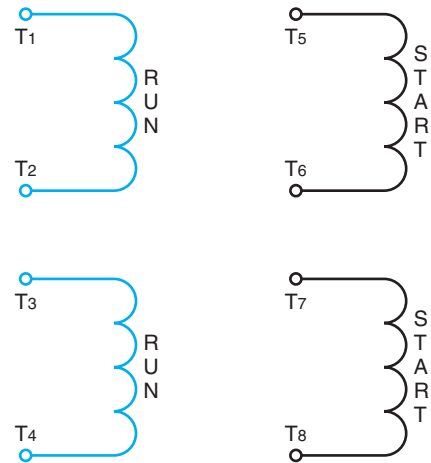


► **Figure 11-18**
Because these windings are connected in parallel, each will have 120 volts applied to it. (Source: Delmar/Cengage Learning)

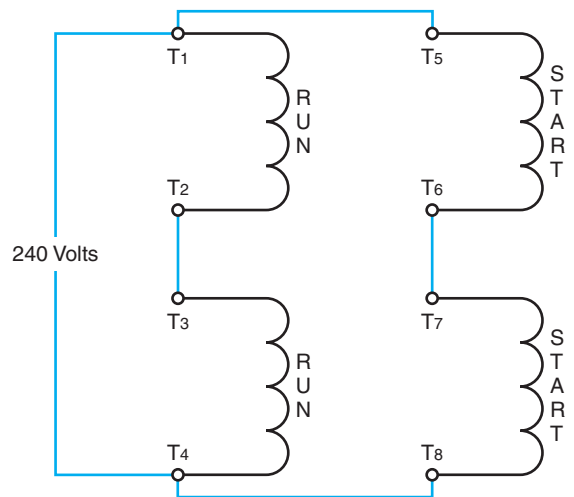
applied voltage of 120 volts also. Notice that each of the windings has 120 volts connected to it, which is the rating of the windings.

If the motor is to be operated on a 120 volt line, the windings are connected in parallel as shown in Figure 11-18. Because these windings are connected in parallel, each will have 120 volts applied to it.

Some dual-voltage motors will contain two start windings as well as two run windings, as shown in Figure 11-19. The run windings are labeled T_1 through T_4 , the same as dual-voltage motors that contain only one start winding. One of the start windings is labeled T_5 and T_6 . The second start winding is labeled T_7 and T_8 . If the motor is to be connected for operation on 240 volts, the run windings are connected in series by connecting T_2 and T_3 together, and the start windings are connected in series by connecting T_6 and T_7 together. The



► **Figure 11-19**
Some dual-voltage single-phase motors contain two start windings as well as two run windings. (Source: Delmar/Cengage Learning)

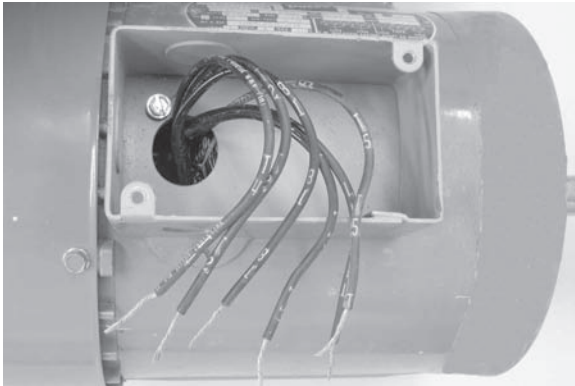
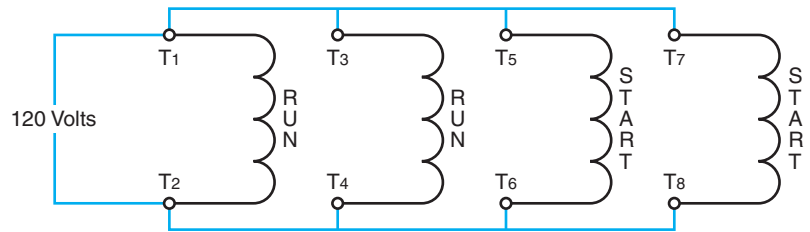


► **Figure 11-20**
The motor is connected for operation on 240 volts. (Source: Delmar/Cengage Learning)

start windings are then connected in parallel with the run windings, as shown in Figure 11-20. The direction of rotation can be changed by reversing T_5 and T_8 .

If the motor is operated on 120 volts, the run and start windings are connected in parallel as shown in Figure 11-21. If the motor is to be reversed, leads T_5 and T_7 are changed with leads T_6 and T_8 . Some

► **Figure 11-21**
The motor is connected for operation on 120 volts. (Source: Delmar/Cengage Learning)



► **Figure 11-22**
Connection leads of a dual-voltage single-phase motor. (Source: Delmar/Cengage Learning)

manufacturers label the start winding leads T_5 and T_8 even if they contain only one start winding. The connection leads of a dual-voltage single-phase motor are shown in Figure 11-22.

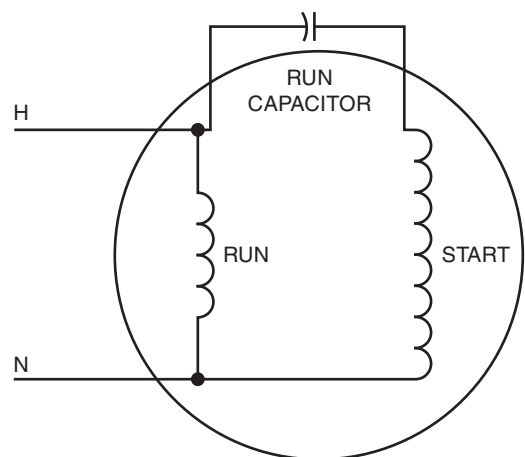
MOTOR POWER CONSUMPTION

It should be noted that the motor does not use less energy when connected to 240 volts than it does when connected to 120 volts. Power is measured in watts, and the watts will be the same regardless of the connection. When the motor is connected to operate on 240 volts, it will have half the current draw as it does on a 120-volt connection. Therefore, the amount of power used is the same. For example, assume the motor has a current draw of 5 amps when connected to 240 volts and 10 amps when connected to 120 volts. Watts can be computed from multiplying volts by amps. When the motor is connected to 240 volts, the amount of power used is $240 \times 5 = 1,200$ watts. When the motor is connected to 120 volts, the power used is $120 \times 10 = 1,200$ watts.

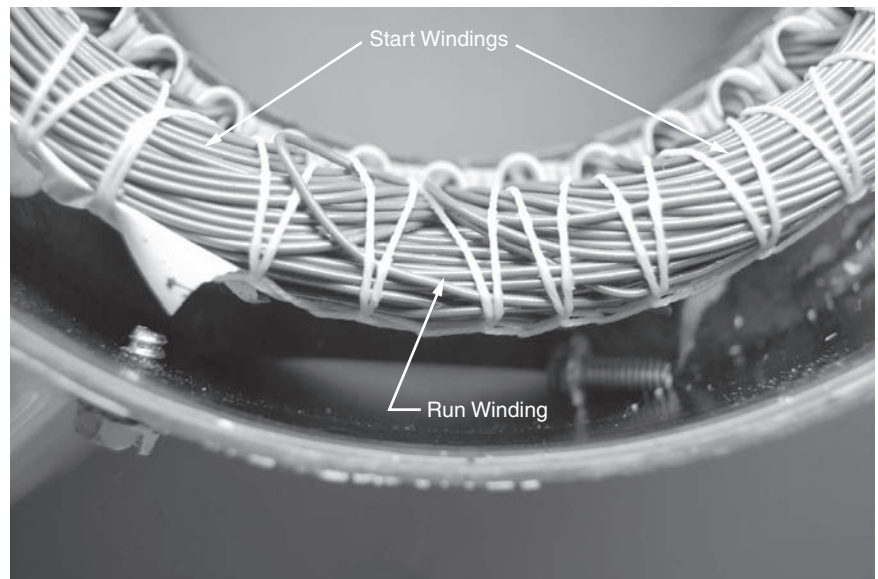
The 240-volt connection is generally preferred, however, because the lower current draw causes less voltage drop on the line supplying power to the motor. If the motor is located a long distance from the panel, voltage drop of the wire can become very important to the operation of the unit.

PERMANENT-SPLIT CAPACITOR MOTOR

The permanent-split capacitor motor has greatly increased in popularity for use in the air conditioning field over the past years. This type of split-phase motor does not disconnect the start windings from the circuit when it is running. This eliminates the need for a centrifugal switch or starting relay to disconnect the start windings from the circuit when the motor reaches about 75% of its full speed, Figure 11-23. This motor has good starting torque



► **Figure 11-23**
A schematic for a permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

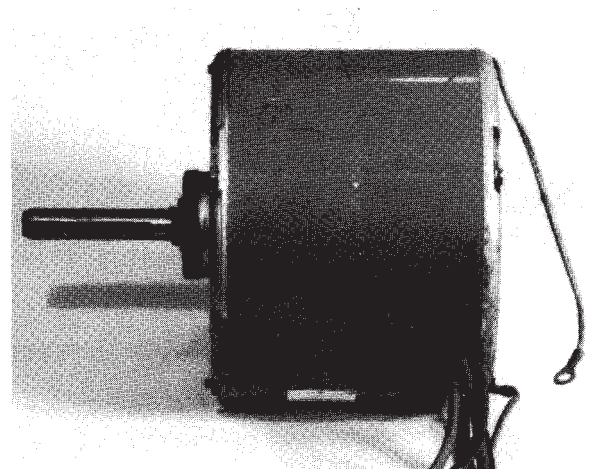


► **Figure 11-24**
The run and start windings
of a permanent-split capacitor
motor. (Source: Delmar/Cengage Learning)

and good running torque. Because the capacitor remains in the circuit during operation, it helps correct power factor for the motor. The stator winding of the permanent-split capacitor (PSC) motor is different from the stator windings of the resistance-start induction-run or capacitor-start induction-run motors. The PSC motor stator winding still contains a run and start winding, but the start winding will generally have the same size wire and just as many turns as the run winding, as shown in Figure 11-24. The run winding is placed lower in the core material, which helps increase the inductance.

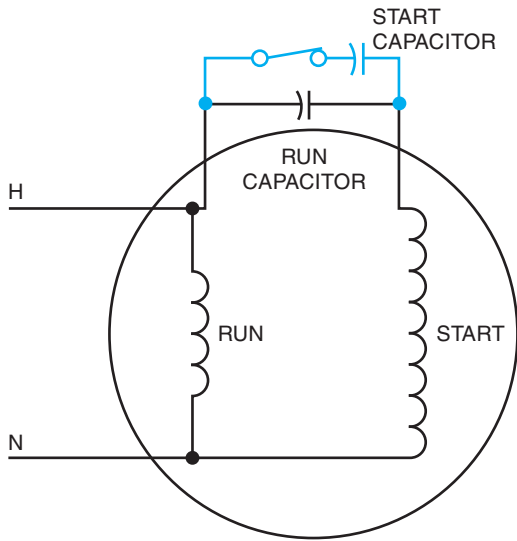
The capacitor used in this type of motor is generally the AC oil-filled type. A photograph of a permanent-split capacitor motor is shown in Figure 11-25. Because this capacitor remains connected in the circuit, an AC electrolytic capacitor cannot be used to replace the run capacitor for this type of motor.

The permanent-split capacitor motor will sometimes use an extra capacitor to aid in starting. When this is done, the start capacitor is connected in parallel with the run capacitor. During the time of starting, both of these capacitors are connected in the circuit, Figure 11-26. When the motor has



► **Figure 11-25**
Permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

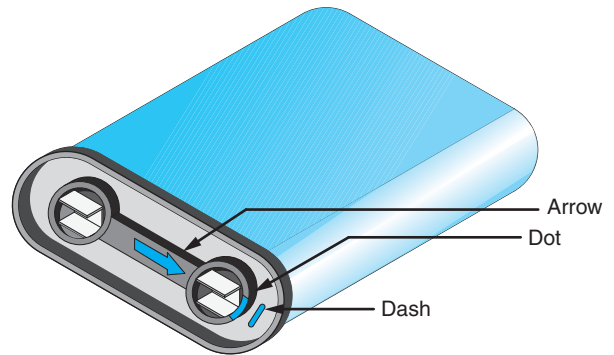
accelerated to about 75% of full speed, the start capacitor is disconnected from the circuit. If the motor is an open type, the start capacitor will be disconnected by a centrifugal switch. If the motor is sealed, such as a hermetically sealed compressor, the start capacitor will be disconnected by a starting relay.



► **Figure 11-26**
An extra starting capacitor used with a permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

IDENTIFYING CAPACITOR TERMINALS

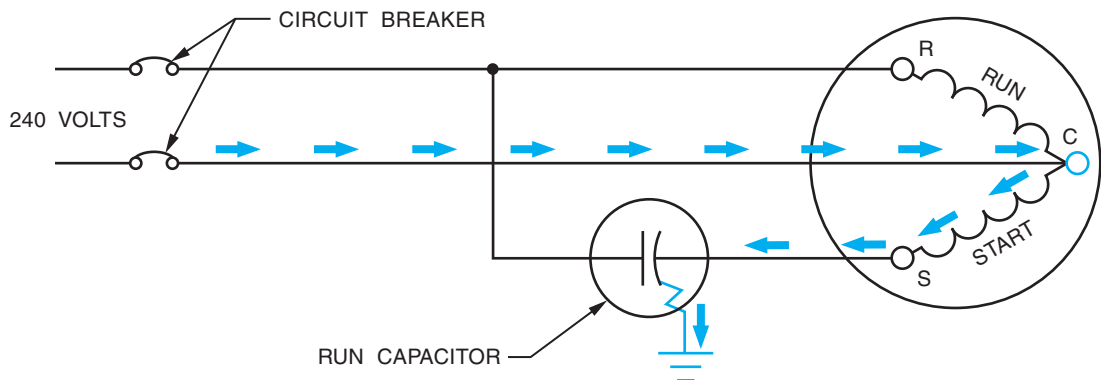
Most run capacitors and some starting capacitors are of the oil-filled type, Figure 8-15. This is especially true for high current motors such as those used to operate compressors. Many manufacturers



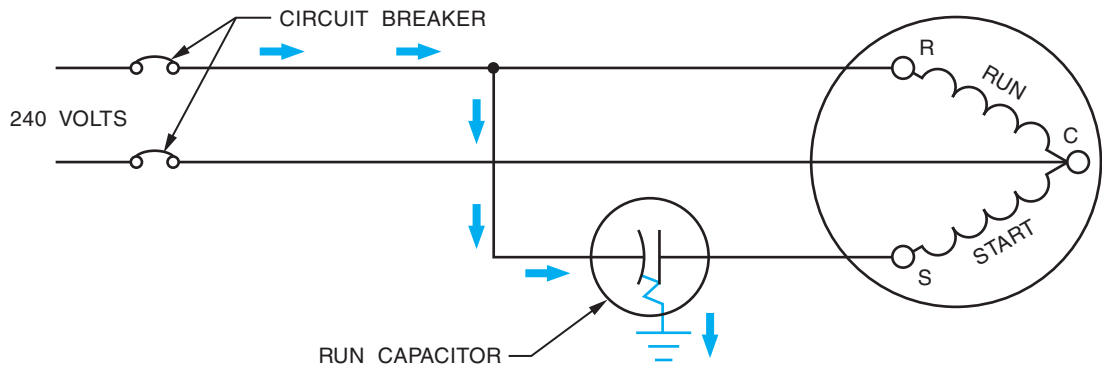
► **Figure 11-27**
The markings indicate the terminal that connects to the plate located closest to the case of the capacitor.
(Source: Delmar/Cengage Learning)

of oil-filled capacitors will identify one terminal with an arrow, a painted dot, or by stamping a dash in the capacitor can, Figure 11-27. This identified terminal 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 nearer to the outside case that becomes grounded. For this reason, it is desirable to connect the identified capacitor terminal to the line side instead of to the motor start winding.

In Figure 11-28, the run capacitor has been connected in such a manner that the identified terminal is connected to the start winding of a compressor



► **Figure 11-28**
Identified capacitor terminal connected to motor start winding. (Source: Delmar/Cengage Learning)



► **Figure 11-29**
Identified capacitor terminal connected to the line. (Source: Delmar/Cengage Learning)

motor. If the capacitor shorts to ground, a current path would 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 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 11-29, the run capacitor has been connected in such a manner that the identified terminal is connected to the line side. If the capacitor shorts to ground, a current path would exist 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 allows the fuse or circuit breaker to open almost immediately.

SUMMARY

- Split-phase motors fall into three general classifications:
 - A. The resistance-start induction run.
 - B. The capacitor-start induction run.
 - C. The permanent-split capacitor motor.
- The voltages of a two-phase system are 90° out of phase with each other.
- Split-phase motors receive their name from the fact that they split the current flow through two windings to produce an out of phase condition that produces a rotating magnetic field.
- The resistance-start induction run and capacitor-start induction run motors disconnect their start winding when they have accelerated to about 75% of their rated speed.
- Split-phase motors that are not hermetically sealed generally use a centrifugal switch to disconnect the start winding when the motor has reached about 75% of its rated speed.
- The direction of rotation of a split-phase motor can be reversed by changing the connections of the run winding or the start winding, but not both.
- Dual voltage split-phase motors can be connected to operate on 120 or 240 volts.

- ④ The capacitor-start induction run motor develops a higher starting torque than the resistance-start induction run motor.
- ④ The capacitor-start motor develops a higher starting torque by using the capacitor to produce a 90° phase shift between the current flow in the run winding and the current flow in the start winding.
- ④ Maximum starting torque for the split-phase motor is produced when the run winding current and start winding current are 90° out of phase with each other.
- ④ Permanent-split capacitor motors do not disconnect the start winding when the motor is in operation.
- ④ Some permanent-split capacitor motors use an extra capacitor during the starting period.
- ④ The identifying mark on an oil-filled capacitor should be connected to the line side of the circuit.

KEY TERMS

capacitor-start
induction-run motor
capacitor-start
capacitor-run motor
centrifugal switch

permanent-split
capacitor motor (PSC)
resistance-start
induction-run motor
rotating field speed

run winding
split-phase motor
start winding
torque
two-phase power

REVIEW QUESTIONS

1. What is a split-phase motor?
2. What are the three basic types of split-phase motors?
3. Explain the difference in construction of run windings and start windings.
4. How many degrees out of phase should the current in the start winding be with the current in the run winding to develop maximum starting torque?
5. What type of capacitor is generally used with a capacitor start induction-run motor?
6. Can the micro-farad value of this capacitor be increased to improve starting torque?
7. What type of capacitor is used with a permanent-split capacitor motor?
8. Does the capacitor of a capacitor start induction-run motor help correct power factor?
9. If necessary, can an AC electrolytic capacitor of higher voltage rating be used as the starting capacitor?
10. What is a centrifugal switch used for?

UNIT 12

The Shaded-Pole Induction Motor

OBJECTIVES

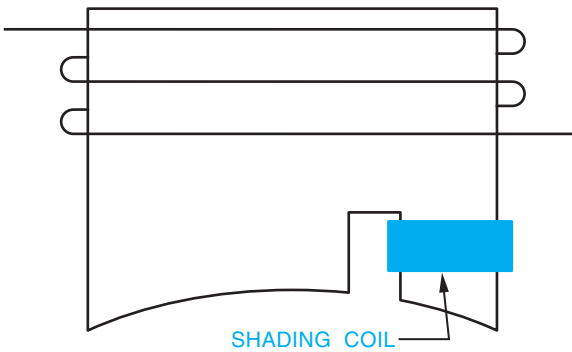
After studying this unit the student should be able to:

- » Discuss the operation of a shaded-pole induction motor
- » Define a shading coil
- » List common uses for the shaded-pole induction motor

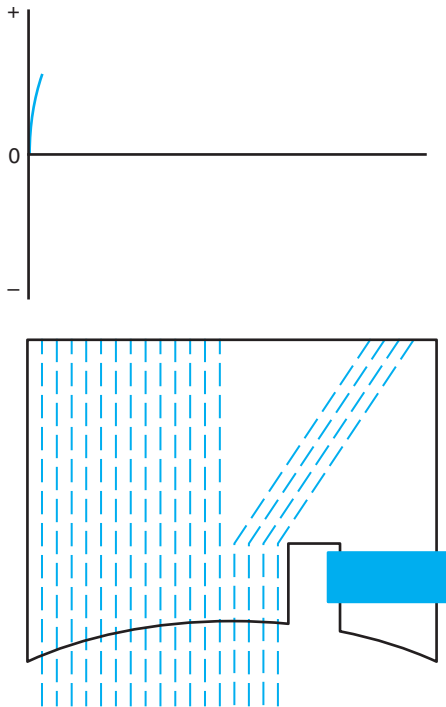
The **shaded-pole induction motor** is another type of AC single-phase motor used to a large extent in the air conditioning field. This motor is popular because of its simplicity and long life. The shaded-pole motor contains no start winding or centrifugal switch. The rotating magnetic field is created by a **shading coil** wound around one side of each pole piece.

THE SHADING COIL

The shading coil is wound around one end of the pole piece, Figure 12–1. The shading coil is actually a large loop of copper wire or a copper band. Both ends of the loop are connected together to form a complete circuit. The shading coil acts in the same manner as a transformer with a shorted secondary winding. When the voltage of the AC



► **Figure 12-1**
A shaded pole. (Source: Delmar/Cengage Learning)



► **Figure 12-2**
The shading coil opposes a change of magnetic flux as voltage increases. (Source: Delmar/Cengage Learning)

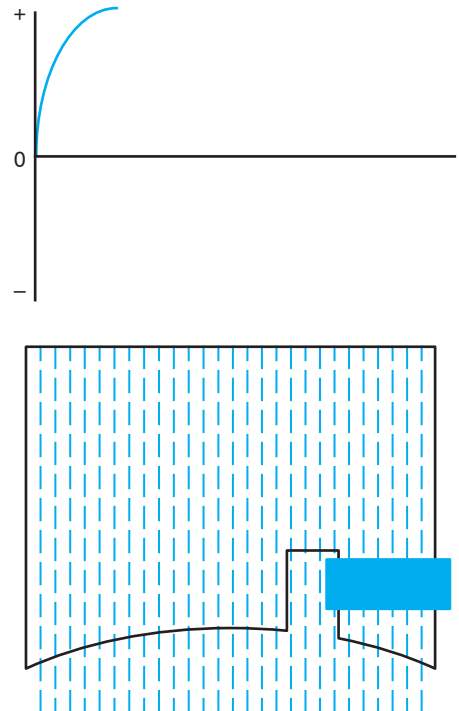
waveform increases from zero toward its positive peak, a magnetic field is created in the pole piece. As magnetic lines of flux cut through the shading coil, a voltage is induced in the coil. Because the coil is a low-resistance short circuit, a large amount of current flows in the loop. This current flow causes an **opposition** to the change of **magnetic flux**, Figure 12-2. As long as voltage is induced into

the shading coil, there will be an opposition to the change of magnetic flux.

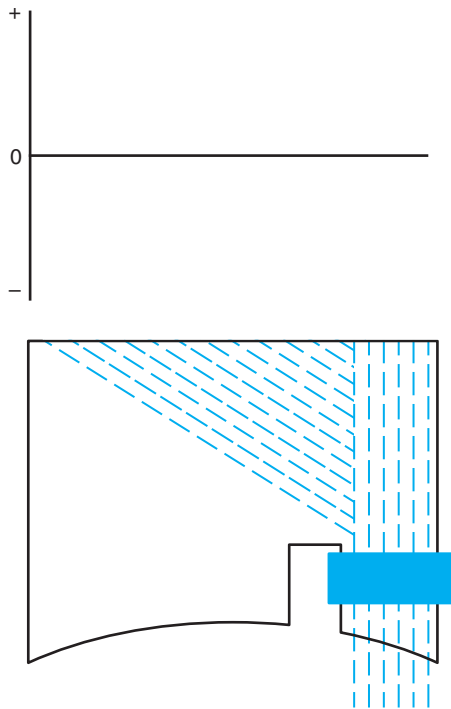
When the AC voltage reaches its peak value, it is no longer changing and there is no voltage being induced into the shaded coil. Since there is no current flow in the shading coil, there is no opposition to the magnetic flux. The magnetic flux of the pole piece is now uniform across the pole face, Figure 12-3.

When the AC voltage begins to decrease from its peak value back toward zero, the magnetic field of the pole piece begins to collapse. A current is again induced into the shading coil. The induced current opposes the change of magnetic flux, Figure 12-4. This causes the magnetic flux to be concentrated in the shaded section of the pole piece.

When the AC voltage 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



► **Figure 12-3**
There is no opposition to magnetic flux when the voltage is not changing. (Source: Delmar/Cengage Learning)



► **Figure 12-4**
The shading coil opposes a change of flux when the voltage decreases. (Source: Delmar/Cengage Learning)

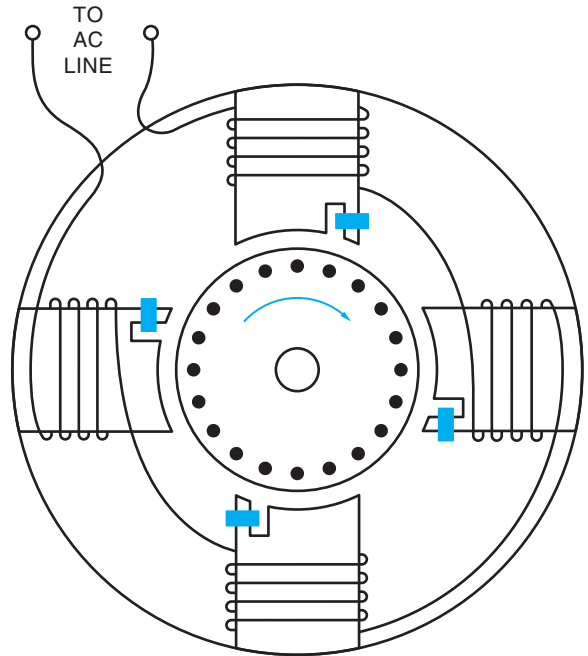
seen in rapid order, it could be seen that the magnetic field rotates across the face of the pole piece.

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 12-5 shows a drawing of a four-pole motor.

REVERSING DIRECTION OF ROTATION

The direction the magnetic field moves across the face of the pole piece is determined by the side of the pole piece that has the shaded coil. The rotor will turn in the direction of the shaded pole as shown by

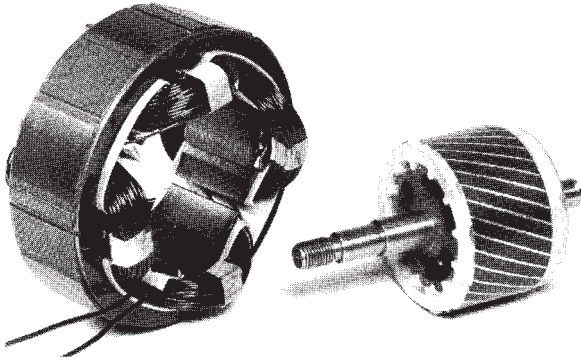


► **Figure 12-5**
A four-pole shaded-pole induction motor. (Source: Delmar/Cengage Learning)

the arrow in Figure 12-5. If the direction of rotation 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.

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 current and stator current. The shaded-pole motor has a low starting torque and running torque. This motor is generally used in applications that do not require a large amount of starting torque, such as fans and blowers. Figure 12-6 shows a photograph of a shaded-pole induction motor.



► **Figure 12-6**
Stator winding and rotor of a shaded-pole induction motor. (Courtesy of Westinghouse Electric Corp.).

SUMMARY

- The shaded-pole induction motor is popular because of its simplicity and long life.
- Shaded-pole induction motors do not contain a start winding or centrifugal switch.
- Shaded-pole induction motors operate on the principle of a rotating magnetic field.
- A shading coil or loop is used to produce an out of phase flux across the face of the pole piece, thus producing a rotating magnetic field.
- The speed of a shaded-pole induction motor is determined by the number of stator poles and the frequency of the applied voltage.
- Shaded-pole induction motors are generally considered to be nonreversible.

KEY TERMS

magnetic flux
opposition

shaded-pole induction motor

shading coil

REVIEW QUESTIONS

1. What is a shading coil?
2. What determines the synchronous speed of a shaded-pole motor?
3. In general, how is the direction of a shaded-pole induction motor reversed?
4. What type of rotor does the shaded-pole motor contain?
5. Name two advantages of the shaded-pole motor over the split-phase induction motor.

UNIT 13



Multispeed Motors

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation of a consequent pole motor
- List the factors that determine the synchronous field speed of an AC motor
- Discuss the operation of multispeed fan motors
- Connect a multispeed fan motor for operation at different speeds

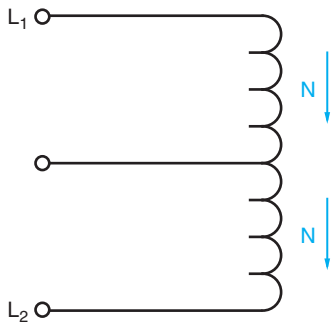
Multispeed AC motors have been used to a great extent in the air conditioning field for many years. There are two basic types of multispeed motors used. One type is known as the **consequent pole motor**. The other type is generally a permanent-split capacitor motor.

THE CONSEQUENT POLE MOTOR

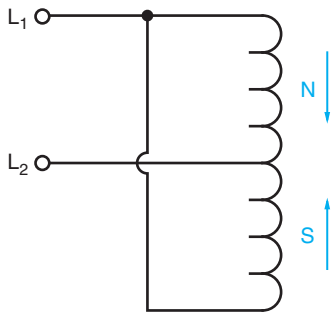
The speed of the rotating magnetic field of an AC induction motor can be changed in either of two ways. These are:

1. Change the frequency of the AC voltage.
2. Change the number of stator poles.

The consequent pole motor changes the motor speed by changing the number of its stator poles. The run winding in Figure 13–1 has been **tapped**



► **Figure 13-1**
Center-tapped run winding. (Source: Delmar/Cengage Learning)



► **Figure 13-2**
Two magnetic poles are produced. (Source: Delmar/Cengage Learning)

in the center. If the AC line is connected to each end of the winding as shown, current flows through the winding in only one direction. Therefore, only one magnetic **polarity** is produced in the winding. If the winding is connected as shown in Figure 13-2, current flows in opposite directions in each half of the winding. Because current flows through each half of the winding in opposite directions, the polarity of the magnetic field is different in each half of the winding. The run winding now has two polarities instead of one. There are now two magnetic poles instead of one. If the windings of a two-pole motor were to be tapped in this manner, the motor could become a four-pole motor. The synchronous speed of a two-pole motor is 3,600 RPM, and the synchronous speed of a four-pole motor is 1,800 RPM.

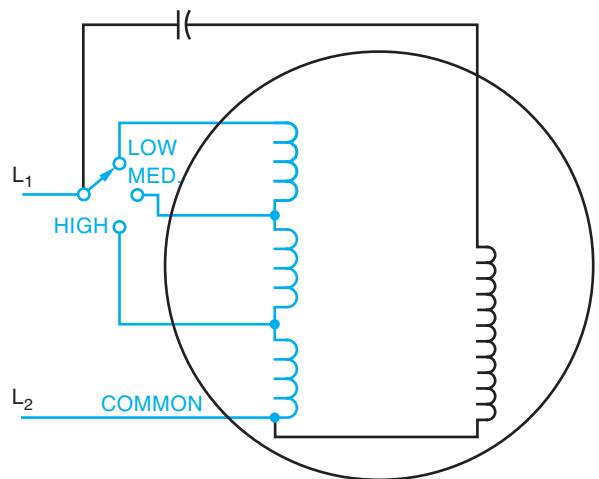
The consequent pole motor has the disadvantage of having a wide variation in speed. When the speed is changed, it changes from a synchronous speed of 3,600 RPM to 1,800 RPM. The speed cannot be

changed by a small amount. This wide variation in speed makes the consequent pole motor unsuitable for some loads, such as fans and blowers.

The consequent pole motor, however, does have some advantages over the other type of multispeed motor. When the speed of the consequent pole motor is reduced, its torque increases. For this reason, the consequent pole motor can be used to operate heavy loads, such as **two-speed compressors**.

MULTISPEED FAN MOTORS

Multispeed fan motors have been used in the air conditioning industry for many years. These motors are generally wound for two to five steps of speed, and are used to operate fans and squirrel-cage blowers. A schematic drawing of a three-speed motor is shown in Figure 13-3. 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 lead is connected to an external oil-filled run capacitor. This motor obtains a change in speed by inserting inductance in series with the run winding. The actual run winding for this motor is between the terminals marked High and C. The windings shown between High and Medium are 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



► **Figure 13-3**
Three-speed fan motor. (Source: Delmar/Cengage Learning)

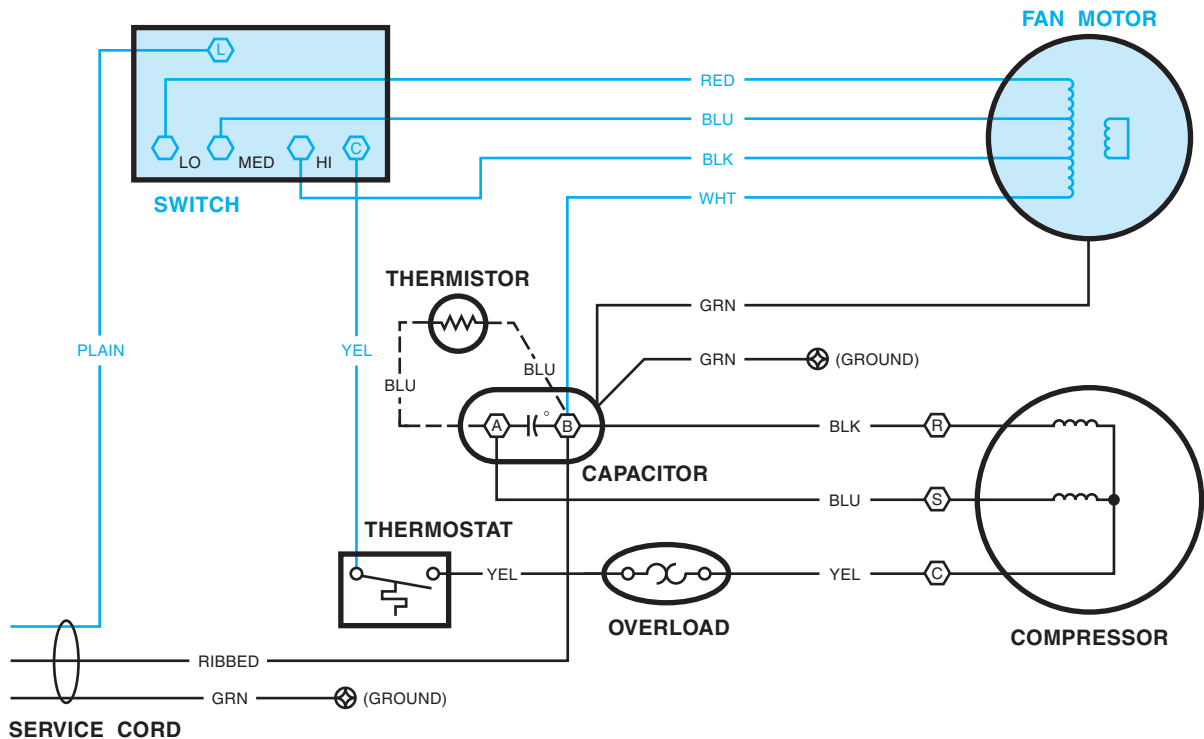
of current flow through the run winding. When the current of the run winding is reduced, the strength of the magnetic field of the run winding is reduced and the motor produces less torque. This causes the motor speed to decrease.

If the rotary switch is changed to the low position, more inductance is connected in series with the run winding. This causes less current to flow through the 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 1,625, 1,500, and 1,350 RPM. Notice that this motor does not have the wide range between speeds as the consequent pole motor does. Most induction motors would overheat and damage the

motor windings if the speed were to be reduced to this extent. This motor, however, has much higher impedance in its windings than most motors. The run windings of most split-phase motors has a wire resistance of 1 to 4 ohms. This motor will generally have a resistance of 10 to 15 ohms in its run winding. It is the high impedance of the windings that permits the motor to be operated in this manner without damage.

Because 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. The schematic in Figure 13-4 shows a multispeed fan motor and switch.



SWITCH POSITION	CONTACTS MADE
LO	L to C, L to LO
MED	L to C, L to MED
HI	L to C, L to HI
OFF	NONE

► **Figure 13-4**
A multispeed fan motor and switch. (Source: Delmar/Cengage Learning)

VARIABLE FREQUENCY DRIVES

One of the factors that determines the speed of the rotating magnetic field of an AC induction motor is the frequency of the applied voltage. If the frequency is changed, the speed of the rotating magnetic field changes also. A four-pole stator will have a synchronous speed (speed of the rotating magnetic field) of 1,800 RPM when connected to a 60-Hz line. If the frequency is lowered to 30 Hz, the synchronous speed decreases to 900 RPM.

When the frequency is lowered, care must be taken not to damage the stator windings. The current flow through the winding is limited to a great extent by inductive reactance. When the frequency is lowered, inductive reactance is lowered also ($X_L = 2\pi FL$). For this reason, **variable frequency** drives must employ some method of lowering the applied voltage to the stator as frequency is reduced.

In the air conditioning field, variable frequency drive is often used to control the speed of blower motors. This method of controlling air flow can be more efficient than inserting dampers into the duct system. Variable frequency drives are very popular in zone controlled systems.

Most variable frequency drives operate by first changing the AC voltage into DC and then changing it back to AC at the desired frequency. A variable frequency drive is shown in Figure 13–5. There are several methods used to change the DC voltage back into AC. The method employed is generally determined by the manufacturer, age of the equipment, and the size motor the drive must control. Variable frequency drives intended to control the speed of motors up to 500 horsepower generally use transistors. In the circuit shown in Figure 13–6, a three-phase bridge changes the three-phase alternating-current into direct current. The bridge rectifier uses **SCRs (silicon controlled rectifiers)** instead of diodes. The SCRs permit the output voltage of the rectifier to be controlled. As the frequency decreases, the SCRs fire later in the cycle and lower the output voltage to the transistors. A choke coil and capacitor bank are used to filter the output voltage before transistors Q1 through Q6 change the DC voltage back into AC. An electronic control unit is connected to the bases of transistor Q1 through Q6. The control

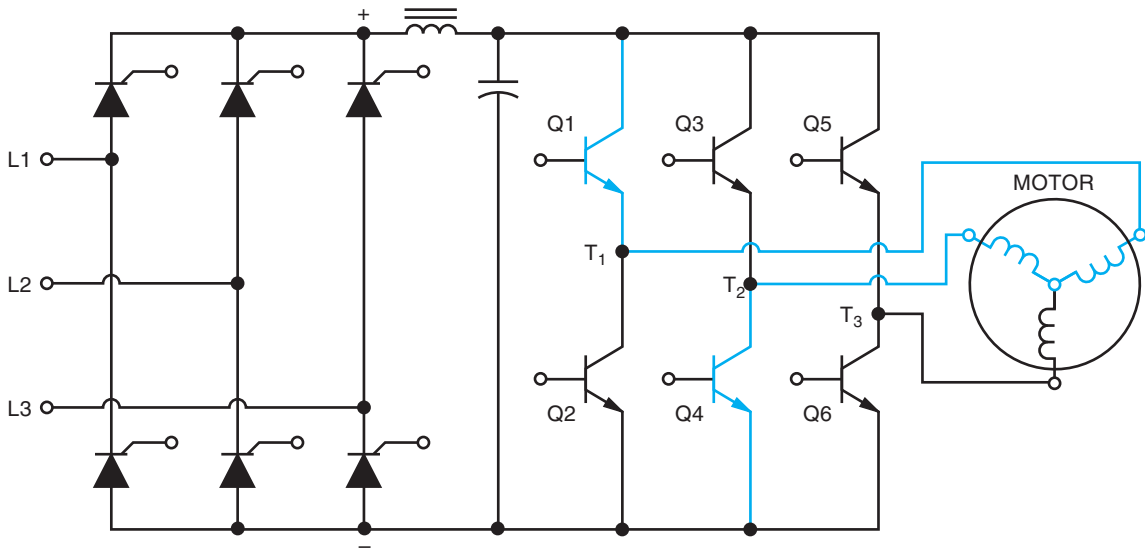


► **Figure 13–5**
Variable frequency drive. (Courtesy of Toshiba Corp.).

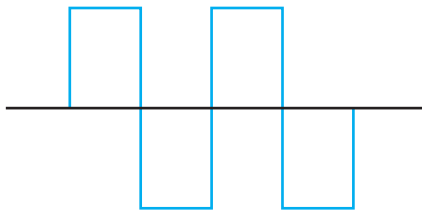
unit converts the DC voltage back into three-phase alternating current by turning transistors on or off at the proper time and in the proper sequence. Assume, for example, that transistors Q1 and Q4 are switched on at the same time. This permits stator winding T_1 to be connected to a positive voltage and T_2 to be connected to a negative voltage. Current can flow through Q4 to T_2 , through the motor stator winding and through T_1 to Q1.

Now assume that transistors Q1 and Q4 are switched off and transistors Q3 and Q6 are switched on. Current will now flow through Q6 to stator winding T_3 , through the motor to T_2 , and through Q3 to the positive of the power supply.

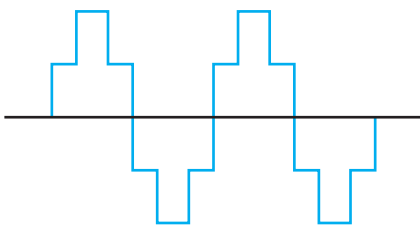
Because the transistors are turned completely on or completely off, the waveform produced is a square wave instead of a sine wave, Figure 13–7. Induction motors will operate on a square wave



► **Figure 13-6**
Variable frequency drive using bipolar transistor to change the direct current back into alternating current.
(Source: Delmar/Cengage Learning)



► **Figure 13-7**
Square wave. (Source: Delmar/Cengage Learning)



► **Figure 13-8**
Stepped wave. (Source: Delmar/Cengage Learning)

without much of a problem. Some manufacturers design units that will produce a stepped waveform as shown in Figure 13-8. The stepped waveform is used because it closely approximates a sine wave.

Some Related Problems

The circuit illustrated in Figure 13-6 employs the use of SCRs in the power supply and junction transistors in the output stage. SCR power supplies control the output voltage by chopping the incoming waveform. This can cause **harmonics** on the line that cause overheating of transformers and motors, and can cause fuses to blow and circuit breakers to trip. When bipolar junction transistors are employed as switches, they are generally driven into saturation by supplying them with an excessive amount of base-emitter current. Saturating the transistor causes the collector-emitter voltage to drop to between 0.04 and 0.03 volts. This small voltage drop allows the transistor to control large amounts of current without being destroyed. When a transistor is driven into saturation, however, it cannot recover or turn off as quickly as normal. This greatly limits the frequency response of the transistor.

IGBTs

Many transistor-controlled variable drives now employ a special type of transistor called an **insulated gate bipolar transistor (IGBT)**. IGBTs

have an insulated gate very similar to some types of field effect transistors (FETs). Because the gate is insulated, it has a very high impedance. The IGBT is a voltage controlled device, not a current controlled device. This gives it the ability to turn off very quickly. IGBTs can be driven into saturation to provide a very low voltage drop between emitter and collector, but they do not suffer from the slow recovery time of common junction transistors.

Drives using IGBTs generally use diodes to rectify the AC voltage into DC, not SCR, Figure 13–9. The three-phase rectifier supplies a constant DC voltage to the transistors. The output voltage to the motor is controlled by **pulse width modulation (PWM)**. PWM is accomplished by turning the transistor on and off several times during each half cycle, Figure 13–10. The output voltage is an average of the peak or maximum voltage and the amount of time the transistor is turned on or off. Assume that 480 volts 3 phase AC is rectified to DC and filtered. The DC voltage applied to the IGBTs is approximately 630 volts. The output voltage to the motor is controlled by the switching of the transistors. Assume that the transistor is on for 10 microseconds and off for 20 microseconds. In this example

the transistor is on for one-third of the time and off for two-thirds of the time. The voltage applied to the motor would be 210 volts ($630/3$).

Advantages and Disadvantages of IGBT Drives

A great advantage of drives using IGBTs is the fact that SCRs are generally not used in the power supply and this greatly reduces problems with line harmonics. The greatest disadvantage is that the fast switching rate of the transistors can cause voltage spikes in the range of 1,600 volts to be applied to the motor. These voltage spikes can destroy some motors. Line length from the drive to the motor is of great concern with drives using IGBTs. The shorter the line length the better.

Inverter Rated Motors

Because of the problem of excessive voltage spikes caused by IGBT drives, some manufacturers produce a motor that is “inverter rated.” These motors are specifically designed to be operated by variable

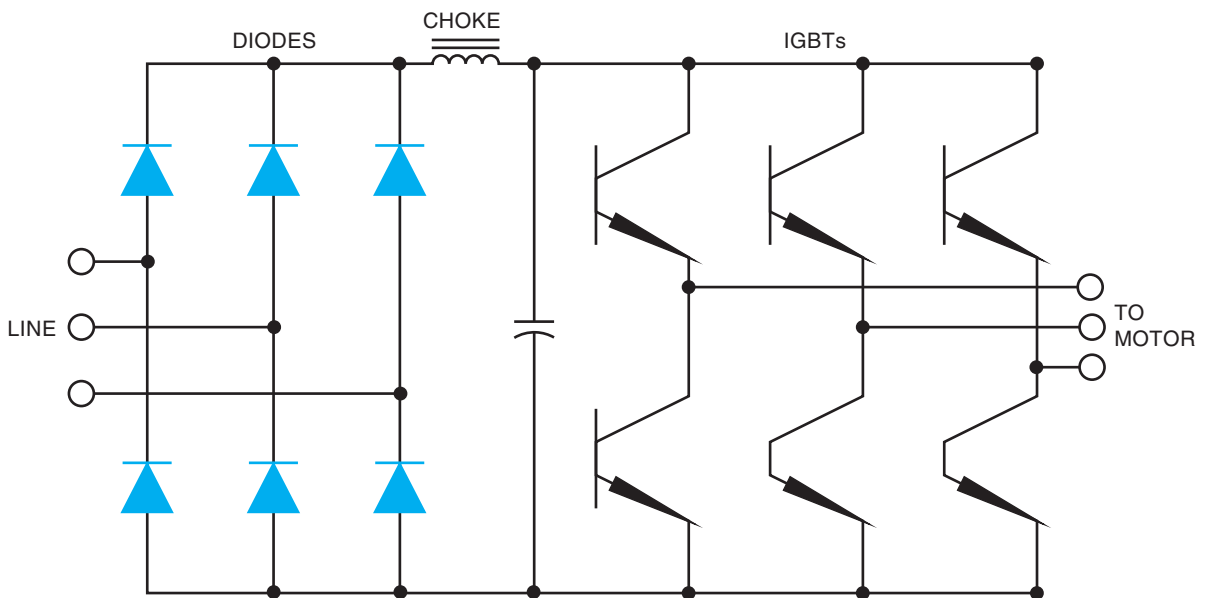
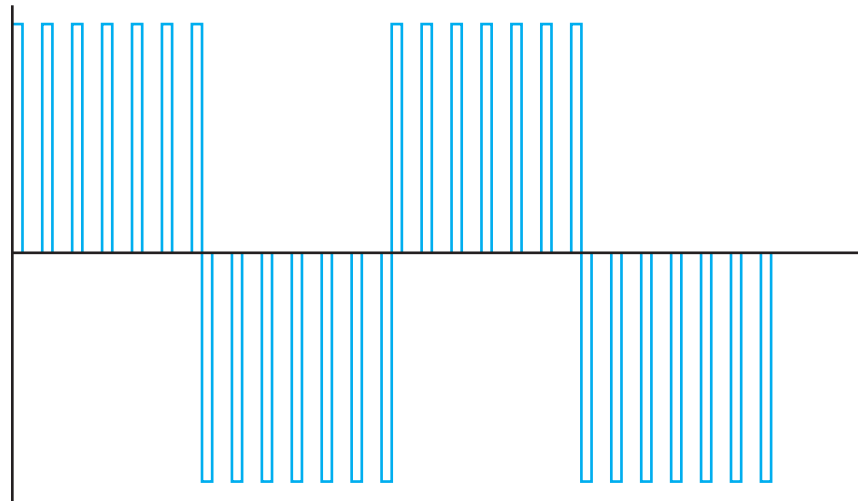


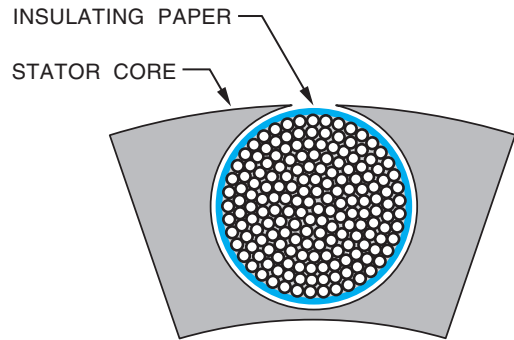
Figure 13–9 Variable frequency drives using IGBTs generally use diodes in the rectifier instead of SCRs. (Source: Delmar/Cengage Learning)



► **Figure 13-10**
Pulse width modulation is accomplished by turning the voltage on and off several times during each half cycle.
(Source: Delmar/Cengage Learning)

frequency drives. They differ from standard motors in several ways:

1. Many inverter rated motors contain a separate blow to provide continuous cooling for the motor regardless of the speed. Many motors use a fan connected to the motor shaft to help draw air through the motor. When the motor speed is reduced, the fan cannot maintain sufficient air flow to cool the motor.
2. Inverter rated motors generally have insulating paper between the windings and the stator core, Figure 13-11. The high voltage spikes produce high currents that produce a high magnetic field. This increased magnetic field causes the motor windings to move. This movement can eventually cause the insulation to wear off the wire and produce a grounded motor winding.
3. Inverter rated motors generally have phase paper added to the terminal leads. Phase paper is insulating paper added to the terminal leads that exit the motor. The high voltage spikes affect the beginning lead of a coil much more than the wire inside the coil. The coil is an inductor that naturally opposes a change of current. Most of the insulation stress caused by high voltage spikes occurs at the beginning of a winding.
4. The magnet wire used in the construction of the motor windings has a higher rated insulation than other motors.



► **Figure 13-11**
Insulating paper is between the windings and the stator frame. (Source: Delmar/Cengage Learning)

5. The case size is larger than most three phase motors. The case size is larger because of the added insulating paper between the windings and the stator core. Also, a larger case size helps cool the motor by providing a larger surface area for the dissipation of heat.

Variable Frequency Drives Using SCRs and GTOs

Variable frequency drives intended to control motors over 500 horsepower generally use SCRs or GTOs (gate turn off device). GTOs are similar to SCRs except that conduction through the GTO can be stopped by applying a negative voltage, negative with respect to the cathode, to the gate. SCRs and

GTOs are thyristors and have the ability to handle a greater amount of current than transistors. An example of a single-phase circuit used to convert DC voltage to AC voltage with SCRs is shown in Figure 13–12. In this circuit, the SCRs are connected to a control unit which controls the sequence and rate at which the SCRs are gated on. The circuit is constructed so that SCRs A and A' are gated on at the same time and SCRs B and B' are gated on at the same time. Inductors L_1 and L_2 are used for filtering and wave shaping. Diodes D1 through D4 are clamping diodes and are used to prevent the output voltage from becoming excessive. Capacitor C_1 is used to turn one set of SCRs off when the other set is gated on. This capacitor must be a true AC capacitor because it will be charged to the alternate polarity each half cycle. In a converter intended to handle large amounts of power, capacitor C_1 will be

a bank of capacitors. To understand the operation of the circuit, assume that SCRs A and A' are gated on at the same time. Current will flow through the circuit as shown in Figure 13–13. Notice the direction of current flow through the load, and also that capacitor C_1 has been charged to the polarity shown. When an SCR is gated on, it can only be turned off by permitting the current flow through the anode-cathode section to drop below a certain level called the holding current level. As long as the current continues to flow through the anode-cathode the SCR will not turn off.

Now assume that SCRs B and B' are turned on. Because SCRs A and A' are still turned on, two current paths now exist through the circuit. The positive charge on capacitor C_1 , however, causes the negative electrons to see an easier path. The current will rush to charge the capacitor to the opposite

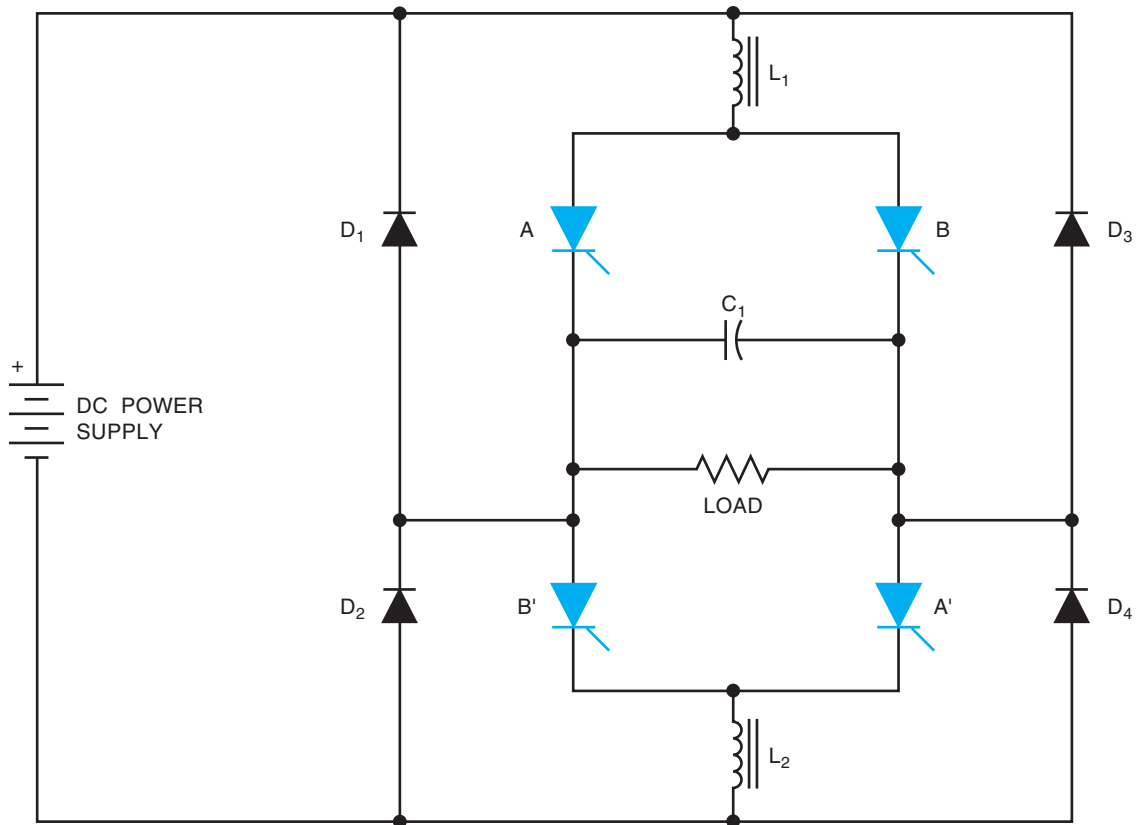
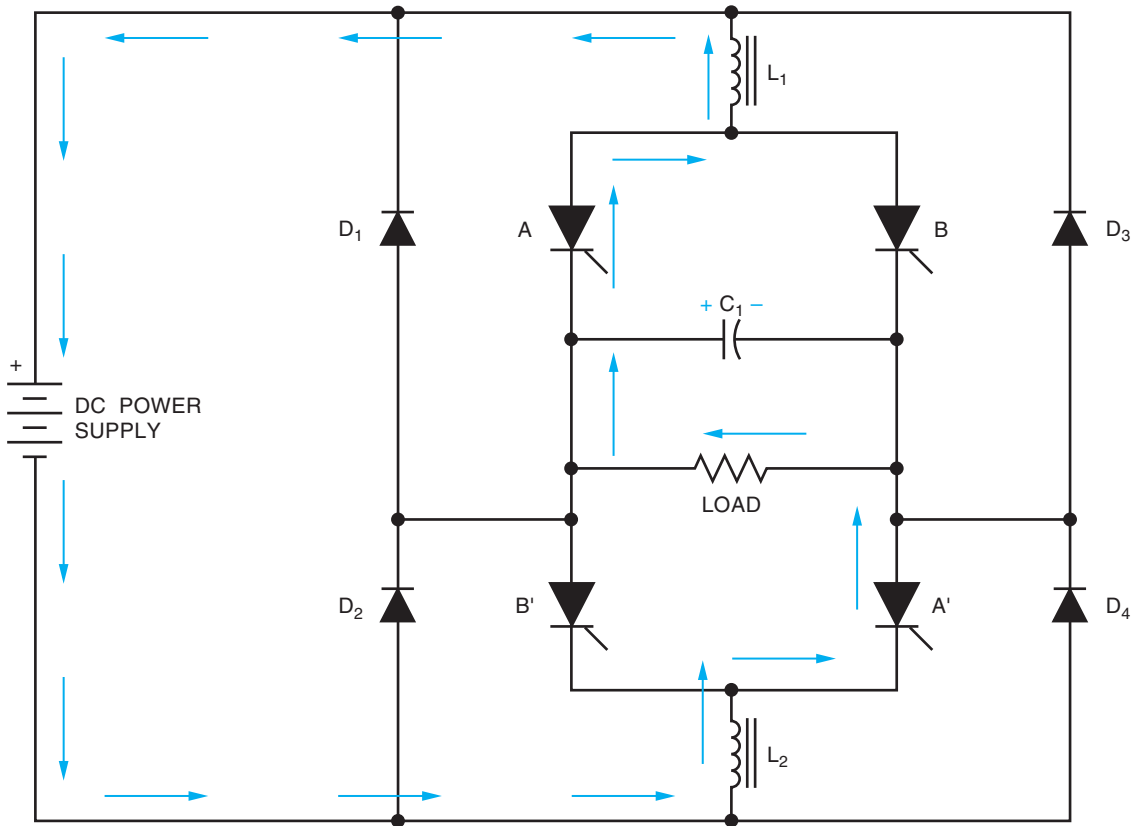


Figure 13–12
Changing DC to AC using SCRs. (Source: Delmar/Cengage Learning)



► **Figure 13-13**
Current flows through SCRs A and A'. (Source: Delmar/Cengage Learning)

polarity, stopping the current flowing through SCRs A and A' permitting them to turn off. The current now flows through SCRs B and B' and charges the capacitor to the opposite polarity, Figure 13-14. Notice that the current now flows through the load in the opposite direction, which produces alternating current across the load.

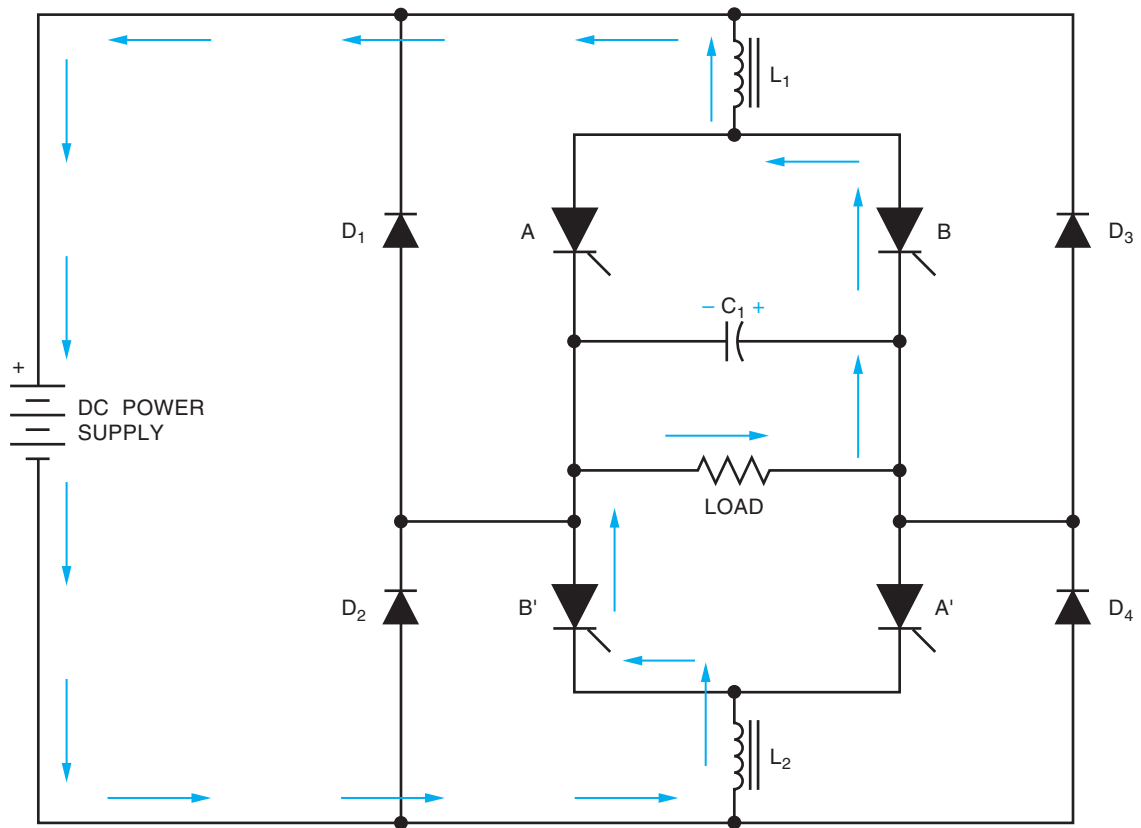
To produce the next half cycle of AC current, SCRs A and A' are gated on again. The positively charged side of the capacitor will now cause the current to stop flowing through SCRs B and B' permitting them to turn off. The current again flows through the load in the direction indicated in Figure 13-14. The frequency of the circuit is determined by the rate at which the SCRs are gated on.

FEATURES OF VARIABLE FREQUENCY CONTROL. Although the primary purpose of a variable frequency drive

is to provide speed control for an AC motor, most drives provide functions that other types of controls do not. Many variable frequency drives can provide the low speed torque characteristic that is so desirable in DC motors. It is this feature that permits AC squirrel-cage motors to replace DC motors for many applications.

Many variable frequency drives also provide current limit and automatic speed regulation for the motor. Current limit is generally accomplished by connecting current transformers to the input of the drive and sensing the increase in current as load is added. Speed regulation is accomplished by sensing the speed of the motor and feeding this information back to the drive.

Another feature of variable frequency drives is acceleration and deceleration control, sometimes



► **Figure 13-14**
Current flows through SCRs B and B'. (Source: Delmar/Cengage Learning)

called “ramping.” Ramping is used to accelerate or decelerate a motor over some period of time. Ramping permits the motor to bring the load up to speed slowly as opposed to simply connecting the motor directly to the line. Even if the speed control is set in the maximum position when the start button is pressed, ramping permits the motor to accelerate the load from zero to its maximum RPM over several seconds. This feature can be a real advantage for some types of loads, especially gear drive loads. In some units the amount of acceleration and deceleration time can be adjusted by setting potentiometers on the main control board. Other units are completely digitally controlled and the acceleration and deceleration times are programmed into the computer memory.

Some other adjustments that can usually be set by changing potentiometers or programming the unit are as follows:

Current Limit: These controls set the maximum amount of current the drive is permitted to deliver to the motor.

Volts per Hertz: This sets the ratio by which the voltage increases as frequency increases or decreases as frequency decreases.

Maximum Hertz: These controls set the maximum speed of the motor.

Minimum Hertz: This sets the minimum speed the motor is permitted to run.

SUMMARY

- ▶ Consequent pole motors change speed by changing the number of stator poles.
- ▶ The disadvantage of consequent pole motors is that they have a wide range between speeds.
- ▶ The advantage of the consequent pole motor is that it maintains a high torque.
- ▶ Consequent pole motors are generally used to operate two-speed compressors because of their ability to maintain high torque.
- ▶ Multispeed fan motors insert inductance in series with the main run winding to produce a change of speed.
- ▶ The run windings of multispeed fan motors have a high resistance so they will not overheat when the motor slows down.
- ▶ Multispeed fan motors cannot be used to operate high torque loads.
- ▶ Variable frequency drives change the speed of the motor by changing the frequency of the applied voltage.
- ▶ The synchronous speed of an induction motor is the speed of the rotating magnetic field.
- ▶ Synchronous speed is determined by two factors: number of stator poles per phase, and frequency of the applied voltage.
- ▶ When the frequency to the motor is reduced, the voltage must be reduced also.
- ▶ Variable frequency drives up to 500 horsepower generally use transistors to change the DC voltage back into AC voltage.
- ▶ Variable frequency drives above 500 horsepower generally use SCRs or GTOs to change the DC voltage back into AC voltage.
- ▶ Insulated gate bipolar transistors are used in many variable frequency drives because they can be switched on or off at a faster rate.
- ▶ Units employing IGBTs can produce voltage spikes on the motor as high as 1,600 volts.
- ▶ Inverter rated motors are designed to operate with variable frequency drives.
- ▶ Some variable frequency drives use potentiometers to change settings, and others are digital and must have the setting programmed into the drive.

KEY TERMS

consequent pole motor
harmonics
insulated gate bipolar
transistors (IGBTs)

multispeed AC motors
polarity
pulse width
modulation (PWM)

silicon controlled
rectifiers (SCRs)
tapped
two-speed compressors
variable frequency

REVIEW QUESTIONS

1. Name two ways of changing the speed of a rotating magnetic field.
2. How does the consequent pole motor change speed?
3. Name a disadvantage of the consequent pole motor.
4. Name an advantage of a consequent pole motor.
5. How many steps of speed are common to a multispeed fan motor?
6. Refer to Figure 13–3. Explain what would happen to motor operation if the winding between low and medium should become open.
7. What is an advantage of the multispeed fan motor over the consequent pole motor?
8. What is a disadvantage of the multispeed fan motor when compared with the consequent pole motor?
9. How much wire resistance is common for the run winding of most split-phase motors?
10. How much wire resistance is common for the multispeed fan motor?
11. What is synchronous speed?
12. What is the disadvantage of a variable frequency drive unit that uses SCRs to convert the AC voltage into DC voltage?
13. What is the disadvantage of driving a common bipolar junction transistor into saturation?
14. What is the main advantage of the insulated gate bipolar transistor over the common bipolar junction transistor?
15. What is an inverter rated motor?

TROUBLESHOOTING QUESTIONS

Refer to the schematic shown in Figure 13–4 to answer the following questions.

1. If the switch is set in the HI position, the thermostat will control the operation of:
 - A. The compressor only.
 - B. The fan motor only.
 - C. The speed of the fan motor.
 - D. Both the compressor and the speed of the fan motor.
2. When the switch is set in the HI position, both the fan motor and compressor operate. If the switch is changed to the MED or LOW position, the compressor continues to operate, but the fan motor stops. Which of the following could cause this problem?
 - A. The fan motor start winding is open.
 - B. The section of run winding between the red and blue wires is open in the fan motor.
 - C. The section of run winding between the blue and black wires is open in the fan motor.
 - D. The section of run winding between the black and white wires is open in the fan motor.

3. The fan motor will operate in any of its three speeds, but the compressor motor will not start. Which of the following could cause this problem?
 - A. The switch is not making connection between L and C.
 - B. The switch is not making connection between L and LO.
 - C. The switch is not making connection between L and MED.
 - D. The switch is not making connection between L and HI.
4. If it is assumed that this unit operates on 120 volts AC, how is the neutral conductor identified on the schematic shown in Figure 13–4?
 - A. The wire color is green.
 - B. The wire color is white.
 - C. The conductor is ribbed.
 - D. The conductor is plain.
5. If the unit is in operation and the overload protector should open:
 - A. Both the fan motor and compressor will stop operating.
 - B. Only the compressor will stop operating.
 - C. Only the fan motor will stop operating.
 - D. Both the fan motor and compressor will continue to operate.

UNIT 14

Three-Phase Motor Principles

OBJECTIVES

After studying this unit the student should be able to:

- List the three major types of three-phase motors
- Discuss the operating principle of a three-phase motor
- List the factors that determine synchronous speed
- Discuss the operation of dual-voltage motors
- Connect dual-voltage three-phase motors for operation on low voltage or high voltage

There are three basic types of **three-phase motors**. These are:

1. The squirrel-cage induction motor.
2. The wound rotor induction motor.
3. The synchronous motor.

The type of three-phase motor is determined by the rotor or rotating member. The stator windings for any of these motors is the same. In this unit, the basic principles of operation for three-phase motors will be discussed.

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. These are:

1. The voltages of a three-phase system are 120° out of phase with each other.

2. The three voltages change polarity at regular intervals.
3. The arrangement of the stator windings around the inside of the motor.

Figure 14–1A shows three AC voltages 120° out of phase with each other, and the stator winding of a three-phase motor. The stator illustrates a two-pole, three-phase motor. Two-pole means that there are two poles per phase. AC motors do not generally have actual pole pieces as shown in Figure 14–1A, but they will be used here to aid in understanding how the rotating magnetic field is created in a three-phase motor. Notice that pole pieces 1A and 1B are located opposite each other. The same is true for poles 2A and 2B, and 3A and 3B. The pole pieces 1A and 1B are wound with wire that is connected to phase one of the three-phase system. Notice also that the pole pieces are wound in such a manner that they will always have opposite magnetic polarities. If pole piece 1A has a north magnetic polarity, pole piece 1B will have a south magnetic polarity at the same time.

The windings of pole pieces 2A and 2B are connected to line 2 of the three-phase system. The windings of pole pieces 3A and 3B are connected to line 3 of the three-phase system. These pole pieces are also wound in such a manner as to have the opposite polarity of magnetism.

To understand how the magnetic field rotates around the inside of the motor, refer to Figure 14–1B. Notice a line, labeled “A,” has been drawn through the three voltages of the system. This line is used to illustrate the condition of the three voltages at this point in time. The arrow drawn inside the motor indicates the greatest strength of the magnetic field at the same point in time. It is to be assumed that the arrow is pointing in the direction of the north magnetic field. Notice in Figure 14–1B, that phase 1 is at its maximum positive peak, and that phases 2 and 3 are less than maximum. The magnetic field is, therefore, strongest between pole pieces 1A and 1B.

In Figure 14–1C, line B indicates that the voltage of line 3 is zero. The voltage of line 1 is less than maximum positive; and line 2 is less than maximum negative. The magnetic field at this point is concentrated between the pole pieces of phase 1 and phase 2.

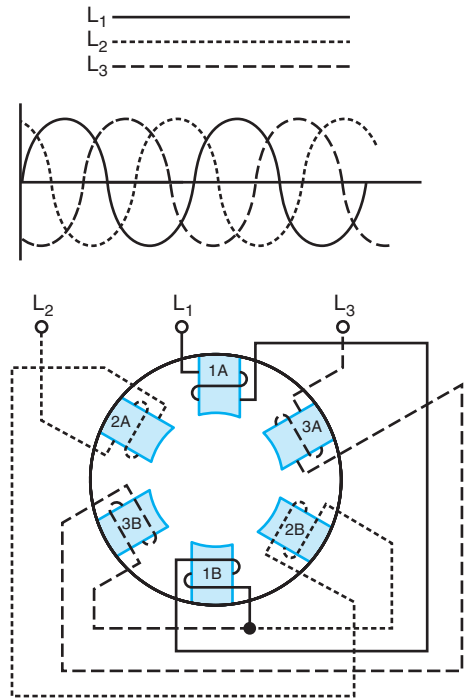


Figure 14–1A
Basic stator winding. (Source: Delmar/Cengage Learning)

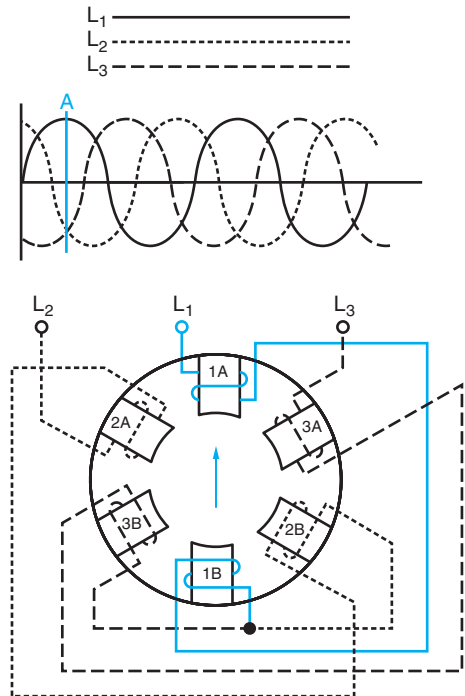
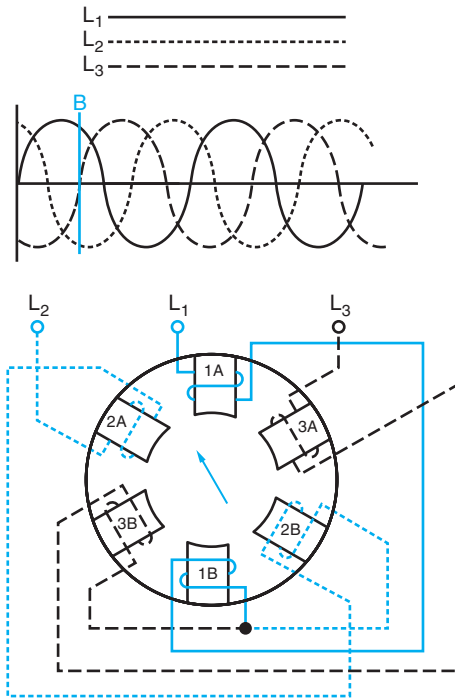


Figure 14–1B
The magnetic field is concentrated between the poles of phase 1. (Source: Delmar/Cengage Learning)



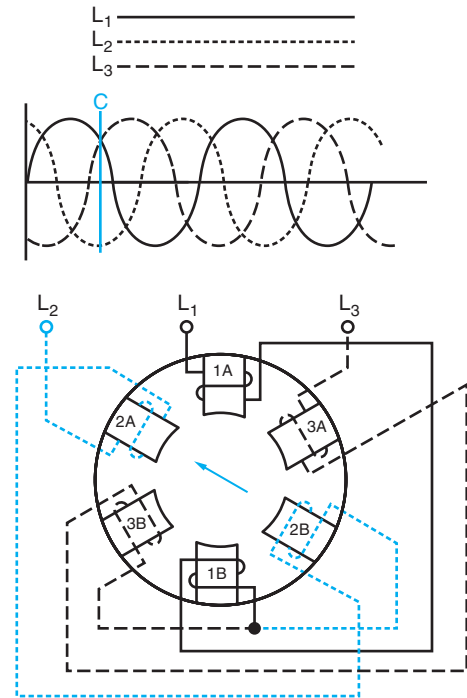
► **Figure 14-1C**
The magnetic field is concentrated between phases 1 and 2. (Source: Delmar/Cengage Learning)

In Figure 14-1D, line C indicates that line 2 is at its maximum negative peak and that lines 1 and 3 are less than maximum positive. The magnetic field at this point is concentrated between pole pieces 2A and 2B.

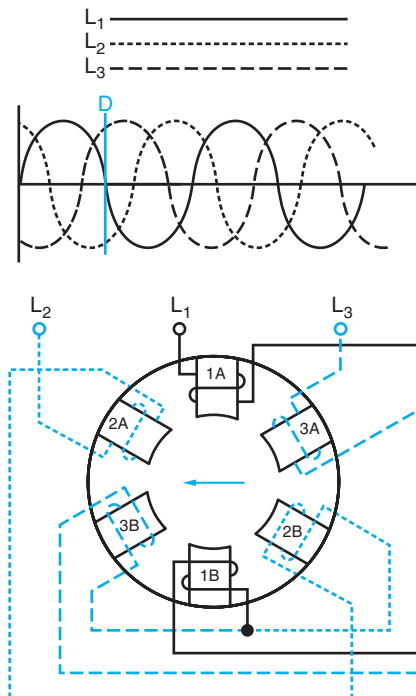
In Figure 14-1E, line D indicates that line 1 is zero. Lines 2 and 3 are less than maximum and in opposite directions. At this point, the magnetic field is concentrated between the pole pieces of phase 2 and phase 3.

In Figure 14-1F, line E indicates that phase 3 is at its maximum positive peak and lines 1 and 2 are less than maximum and in the opposite direction. The magnetic field at this point is concentrated between pole pieces 3A and 3B.

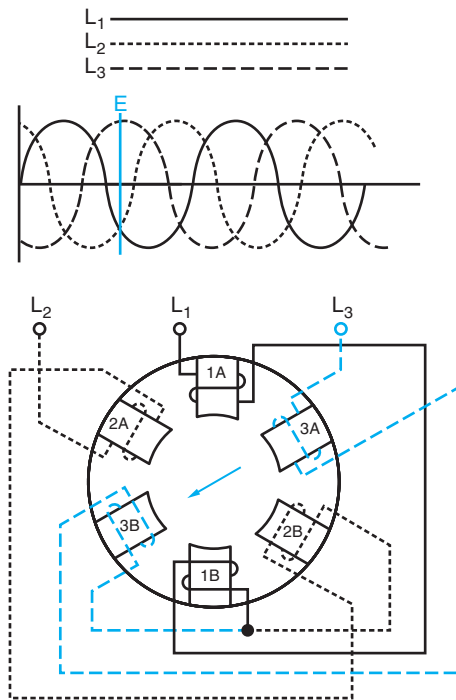
In Figure 14-1G, line F indicates that phase 2 is 0. Line 3 is less than maximum positive; and line 1 is less than maximum negative. The magnetic field at this time is concentrated between the pole pieces of phase 1 and phase 3.



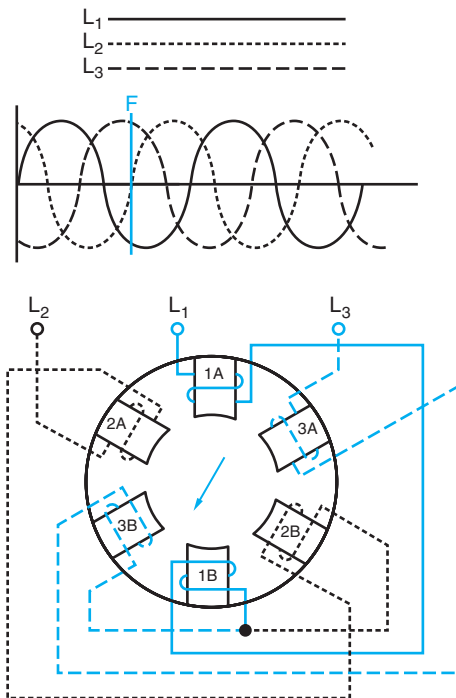
► **Figure 14-1D**
The magnetic field is concentrated between the poles of phase 1. (Source: Delmar/Cengage Learning)



► **Figure 14-1E**
The magnetic field is concentrated between phases 2 and 3. (Source: Delmar/Cengage Learning)



► **Figure 14-1F**
The magnetic field is concentrated between the poles of phase 3. (Source: Delmar/Cengage Learning)



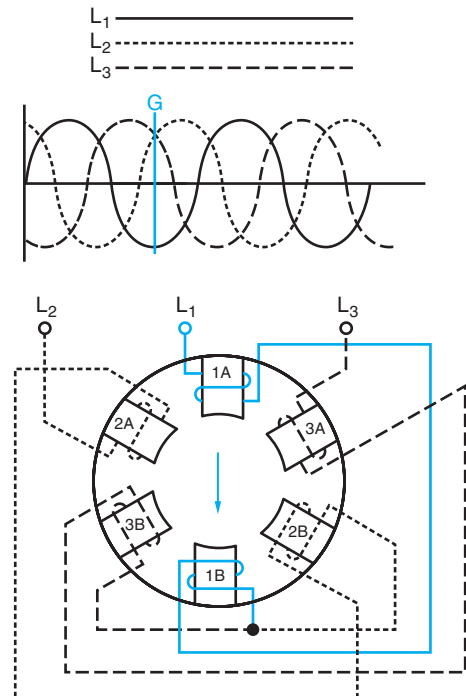
► **Figure 14-1G**
The magnetic field is concentrated between phases 1 and 3. (Source: Delmar/Cengage Learning)

In Figure 14-1H, line G indicates that phase 1 is at its maximum negative peak; and phase 2 and 3 are less than maximum and in the opposite direction. Notice that the magnetic field is again concentrated between pole pieces 1A and 1B. This time, however, the magnetic polarity is reversed because the current has reversed in the stator winding.

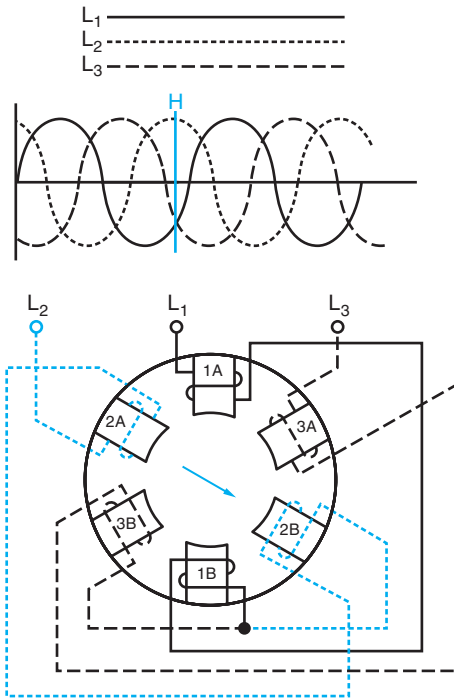
In Figure 14-1I, line H indicates phase 2 is at its maximum positive peak and phases 1 and 3 are less than maximum and in the negative direction. The magnetic field is concentrated between pole pieces 2A and 2B.

In Figure 14-1J, line I indicates that phase 3 is maximum negative; and phases 1 and 2 are less than maximum in the positive direction. The magnetic field at this point is concentrated between pole pieces 3A and 3B.

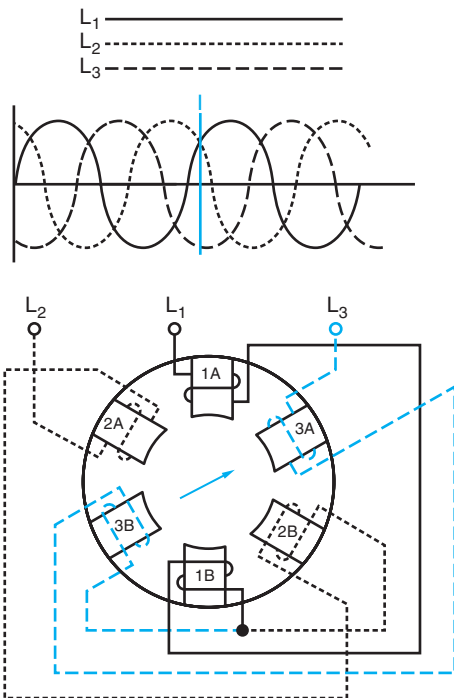
In Figure 14-1K, line J indicates that phase 1 is at its positive peak; and phases 2 and 3 are less than maximum and in the opposite direction. The



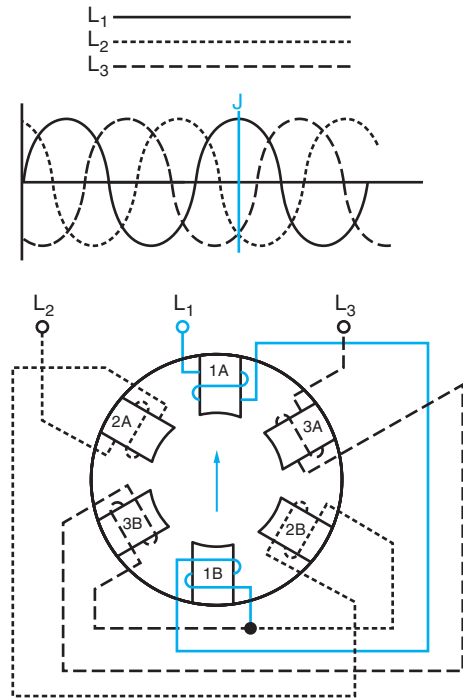
► **Figure 14-1H**
The magnetic field is concentrated between the poles of phase 1. (Source: Delmar/Cengage Learning)



► **Figure 14-1I**
The magnetic field is concentrated between the poles of phase 2. (Source: Delmar/Cengage Learning)



► **Figure 14-1J**
The magnetic field is concentrated between the poles of phase 3. (Source: Delmar/Cengage Learning)



► **Figure 14-1K**
The magnetic field has rotated 360°. (Source: Delmar/Cengage Learning)

magnetic field is again concentrated between pole pieces 1A and 1B. Notice that in one complete cycle of three-phase voltage, the magnetic field has rotated 360° around the inside of the stator winding.

If any two of the stator leads is connected to a different line, the relationship of the voltages will change and the magnetic field will rotate in the opposite direction. The direction of rotation of a three-phase motor can be reversed by changing any two stator leads.

SYNCHRONOUS SPEED

The speed at which the magnetic field rotates is known as the **synchronous speed**. The synchronous speed of a three-phase motor is determined by two factors. These are:

1. The number of stator poles.
2. The frequency of the AC line.

Because 60 Hz is a standard frequency throughout the United States and Canada, the following gives

the synchronous speeds for motors with different numbers of poles.

2 Poles	3,600 RPM
4 Poles	1,800 RPM
6 Poles	1,200 RPM
8 Poles	900 RPM

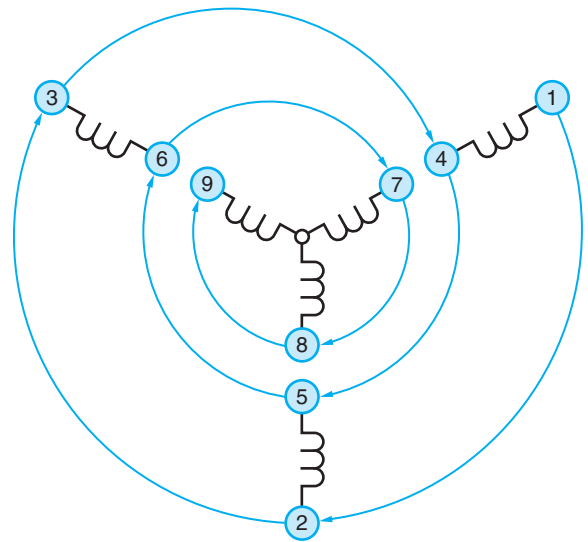
STATOR WINDINGS

The stator windings of three-phase motors are connected in either a wye or delta. Some stators are designed in such a manner as to be connected in either wye or delta, depending on the operation of the motor. Some motors, for example, are started as a wye-connected stator to help reduce starting current, and then changed to a delta connection for running.

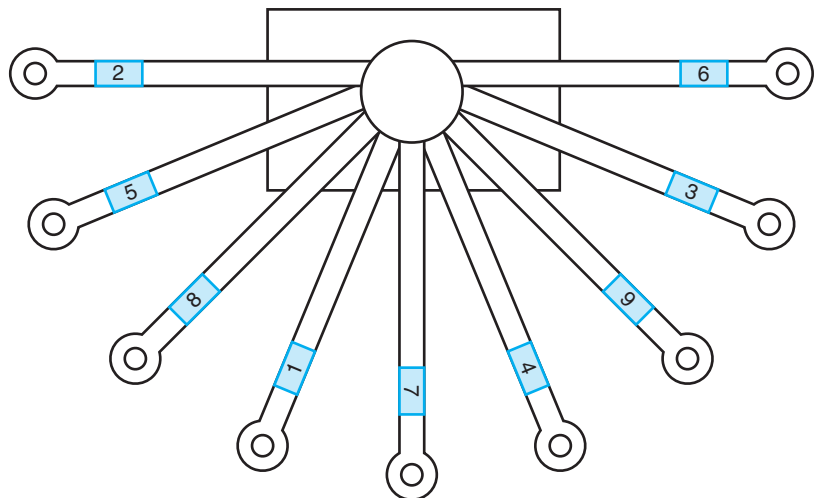
Many three-phase motors have dual-voltage stators. These stators are designed to be connected to 240 volts or 480 volts. The leads of a dual-voltage stator use a standard numbering system. Figure 14-2 shows a dual-voltage wye-connected stator. Notice the stator leads have been numbered in a spiral. This diagram shows that numbers 1 and 4 are opposite ends of the same coil. Lead number 7 begins another coil, and this coil is to be connected to the same phase as 1 and 4. Leads 2 and 5 are opposite ends of the same coil. Coil number 8 must be connected with the same phase as leads 2 and 5. Leads 3 and 6 are opposite ends of a coil and must be connected with lead number 9. Keep in mind that Figure 14-2

is a schematic diagram, and that when connecting a three-phase motor for operation at the proper voltage, the leads will look more like Figure 14-3. This figure illustrates the leads coming out of the terminal connection box on the motor. Some leads are numbered with metal or plastic bands on the wires, and some leads have numbers printed on the insulation of the wire.

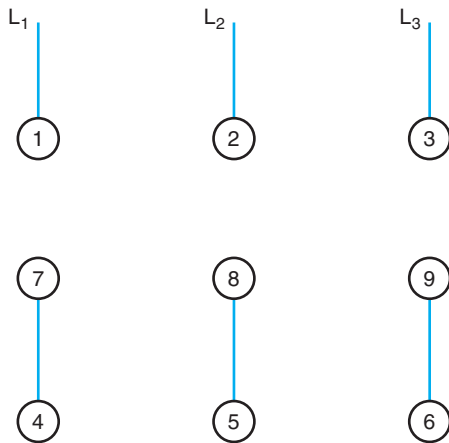
Figure 14-4 shows the stator connection for operation on a 480-volt line. Figure 14-5 shows



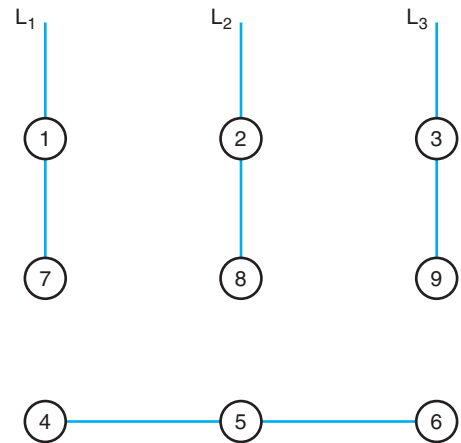
► **Figure 14-2**
Numbering a dual-voltage stator. (Source: Delmar/Cengage Learning)



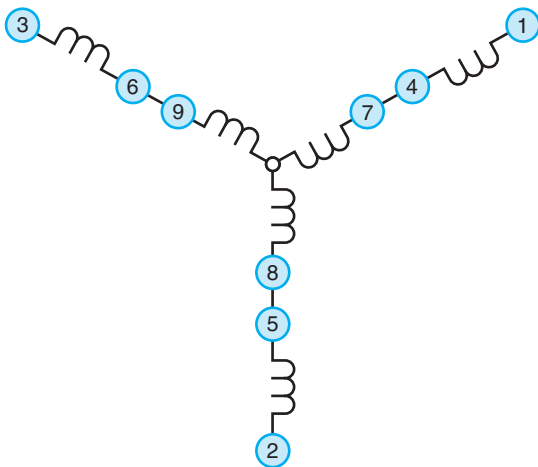
► **Figure 14-3**
Leads of a dual-voltage motor.
(Source: Delmar/Cengage Learning)



► **Figure 14-4**
High-voltage connection. (Source: Delmar/Cengage Learning)

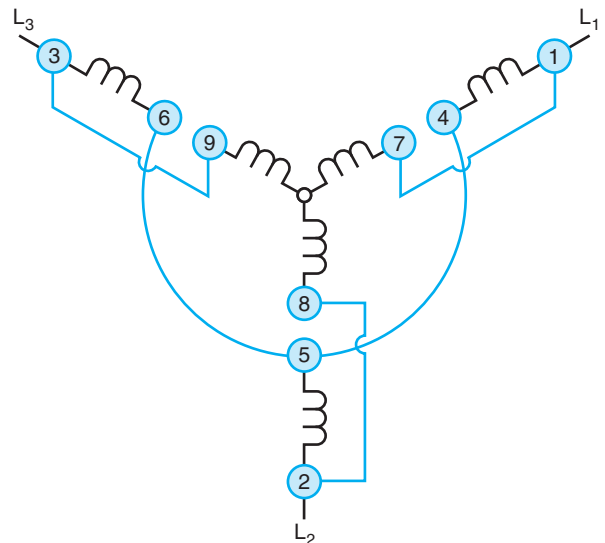


► **Figure 14-6**
Low-voltage connection. (Source: Delmar/Cengage Learning)



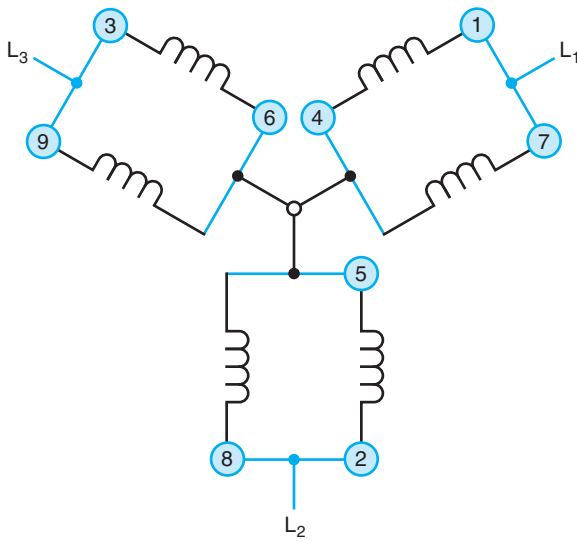
► **Figure 14-5**
Windings connected in series. (Source: Delmar/Cengage Learning)

the schematic equivalent of this connection. Notice that the windings have been connected in series. Figure 14-6 shows the stator connection for operation on a 240-volt line. Figure 14-7 shows the schematic equivalent of this connection. When the motor is to be operated on 240 volts, the stator windings are connected in parallel. Notice that leads 4, 5, and 6 are connected together to form another center point. This centerpoint is electrically the same as the point where leads 7, 8, and 9 join together. Figure 14-8 shows the equivalent circuit.

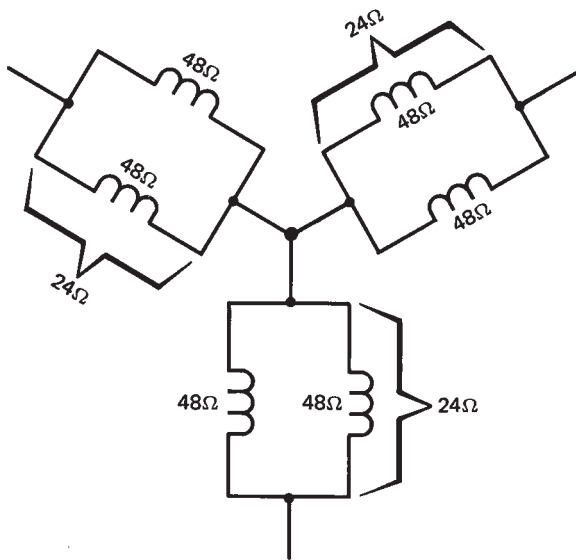


► **Figure 14-7**
Windings connected in parallel. (Source: Delmar/Cengage Learning)

When a motor is operated on a 240-volt line, the current draw of the motor is double the current draw of a 480-volt connection. For example, if a motor draws 10 amps of current when connected to 240 volts, it will draw 5 amps when connected to 480 volts. The reason for this is the difference of impedance in the windings between a 240-volt connection and a 480-volt connection. For instance, assume the stator windings of a motor have an



► **Figure 14-8**
Equivalent parallel circuit. (Source: Delmar/Cengage Learning)



► **Figure 14-9**
Total impedance of a parallel connection. (Source: Delmar/Cengage Learning)

impedance of 48 ohms. If the stator windings are connected in parallel as shown in Figure 14-9, the total impedance of the windings is 24 ohms.

$$R_t = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_t = \frac{48 \times 48}{48 + 48}$$

$$R_t = \frac{2304}{96}$$

$$R_t = 24 \text{ ohms}$$

If 240 volts is applied to this connection, 10 amps of current will flow.

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

$$I = \frac{240}{24}$$

$$I = 10 \text{ amps}$$

If the windings are connected in series for operation on a 480-volt line as shown in Figure 14-10, the total impedance of the winding is 96 ohms.

$$R_t = R_1 + R_2$$

$$R_t = 48 + 48$$

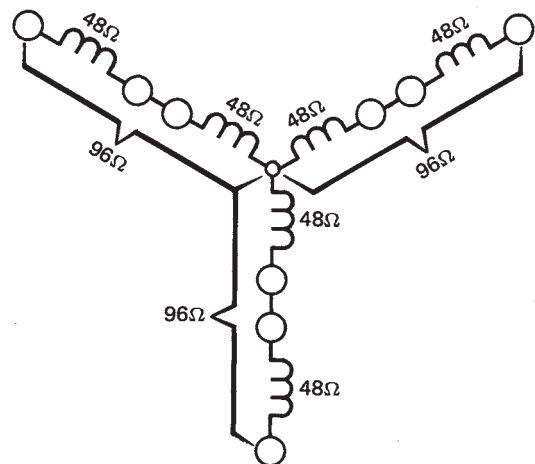
$$R_t = 96 \text{ ohms}$$

If 480 volts is applied to this winding, 5 amps of current will flow.

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

$$I = \frac{480}{96}$$

$$I = 5 \text{ amps}$$



► **Figure 14-10**
Impedance adds in series. (Source: Delmar/Cengage Learning)

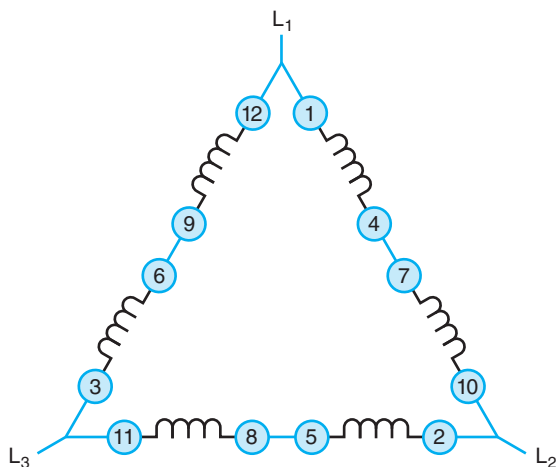
DELTA CONNECTIONS

Three-phase motors are also connected in delta. The same standard numbering system is used for delta-connected motors. If a dual-voltage motor is to be connected in delta, there must be 12 leads instead of 9 leads brought out at the terminal box.

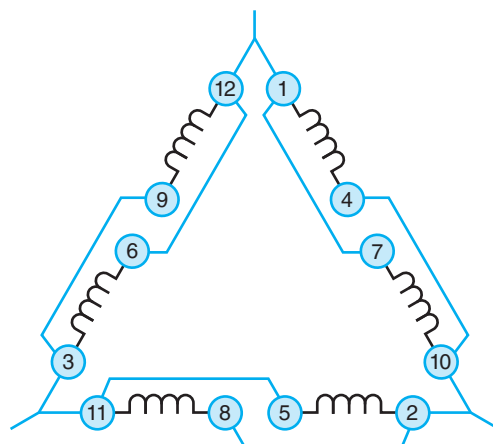
Figure 14–11 shows the schematic diagram of a motor connected for operation as a high-voltage delta. Notice that the stator windings for each phase have been connected in series for operation on high voltage. If the motor is to be connected for operation on a low voltage, the windings will be connected in parallel as shown in Figure 14–12. Figure 14–13 shows an equivalent parallel connection.

SPECIAL CONNECTIONS

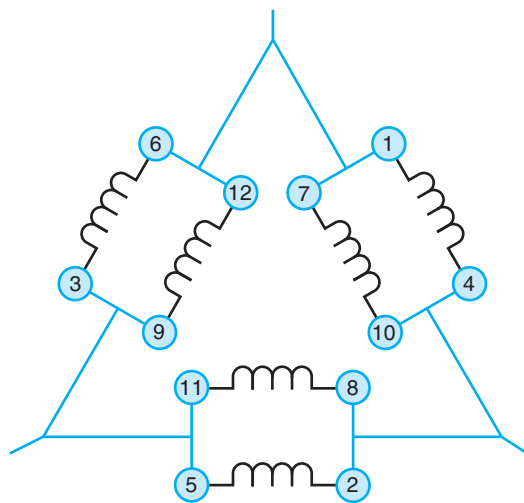
Some three-phase motors designed for operation on voltages higher than 600 volts may have more than 9 or 12 leads brought out at the terminal box. A motor with 15 or 18 leads can be found in high-voltage installations. A 15-lead motor has 3 coils per phase instead of 2. Figure 14–14 shows the proper number sequence for a 15-lead motor. Notice the leads are numbered in the same spiral as a 9-lead motor.



► **Figure 14–11**
High-voltage delta connection. (Source: Delmar/Cengage Learning)



► **Figure 14–12**
Low-voltage delta connection. (Source: Delmar/Cengage Learning)



► **Figure 14–13**
Equivalent parallel delta connection. (Source: Delmar/Cengage Learning)

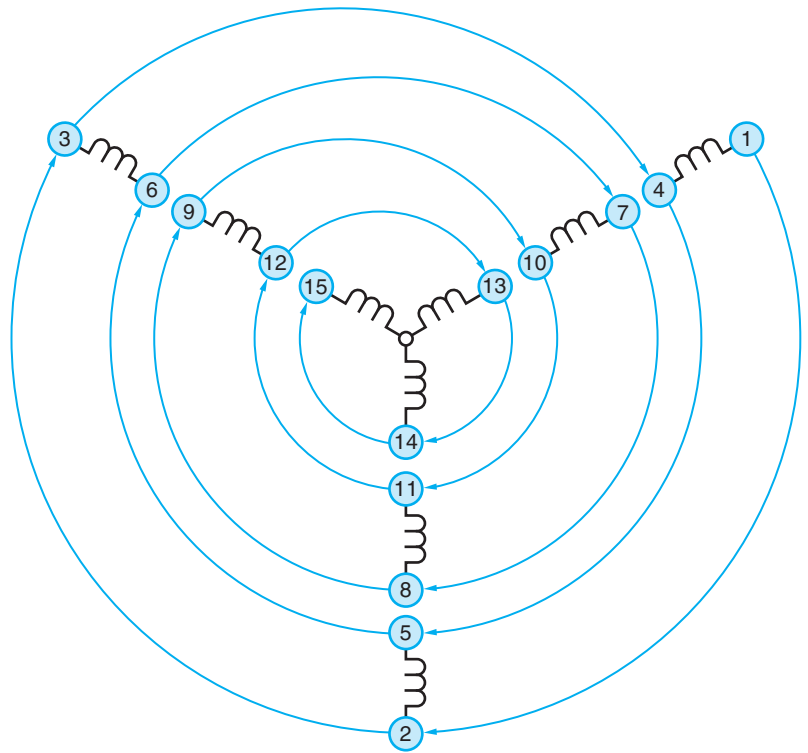


Figure 14-14
Fifteen-lead motor.
(Source: Delmar/Cengage Learning)

SUMMARY

- ▶ The three basic types of three-phase motors are:
 - A. Squirrel-cage induction.
 - B. Wound rotor induction.
 - C. Synchronous.
- ▶ All three-phase motors operate on the principle of a rotating magnetic field.
- ▶ Three factors that cause a magnetic field to rotate are:
 - A. The voltages of a three-phase system are 120° out of phase with each other.
 - B. The three voltages change polarity at regular intervals.
 - C. The arrangement of the stator winding around the inside of the motor.
- ▶ The speed of the rotating magnetic field is determined by two factors:
 - A. The number of stator poles.
 - B. The frequency of the applied voltage.
- ▶ The ends of the stator windings are numbered in a standard manner.
- ▶ The stator windings of some three-phase motors are connected in a wye configuration and some are connected in a delta configuration.

- ⌚ When a dual-voltage motor is to be connected for operation at low voltage, the stator windings will be connected in parallel.
- ⌚ When a dual-voltage motor is to be connected for operation on high voltage, the stator windings will be connected in series.

KEY TERMS

rotating magnetic field
synchronous speed
three-phase motors

REVIEW QUESTIONS

1. What are the three basic types of three-phase motors?
2. Name three factors that produce a rotating magnetic field.
3. What is synchronous speed?
4. What two factors determine the synchronous speed of a three-phase motor?
5. How is the direction of rotation of a three-phase motor changed?
6. What is the synchronous speed of a four-pole motor when connected to a 60-Hz line?
7. A dual-voltage three-phase motor has a current draw of 50 amps when connected to a 240-volt line. How much current will flow if the motor is connected for operation on 480 volts?
8. If the stator windings of a three-phase motor are connected for operation on high voltage, will the windings be connected in series or parallel?
9. If a dual-voltage motor is connected for operation on low voltage, and the motor is then connected to high voltage, will the motor operate at a faster speed?
10. Why does a dual-voltage motor draw more current when connected to low voltage than it does when connected to high voltage?

UNIT 15



The Squirrel-Cage Induction Motor

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the principle of operation of a squirrel-cage three-phase motor
- List the factors that determine the amount of torque developed by a squirrel-cage motor
- Discuss code letters and their meaning
- Perform an ohmmeter test on a three-phase squirrel-cage motor

The **squirrel-cage induction motor** receives its name from the fact that the rotor contains a set of bars that resemble a squirrel cage. If the soft-iron laminations were to be removed from the rotor, it would be seen that the rotor contains a set of metal bars joined together at each end by a metal ring, Figure 15–1. Figure 15–2 shows a complete squirrel-cage rotor and stator winding.

PRINCIPLE 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 15–3, a squirrel-cage rotor is shown inside the stator winding of a three-phase motor. It will be assumed that the motor shown in Figure 15–3 contains four poles per phase, which

(1,800 RPM – 600 RPM = 1,200 RPM). Because the rotor is being cut at a slower rate, less voltage is induced into the rotor. This produces less current flow through the rotor. When the current flow in the rotor is reduced, the current flow in the stator is reduced also.

As the rotor continues to accelerate, the rotating magnetic field cuts the rotor bars at a slower rate. This causes less voltage to be induced into the rotor, and therefore, less current flow in the rotor. Notice that the maximum amount of induced voltage and current occurs when the rotor is not turning at the instant of start. This is the reason that AC induction motors require more current to start than to run.

TORQUE

Torque is the amount of turning or twisting force developed by a motor. It is generally measured in pound-inches or pound-feet depending on the application. Imagine a bar one foot in length attached to the shaft of a motor. A torque of one pound-foot would be the force exerted by applying a pressure of one pound on the end of the bar.

The amount of torque produced by an AC induction motor is determined by three factors. These are:

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 stator and rotor flux.

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 cannot run at synchronous speed.* If the rotor was to accelerate to the speed of the rotating magnetic field, there would be no cutting action of the squirrel-cage bars and, therefore, no current flow in the rotor. If there was no current flow in the rotor, there could be no rotor magnetic field and, therefore, no torque.

When an induction motor is operating with no load connected to it, it will run close to the synchronous speed. For example, a four-pole motor that has a synchronous speed of 1,800 RPM could run at 1,795 RPM at no load. The speed of an AC induction motor is determined by the amount of torque needed. When the motor is operating at no load, it will produce only the amount of torque needed to overcome its own friction and windage losses. This low torque requirement permits the motor to operate at a speed close to that of the rotating magnetic field.

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 by the motor. As the current flow increases in the rotor, it causes more current flow to be produced in the stator. This is why motor current will increase as load is added to the motor.

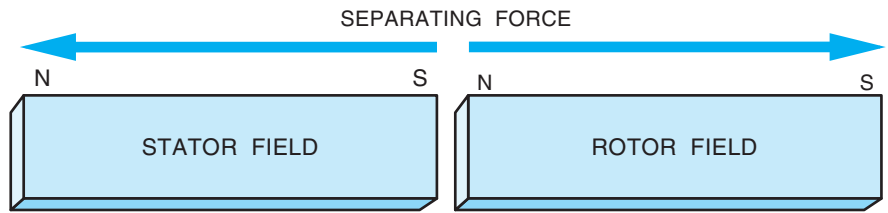
Another factor that determines the amount of torque produced by an induction motor is the phase angle difference between rotor and stator flux. Motor torque is basically the attracting force of two magnetic fields. Imagine two bar magnets representing the magnetic fields of the stator and rotor, Figure 15–4. If the north end of one magnetic is placed close to the south end of the other, they will be attracted to each other, Figure 15–5. Torque can be compared to the amount of force necessary to separate the two magnets. When the magnets are in line with each other, as shown in Figure 15–5, the attraction is strongest and the amount of force necessary to separate them is the greatest. This compares to the stator flux and rotor flux being in phase with each other.

► **Figure 15–4**
Stator and rotor magnetic fields are compared to two bar magnets. (Source: Delmar/Cengage Learning)



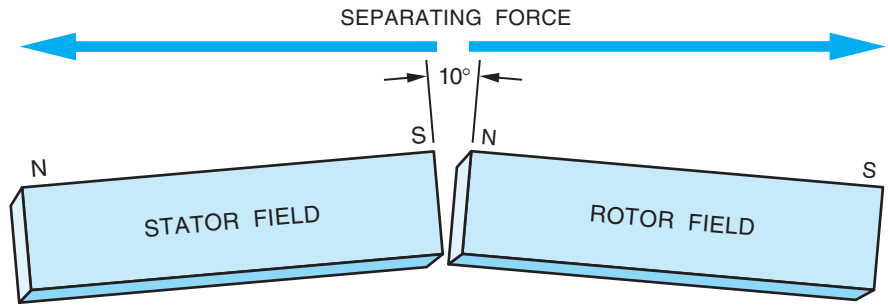
► **Figure 15-5**
Torque is the force attract-
ing the two magnets.

(Source: Delmar/Cengage Learning)



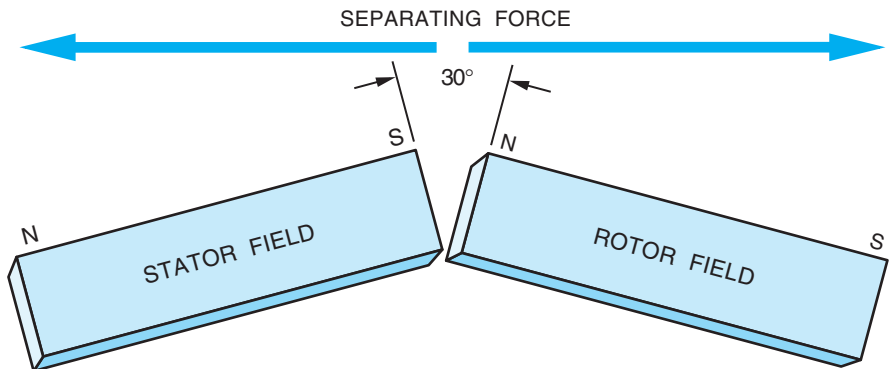
► **Figure 15-6**
Magnets are separated
by an angle of 10° .

(Source: Delmar/Cengage Learning)



► **Figure 15-7**
Magnets are separated
by an angle of 30° .

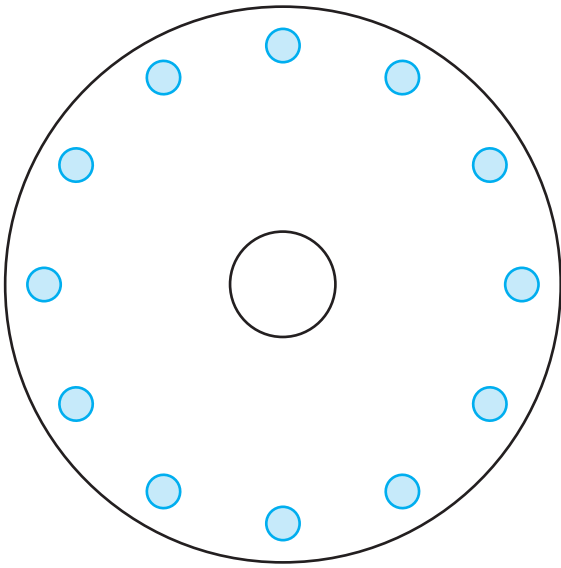
(Source: Delmar/Cengage Learning)



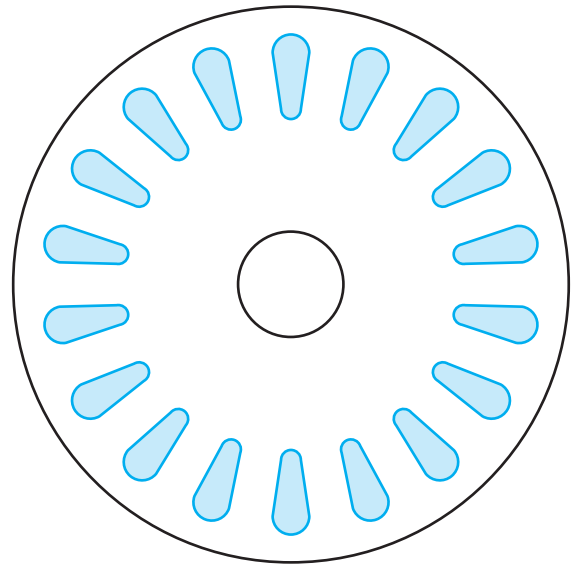
Now assume that the two magnets are placed at an angle of 10° to each other, Figure 15-6. The 10-degree angle produces a greater amount of separation between the two magnetic fields. The magnets can now be separated with less force. Now assume that the magnets are placed at a 30° angle to each other, Figure 15-7. The amount of force necessary to separate the two magnets is less than it was at a 10° angle. The greater the angle between the two magnets, the less force required to separate them. This corresponds to the phase angle difference between rotor and stator flux. The greater the phase angle between rotor and stator flux, the less torque that is developed by the motor.

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 motors are given a **code letter** on their nameplate. The code letter indicates the type of bars used in the rotor. Figure 15-8 shows a rotor with type "A" bars. A type "A" rotor has the highest resistance of any squirrel-cage rotor. This means that the starting torque is high since the rotor current is closer to being 90° out of phase with the stator current than the other types of rotors. The high resistance of the



► **Figure 15-8**
Type "A" rotor. (Source: Delmar/Cengage Learning)



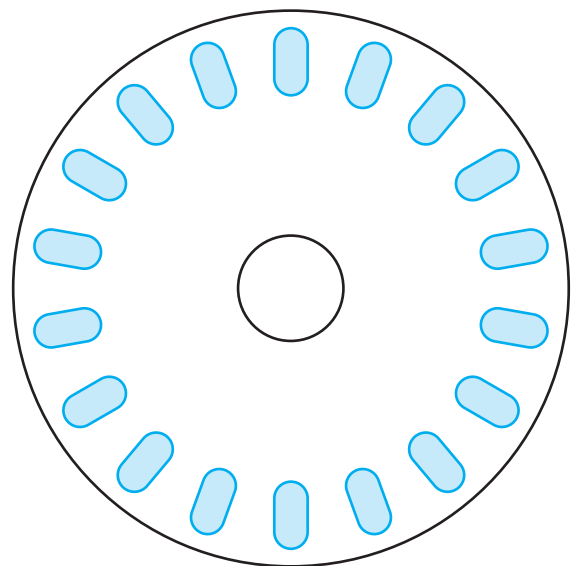
► **Figure 15-9**
Type "B-E" rotor. (Source: Delmar/Cengage Learning)

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 type "A" bars has very poor running characteristics, however. Because 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.

Figure 15-9 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 type "A" rotor. This rotor has fair starting torque, low starting current, and fair speed regulation.

Figure 15-10 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. This type of rotor also has good speed regulation.

The code letter found on the nameplate is also used to determine the amount of **locked rotor current** for the motor. Locked rotor current is the amount of current the motor will draw at the moment of starting. Figure 15-11 shows *Table 430.7(B)* of the *National*



► **Figure 15-10**
Type "F-V" rotor. (Source: Delmar/Cengage Learning)

Electrical Code.® This table is used to determine the locked rotor current for a squirrel-cage rotor. To use the table, the horsepower, code letter, and voltage of the motor must be known. For this example, assume

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 15-11

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the motor is 10 horsepower, has a code letter J, and is operated on a 480-volt line. The table lists the locked rotor currents in kilovolt-amperes per horsepower. The table shows that code letter J is 7.1 to 7.99. For this calculation, a midvalue of 7.5 will be used. Because the values are listed in kilovolt-amperes, 7.5 is actually 7,500 volt-amperes. To find the locked rotor current, multiply the kVA rating by the horsepower, and then divide by the voltage.

$$I = 7500 \text{ VA} \times 10 \text{ hp}$$

$$I = \frac{75000}{480}$$

$$I = 156.25 \text{ amps}$$

THE NAMEPLATE

Electric motors have **nameplates** that give a great deal of information about the motor. Figure 15-12 illustrates the nameplate of a three-phase induction motor. The nameplate shows that the motor is 10 horsepower, it is a three-phase motor and operates on 240 or 480 volts. The full-load running current of the motor is 28 amps when operated on 240 volts, or 14 amps when operated on 480 volts.

MOTOR NAMEPLATE

HP	Phase
10	3
Volts	Amps
240/480	28/14
Hz	FL Speed
60	1,745 RPM
Code	SF
J	1.25
Frame	Model No.
XXXX	XXXX

Figure 15-12

Motor nameplate. (Source: Delmar/Cengage Learning)

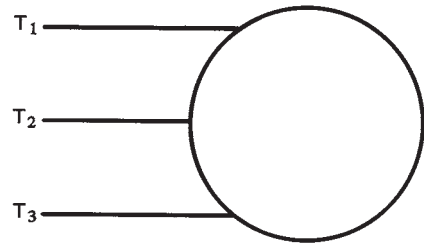


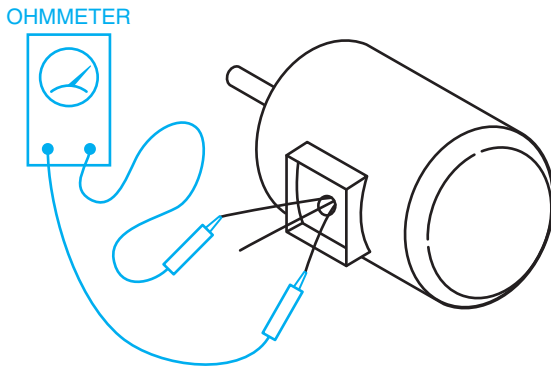
Figure 15-13

Schematic symbol of a three-phase squirrel-cage induction motor. (Source: Delmar/Cengage Learning)

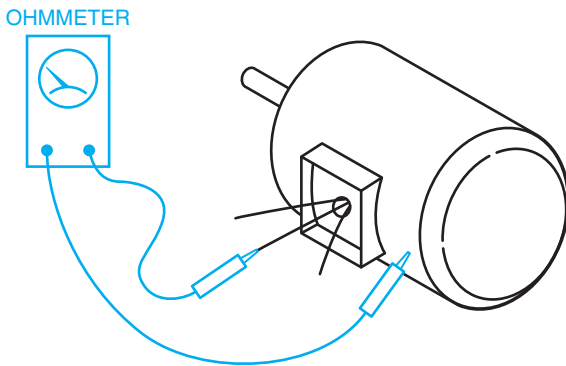
The motor is designed to be operated on a 60-Hz AC voltage, and has a full-load speed of 1,745 RPM. The speed indicates that this motor has four poles per phase. Since the full-load speed is 1,745 RPM, the synchronous speed would be 1,800 RPM. The motor contains a type J squirrel-cage rotor, and has a service factor of 1.25. The service factor is used to determine the amperage rating of the overload protection for the motor. The frame indicates the type of mounting the motor has. Figure 15-13 shows the schematic symbol for a three-phase squirrel-cage induction motor.

TESTING THE MOTOR

Most service technicians test a three-phase motor with an ohmmeter. The ohmmeter can be used to check the stator winding for an open condition or



► **Figure 15-14**
Testing the stator winding for opens. (Source: Delmar/
Cengage Learning)



► **Figure 15-15**
Testing the stator winding for grounds. (Source: Delmar/
Cengage Learning)

a grounded condition. To test the stator winding for an open condition, check the continuity of each winding by measuring the resistance between each of the three windings as shown in Figure 15-14. The resistance of each pair of windings should be the same. To test for a grounded motor, connect one ohmmeter lead to the case of the motor, and the other lead to one of the motor leads. There should be no continuity between any of the leads and the case of the motor, Figure 15-15. The ohmmeter, however, will not generally detect a shorted winding. The resistance of the stator windings of most large horsepower motors is so low that they appear under normal conditions to be a short circuit to the ohmmeter. To test for a shorted winding, some method must be used to measure the reactance of the windings instead of their resistance. If the motor will run,

an ammeter can be used to measure the current draw of the motor. The current of each line should be equal and within the full-load current rating of the motor. If one line has a higher current reading than the others, it is an indication of a shorted stator winding. If it is not possible to operate the motor, an instrument that measures the actual inductance of the winding can be used. If one winding has a lower inductance than the others, it is shorted.

STARTING METHODS FOR SQUIRREL-CAGE MOTORS

There are several methods that can be employed to start three-phase squirrel-cage motors. These methods include:

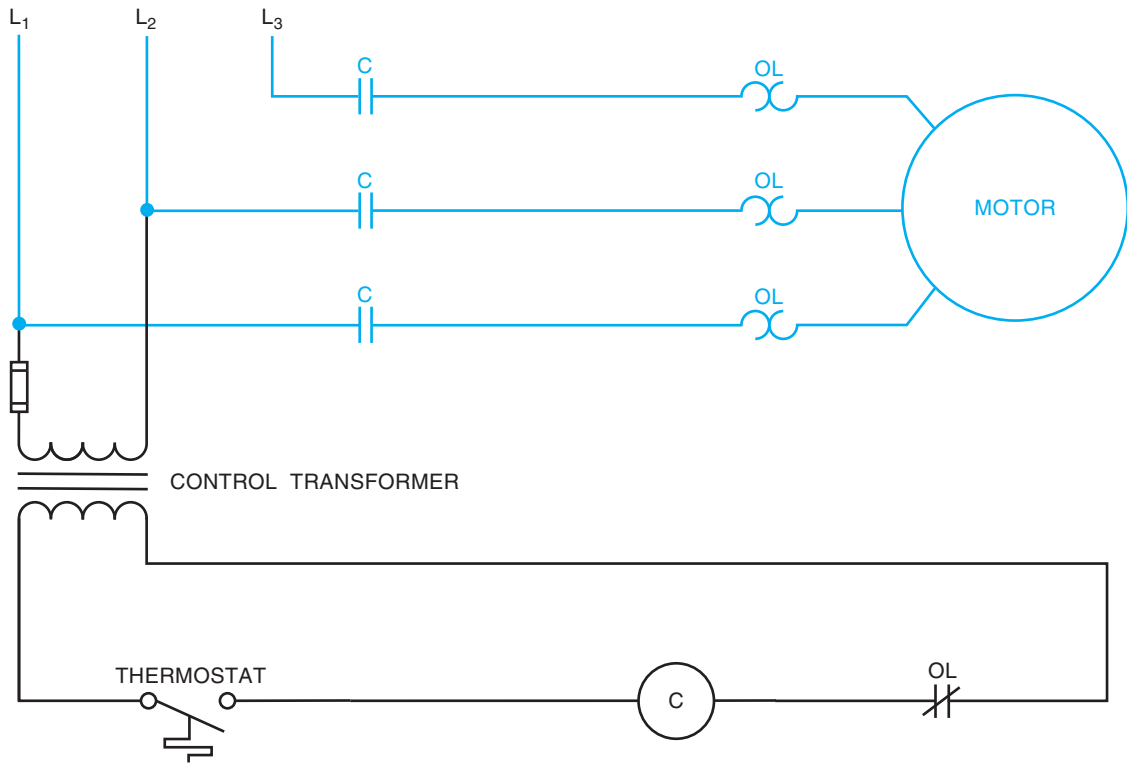
1. Across-the-line starting.
2. Resistor/reactor starting.
3. Autotransformer starting.
4. Wye-delta starting.
5. Part winding starting.

Across-the-Line Starting

The simplest of these methods is across-the-line starting. Across-the-line starting is accomplished by connecting the motor directly to the power line, Figure 15-16. This method of starting is used when the inrush current, called locked rotor current, is not so great as to adversely affect the power line. Across-the-line starting is employed for all small horsepower motors, and depending on the local power base, may be used for motors of several hundred horsepower.

Resistor/Reactor Starting

Often it is necessary to reduce the inrush current during the starting period of large motors. One method of reducing the starting current is to connect resistors or reactors (choke coils or inductors) in series with the motor during the starting period, Figure 15-17. This permits the resistance of the resistors or the inductive reactance of the reactors to limit the inrush current when the motor is first started. After the motor has accelerated to near full



► **Figure 15-16**

Across-the-line starting is accomplished by connecting the motor directly to the power line. (Source: Delmar/Cengage Learning)

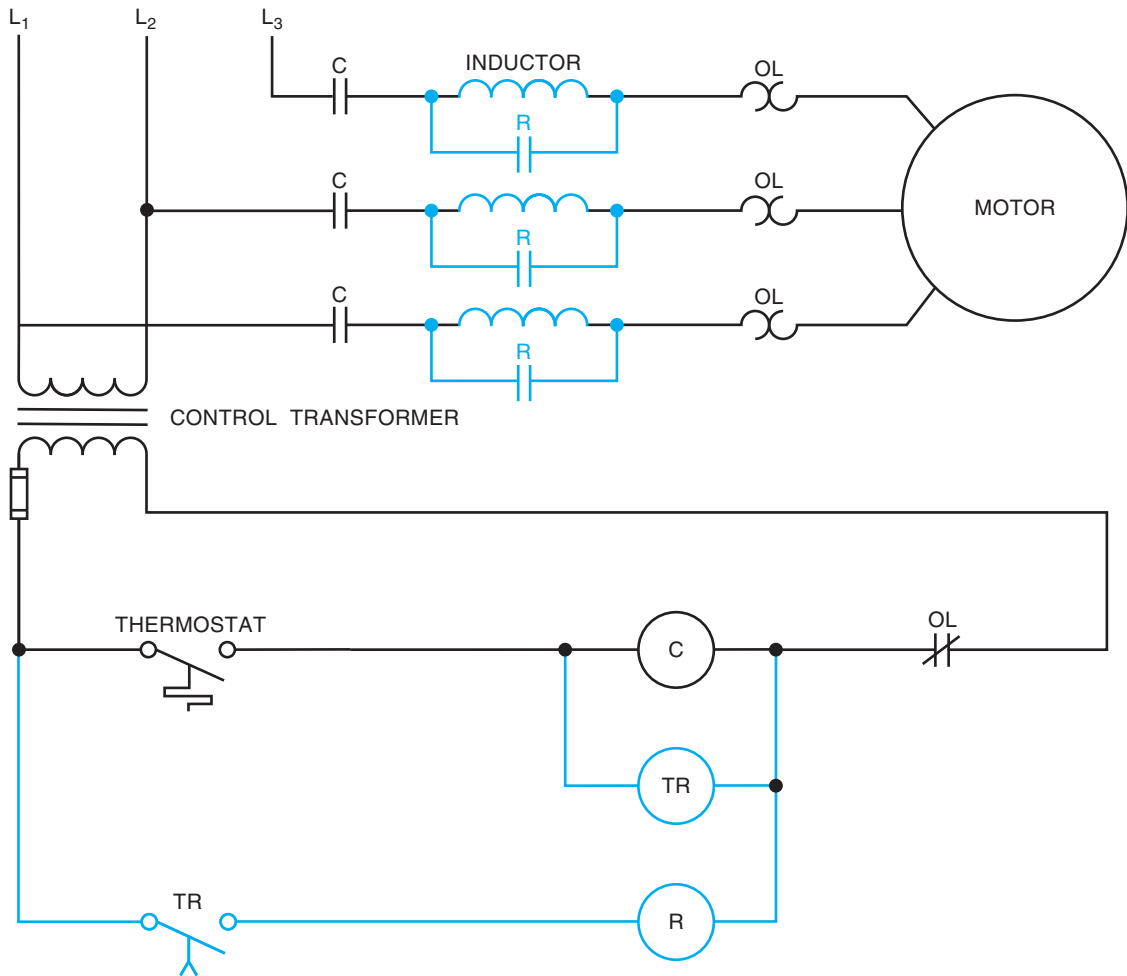
load speed, the resistors or reactors are shunted out of the circuit. Several methods may be employed for shunting the resistors or reactors out of the line. The circuit shown in Figure 15-17 uses a time delay relay to energize R contactor after some period of time. The circuit operates as follows:

- When the thermostat contact closes, the coils of the compressor contactor (C) and the on-delay timer (TR) energize.
- When the compressor contactor energizes, C contacts close and connect the motor and reactors to the power line.
- After some period of time, timed contact TR closes and energizes the R contactor causing the R contacts connected in parallel with the current limiting inductors to close and shunt the inductors out of the line. The motor is now connected to full voltage.

Autotransformer Starting

Autotransformer starting differs from resistor or reactor starting by decreasing the voltage applied to the motor during the starting period instead of inserting resistance or inductive reactance in series with the motor. It should be noted that when the voltage to the motor is reduced, the torque is reduced also. A 50% reduction of voltage will produce a 50% reduction of current also, but the torque is reduced to 25% of the value produced by full voltage starting.

Several methods can be employed when using autotransformer starting. Some starters used three transformers, but most use two transformers connected in an open delta, Figure 15-18. In this circuit, notice the addition of the normally closed R contact connected in series with S coil and the



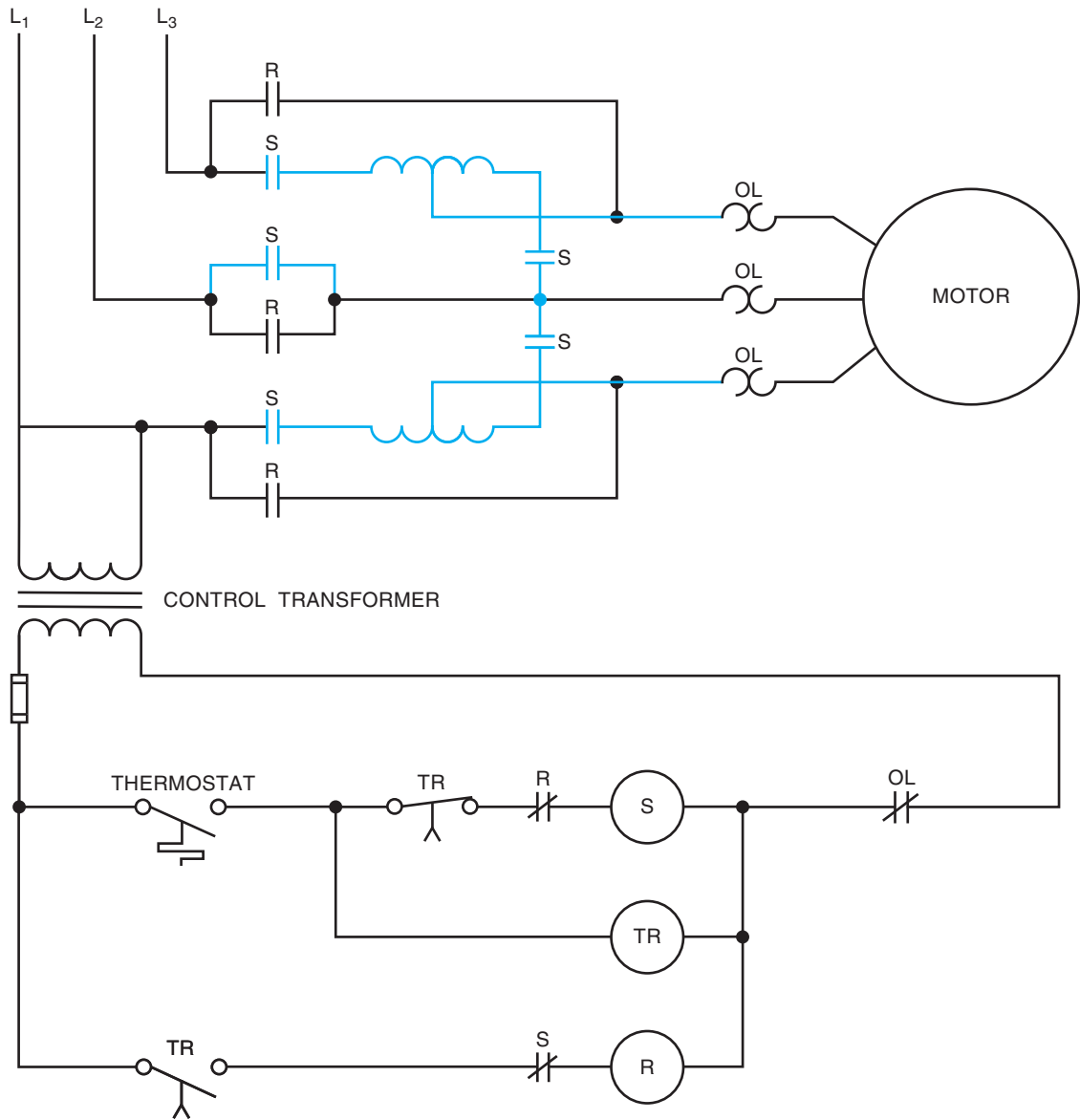
► **Figure 15-17**
Reactor starter for a three-phase squirrel-cage motor. (Source: Delmar/Cengage Learning)

normally closed S contact connected in series with the R coil. This is referred to as **interlocking**. Interlocking is used to prevent one contactor being energized while some other contactor is energized. In this circuit, coils R and S can never be energized at the same time. The circuit operates as follows: (It will be assumed that timer TR is set for a delay of 3 seconds).

- When the thermostat contact closes, coils S and TR energize.
- All S contacts change position. The normally open S contacts close and connect the autotransformer to the line. The motor is now connected to

reduced voltage. The normally closed S contact connected in series with the coil of the R contactor opens and prevents the possibility of the R coil being energized.

- After a delay of 3 seconds, the TR timed contacts change position.
- The normally closed TR contact connected in series with the S coil opens and disconnects it from the line.
- When the S coil deenergizes, all S contacts return to their normal position. The autotransformer is now disconnected from the line and the contact connected in series with R coil is now closed.



► **Figure 15-18**

Autotransformer starter using an open delta connection. (Source: Delmar/Cengage Learning)

- When the normally open TR contact closes, the R coil energizes and all R contacts change position.
- The normally open R contacts close and connect the motor directly to the power line. The normally closed R contact opens and prevents the possibility of S coil being energized at the same time.

Wye-Delta Starting

Wye-delta starting is also known as star-delta starting. Wye-delta starting is used to reduce the inrush current during the starting period by connecting the stator windings of the motor in a wye configuration

during the starting period and then reconnecting them in delta during the run period. If the stator windings are connected in wye, the inrush current will be one-third the value it would be if they were connected in delta. Assume that the motor stator windings have an impedance of 2.5 ohms each. Now assume that the windings are connected in delta, Figure 15–19. It will also be assumed that the motor is connected to a line voltage of 480 volts. In a delta connection, the phase voltage is the same as the line voltage. Therefore, when the C contacts close, 480 volts will be applied across 2.5 ohms. This will produce a current in each phase of 192 amperes.

$$I_{\text{PHASE}} = \frac{480}{2.5}$$

In a delta connection, the line current is greater than the phase current by a factor of the square root of 3 (1.732). Therefore, the line current supplied to the motor is 332.5 amperes (192×1.732).

Now assume that the same stator windings are connected in wye, Figure 15–20. In a wye connection, the phase voltage is less than the line voltage

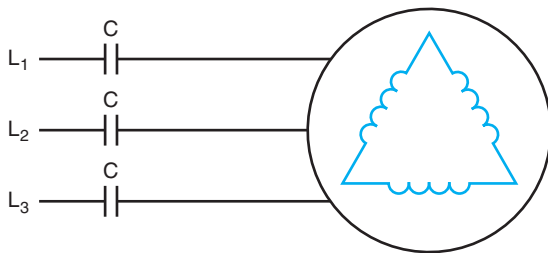


Figure 15-19
The stator windings are connected in delta. (Source: Delmar/Cengage Learning)

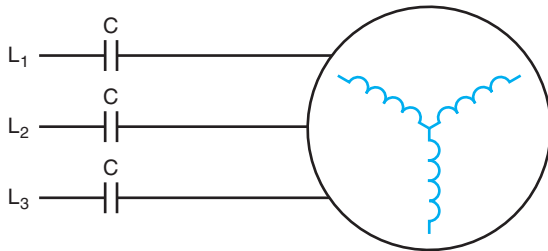


Figure 15-20
The stator windings are connected in wye. (Source: Delmar/Cengage Learning)

by a factor of the square root of 3 (1.732). Therefore, 277 volts is applied across each stator winding instead of 480 volts ($480/1.732$). This produces a phase current of 110.8 amperes. Because the stator windings are now connected in wye instead of delta, the line current is the same as the phase current. The motor inrush current has been reduced from 332.5 amperes to 110.8 amperes by reconnecting the stator windings from delta to wye.

There are two conditions that must be met when wye-delta starting is to be used.

1. The motor must be designed to operate with its stator windings connected in delta during the normal run period.
2. All stator winding leads must be accessible at the terminal connection box. This would be leads T1 through T6 for a single voltage motor and T1 through T12 for a dual voltage motor.

Another consideration when using wye-delta starting is that the overload heaters should be sized for the phase current value and not the line current value. The basic stator connection for wye-delta starting is shown in Figure 15–21. Notice that the overload heaters are connected in the phase windings not in the line leads.

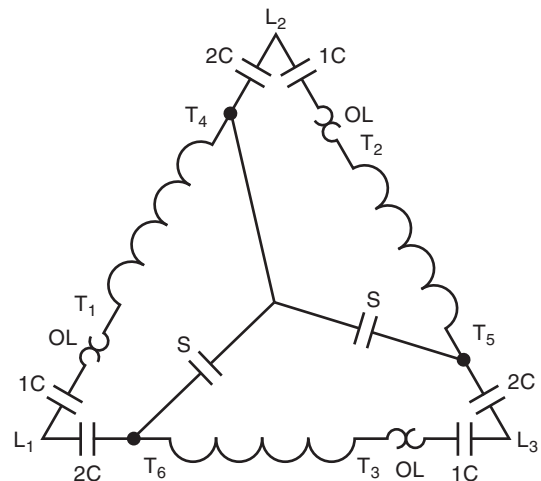


Figure 15-21
Stator connection for a single voltage wye-delta starter. (Source: Delmar/Cengage Learning)

A basic control schematic for a wye-delta starter is shown in Figure 15–22. To understand the operation of this circuit assume that timer TR has been set for a delay of 3 seconds.

- When the thermostat contact closes, a current path exists through coils 1C, TR, and S, Figure 15–23.
- The 1C load contacts close to supply power to the motor T leads.
- The S contacts change position also. The two S load contacts close and connect the stator winding in a wye configuration by shorting T4, T5, and T6 together. The normally open S contact connected in series with coil 2C opens to provide interlocking protection.
- After a delay of 3 seconds, both TR contacts change position, Figure 15–24.
- The normally closed TR contact connected in series with S coil opens and deenergizes S contactor

causing all S contacts to return to their normal position. The normally closed S contact connected in series with coil 2C recloses to provide a current path to coil 2C.

- When the normally open TR contact connected in series with coil 2C closes, coil 2C energizes causing all 2C contacts to change position. The 2C load contacts close and reconnect the motor stator windings in a delta configuration. The normally closed 2C contact connected in series with S coil opens to provide interlocking protection.

Part Winding Starters

Another method for reducing the starting current of large three-phase squirrel-cage motors is part winding starting. Motors intended for use with part winding starting contains two separate stator windings, Figure 15–25. Each winding is rated for

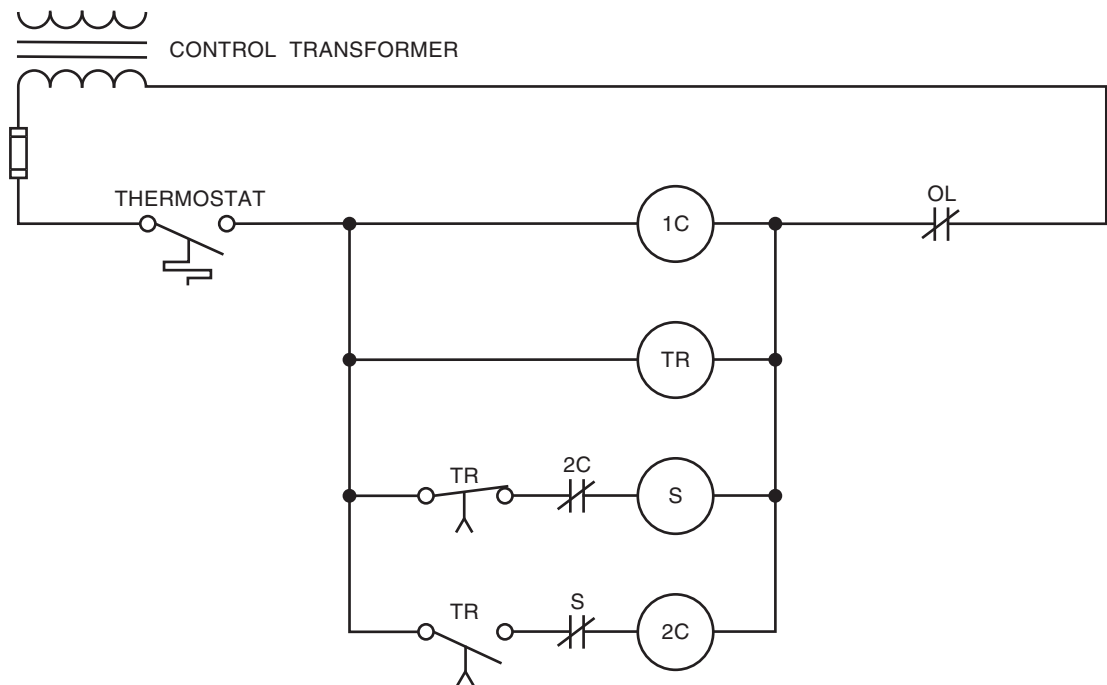
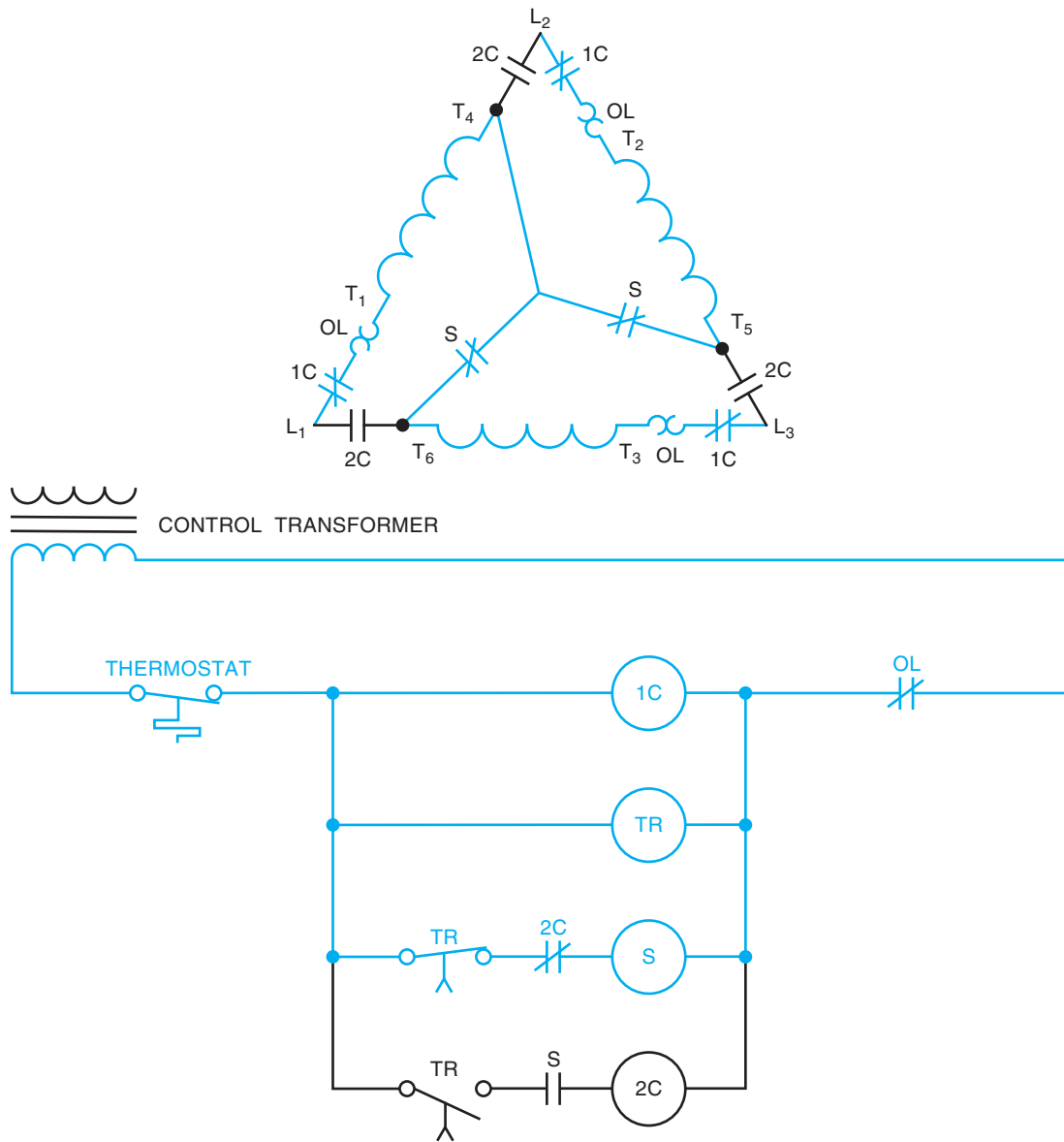
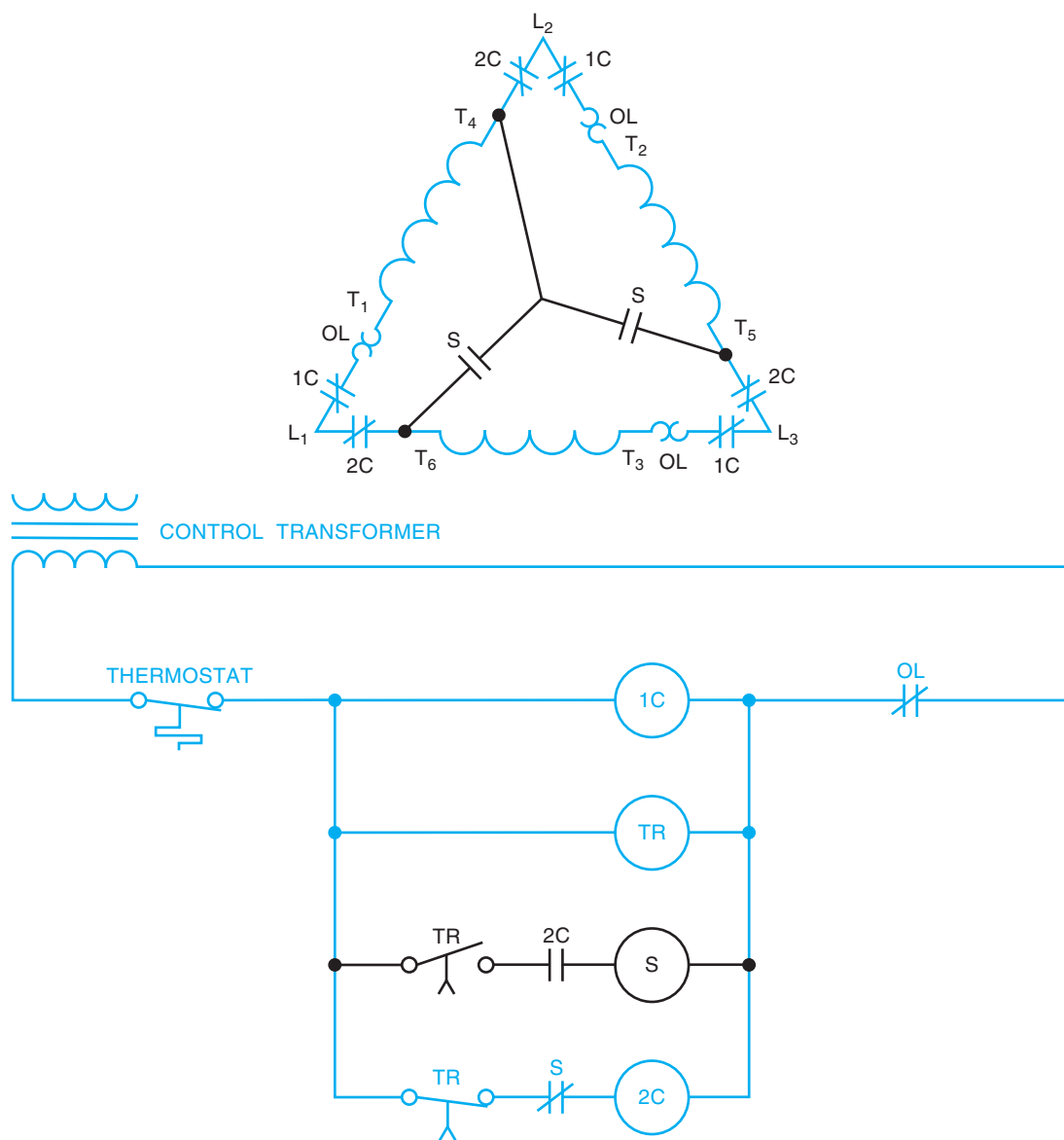


Figure 15–22
Basic control schematic for wye-delta starting. (Source: Delmar/Cengage Learning)



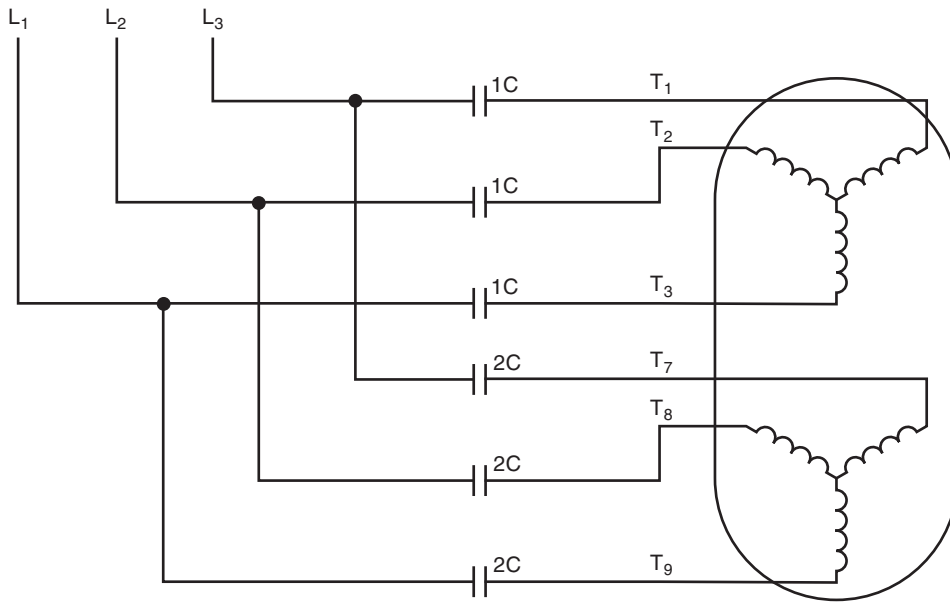
► **Figure 15-23**

The stator windings are connected in wye during starting. (Source: Delmar/Cengage Learning)



► **Figure 15-24**

The stator windings are connected in delta during the run period. (Source: Delmar/Cengage Learning)

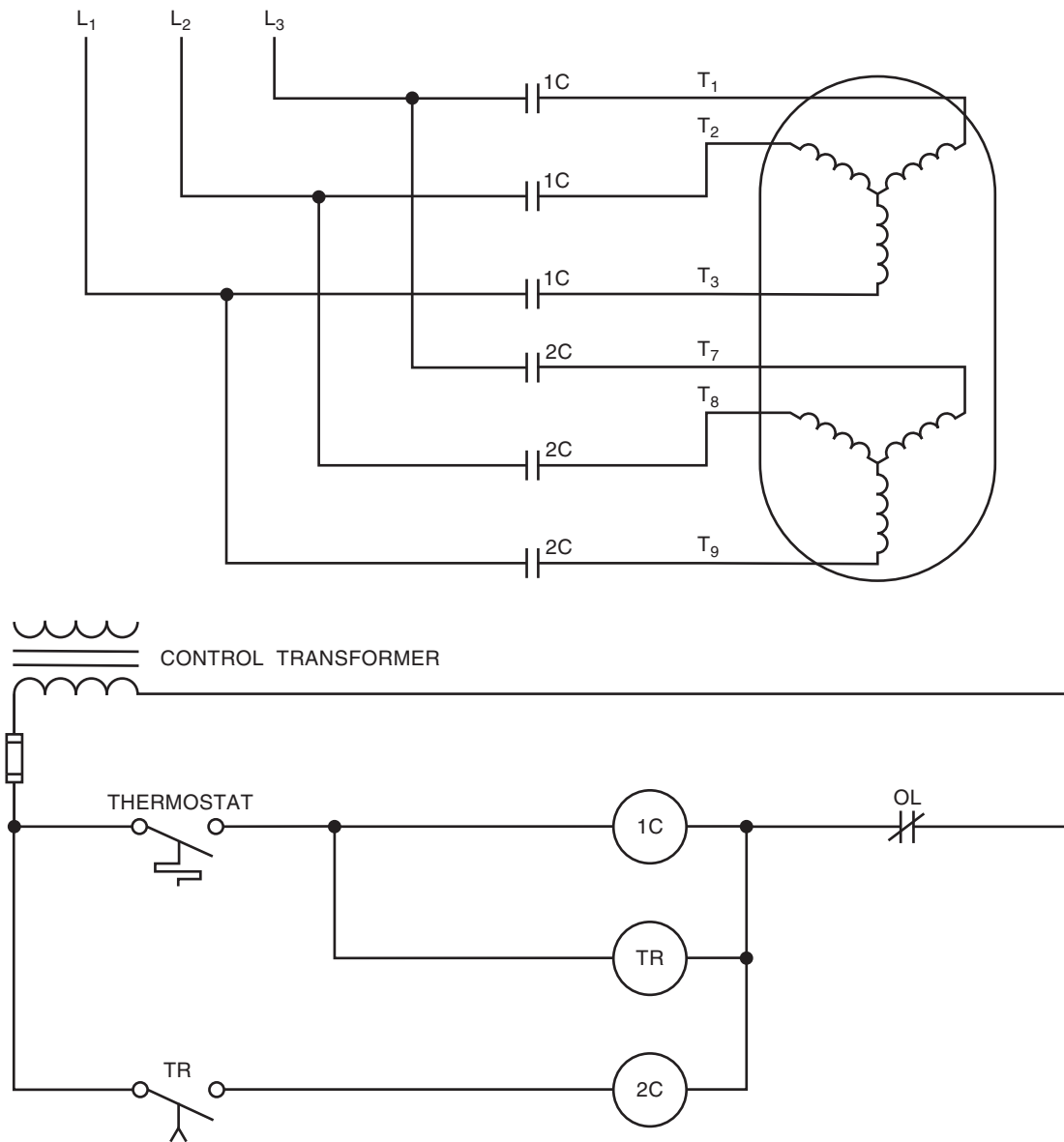


► **Figure 15-25**
A motor intended for part windings starting contains two stator windings. (Source: Delmar/Cengage Learning)

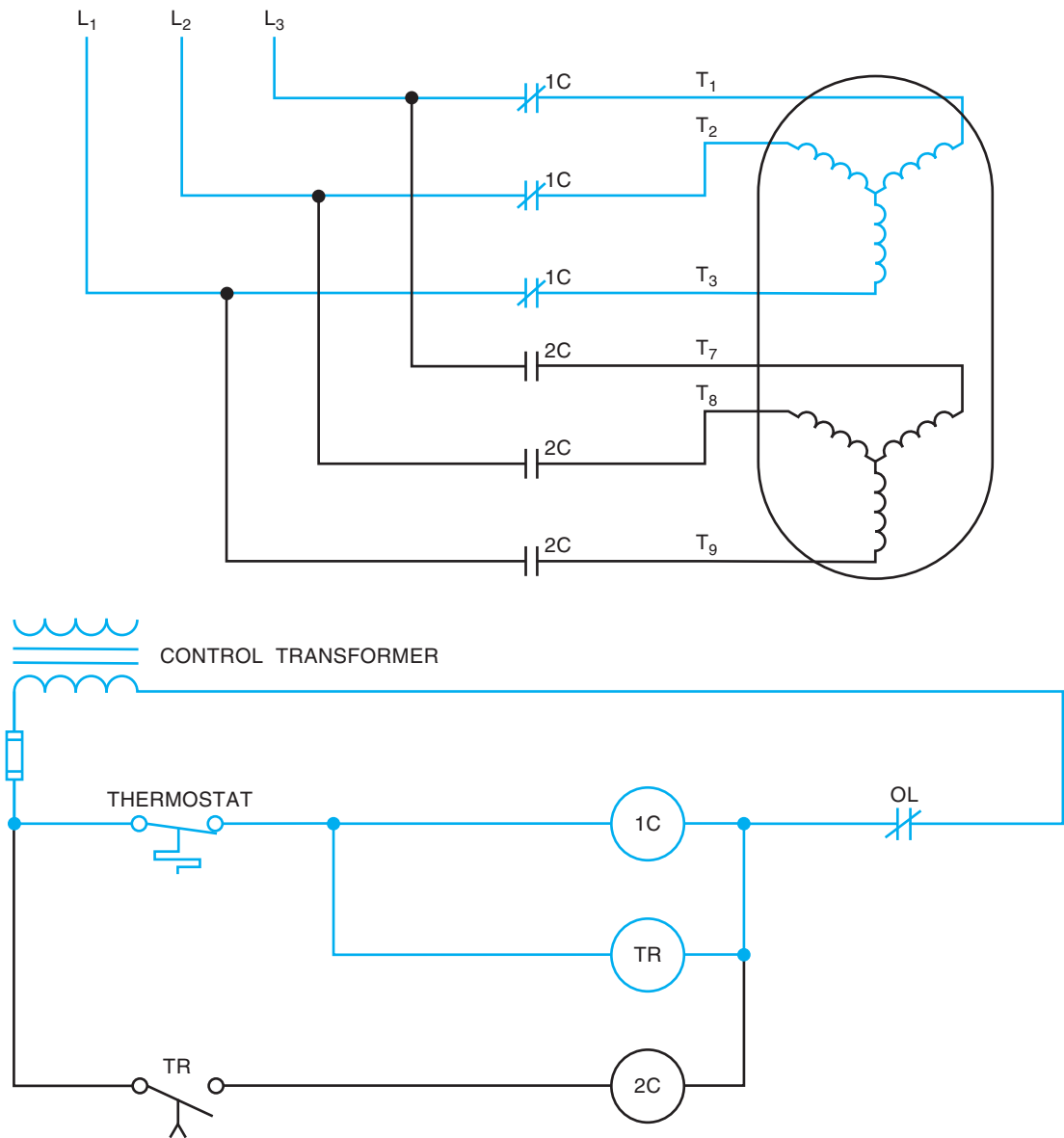
the intended line voltage. The impedance of a single stator winding is double that of the two windings connected in parallel. Dual voltage motors can also be used for part winding starting provided the line voltage corresponds to the low voltage rating of the motor. A 480/240-volt motor could employ part winding starting provided the motor is connected to 240 volts and not 480 volts. In this situation T4, T5, and T6 are connected and power is connected to T1, T2, and T3 during the starting period. After some period of time, power is also connected to T7, T8, and T9. This has the same effect as connecting the stator windings in parallel.

A basic circuit for part winding starting is shown in Figure 15-26. To understand the operation of the circuit, assume that timer TR has been set for a delay of 3 seconds.

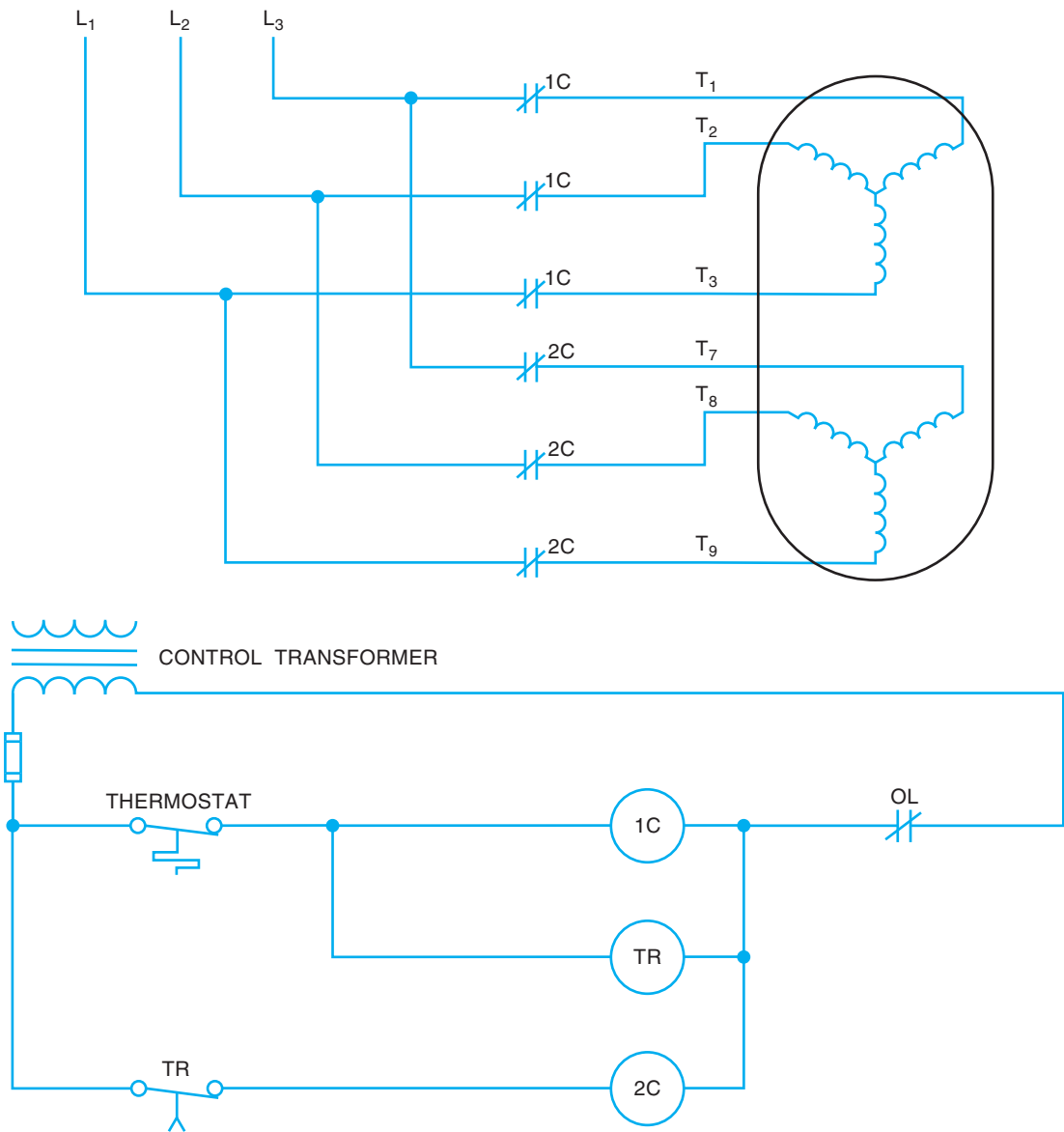
- When the thermostat contact closes power is provided to coils C1 and TR, Figure 15-27. All 1C contacts close and connect T1, T2, and T3 to the power line.
- After a delay of 3 seconds, the normally open TR contact connected in series with 2C closes and energizes coil 2C, Figure 15-28.
- When the 2C load contacts close, power is connected to T7, T8, and T9. This has the same effect as connecting the two windings in parallel.



► **Figure 15-26**
Basic part winding starting circuit. (Source: Delmar/Cengage Learning)



► **Figure 15-27**
During the starting period only one stator winding is energized. (Source: Delmar/Cengage Learning)



► **Figure 15-28**

During the run period both stator windings are connected. (Source: Delmar/Cengage Learning)

SUMMARY

- ▶ The squirrel-cage motor receives its name from the fact that the rotor contains a set of bars connected together at each end, and the entire assembly resembles a squirrel cage.
- ▶ Three factors that determine the amount of voltage induced into the rotor are:
 - A. The strength of the magnetic field of the stator.
 - B. The number of stator bars contained in the rotor.
 - C. The difference in speed between the speed of the rotating magnetic field and the speed of the rotor.
- ▶ The greatest amount of current draw for a squirrel-cage motor is during the starting period.
- ▶ Three factors that determine the amount of torque produced by a squirrel-cage motor are:
 - 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 stator current and rotor current.
- ▶ The direction of rotation of a squirrel-cage motor can be changed by reversing any two stator leads.
- ▶ The code letter found on the motor nameplate indicates the type of bars used in the construction of the rotor.
- ▶ The simplest method of starting a squirrel-cage motor is across-the-line starting.
- ▶ Resistor/reactor starting is accomplished by connecting resistors or inductors in series with the motor during the starting period.
- ▶ Autotransformer starting reduces starting current by lowering the applied voltage to the motor during the starting period.
- ▶ If the applied voltage is reduced by 50% of normal during the starting period, the starting torque is reduced to 25% of normal.
- ▶ Wye-delta starting is accomplished by connecting the stator windings in wye during the starting period and changing them to a delta connection during the normal run time.
- ▶ A motor will draw one-third as much current during the starting period with its windings connected in wye as it will if they are connected in delta.
- ▶ Two requirements for motors intended for wye-delta starting are:
 - A. All stator winding leads must be brought out at the terminal connection box.
 - B. The motor must be designed to run with its stator windings connected in delta.
- ▶ Motors intended to be used for part winding starting have two separate stator windings.
- ▶ Dual voltage motors can be used for part winding starting provided the motor is connected for low voltage operation.

KEY TERMS

code letter
interlocking

locked rotor current
nameplates

rotor bars
squirrel-cage induction motor

REVIEW QUESTIONS

1. What three factors determine the amount of torque produced by an AC induction motor?
2. When does an AC induction motor draw more current when starting than it does when running?
3. Why does the current flow to the motor increase when load is added to the motor?
4. What does the code letter found on the nameplate of the motor indicate?
5. At what degree angle between the stator current and the rotor current is the maximum torque developed?
6. What type of squirrel-cage rotor has the highest starting torque?
7. What type of squirrel-cage rotor has the best speed regulation?
8. Why can an induction motor never operate at synchronous speed?
9. What does the locked rotor current of a motor indicate?
10. The nameplate of a squirrel-cage motor indicates that the motor has a full-load speed of 875 RPM. How many poles per phase does the motor have?
11. What is the simplest of all starting methods for a squirrel-cage motor?
12. Explain interlocking.
13. How does autotransformer starting differ from resistor/reactor starting?
14. A three-phase squirrel-cage induction motor has its stator windings connected in a delta connection. During the starting period, the motor has a current draw of 360 amperes. If the stator windings were reconnected to form a wye connection during the starting period how much starting current would the motor draw?
15. What two conditions must be met before a motor can be used with a wye-delta starter?

UNIT 16

The Wound Rotor Induction Motor

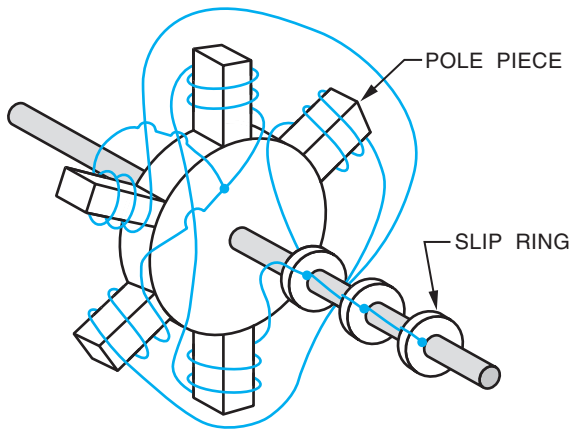
OBJECTIVES

After studying this unit the student should be able to:

- Describe the construction of a wound rotor induction motor
- Discuss the difference in operation between wound rotor and squirrel-cage induction motors
- Discuss the starting and running characteristics of a wound rotor induction motor
- Connect a wound rotor induction motor for operation
- Draw the standard schematic symbol for a wound rotor induction motor
- Perform an ohmmeter test on a wound rotor induction motor

Another type of three-phase induction motor used for operating large air conditioning units is the **wound rotor induction motor**. The stator winding of this motor is the same as the stator of a squirrel-cage induction motor. The rotor of the wound rotor motor, however, does not contain squirrel-cage bars. The rotor of this motor contains wound coils of wire as illustrated in Figure 16–1. The rotor will contain as many poles as there are stator poles. The motor shown in Figure 16–1 would be for a two-pole stator. Notice that there are three separate windings on the rotor. The finish end of each winding is connected together. This forms a wye connection for the rotor winding. The start end of each winding is connected to a separate **slip ring** on the rotor shaft.

The slip rings permit the connection of external resistance to the rotor windings. Figure 16–2 shows



► **Figure 16-1**
A wound rotor. (Source: Delmar/Cengage Learning)

a schematic diagram of the stator connection and rotor connection of a wound rotor motor. Notice that the wye-connected stator winding is connected directly to the incoming power. The wye-connected rotor is connected to three variable resistors. The dashed line drawn between the resistors indicates that they are mechanically connected together. If the resistance of one is changed, the resistance of the other two changes also.

Resistance is connected to the slip rings by means of **carbon brushes** as shown in Figure 16-3. Because the resistance connection to the rotor is external, the amount of resistance used in the circuit can be controlled. This permits the amount of current flow in the rotor to be controlled. If the current flow in the rotor is limited by the amount of resistance connected in the circuit, the stator current is limited also. A great advantage of the

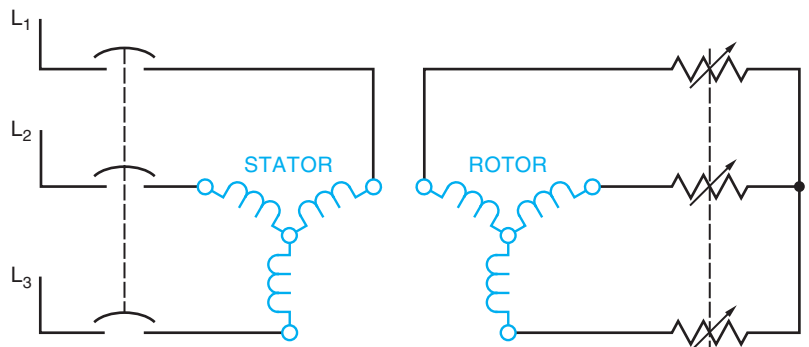
wound rotor motor is that it limits the amount of inrush current when the motor is first started. This eliminates the need for reduced voltage starters or wye-delta starting.

Another advantage of the wound rotor motor is its high starting torque. Because resistors are used to limit current flow in the rotor, the phase angle between the stator current and the rotor current is close to 90° . The schematic symbol for a wound rotor motor is shown in Figure 16-4.

MOTOR OPERATION

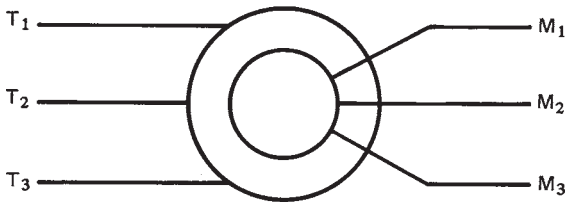
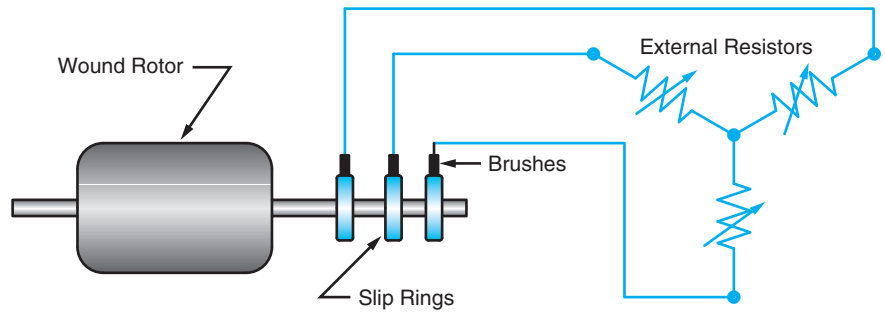
When power is applied to the stator winding, a rotating magnetic field is created in the motor. This magnetic field cuts through the windings of the rotor and induces a voltage into them. The amount of voltage induced in the rotor windings is determined by the same three factors that determined the amount of voltage induced in the squirrel-cage rotor. The amount of current flow in the rotor is determined by the amount of induced voltage and the amount of resistance connected to the rotor ($I = E/R$). 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 resistance is reduced, more current can flow, which will increase motor torque, and the rotor will increase in speed. This action continues until the rotor is operating at maximum speed and all resistance has been shorted out of the rotor circuit. When all of the resistance has been



► **Figure 16-2**
A wye-connected stator and wye-connected rotor.
(Source: Delmar/Cengage Learning)

► **Figure 16-3**
External resistance is connected to the rotor circuit with brushes and slip rings.
(Source: Delmar/Cengage Learning)



► **Figure 16-4**
Schematic symbol of a wound rotor induction motor.
(Source: Delmar/Cengage Learning)

shorted out, the motor operates like a squirrel-cage induction motor.

STARTING

Most large wound rotor motors use a method of **step starting** as opposed to actual variable resistors. Step starting is similar to shifting the gears in the transmission of an automobile. The transmission is placed in first gear when the car is first started. As the car gains speed, the transmission is shifted to second gear, then third gear, and so on until the car is operating in its highest gear. When a wound rotor motor is step started, it begins with maximum resistance connected in the rotor circuit. As the motor speed increases, resistance is shorted out of the circuit until the windings of the rotor are shorted together. The number of steps can vary from one motor to another, depending on the size of the motor and how smooth a starting action is desired.

There are different control methods used to short out the steps of resistance when starting a wound rotor motor. Some controllers sense the amount of

current flow to the stator. This method is known as current limit control. Another method detects the speed of the rotor. This method is known as slip frequency control. One of the most common methods uses time relays to control when resistance is shorted out of the circuit. This method is known as **definite time control**. Figure 16-5 shows a schematic diagram of a time-controlled starter for a wound rotor motor. In this schematic, the motor circuit is shown at the top of the diagram. A control transformer is used to step the line voltage down to the value of voltage used in the control circuit. The operation of the circuit is as follows:

1. When the start button is pressed, a circuit is completed through M motor starter coil, TR1 coil, and the overload contact. When M coil energizes, all M contacts close. The three large load contacts located at the top of the diagram close and connect the stator winding to the line. The M contact located beneath the start button is known as the **holding, sealing, or maintaining contact**. Its job is to provide a continued circuit to the M coil when the start button is released. The motor now begins to run in its lowest speed. Maximum resistance is connected in the rotor circuit.
2. TR1 relay is a timer. For this example, it shall be assumed that all timers are set for a delay of 3 seconds. When TR1 coil energizes, it begins a time operation. After 3 seconds, TR1 contact closes. This completes a circuit to S1 coil and TR2 coil.

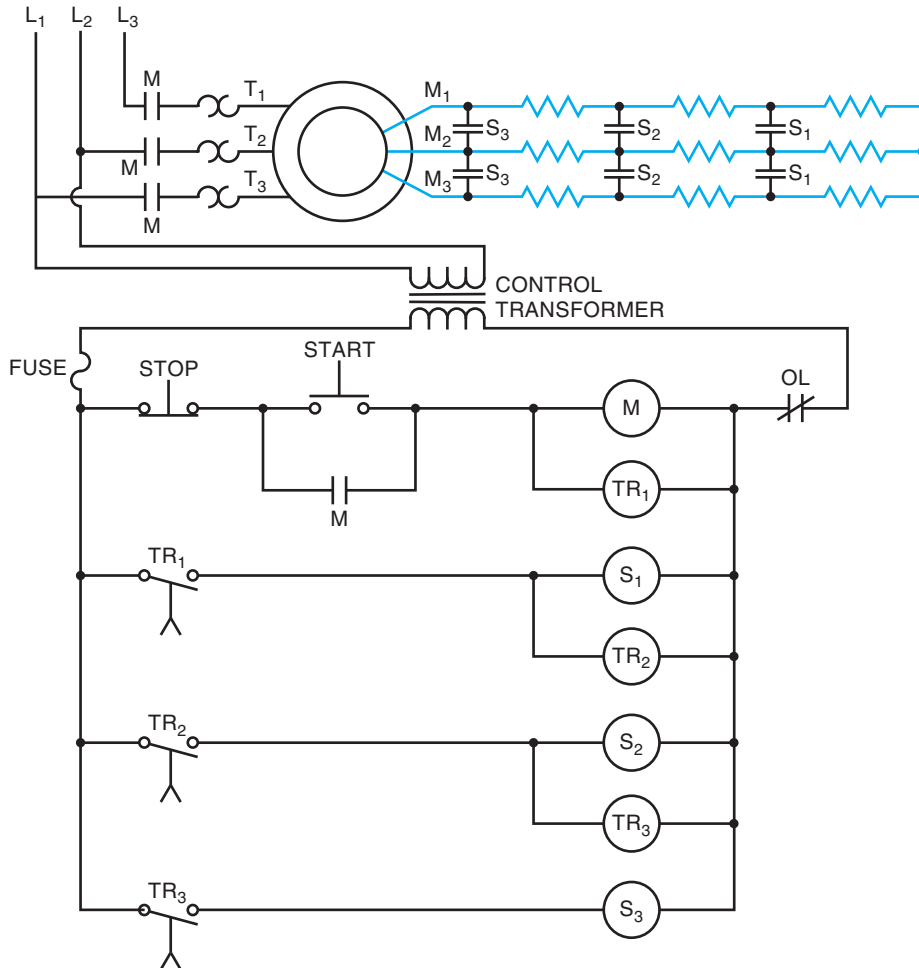


Figure 16-5
Definite time starting for a wound rotor motor. (Source: Delmar/Cengage Learning)

3. When S1 coil energizes, both S1 contacts close and short out the last three resistors in the rotor circuit. This causes the motor to accelerate to the next higher speed. When TR2 coil energizes, it begins timing.
4. At the end of a 3-second time period, TR2 contact closes and completes a circuit to coil S2 and TR3.
5. When S2 coil energizes, both S2 contacts close and short out the next set of resistors. This permits the motor to accelerate to a higher speed. When TR3 coil energizes, it begins its timing sequence.
6. After a 3-second time period, contact TR3 closes and provides a complete circuit for coil S3. This causes both S3 contacts to close and short out the last set of resistors. The motor now accelerates to its highest speed.
7. When the stop button is pressed, the circuit to coil M and coil TR1 is broken. When coil M deenergizes, all M contacts open. This disconnects the stator winding from the line. When TR1 coil deenergizes, contact TR1 opens immediately. This deenergizes coil S1 and coil TR2. When coil S1 deenergizes, both S1 contacts return to their open position.

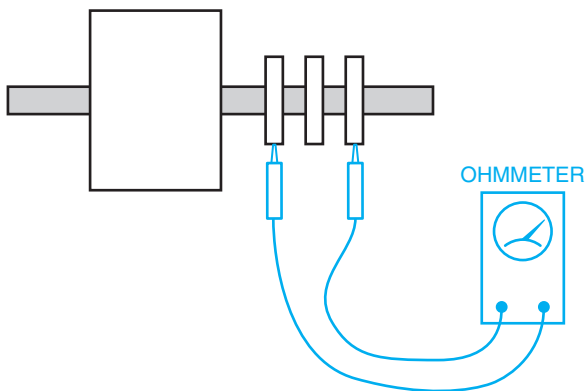
When coil TR1 deenergizes, contact TR2 opens immediately. When contact TR2 opens, it breaks the circuit to coil S2 and coil TR3. When coil S2 deenergizes, both S2 contacts reopen. Contact TR3 opens immediately when coil TR3 deenergizes. This causes coil S3 to deenergize and open both S3 contacts.

8. If the fuse should blow, or the overload contact open, it has the same effect as pressing the stop button.

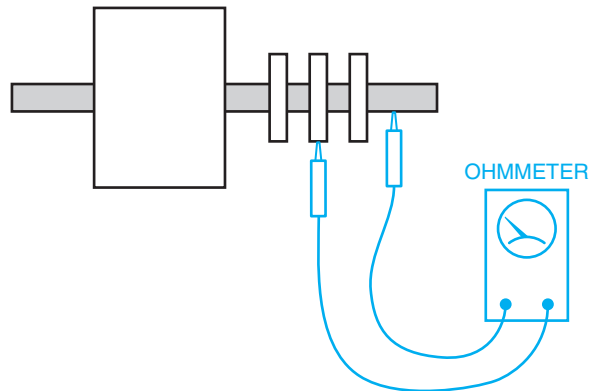
TESTING A WOUND ROTOR MOTOR

Because the stator winding of the wound rotor motor is the same as the squirrel-cage motor, the

same test procedure can be followed. Testing the rotor of a wound rotor motor is very similar to testing the stator. The rotor can be tested for an open winding with an ohmmeter by checking the continuity between each of the slip rings, Figure 16–6. The resistance readings should be the same between each pair of slip rings. To test the rotor for a ground, connect one ohmmeter lead to the shaft, and connect the other lead to each one of the slip rings, Figure 16–7. The ohmmeter should show no continuity between the rotor windings and ground. Like the stator winding, the rotor is difficult to test for a shorted winding. To test the rotor for a shorted winding it is generally necessary to use equipment that will measure the inductance of the winding instead of its resistance.



► **Figure 16–6**
Testing a rotor for an open winding. (Source: Delmar/Cengage Learning)



► **Figure 16–7**
Testing a rotor for a grounded winding. (Source: Delmar/Cengage Learning)

SUMMARY

- The stator winding of a wound rotor induction motor is the same as the stator winding of a squirrel-cage induction motor.
- The rotor of a wound rotor induction motor contains windings instead of squirrel-cage bars.
- The rotor of a wound rotor induction motor will contain as many poles per phase as the stator winding.

- Ⓛ The finish ends of each winding of a wound rotor are connected together to form a wye connection and the other ends of each winding are connected to a slip ring on the shaft.
- Ⓛ Wound rotor induction motors are sometimes called slip ring motors because they contain three slip rings on their shaft.
- Ⓛ Wound rotor induction motors have a higher starting torque per amp of starting current than any other type of three-phase motor.
- Ⓛ The speed of a wound rotor induction motor can be controlled by permitting resistance to remain in the rotor circuit during operation.
- Ⓛ The brushes of a wound rotor induction motor are used to provide connection of the rotor windings to external resistors.
- Ⓛ The stator winding leads of a wound rotor induction motor are labeled T_1 , T_2 , and T_3 .
- Ⓛ The rotor leads of a wound rotor induction motor are labeled M_1 , M_2 , and M_3 .

KEY TERMS

carbon brushes
definite time control
holding, sealing, or
maintaining contact

slip ring
step starting

wound rotor induction
motor

REVIEW QUESTIONS

1. How many slip rings are located on the shaft of the rotor of a wound rotor induction motor?
2. What is the purpose of the slip rings?
3. Name two advantages of the wound rotor motor over the squirrel-cage motor.
4. What two factors determine the amount of current flow in the rotor of a wound rotor motor?
5. What does the dashed line drawn between the three resistors shown in Figure 16-2 indicate?
6. Why is the starting torque of a wound rotor induction motor higher than the starting torque of a squirrel-cage induction motor?
7. The stator of a wound rotor motor has a synchronous speed of 1,200 RPM when connected to a 60-Hz line. How many poles per phase are there in the rotor?
8. Refer to Figure 16-5. Describe what would happen in this circuit if coil S1 should be open when the motor started.
9. Refer to Figure 16-5. Describe what would happen in this circuit if coil TR2 should be open when the motor is started.
10. Refer to Figure 16-5. Describe what would happen in this circuit if holding contact M should become stuck together when the motor is started and not open.

▶ TROUBLESHOOTING QUESTIONS

Refer to the schematic shown in Figure 16–5 to answer the following questions. It is to be assumed that all timers are set for a delay of 3 seconds.

1. When the start button is pressed, the motor starts in its lowest speed. After a delay of 6 seconds, the motor accelerates to third speed and 3 seconds later accelerates to the fourth or highest speed. Which of the following could cause this problem?
 - A. Coil TR_1 is open.
 - B. Timed contact TR_1 did not close.
 - C. Coil S_1 is open.
 - D. Coil TR_2 is open.
2. When the start button is pressed, the motor starts and accelerates through all speeds normally. When the stop button is pressed, the motor continues to operate normally. Which of the following could cause this condition?
 - A. The start button is shorted. (Shorted means contacts welded together.)
 - B. The stop button is shorted.
 - C. M auxiliary contact is shorted.
 - D. Any of the above.
3. When the start button is pressed, the motor accelerates through the first three steps of speed normally. When the motor tries to accelerate to the fourth speed, however, the motor stops. It is found that the control circuit fuse has blown. Which of the following conditions could cause this problem?
 - A. The overload (OL) contact has shorted.
 - B. Coil S_2 is shorted.
 - C. Coil TR_3 is shorted.
 - D. Coil S_3 is shorted.
4. When the start button is pressed, the motor immediately starts operating in third speed. Three seconds later, the motor accelerates to fourth speed. Which of the following could cause this condition?
 - A. TR_2 timed contact is shorted.
 - B. TR_3 timed contact is shorted.
 - C. S_2 load contacts are shorted.
 - D. None of the above.
5. When the start button is pressed, the motor will not start. Which of the following could cause this condition?
 - A. The control transformer is defective.
 - B. The control circuit fuse is blown.
 - C. The overload contact is open.
 - D. All of the above.

UNIT 17

The Synchronous Motor

OBJECTIVES

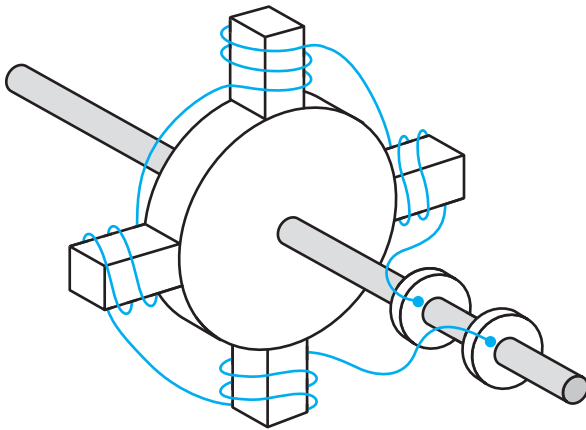
After studying this unit the student should be able to:

- Describe the construction of a synchronous motor
- Compare the operating characteristics of a synchronous motor with those of a squirrel-cage induction motor and a wound rotor induction motor
- Discuss the starting and running characteristics of a synchronous motor
- Describe the function of the field discharge resistor
- Discuss power factor correction using the synchronous motor
- Perform an ohmmeter test of a synchronous motor

The third type of three-phase motor to be discussed is the **synchronous motor**. This motor has several characteristics that no other type of motor has. Some of the characteristics of a synchronous motor are:

1. The synchronous motor is not an induction motor. This means that it does not depend on induced voltage from the stator to produce a magnetic field in the rotor.
2. The synchronous motor will run at a constant speed from no load to full load.
3. The synchronous motor has the ability to not only correct its own power factor, but can also correct the power factor of other motors connected to the same line.

The synchronous motor has the same type of stator windings as the other two three-phase motors. The rotor of a synchronous motor has

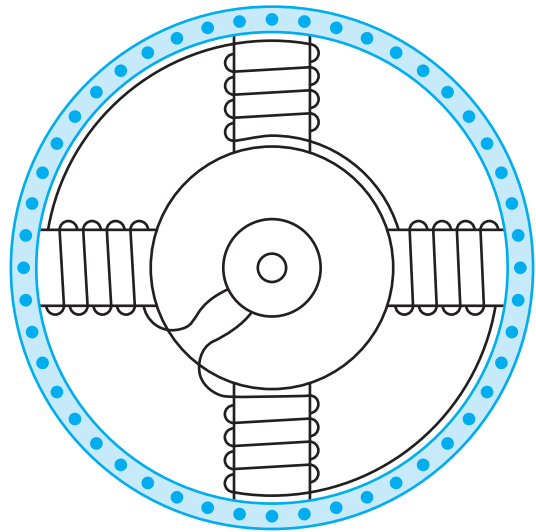


► **Figure 17-1**
Rotor. (Source: Delmar/Cengage Learning)

windings similar to the wound rotor induction motor, Figure 17-1. Notice that the winding in the rotor of a synchronous motor is different, however. The winding of a synchronous motor is one continuous set of coils instead of three different sets as is the case with the wound rotor motor. Notice also that the synchronous motor has only two slip rings on its shaft as opposed to three on the shaft of a wound rotor motor.

STARTING A SYNCHRONOUS MOTOR

The rotor of a synchronous motor also contains a set of type “A” squirrel-cage bars. This set of squirrel-cage bars is used to start the motor and is known as the **amortisseur** winding, Figure 17-2. When power is first connected to the stator, the rotating magnetic field cuts through the type “A” squirrel-cage bars. The cutting action of the field induces a current into the squirrel-cage bars. 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, DC is connected to the rotor through the



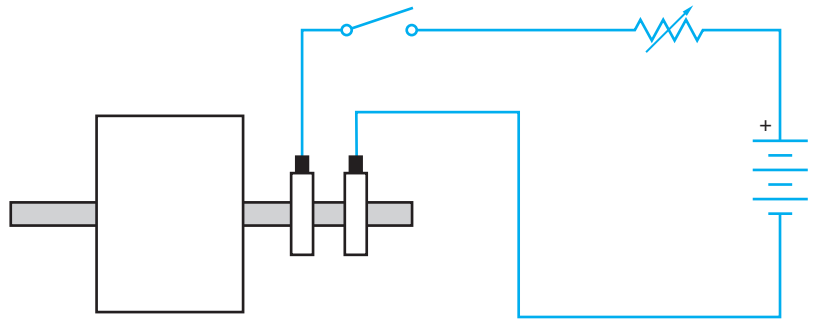
► **Figure 17-2**
Amortisseur winding. (Source: Delmar/Cengage Learning)

slip rings on the rotor shaft, Figure 17-3. When DC is applied to the rotor, the windings on 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 begins to turn at the synchronous speed of the field, there is no more cutting action between the field and the amortisseur winding. This causes the current flow in the amortisseur winding to cease.

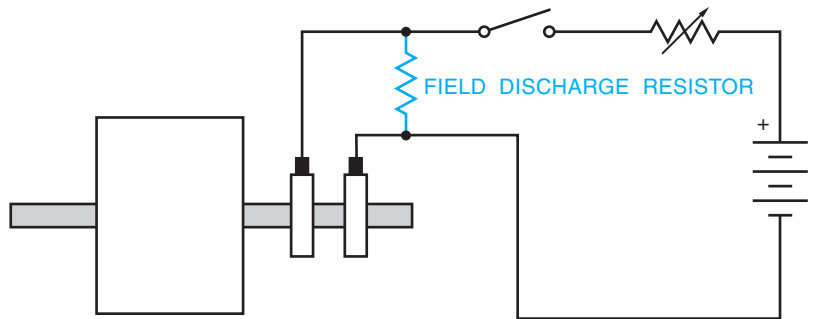
Notice that the synchronous motor starts as a squirrel-cage induction motor. Because the rotor bars used are type “A,” they have a relatively high resistance, which gives the motor good starting torque and low starting current. A synchronous motor must never be started with DC connected to the rotor. If DC 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 of the rotor are attracted to the rotating magnetic field of the stator and are alternately attracted and repelled 60 times a second. As a result, the rotor does not turn.

► **Figure 17-3**
Direct current is applied to the rotor through the slip rings.

(Source: Delmar/Cengage Learning)



► **Figure 17-4**
A field discharge resistor protects the rotor circuit. (Source: Delmar/Cengage Learning)



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 voltage from becoming excessive, a resistor is connected across the winding. This resistor is known as the **field discharge resistor**, Figure 17-4. It also helps to reduce the voltage induced into the rotor by the collapsing magnetic field when the DC is disconnected from the rotor.

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 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 applied to the rotor. This is the reason that 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 and the rotor continues to turn at the same speed.

POWER FACTOR CORRECTION

The power factor of the synchronous motor can be changed by adjusting the **DC excitation current** to the rotor. When the DC is adjusted to the point that the motor current is in phase with the voltage, the motor has a power factor of 100%. This is considered to be normal excitation for the motor. For this example, assume this current to be 10 amps. If the DC power supply is adjusted to a point that the excitation current is less than 10 amps, the rotor is under excited. This causes the motor to have a

lagging power factor like an induction motor. If the excitation current is adjusted above 10 amps, the rotor is overexcited. This causes the motor to have a leading power factor like a capacitor. When a synchronous motor is operated at no load and used for power factor correction, it is generally referred to as a **synchronous condenser**. Utility companies generally charge industries extra for poor power factor in the plant. For this reason, synchronous motors are often used when a large horsepower motor must be used. Commercial and industrial air conditioning systems are often the largest single load in a plant or building. It is not uncommon to find synchronous motors being used to operate the compressors of large air-conditioning systems.

THE POWER SUPPLY

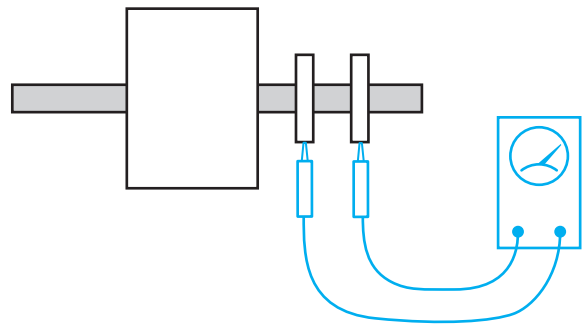
DC power supply of a synchronous motor can be provided by several methods. The most common of these methods is either a small DC generator mounted to the shaft of the motor, or an electronic power supply that converts the AC line voltage to DC voltage.

TESTING THE SYNCHRONOUS MOTOR

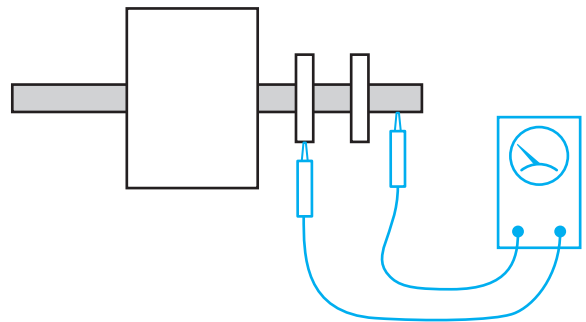
The procedure for testing the stator winding of a synchronous motor is the same as that described for testing the stator of a squirrel-cage induction motor. The rotor can be tested with an ohmmeter for an open winding or a grounded winding. To test the rotor for an open winding, connect one of the ohmmeter leads to each of the slip rings on the rotor shaft, Figure 17-5. Since the rotor winding of a synchronous motor is intended for DC current, the resistance of the wire will be high as compared with the wire resistance of a wound rotor motor. Owing to the fact that alternating current flows in the rotor of a wound rotor motor, the current is limited by the inductance of the coil and not its resistance.

To test the rotor for a grounded winding, connect one ohmmeter lead to the shaft of the motor, and the other lead to one of the slip rings. There should be no continuity between the winding and the motor shaft, Figure 17-6.

Because the resistance of the rotor is relatively high, a shorted winding can often be found with



► **Figure 17-5**
Testing the rotor for an open winding. (Source: Delmar/Cengage Learning)



► **Figure 17-6**
Testing the rotor for a grounded winding. (Source: Delmar/Cengage Learning)

the ohmmeter. In coils designed for DC current, the resistance of the wire is used to limit the flow of current. For example, assume the specifications of a synchronous motor indicate that the DC excitation voltage should be 125 volts, and that maximum rotor current should be 10 amps. The resistance of the rotor can now be calculated by using Ohm's law:

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

$$R = \frac{125}{10}$$

$$R = 12.5 \text{ ohms}$$

If the ohmmeter measures a rotor resistance close to 12.5 ohms, the rotor is good. If the ohmmeter measures a much lower resistance, however, the rotor is shorted.

THE BRUSHLESS EXCITER

Many large synchronous motors use a brushless exciter instead of slip rings and brushes. The **brushless exciter** is constructed by incorporating a small three-phase alternator winding on the shaft of the motor, Figure 17-7. The three-phase winding is placed inside the field of electromagnets, Figure 17-8. A variable source of direct current is used to control the strength of the electromagnets. The amount of voltage induced into the armature winding is determined by three factors:

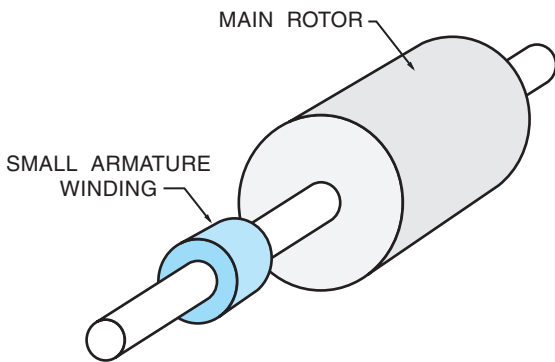
1. The number of turns of wire in the armature winding.

2. The speed of the armature.

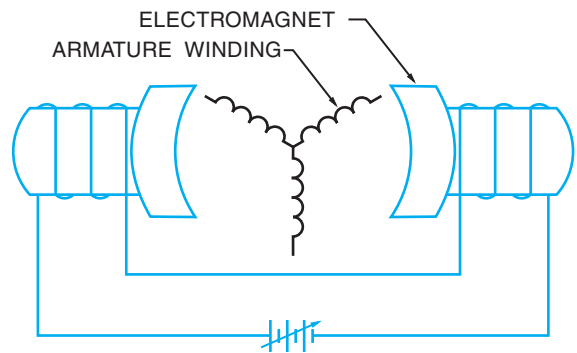
3. The strength of the electromagnets.

Because the amount of DC current that flows through the windings of the electromagnets determines their strength, the output voltage of the three-phase armature can be controlled by the DC excitation current.

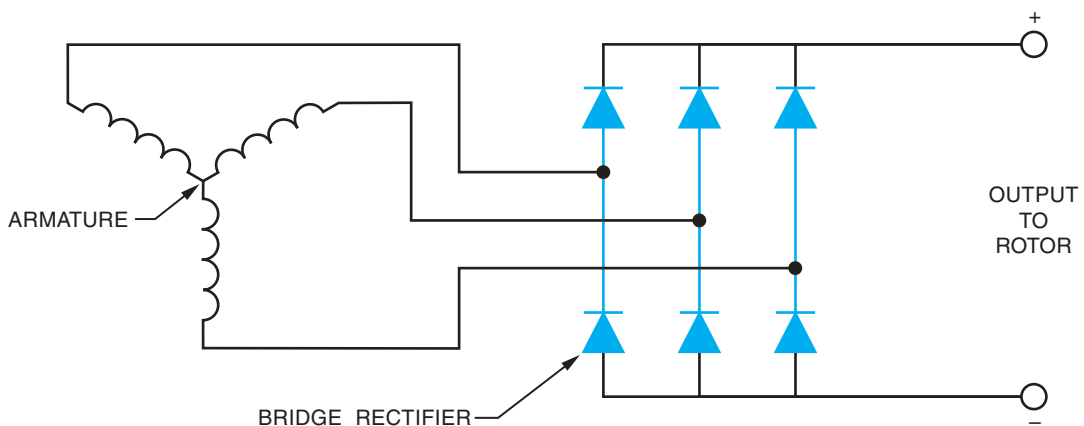
The output voltage of the alternator winding is then rectified to direct current with a three-phase bridge rectifier, Figure 17-9. The bridge rectifier and all protective devices such as fuses are mounted on the motor shaft with the armature winding. The output of the bridge rectifier is connected to the



► **Figure 17-7**
A brushless exciter contains a small three-phase winding on the motor shaft. (Source: Delmar/Cengage Learning)



► **Figure 17-8**
The armature winding is between two electromagnets. (Source: Delmar/Cengage Learning)



► **Figure 17-9**
The output of the armature winding is connected to a three-phase bridge rectifier. (Source: Delmar/Cengage Learning)

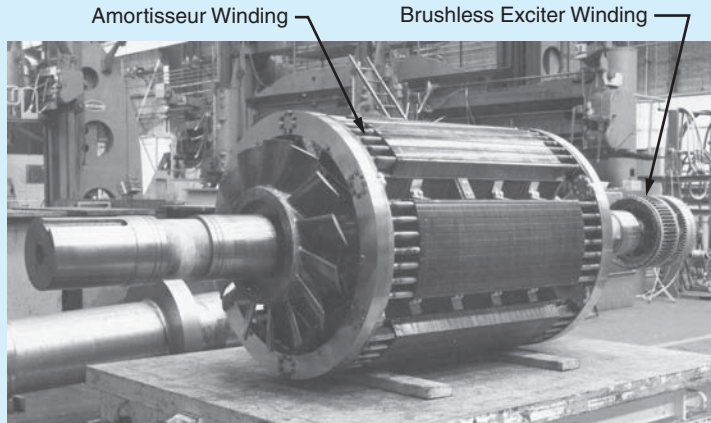


Figure 17-10
Rotor of a large synchronous motor. (Courtesy of Electric Machinery Corp.)

winding of the main rotor. The amount of DC excitation in the rotor of the synchronous motor is now controlled by the amount of DC excitation current supplied to the windings of the electromagnets.

The rotor of a large synchronous motor is shown in Figure 17-10. The amortisseur winding and the brushless exciter winding can be seen in the photograph.

SUMMARY

- ▶ The synchronous motor is not an induction motor.
- ▶ The synchronous motor must have an external source of direct current supplied to the rotor during normal operation.
- ▶ The DC current supplied to the rotor is known as the excitation current.
- ▶ Synchronous motors operate at a constant speed from no load to full load.
- ▶ Synchronous motors run at the speed of the rotating magnetic field.
- ▶ The two factors that determine the speed of a synchronous motor are:
 - A. Number of stator poles per phase.
 - B. Frequency of the applied voltage.
- ▶ Synchronous motors use a special squirrel-cage winding called the amortisseur winding for starting.
- ▶ A synchronous motor can be made to have a leading power factor by over excitation of the rotor current.

 KEY TERMS

amortisseur
brushless exciter
DC excitation current

electromagnetic field
field discharge resistor
synchronous condenser

synchronous motor

 QUESTIONS

1. Name three characteristics of a synchronous motor that the squirrel-cage induction motor and the wound rotor motor do not have.
2. What is an amortisseur winding?
3. How many slip rings are located on the shaft of a synchronous motor?
4. How many slip rings are located on the shaft of a wound rotor induction motor?
5. Is a synchronous motor started with DC excitation voltage applied to the rotor?
6. What is the field discharge resistor used for?
7. A synchronous motor has an eight-pole stator. What will be the speed of the rotor when it is under full load?
8. How is it possible to know when a synchronous motor has normal excitation applied to its rotor?
9. How can a synchronous motor be made to have a leading power factor?
10. What is a synchronous condenser?

UNIT 18



Brushless DC Motors

OBJECTIVES

After studying this unit the student should be able to:

- ▶ Describe the operation of a brushless DC motor
- ▶ Discuss applications for brushless DC motors
- ▶ List differences in construction between brushless DC motors and other types of motors
- ▶ Discuss the operation and advantages of variable speed air handlers

Brushless direct current motors have become very popular for operating variable speed air handlers found in many residential central heating and cooling systems. The typical air handler is powered by a multispeed motor that can generally operate at three speeds. When the fan motor is started, however, it operates at its set speed until it is turned off. Basically, the blower motor is either full on or completely off. **Variable speed** air handlers permit the motor to operate at different speeds in accord with the demands of the system. Many variable speed air handlers are operated at a low speed continuously to maintain air circulation throughout the dwelling at all times. When the heating or cooling system turns on, the fan speed can be increased gradually and in steps instead of all at once.

Variable speed air handlers exhibit several advantages over air handlers that operate at a single speed. Some of these advantages are:

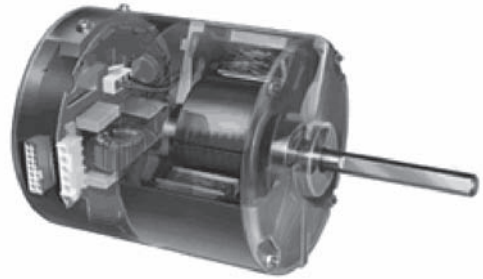
Dust collection. Single speed air handlers pull dust through the filter at a high rate of speed. This lessens the filter's ability to trap dust particles. Variable speed air handlers operate at a very low speed most of the time, causing more dust particles to be collected by the filter.

Less temperature variation. Typically, the inside temperature will vary from three to five degrees before the heating or cooling system turns on. The variable speed air handler can be operated at different speeds between the cycling of the heating or cooling system to provide more or less air flow as needed. This can greatly reduce the temperature variation and permits the temperature to remain closer to the comfort zone setting.

Better humidity control during cooling. When the air-conditioning compressor starts, the speed of the air handler is increased gradually instead of all at once. This permits the warm air to flow across the evaporator coil at a slower rate, permitting the coil to rapidly cool down. This **rapid cooldown** results in increased moisture removal.

THE BRUSHLESS DC MOTOR

The brushless DC motor operates by converting direct current into three-phase alternating current at different frequencies. The motor contains a **permanent magnet rotor**, a stator, and the electronics necessary to change direct current into three-phase alternating current, Figure 18–1. The speed of the motor is determined by the frequency of the three-phase current. The motor operates on the principle of a rotating magnetic field very similar to that of a three-phase induction motor. The brushless DC motor, however, is *not* an induction motor. It does not depend on current being induced into the rotor to produce a rotor magnetic field. Because permanent magnets supply the rotor magnetic field, the brushless DC motor does not exhibit the high inrush current during starting that is a characteristic of



► **Figure 18–1**
Brushless DC motor. (Courtesy of GE ECM™ Technologies).

induction type motors. The starting current and the running current of the motor are basically the same. This feature greatly reduces the current-handling requirement of the electronic components needed to change direct current into three-phase alternating current.

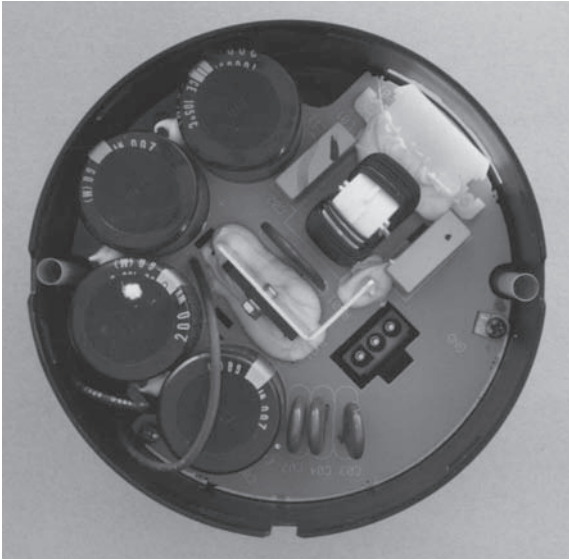
The factors that determine the amount of torque produced by the brushless DC motor are the same as those for any other electric motor:

1. Strength of the magnetic field of the stator.
2. Strength of the magnetic field of the rotor.
3. Phase angle difference between rotor and stator flux.

Because the rotor magnetic field is supplied by permanent magnets, the flux of the rotor and stator are always in phase with each other. This produces a strong torque for this type of motor.

The electronic components necessary to change single-phase alternating current into direct current and then into three-phase alternating current are located inside the motor housing, Figure 18–2. Most variable frequency type controls first change alternating current into direct current because it is a simpler process to produce multiphase alternating current from direct current than to change the frequency and number of phases of an existing alternating current source.

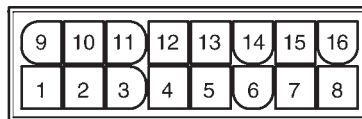
Brushless DC motors are operated in one of two modes, the thermostat mode or the variable speed mode. When used in the thermostat mode, the motor is controlled by a 24-VAC signal from the thermostat. When used in the variable speed mode, the motor is controlled by a pulse width modulating signal.



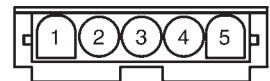
► **Figure 18-2**
Electronic control unit for a brushless
DC motor. (Courtesy of GE ECM™ Technologies).

The motor is provided with two terminal connections. One is a 16-pin connector and is called the **control connector**. This connector receives the information necessary to control the operation of the motor. The other connection is a 5-pin connector and is called the **power connector**. This connector provides the power to operate the motor. A pin connection diagram is shown in Figure 18-3.

Brushless DC motors can generally be obtained in 1/3, 1/2, 3/4, or 1 horsepower ratings. They can exhibit efficiency as high as 82% and can operate on 120/240 and 277 VAC at 50 or 60 Hz. The speed range is from 300 to 1,200 RPM. Although the motor can be operated at 1,200 RPM, it is generally recommended not to operate the motor above 1,050 RPM when used for continuous operation.



CONTROL CONNECTOR	
PIN	DESCRIPTION
1	C1
2	W/W1
3	C2
4	DELAY
5	COOL
6	Y1
7	ADJUST
8	OUT -
9	O
10	BK/PWM
11	HEAT
12	R
13	EM/W2
14	Y/Y2
15	G
16	OUT +



POWER CONNECTOR	
PIN	DESCRIPTION
1	JUMPER PIN 1 TO PIN 2 FOR 120 VAC INPUT ONLY
2	
3	CHASSIS GRD.
4	AC LINE
5	AC LINE

WARNING—APPLYING 240 VAC LINE INPUT WITH PINS 1 AND 2 JUMPED WILL PERMANENTLY DAMAGE THE UNIT.

► **Figure 18-3**
Pin connection diagram for a brushless
DC motor. (Source: Delmar/Cengage Learning)

Electronic Control

The brushless DC motor is controlled by a circuit board located in the air handler. The board supplies both direct current to the motor and the signals that determine motor speed. Some boards are preset at the factory for the specific type of air handler unit. Other boards contain DIP (Dual Inline Package)

switches that permit the air handler to be set for different operating conditions. Typical DIP switch configurations for some systems are:

Switches 1 and 2. Set for system tonnage.

Switches 3 and 4. Set for 300, 400, or 450 cfm/ton.

Switches 5 and 6. Set for time delay or mode.

Switches 7 and 8. Set for desired heating flow.

SUMMARY

- Ⓢ Brushless DC motors are generally used to power the blower in variable speed air handlers.
- Ⓢ The circuitry necessary to change single-phase alternating current into three-phase alternating current is located inside the motor housing.
- Ⓢ Brushless DC motors operate on the principle of a rotating magnetic field.
- Ⓢ Brushless DC motors are not induction motors. They do not depend on an inducted current to produce a magnetic field in the rotor.
- Ⓢ Brushless DC motors are operated in one of two modes.
- Ⓢ Brushless DC motors can have efficiencies as high as 82%.
- Ⓢ Because brushless DC motors are not induction motors, they do not exhibit the high starting current associated with induction-type motors.

KEY TERMS

brushless
control connector
frequency

permanent magnet rotor
power connector
rapid cooldown

rotating magnetic field
variable speed

REVIEW QUESTIONS

1. What is the operating voltage of a brushless DC motor?
2. What is the recommended maximum operating speed for a brushless DC motor when used for continuous operation?
3. If the motor is to be operated on 120 VAC, what must be done to permit the motor to operate on this voltage?
4. Referring to the power connector, which pins are used to connect AC line voltage to the motor?
5. When the brushless DC motor is used in the thermostat mode, what controls the operation of the motor?



6. Name three factors that determine the amount of torque produced by a brushless DC motor.
7. Referring to the control connector, to which pin would Y/Y2 be connected?
8. Name three advantages of a variable speed air handler over a single speed air handler.

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SECTION 4

Transformers

UNIT 19



Isolation Transformers

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the different types of transformers
- Calculate values of voltage, current, and turns for single-phase transformers using formulas
- Calculate values of voltage, current, and turns for a single-phase 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 HVAC field. They range in size from occupying a space of less than 1 cubic inch to requiring rail cars to move them after they have been broken into sections. Their ratings can range from mVA (millivolt amps) to GVA (gigavolt amps).

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 such as:

- A. Isolation.
- B. Auto.
- C. Current.

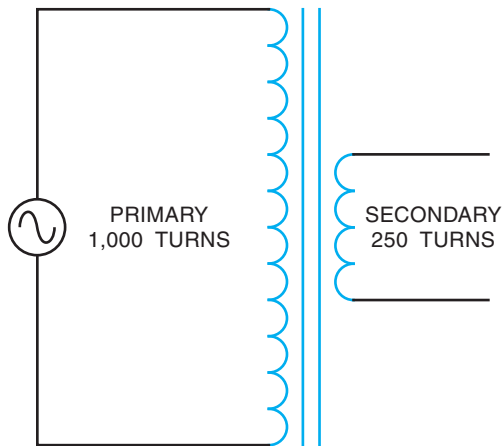
A basic law concerning transformers is that *all values of a transformer are proportional to its turns ratio*. This does not mean that the exact number of turns of wire on each winding must be known to determine different values of voltage and current for a transformer. What must be known is the *ratio* 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 19–1. The turns ratio of this transformer is 4 to 1 or 4:1 ($1,000/250 = 4$). This indicates there are four turns of wire on the primary for every one turn of wire on the secondary.

TRANSFORMER FORMULAS

There are different formulas that 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



► **Figure 19–1**
All values of a transformer are proportional to its turns ratio. (Source: Delmar/Cengage Learning)

N_s = Number of turns in the secondary

E_p = Voltage of the primary

E_s = Voltage of the secondary

I_p = Current in the primary

I_s = Current in the secondary

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} \quad \frac{E_p}{E_s} = \frac{I_s}{I_p} \quad \frac{N_p}{N_s} = \frac{I_s}{I_p}$$

or

$$E_p \times N_s = E_s \times N_p$$

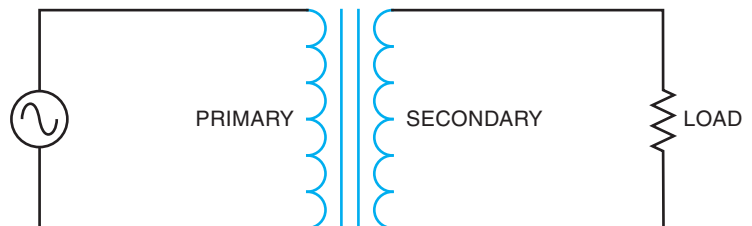
$$E_p \times I_p = E_s \times I_s$$

$$N_p \times I_p = N_s \times I_s$$

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 19–2. Any winding of a transformer can be used as a primary or secondary winding provided its voltage or current rating is not exceeded. Transformers can also be operated at a lower voltage than their rating indicates, but they cannot be connected to a higher voltage. Assume the transformer shown in Figure 19–2, for example, has a primary voltage rating of 480 volts and the secondary has a voltage rating of 240 volts. Now assume that the primary winding is connected to a 120-volt source. No damage would occur to the transformer, but the secondary winding would produce only 60 volts.

ISOLATION TRANSFORMERS

The transformers shown in Figures 19–1 and 19–2 are **isolation transformers**. This means that the secondary winding is physically and electrically isolated from the primary winding. There is



► **Figure 19–2**
Isolation transformer.
(Source: Delmar/Cengage Learning)

no electrical connection between the primary and secondary winding. This transformer is magnetically coupled, not electrically coupled. This “line isolation” is often a very desirable characteristic. Because 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. The current in an inductor rises at an exponential rate, Figure 19–3. 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 the 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 19–4. 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 19–5.

Another purpose of isolation transformers is to remove some piece of electrical equipment from ground. It is sometimes desirable that a piece of electrical equipment not be connected directly to ground. This is often done as a safety precaution to eliminate the hazard of an accidental contact between a person at ground potential and the ungrounded conductor. If the case of the equipment should come in contact with the ungrounded conductor, the isolation transformer would prevent a circuit being completed to ground through someone touching the case of the equipment. Many alternating current circuits have one side connected to ground. A familiar example of this is the common

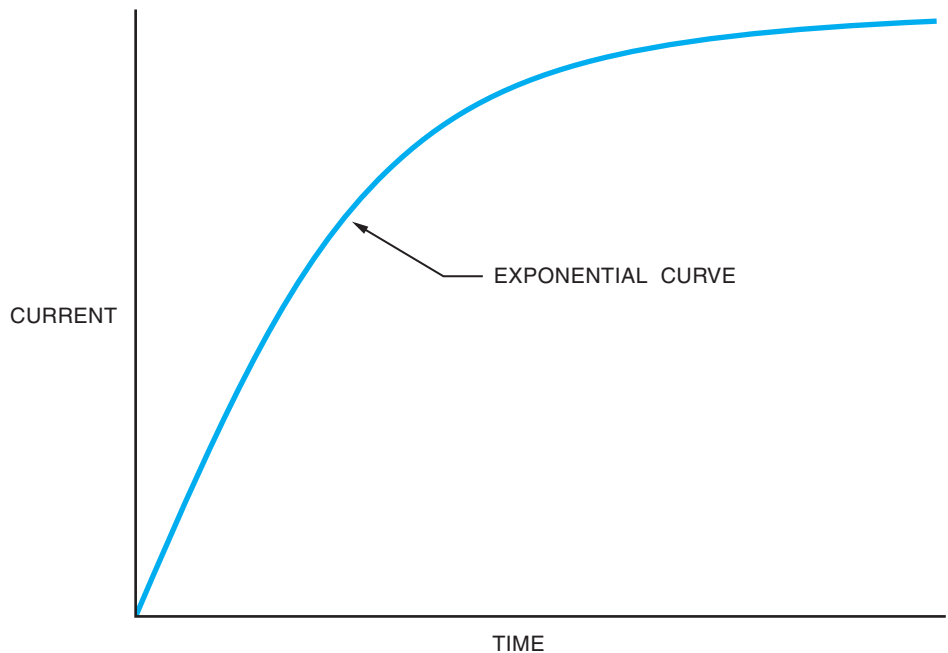
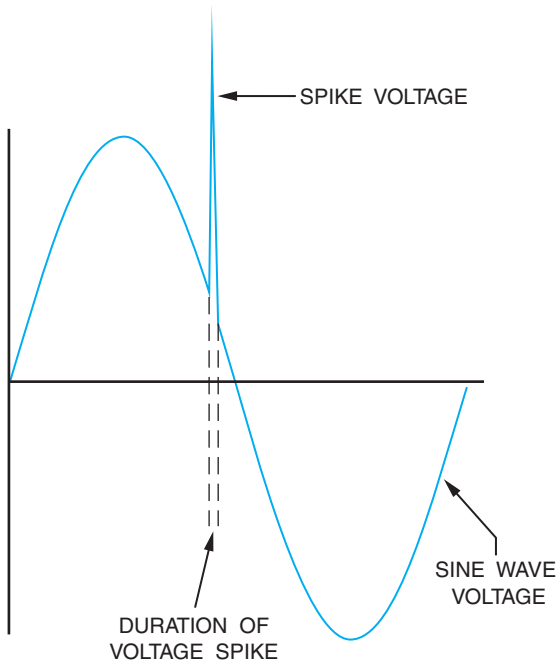


Figure 19–3
The current through an inductor rises at an exponential rate.

(Source: Delmar/Cengage Learning)

120-volt circuit with a grounded neutral conductor, Figure 19–6. An isolation transformer can be used to remove a piece of equipment from circuit ground.



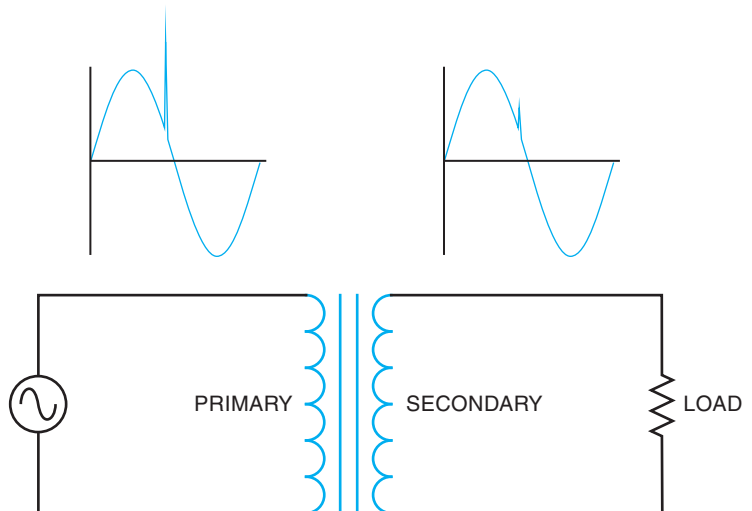
► **Figure 19–4**
Voltage spikes are generally of short duration.
(Source: Delmar/Cengage Learning)

TRANSFORMER CONSTRUCTION

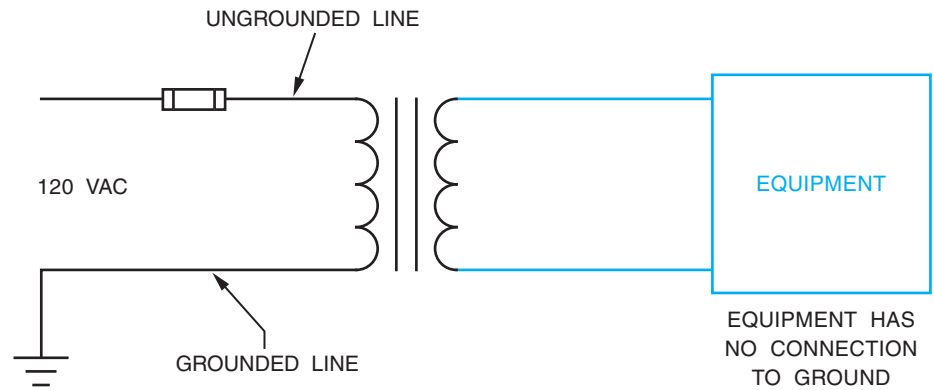
The basic construction of an isolation transformer is shown in Figure 19–7. A metal core is used to provide good magnetic coupling between the two windings. The core is generally made of laminations stacked together. Laminating the core helps reduce power losses due to eddy current induction. Figure 19–7 shows the basic design of electrically separated winding.

TRANSFORMER CORE TYPES

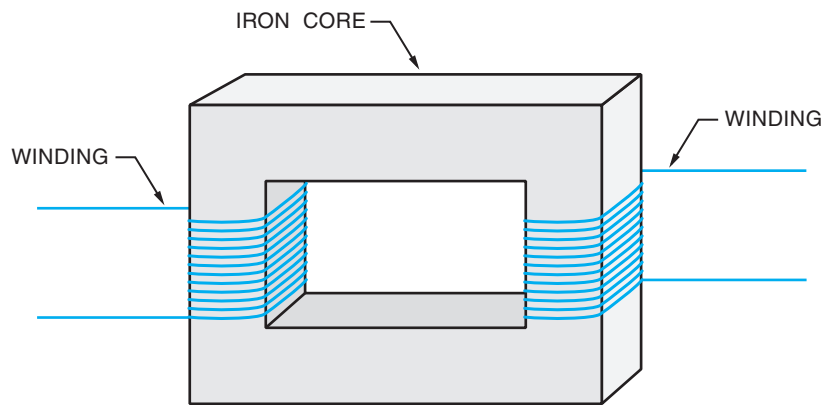
There are several different types of cores used in the construction of transformers. Most cores are made from thin steel punchings laminated together to form a solid metal core. Laminated cores are preferred because a thin layer of oxide forms on the surface of each lamination, which acts as an insulator to reduce the formation of eddy currents inside the core material. The amount of core material needed for a particular transformer is determined by the power rating of the transformer. The amount of core material must be sufficient to prevent saturation at full load. The type and shape of the core generally determines the amount of magnetic coupling between the windings and to some extent the efficiency of the transformer.



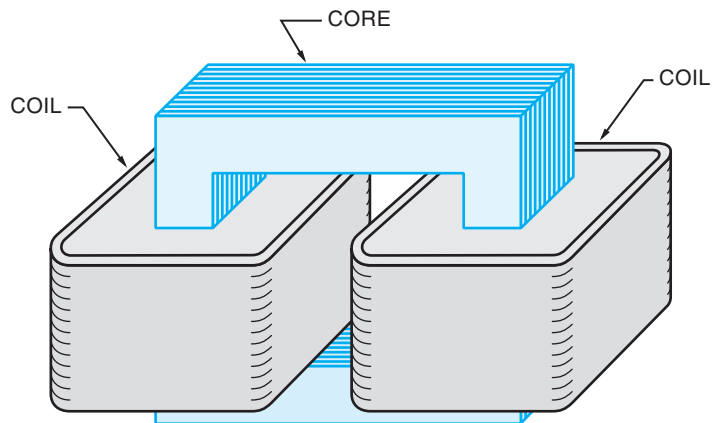
► **Figure 19–5**
The isolation transformer greatly reduces the voltage spike. (Source: Delmar/Cengage Learning)



► **Figure 19-6**
Isolation transformer
used to remove a
piece of electrical
equipment from
ground. (Source: Delmar/
Cengage Learning)



► **Figure 19-7**
Basic construction of an isolation
transformer. (Source: Delmar/Cengage
Learning)

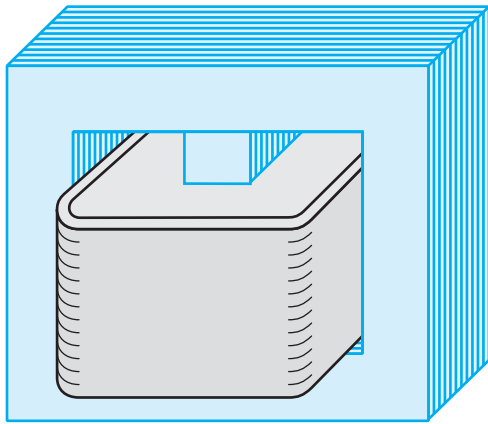


► **Figure 19-8**
Core-type transformer. (Source: Delmar/Cengage
Learning)

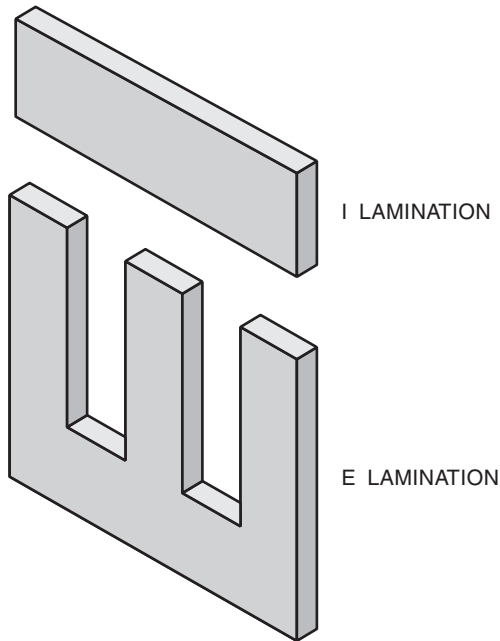
The transformer illustrated in Figure 19-8 is known as a **core transformer**. The windings are placed around each end of the core material. The metal core provides a good magnetic path between the two windings.

The **shell transformer** is constructed in a similar manner as the core type, except that the

shell type has a metal core piece through the middle of the window, Figure 19-9. The primary and secondary windings are wound around the center core piece with the low voltage winding being closest to the metal core. This arrangement permits the transformer to be surrounded by the core, which provides



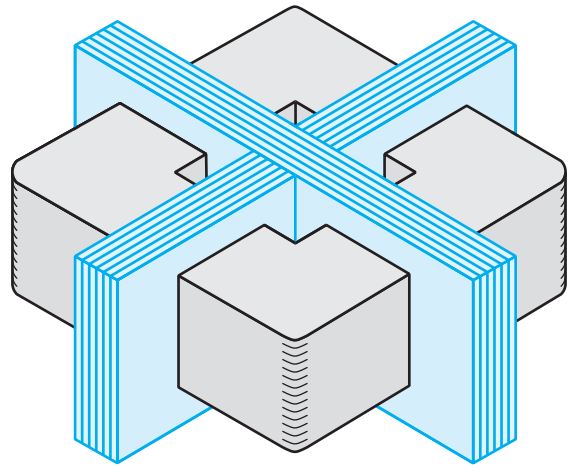
► **Figure 19-9**
Shell-type transformer. (Source: Delmar/Cengage Learning)



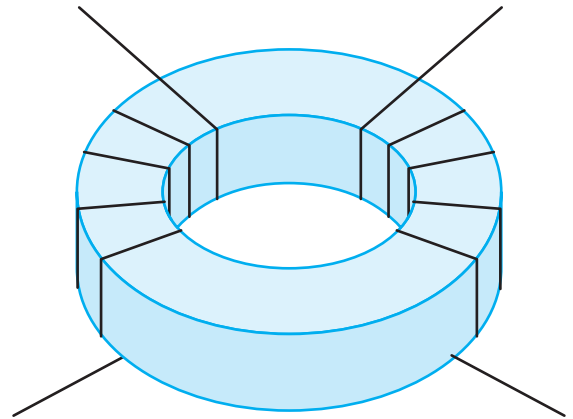
► **Figure 19-10**
Shell-type cores are made of E and I laminations.
(Source: Delmar/Cengage Learning)

excellent magnetic coupling. When the transformer is in operation, all the magnetic flux must pass through the center core piece. It then divides through the two outer core pieces. Shell type cores are sometimes referred to as **E-I cores** because the steel punchings used to construct the core are in the shape of an E and an I, Figure 19-10.

The H-type core shown in Figure 19-11 is similar to the shell type core in that it has an iron core



► **Figure 19-11**
Transformer with H-type core. (Source: Delmar/Cengage Learning)



► **Figure 19-12**
Toroid transformer. (Source: Delmar/Cengage Learning)

through its center around which the primary and secondary windings are wound. The H core, however, surrounds the windings on four sides instead of two. This extra metal helps reduce stray leakage flux and improve the efficiency of the transformer. The H-type core is often found on high voltage distribution transformers.

The **tape wound** or **toroid core**, Figure 19-12, is constructed by tightly winding one long continuous silicon steel tape into a spiral. The tape may or may not be housed in a plastic container depending on the application. This type core does not require steel punchings that are then laminated together. Because the core is one continuous length

of metal, flux leakage is kept to a minimum. The tape wound core is one of the most efficient core designs available.

BASIC OPERATING PRINCIPLES

In Figure 19–13, 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 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**. It is this induced voltage, inductive reactance, that limits the flow of current in the primary winding. If the resistance of the primary winding is measured with an ohmmeter, it will indicate only the resistance of the wire used to construct the winding and will not give an indication of the actual current limiting effect of the winding. Most

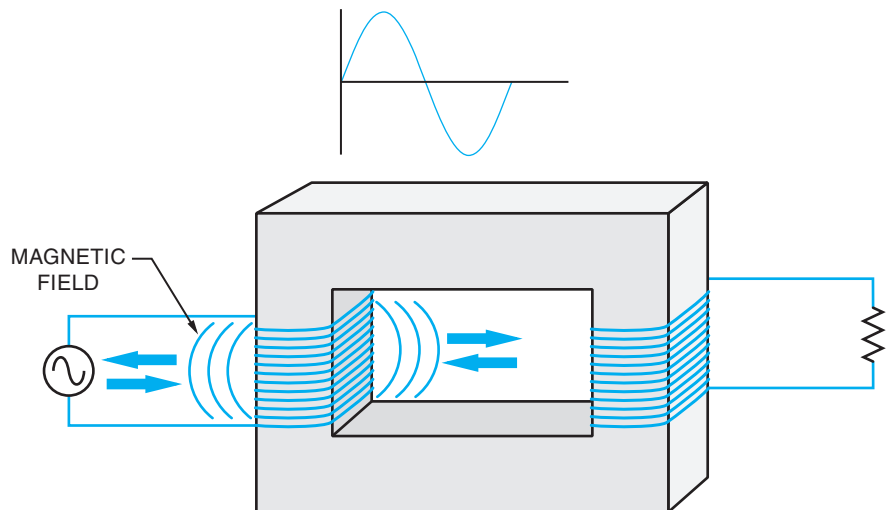
transformers with a large kVA rating will appear to be almost a short circuit when measured with an ohmmeter. When connected to power, however, the actual no load current is generally relatively small.

EXCITATION CURRENT

There will always be some amount of current flow in the primary of a transformer 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.

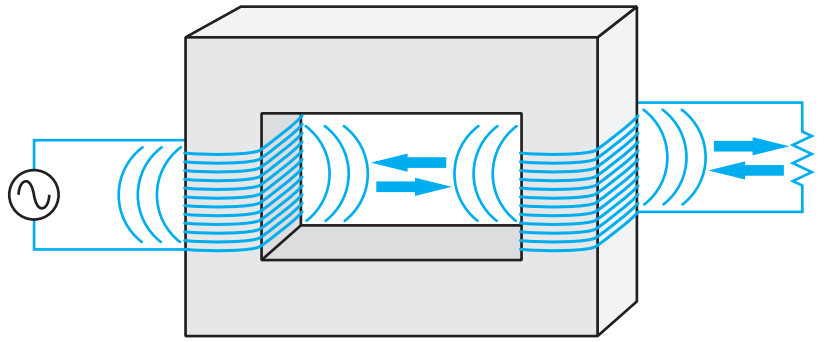
MUTUAL INDUCTION

Because 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 19–14. 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 with



► **Figure 19–13**
Magnetic field produced
by alternating current.

(Source: Delmar/Cengage Learning)



► **Figure 19-14**
The magnetic field of the primary induces a voltage into the secondary. (Source: Delmar/Cengage Learning)

the primary. For example, assume the primary has 240 turns of wire and is connected to 120 volts AC. This gives the transformer a volts-per-turn ratio of 0.5 (120 volts per 240 turns = 0.5 volt per turn). Now assume the secondary winding contains 100 turns of wire. Because the transformer has a volts-per-turn ratio of 0.5, the secondary voltage will be 50 volts ($100 \times 0.5 \times 50$).

TRANSFORMER CALCULATIONS

In the following examples, values of voltage, current, and turns for different transformers will be computed.

EXAMPLE

Assume the isolation transformer shown in Figure 19-2 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 volts is connected to the primary winding. What is the voltage of the secondary winding?

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$\frac{120}{E_s} = \frac{240}{60}$$

$$E_s = 30 \text{ volts}$$

The transformer in this example is known as a **step-down transformer** because it has a lower secondary voltage than primary voltage.

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 can be computed using Ohm's law since the voltage and impedance are known.

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

$$I = \frac{30}{5}$$

$$I = 6 \text{ amps}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p}$$

$$\frac{120}{30} = \frac{6}{I_p}$$

$$120 I_p = 180$$

$$I_p = 1.5 \text{ amps}$$

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 transformers is that *power in must equal power out*. If the primary voltage and current are multiplied together, it should equal the product of the voltage and current of the secondary:

Primary

$$120 \times 1.5 = 180 \text{ volt amps}$$

Secondary

$$30 \times 6 = 180 \text{ volt amps}$$

EXAMPLE

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 ($1,200/240 = 5$). Now assume that 120 volts is connected to the primary winding. Compute the voltage output of the secondary winding.

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$\frac{120}{E_s} = \frac{240}{1200}$$

$$240 E_s = 144,000$$

$$E_s = 600 \text{ volts}$$

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**.

Now assume that the load connected to the secondary has an impedance of $2,400 \Omega$. 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.

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

$$I = \frac{600}{2400}$$

$$I = 0.25 \text{ amp}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p}$$

$$\frac{120}{600} = \frac{0.25}{I_p}$$

$$120 I_p = 150$$

$$I_p = 1.25 \text{ amps}$$

Notice that the amount of power input equals the amount of power output.

Primary

$$120 \times 1.25 = 150 \text{ volt amps}$$

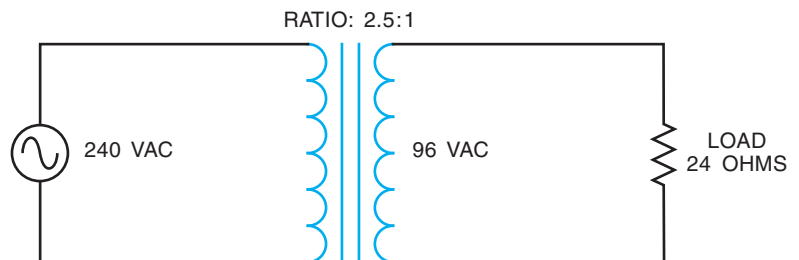
Secondary

$$600 \times 0.25 = 150 \text{ volt amps}$$

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. There are several ways in which turns ratios can be expressed. One method is to use a whole number value such as 13:5 or 6:21. The first ratio indicates that one winding has 13 turns of wire for every 5 turns of wire in the other winding. The second ratio indicates that there are 6 turns of wire in one winding for every 21 turns in the other.

A second method is to use the number 1 as a base. When using this method, the number 1 is always assigned to the winding with the lowest voltage rating. The ratio is found by dividing the higher voltage by the lower voltage. The number on the left side of the ratio represents the primary winding, and the number on the right of the ratio represents the secondary winding. For example, assume a transformer has a primary rated at 240 volts and a secondary rated at 96 volts, Figure 19–15. The



► **Figure 19–15**
Computing transformer values using the turns ratio. (Source: Delmar/Cengage Learning)

turns ratio can be computed by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{240}{96}$$

$$\text{Ratio} = 2.5:1$$

Notice in this example that the primary winding has the higher voltage rating and the secondary has the lower. Therefore, the 2.5 is placed on the left and the base unit, 1, is placed on the right. This ratio indicates that there are 2.5 turns of wire in the primary winding for every 1 turn of wire in the secondary.

Now assume that there is a resistance of $24\ \Omega$ connected to the secondary winding. The amount of secondary current can be found using Ohm's law.

$$I_s = \frac{96}{24}$$

$$I_s = 4 \text{ amps}$$

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. Because the primary voltage is greater, the primary current will have to be less than the secondary current. Therefore, the secondary current will be divided by the turns ratio.

$$I_p = \frac{I_s}{\text{Turns Ratio}}$$

$$I_p = \frac{4}{2.5}$$

$$I_p = 1.6 \text{ amps}$$

To check the answer, find the volt amps of the primary and secondary.

Primary

$$240 \times 1.6 = 384$$

Secondary

$$96 \times 4 = 384$$

Now assume that the secondary winding contains 150 turns of wire. The primary turns can also be found by using the turns ratio. Because the primary voltage is higher than the secondary voltage, the primary must have more turns of wire. Because the primary must contain more turns of wire, the secondary turns will be multiplied by the turns ratio.

$$N_p = N_s \times \text{Turns Ratio}$$

$$N_p = 150 \times 2.5$$

$$N_p = 375 \text{ turns}$$

In the next example, assume a transformer has a primary voltage of 120 volts and a secondary voltage of 500 volts. The secondary has a load impedance of $1,200\ \Omega$. The secondary contains 800 turns of wire, Figure 19–16. 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.

$$I_s = \frac{500}{1200}$$

$$I_s = 0.417 \text{ amp}$$

In this example, the primary voltage is lower than the secondary voltage. Therefore, the primary current must be higher. To find the primary current, multiply the secondary current by the turns ratio.

$$I_p = I_s \times \text{Turns Ratio}$$

$$I_p = 0.417 \times 4.17$$

$$I_p = 1.74 \text{ amps}$$

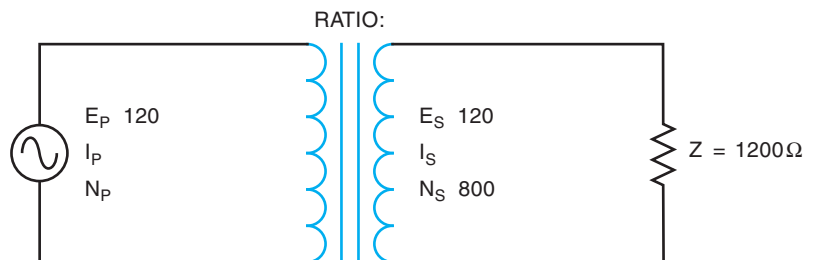
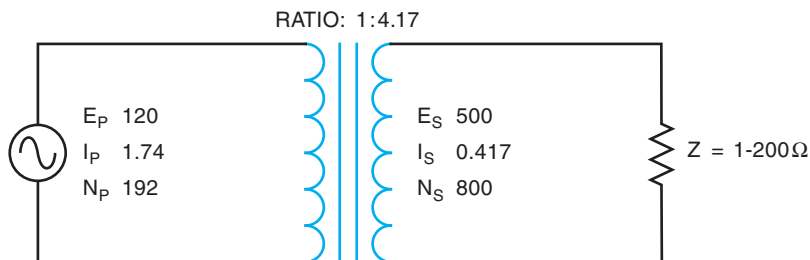


Figure 19–16
Calculating transformer values.
(Source: Delmar/Cengage Learning)

► **Figure 19-17**
Transformer with completed
values. (Source: Delmar/Cengage Learning)



To check this answer, compute the volt amps of both windings.

Primary

$$120 \times 1.74 = 208.8$$

Secondary

$$500 \times 0.417 = 208.8$$

The slight difference in answers is caused by rounding off the values.

Because the primary voltage is less than the secondary voltage, the turns of wire in the primary will be less also. The primary turns will be found by dividing the turns of wire in the secondary by the turns ratio.

$$N_P = \frac{N_S}{\text{Turns Ratio}}$$

$$N_P = \frac{800}{4.17}$$

$$N_P = 192 \text{ turns}$$

Figure 19-17 shows the transformer with all completed values.

MULTIPLE TAPPED WINDINGS

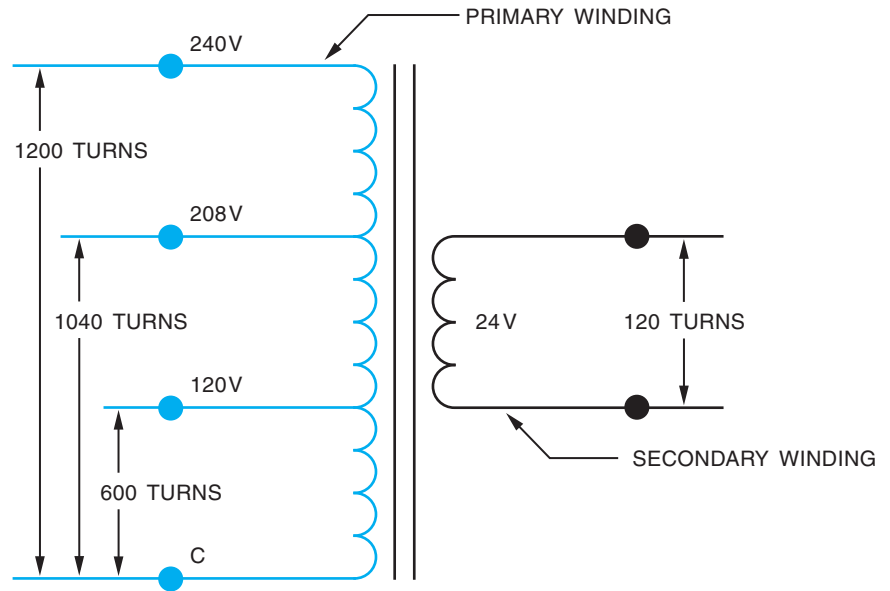
It is not uncommon for transformers to be designed with windings that have more than one set of lead wires connected to the primary or secondary. The transformer shown in Figure 19-18 contains a secondary winding rated at 24 volts. The primary winding contains several taps, however. One of the primary lead wires is labeled C and is the common for the other leads. The other leads are labeled 120, 208, and 240, respectively. 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.

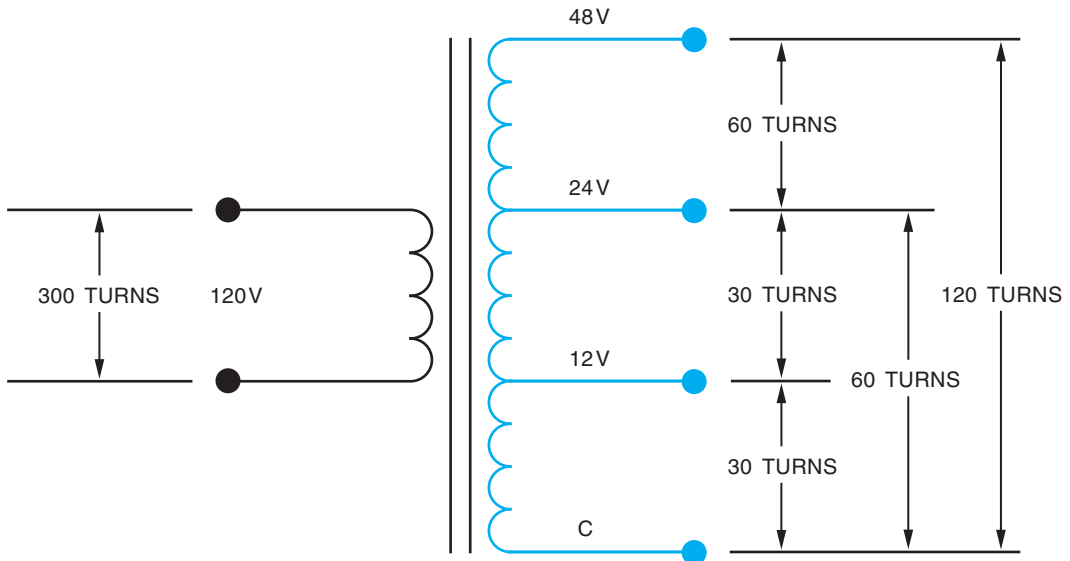
The transformer shown in Figure 19-19 contains a single primary winding. The secondary winding, however, has been tapped at several points. One of the secondary lead wires is labeled C and is common to the other lead wires. When rated voltage is applied to the primary, voltages of 12, 24, and 48 volts 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.

The transformer shown in Figure 19-20 is similar to the transformer in Figure 19-19. The transformer in Figure 19-20, however, has multiple secondary windings instead of a single secondary winding with multiple taps. The advantage of the transformer in Figure 19-20 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.



► **Figure 19-18**
Transformer with multiple
tap primary winding. (Source:
Delmar/Cengage Learning)



► **Figure 19-19**
Transformer secondary with multiple taps. (Source: Delmar/Cengage Learning)

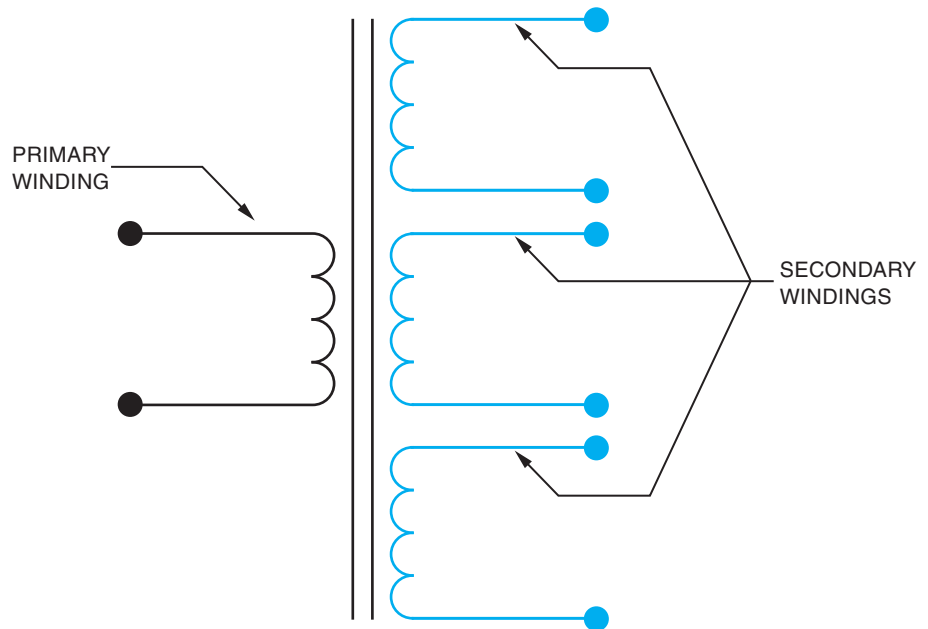


Figure 19-20
Transformer with
multiple secondary
windings. (Source: Delmar/
Cengage Learning)

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 19-21 contains one primary winding and three secondary windings. The primary is connected to 120 volts AC and contains 300 turns of wire. One secondary has an output voltage of 560 volts and a load impedance of 1,000 Ω . The second secondary has an output voltage of 208 volts and a load impedance of 400 Ω , and the third secondary has an output voltage of 24 volts 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.

SOLUTION: 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.

$$\text{Ratio} = \frac{E_{S1}}{E_p}$$

$$\text{Ratio} = \frac{560}{120}$$

$$\text{Ratio} = 1:4.67$$

The current flow in the first secondary can be computed using Ohm's law.

$$I_{S1} = \frac{560}{1000}$$

$$I_{S1} = 0.56 \text{ amps}$$

The number of turns of wire in the first secondary winding will be found using the turns ratio. Because this secondary has a higher voltage than the primary, it must have more turns of wire. The number of primary turns will be multiplied by the turns ratio.

$$N_{S1} = N_p \times \text{Turns Ratio}$$

$$N_{S1} = 300 \times 4.67$$

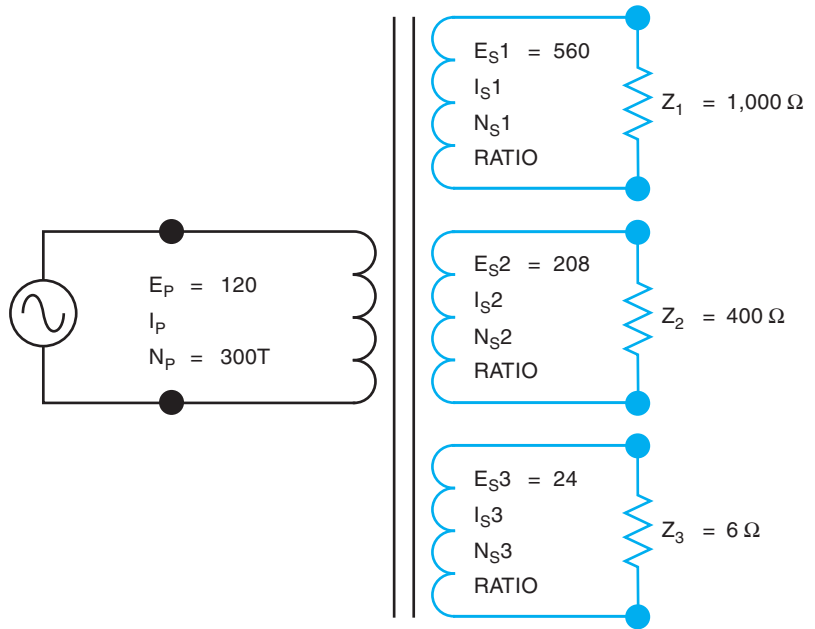
$$N_{S1} = 1,401 \text{ turns}$$

The amount of primary current needed to supply this secondary winding can be found using the turns ratio also. Because the primary has less voltage, it will require more current. The primary current can be determined by multiplying the secondary current by the turns ratio.

$$I_{P(\text{FIRST SECONDARY})} = I_{S1} \times \text{Turns Ratio}$$

$$I_{P(\text{FIRST SECONDARY})} = 0.56 \times 4.67$$

$$I_{P(\text{FIRST SECONDARY})} = 2.61 \text{ amps}$$



► **Figure 19-21**
Computing values for a trans-
former with multiple secondary
windings. (Source: Delmar/Cengage Learning)

The turns ratio of the second secondary winding will be found by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{208}{120}$$

$$\text{Ratio} = 1:1.73$$

The amount of current flow in this secondary can be determined using Ohm's law.

$$I_{S2} = \frac{208}{400}$$

$$I_{S2} = 0.52 \text{ amp}$$

Because 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 by multiplying the turns of the primary by the turns ratio.

$$N_{S2} = N_P \times \text{Turns Ratio}$$

$$N_{S2} = 300 \times 1.73$$

$$N_{S2} = 519 \text{ turns}$$

The voltage of the primary is less than this secondary. The primary will, therefore, require a greater amount of current. The amount of primary current required to operate this secondary will be

computed by multiplying the secondary current by the turns ratio.

$$I_{P(\text{SECOND SECONDARY})} = I_{S2} \times \text{Turns Ratio}$$

$$I_{P(\text{SECOND SECONDARY})} = 0.52 \times 1.732$$

$$I_{P(\text{SECOND SECONDARY})} = 0.9 \text{ amp}$$

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.

$$I_{S3} = \frac{24}{6}$$

$$I_{S3} = 4 \text{ amps}$$

Because the output voltage of the third secondary is less than that of the primary, the number of turns of wire for this secondary will be fewer than the primary turns. To find the number of secondary turns, divide the primary turns by the turns ratio.

$$N_{S3} = \frac{N_P}{\text{Turns Ratio}}$$

$$N_{S3} = \frac{300}{5}$$

$$N_{S3} = 60 \text{ turns}$$

The primary has a higher voltage than this secondary. The primary current will, therefore, be less than the secondary current by the amount of the turns ratio.

$$I_{P(\text{THIRD SECONDARY})} = \frac{I_{S3}}{\text{Turns Ratio}}$$

$$I_{P(\text{THIRD SECONDARY})} = \frac{4}{5}$$

$$I_{P(\text{THIRD SECONDARY})} = 0.8 \text{ amp}$$

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.

$$I_{P(\text{TOTAL})} = I_{P1} + I_{P2} + I_{P3}$$

$$I_{P(\text{TOTAL})} = 2.61 + 0.9 + 0.8$$

$$I_{P(\text{TOTAL})} = 4.31 \text{ amps}$$

The transformer with all computed values is shown in Figure 19–22.

DISTRIBUTION TRANSFORMERS

A very common type of isolation transformer is the distribution transformer, Figure 19–23. This transformer is 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 volt line. The secondary is 240 volts 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 volts will be seen. If voltage is measured from either line to the center tap, half of the secondary voltage, or 120 volts, will be seen, Figure 19–24. Loads that are intended to operate on 240 volts, such as water heaters, electric resistance heating units, and central air conditioners are connected directly across the lines of the secondary. Loads intended to operate on 120 volts 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 in Figure 19–25, it is assumed that one of the secondary lines has a current flow of 30 amperes and the other has current flow of 24 amperes. The neutral will conduct the sum of the unbalanced load.

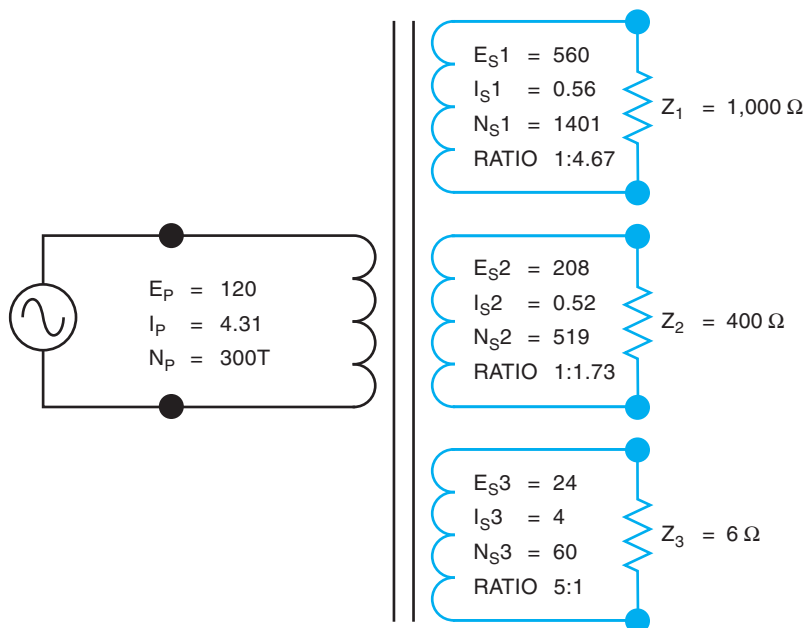
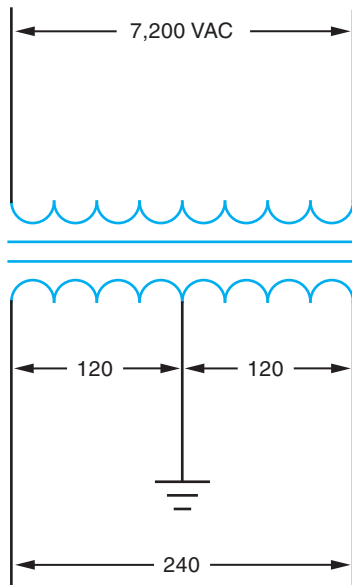
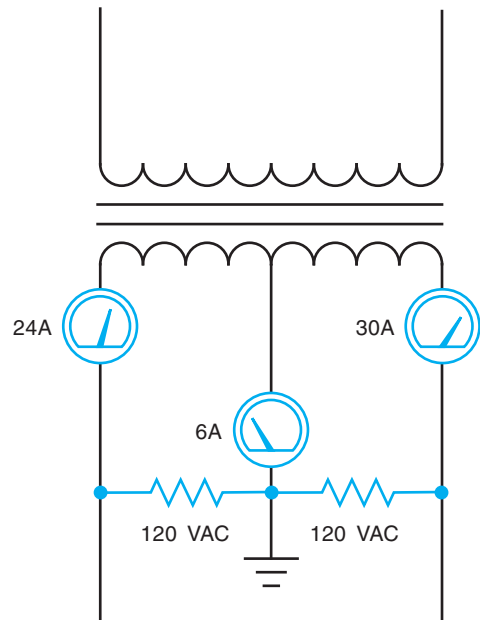


Figure 19–22
The transformer with all computed values. (Source: Delmar/Cengage Learning)



► **Figure 19-23**
Distribution transformer. (Source: Delmar/Cengage Learning)

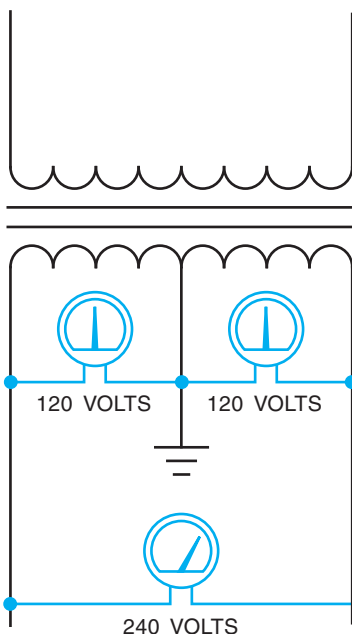


► **Figure 19-25**
The neutral carries the sum of the unbalanced current.
(Source: Delmar/Cengage Learning)

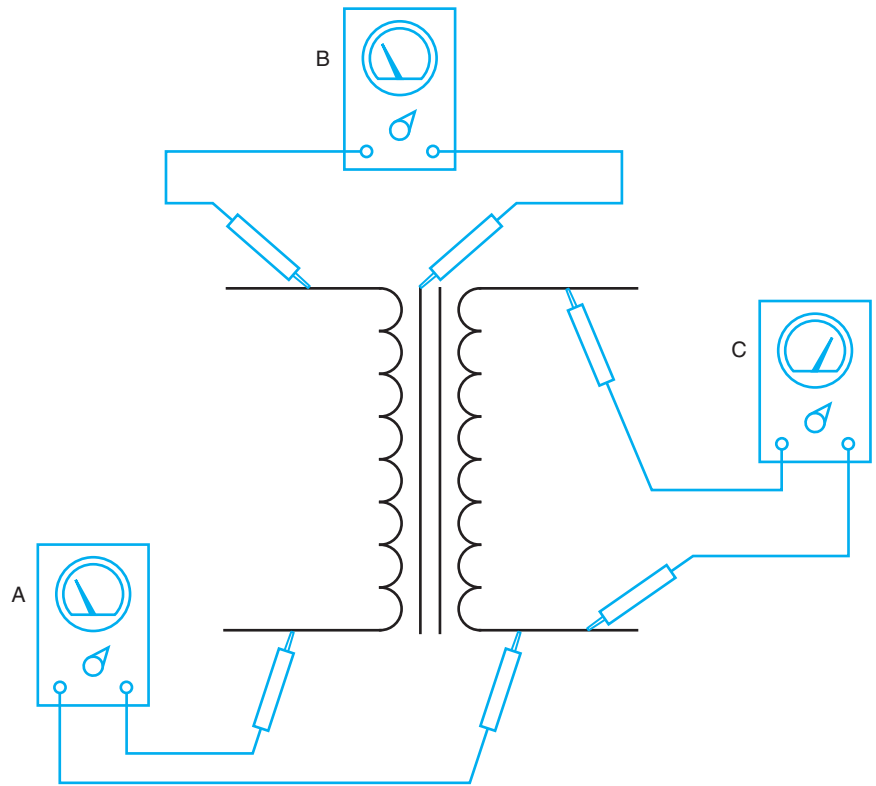
In this example, the neutral current will be 6 amperes ($30 - 24 = 6$).

TESTING THE TRANSFORMER

There are several tests that 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 19-26. 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 illustrates testing the windings for continuity. The wire resistance of the winding should be indicated by the ohmmeter. Each winding should be tested for continuity. If the transformer appears to be in good condition after the ohmmeter



► **Figure 19-24**
The voltage from either line to neutral is 120 volts. The voltage across the entire secondary winding is 240 volts. (Source: Delmar/Cengage Learning)



► **Figure 19-26**
Testing a transformer with
an ohmmeter. (Source: Delmar/
Cengage Learning)

test, it should then be tested for shorts and grounds with a megohmmeter or “megger.” A megger will reveal problems of insulation breakdown that an ohmmeter will not.

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 rating. Transformers are rated in kilovolt amps and not kilowatts because the true power is determined by the power factor of the load. Other information that may or may not be listed is frequency, temperature rise in °C, % impedance (%Z), type of insulating oil, gallon of insulating oil, serial number, type number, model number, and whether the transformer is single phase or three phase.

DETERMINING MAXIMUM CURRENT

Notice that the nameplate does not list the current rating of the windings. Because 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 volts, and a secondary voltage of 120 volts. To determine the maximum current that can be supplied by the secondary, divide the kVA rating by the secondary voltage.

$$I_s = \frac{kVA}{E_s}$$

$$I_s = \frac{500}{120}$$

$$I_s = 4.16 \text{ amps}$$

The primary current can be computed in the same way.

$$I_p = \frac{kVA}{E_p}$$

$$I_p = \frac{500}{480}$$

$$I_p = 1.04 \text{ amps}$$

Transformers with multiple secondary windings will generally have the current rating listed with the voltage rating.

TRANSFORMER LOSSES

Although transformers are probably the most efficient machines known, they are not perfect. A transformer operating at 90% efficiency has a power loss of 10%. Some of these losses are I^2R losses, eddy current losses, hysteresis losses, and magnetic flux leakage. Most of these losses result in heat production. Recall that I^2R is one of the formulas for finding power or watts. In the case of a transformer, it describes the power loss associated with heat due to the resistance of the wire in both primary and secondary windings.

Eddy currents are currents that are induced into the metal core material by the changing magnetic field as alternating current produces a changing flux. Eddy currents are so named because they circulate around inside the metal in a similar manner as the swirling eddies in a river, Figure 19–27. These swirling currents produce heat, which is a power loss. Transformers are constructed with laminated cores to help reduce eddy currents. The surface of each lamination forms a layer of iron oxide, which acts as an insulator to help prevent the formation of eddy currents.

Hysteresis losses are losses due to molecular friction. As discussed previously, the reversal of the

direction of current flow causes the molecules of iron in the core to realign themselves each time the current changes direction. The molecules of iron are continually rubbing against each other as they realign magnetically. The friction of the molecules rubbing together causes heat, which is a power loss. Hysteresis loss is proportional to frequency. The higher the frequency, the greater the loss. A special steel called **silicon steel** is often used in transformer cores to help reduce hysteresis loss. The power loss due to hysteresis and eddy currents is often called core loss.

Magnetic flux leakage does not produce heat, but does constitute a power loss. Flux leakage is caused by magnetic lines of flux radiating away from the transformer and not cutting the secondary windings. Flux leakage can be reduced by better core designs.

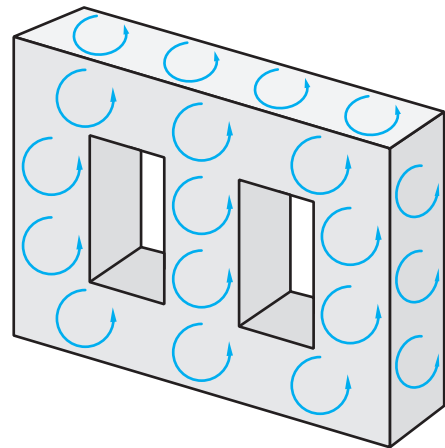


Figure 19–27
Eddy currents circulate inside the core material. (Source: Delmar/Cengage Learning)

SUMMARY

- ⌚ All values of voltage, current, and impedance in a transformer are proportional to the turns ratio.
- ⌚ Transformers can change values of voltage, current, and impedance, but cannot change the frequency.
- ⌚ The primary winding of a transformer is connected to the power line.
- ⌚ The secondary winding is connected to the load.
- ⌚ A transformer that has a lower secondary voltage than primary voltage is a step-down transformer.
- ⌚ A transformer that has a higher secondary voltage than primary voltage is a step-up transformer.
- ⌚ An isolation transformer has its primary and secondary windings electrically and mechanically separated from each other.
- ⌚ When a coil induces a voltage into itself, it is known as self-induction.
- ⌚ When a coil induces a voltage into another coil, it is known as mutual induction.
- ⌚ Either winding of a transformer can be used as the primary or secondary as long as its voltage or current ratings are not exceeded.
- ⌚ Isolation transformers help filter voltage and current spikes between the primary and secondary side.

KEY TERMS

core transformer
E-I core
excitation current
isolation transformer

mutual induction
self-induction
shell transformer
silicon steel

step-down transformer
step-up transformer
tape wound or toroid core

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. A transformer has a primary voltage of 480 volts and a secondary voltage of 20 volts. What is the turns ratio of the transformer?
6. If the secondary of the transformer in question 5 supplies a current of 9.6 amperes to a load, what is the primary current? (Disregard excitation current.)
7. Explain the difference between a step-up and a step-down transformer.

8. A transformer has a primary voltage of 240 volts and a secondary voltage of 48 volts. What is the turns ratio of this transformer?
9. A transformer has an output of 750 volt amps. The primary voltage is 120 volts. What is the primary current?
10. A transformer has a turns ratio of 1:6. The primary current is 18 amperes. What is the secondary current?

PRACTICE PROBLEMS

Refer to Figure 19–28 to answer the following questions. Find all missing values.

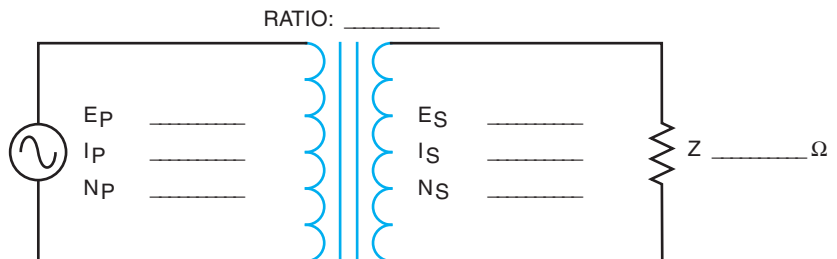


Figure 19–28
Practice problems 1 through 6.
(Source: Delmar/Cengage Learning)

1.

$E_p = 120$	$E_s = 24$
$I_p =$	$I_s =$
$N_p = 300$	$N_s =$
Ratio:	$Z = 3 \Omega$

2.

$E_p = 240$	$E_s = 320$
$I_p =$	$I_s =$
$N_p =$	$N_s = 280$
Ratio:	$Z = 500 \Omega$

3.

$E_p =$	$E_s = 160$
$I_p =$	$I_s =$
$N_p =$	$N_s = 80$
Ratio: 1:2.5	$Z = 12 \Omega$

4.

$E_p = 48$	$E_s = 240$
$I_p =$	$I_s =$
$N_p = 220$	$N_s =$
Ratio: _____	$Z = 360 \Omega$

5.

$E_p =$	$E_s =$
$I_p = 16.5$	$I_s = 3.25$
$N_p =$	$N_s = 450$
Ratio: _____	$Z = 56 \Omega$

6.

$E_p = 480$	$E_s =$
$I_p =$	$I_s =$
$N_p = 275$	$N_s = 525$
Ratio:	$Z = 1.2 \text{ k}\Omega$

Refer to Figure 19–29 to answer the following questions. Find all missing values.

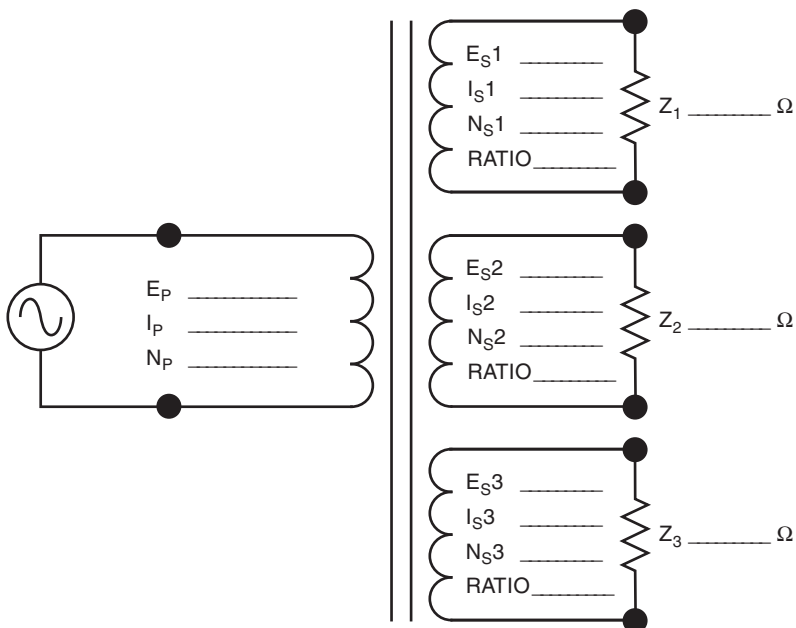


Figure 19–29
Practice problems 7 and 8. (Source:
Delmar/Cengage Learning)

7.

$E_p = 208$	$E_{s1} = 320$	$E_{s2} = 120$	$E_{s3} = 24$
$I_p = \underline{\hspace{1cm}}$	$I_{s1} = \underline{\hspace{1cm}}$	$I_{s2} = \underline{\hspace{1cm}}$	$I_{s3} = \underline{\hspace{1cm}}$
$N_p = 800$	$N_{s1} = \underline{\hspace{1cm}}$	$N_{s2} = \underline{\hspace{1cm}}$	$N_{s3} = \underline{\hspace{1cm}}$
	Ratio ₁ $\underline{\hspace{1cm}}$	Ratio ₂ $\underline{\hspace{1cm}}$	Ratio ₃ $\underline{\hspace{1cm}}$
	$R_1 = 12 \text{ k}\Omega$	$R_2 = 6 \text{ }\Omega$	$R_3 = 8 \text{ }\Omega$

8.

$E_p = 277$	$E_{s1} = 480$	$E_{s2} = 208$	$E_{s3} = 120$
$I_p = \underline{\hspace{1cm}}$	$I_{s1} = \underline{\hspace{1cm}}$	$I_{s2} = \underline{\hspace{1cm}}$	$I_{s3} = \underline{\hspace{1cm}}$
$N_p = 350$	$N_{s1} = \underline{\hspace{1cm}}$	$N_{s2} = \underline{\hspace{1cm}}$	$N_{s3} = \underline{\hspace{1cm}}$
	Ratio ₁ $\underline{\hspace{1cm}}$	Ratio ₂ $\underline{\hspace{1cm}}$	Ratio ₃ $\underline{\hspace{1cm}}$
	$R_1 = 200 \text{ }\Omega$	$R_2 = 60 \text{ }\Omega$	$R_3 = 24 \text{ }\Omega$

UNIT 20



Autotransformers

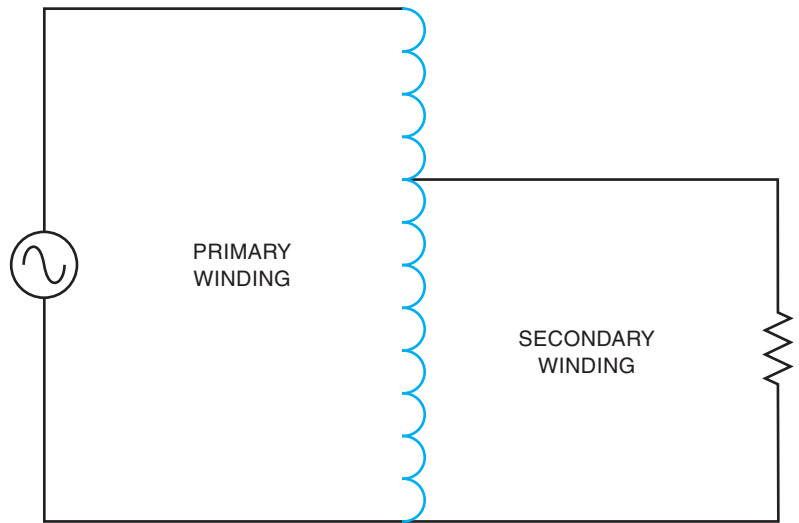
OBJECTIVES

After reading this unit the student should be able to:

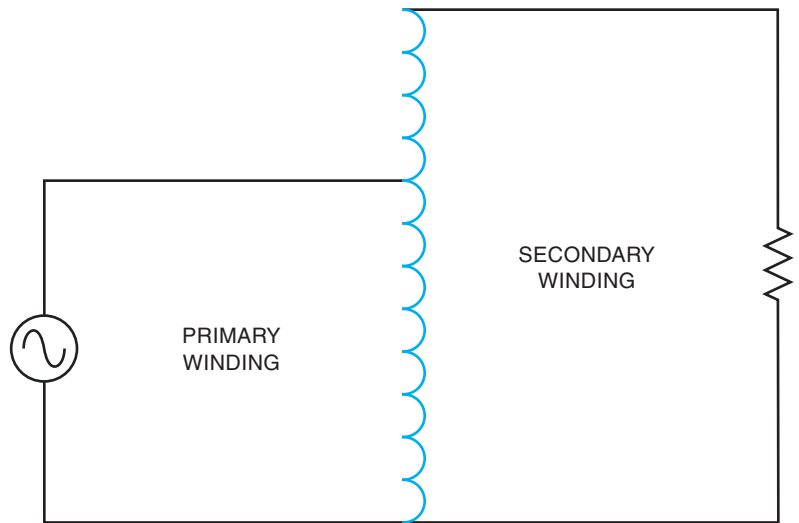
- » Discuss the operation of an autotransformer
- » List differences between isolation transformers and autotransformers
- » Compute values of voltage, current, and turns ratios for autotransformers
- » Connect an autotransformer for operation

The word *auto* means self. An autotransformer is literally a **self-transformer**. It uses the same winding as both the primary and secondary. Recall that the definition of a **primary winding** is a winding that is connected to the source of power, and the definition of a **secondary winding** is a winding that is connected to a load. Autotransformers have very high efficiencies, most in the range of 95% to 98%.

In Figure 20–1, the entire winding is connected to the power source, and part of the winding is connected to the load. In this illustration, all the turns of wire form the primary and part of the turns form the secondary. Because the secondary part of the winding contains fewer turns than the primary section, the secondary will produce less voltage. This autotransformer is a **step-down** transformer.



► **Figure 20-1**
Autotransformer used as a
step-down transformer.
(Source: Delmar/Cengage Learning)

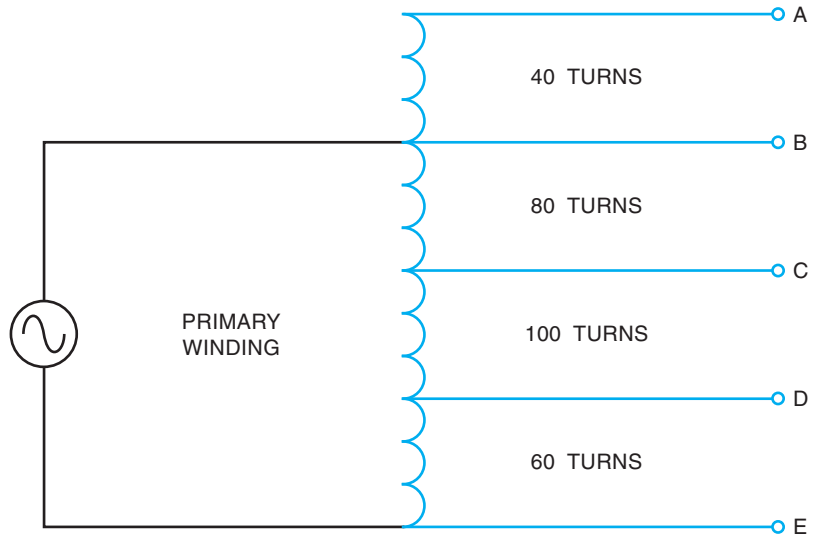


► **Figure 20-2**
Autotransformer used as a
step-up transformer.
(Source: Delmar/Cengage Learning)

In Figure 20-2, the primary section is connected across part of a winding and the secondary is connected across the entire winding. In this illustration the secondary section contains more windings than the primary. This autotransformer is a **step-up** transformer. Notice that autotransformers, like isolation transformers, can be used as step-up or step-down transformers.

DETERMINING VOLTAGE VALUES

Autotransformers are not limited to a single secondary winding. Many autotransformers have **multiple taps** to provide different voltages as shown in Figure 20-3. In this example, there are 40 turns of wire between taps A and B, 80 turns of wire between taps B and C, 100 turns of wire between taps C and D,



► **Figure 20-3**
Autotransformer with multiple taps.
(Source: Delmar/Cengage Learning)

and 60 turns of wire between taps D and E. The primary section of the windings is connected between taps B and E. It will be assumed that the primary is connected to a source of 120 volts. The voltage across each set of taps will be determined.

There is generally more than one method that can be employed to determine values of a transformer. Because the number of turns between each tap is known, the **volts-per-turn** method will be used in this example. *The volts-per-turn for any transformer is determined by the primary winding.* In this illustration, the primary winding is connected across taps B and E. The primary turns are, therefore, the sum of the turns between taps B and E ($80 + 100 + 60 = 240$ turns). Because 120 volts is connected across 240 turns, this transformer will have a volts-per-turn ratio of 0.5 ($240 \text{ turns}/120 \text{ volts} = 0.5 \text{ volts-per-turn}$). To determine the amount of voltage between each set of taps, it becomes a simple matter of multiplying the number of turns by the volts-per-turn.

$$\text{A-B } (40 \text{ turns} \times 0.5 = 20 \text{ volts})$$

$$\text{A-C } (120 \text{ turns} \times 0.5 = 60 \text{ volts})$$

$$\text{A-D } (220 \text{ turns} \times 0.5 = 110 \text{ volts})$$

$$\text{A-E } (280 \text{ turns} \times 0.5 = 140 \text{ volts})$$

$$\text{B-C } (80 \text{ turns} \times 0.5 = 40 \text{ volts})$$

$$\text{B-D } (180 \text{ turns} \times 0.5 = 90 \text{ volts})$$

$$\text{B-E } (240 \text{ turns} \times 0.5 = 120 \text{ volts})$$

$$\text{C-D } (100 \text{ turns} \times 0.5 = 50 \text{ volts})$$

$$\text{C-E } (160 \text{ turns} \times 0.5 = 80 \text{ volts})$$

$$\text{D-E } (60 \text{ turns} \times 0.5 = 30 \text{ volts})$$

USING TRANSFORMER FORMULAS

The values of voltage and current for autotransformers can also be determined by using standard transformer formulas. The primary winding of the transformer shown in Figure 20-4 is between points B and N, and has a voltage of 120 volts applied to it. If the turns of wire are counted between points B and N, it can be seen that 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.

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$\frac{120}{E_s} = \frac{120}{40}$$

$$120 E_s = 4800$$

$$E_s = 40 \text{ volts}$$

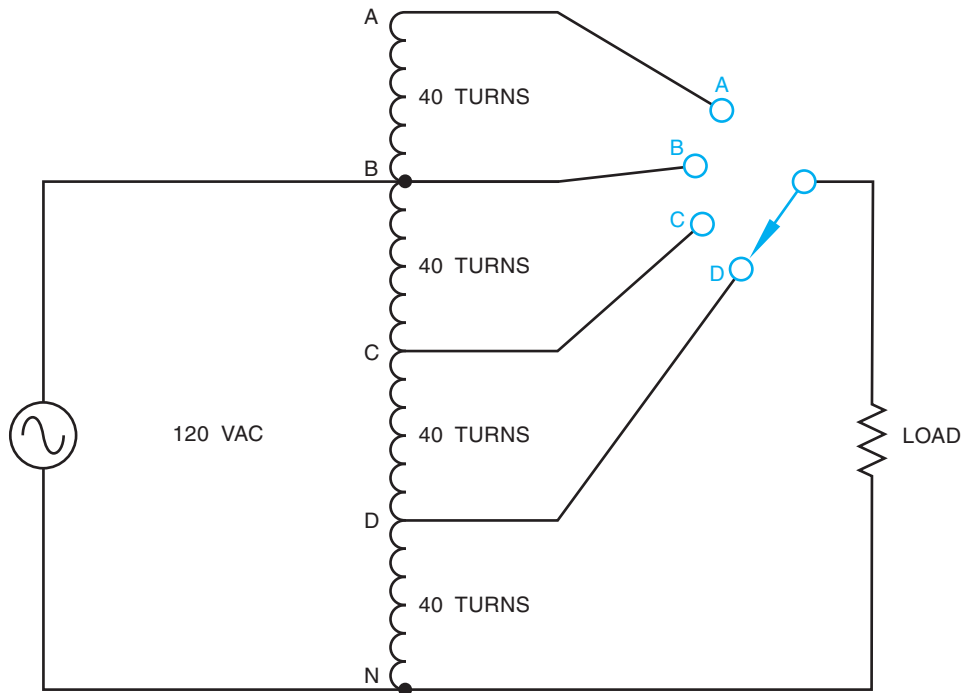


Figure 20-4
Determining voltage
and current values.
(Source: Delmar/Cengage Learning)

Assume that the load connected to the secondary has an impedance of $10\ \Omega$. The amount of current flow in the secondary circuit can be computed using the formula:

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

$$I = \frac{40}{10}$$

$$I = 4\ \text{amps}$$

The primary current can be computed by using the same formula that was used to compute primary current for an isolation type of transformer.

$$\frac{E_p}{E_s} = \frac{I_s}{I_p}$$

$$120\ I_p = 160$$

$$\frac{120}{40} = \frac{4}{I_p}$$

$$I_p = 1.333\ \text{amps}$$

The amount of power input and output for the auto-transformer must also be the same.

Primary

$$120 \times 1.333 = 160\ \text{volt-amps}$$

Secondary

$$40 \times 4 = 160\ \text{volt-amps}$$

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:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

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

$$120\ E_s = 19,200$$

$$E_s = 160\ \text{volts}$$

The amount of secondary current can be computed using the formula:

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

$$I = \frac{160}{10}$$

$$I = 16\ \text{amps}$$

The primary current can be computed using the formula:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p}$$

$$\frac{120}{160} = \frac{16}{I_p}$$

$$120 I_p = 2,560$$

$$I_p = 21.333 \text{ amps}$$

The answers can be checked by determining if the power in and power out are the same.

Primary

$$120 \times 21.333 = 2,560 \text{ volt-amps}$$

Secondary

$$160 \times 16 = 2,560 \text{ volt-amps}$$

CURRENT RELATIONSHIPS

An autotransformer with a 2:1 turns ratio is shown in Figure 20-5. It is assumed that a voltage of 480 volts is connected across the entire winding. Because the transformer has a turns ratio of 2:1, a voltage of 240 volts will be supplied to the load. Ammeters connected in series with each winding indicate the current flow in the circuit. It is assumed

that the load produces a current flow of 4 amperes on the secondary. Note that a current flow of 2 amperes is supplied to the primary.

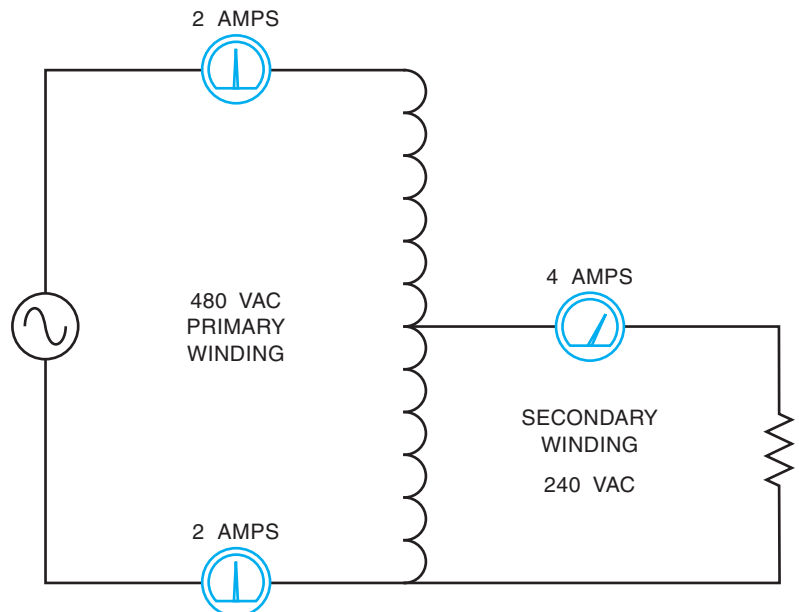
$$I_{\text{PRIMARY}} = \frac{I_{\text{SECONDARY}}}{\text{Ratio}}$$

$$I_p = \frac{4}{2}$$

$$I_p = 2 \text{ amperes}$$

If the rotary switch shown in Figure 20-4 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. The windings are wrapped around a tape-wound toroid core inside a plastic case. The tops of the windings have been milled flat, similar to a commutator. A carbon brush makes contact with the windings. When the brush is moved across the windings, the turns ratio changes, which changes the output voltage. This type of autotransformer provides a very efficient means of controlling AC voltage.

Autotransformers are often used by power companies to provide a small increase or decrease to the line voltage. They help provide voltage regulation to large power lines.



► **Figure 20-5**
Current divides between primary and secondary. (Source: Delmar/Cengage Learning)

The autotransformer does have one disadvantage. Because 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.

SUMMARY

- ▶ The autotransformer has only one winding that is used as both the primary and secondary.
- ▶ Autotransformers have efficiencies that range from about 95% to 98%.
- ▶ Values of voltage, current, and turns can be computed in the same manner as an isolation transformer.
- ▶ Autotransformers can be step-up or step-down transformers.
- ▶ Autotransformers can be made to provide a variable output voltage by connecting a sliding tap to the windings.
- ▶ Autotransformers have the disadvantage of no line isolation between primary and secondary.
- ▶ One of the simplest ways of computing values of voltage for an autotransformer when the turns are known is to use the volts-per-turn method.

KEY TERMS

line isolation
multiple taps
primary winding

secondary winding
self-transformer
step-down

step-up
volts-per-turn

REVIEW QUESTIONS

1. An AC power source is connected across 325 turns of an autotransformer and the load is connected across 260 turns. What is the turns ratio of this transformer?
2. Is the transformer in question 1 a step-up or a step-down transformer?
3. An autotransformer has a turns ratio of 3.2:1. A voltage of 208 volts is connected across the primary. What is the voltage of the secondary?
4. A load impedance of $52\ \Omega$ is connected to the secondary winding of the transformer in question 3. How much current will flow in the secondary?
5. How much current will flow in the primary of the transformer in question 4?
6. The autotransformer shown in Figure 20-3 has the following number of turns between windings: A-B (120 turns), B-C (180 turns), C-D (250 turns), and D-E (300 turns). A voltage of 240 volts is connected across B and E. Find the voltages between each of the following pairs of points:

A-B _____	A-C _____	A-D _____	A-E _____
B-C _____	B-D _____	B-E _____	C-D _____
C-E _____	D-E _____		

UNIT 21



Current Transformers

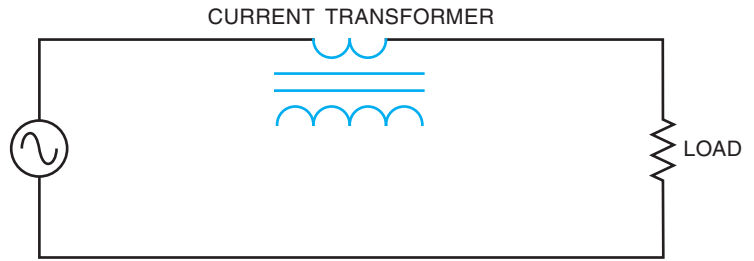
OBJECTIVES

After studying this unit the student should be able to:

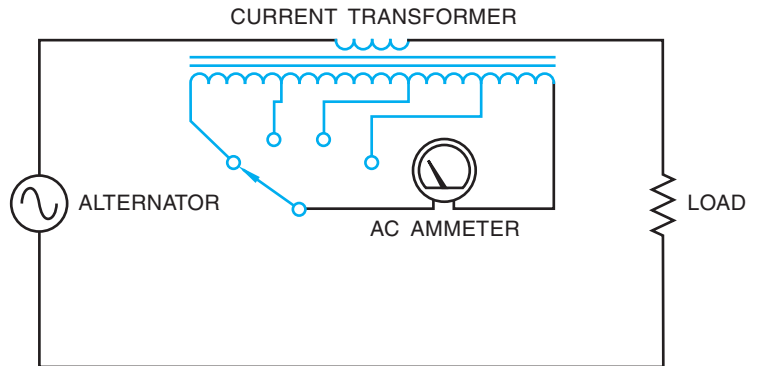
- ▶ Discuss the operation of a current transformer
- ▶ Describe how current transformers differ from voltage transformers
- ▶ Discuss safety precautions that should be observed when using current transformers
- ▶ Connect a current transformer in a circuit

Current transformers differ from voltage transformers in that the primary winding is generally part of the power line. The primary winding of a current transformer must be connected in series with the load, Figure 21-1. Current transformers are used to change the full scale range of AC ammeters. Most **in-line ammeters** (ammeters that must be connected directly into the line) that have multiple range values used a current transformer to provide the different ranges, Figure 21-2. The full scale value of the ammeter is changed by changing the turns ratio. Assume that the ammeter illustrated in Figure 21-2 is to provide range values of **5 amperes**, 2.5 amperes, 1 ampere, and 0.5 ampere. Also assume that the meter movement requires a current flow of 100 mA (0.100) to deflect the meter full scale and that the primary of the current transformer contains 5 turns of wire. Transformer formulas can

► **Figure 21-1**
The primary winding of a current transformer is connected in series with a load. (Source: Delmar/Cengage Learning)



► **Figure 21-2**
A current transformer is used to change the range of an AC ammeter. (Source: Delmar/Cengage Learning)



be used to determine the number of secondary turns needed to produce the desired ranges. Turns needed for a full scale range of 5 amperes.

$$\frac{N_p}{N_s} = \frac{I_s}{I_p}$$

$$\frac{5}{N_s} = \frac{0.1}{5}$$

$$0.1N_s = 25$$

$$N_s = 250 \text{ turns}$$

Turns needed for a full scale range of 2.5 amperes.

$$\frac{5}{N_s} = \frac{0.1}{2.5}$$

$$0.1N_s = 12.5$$

$$N_s = 125 \text{ turns}$$

Turns needed for a full scale range of 1 ampere.

$$\frac{5}{N_s} = \frac{0.1}{1}$$

$$0.1N_s = 5$$

$$N_s = 50 \text{ turns}$$

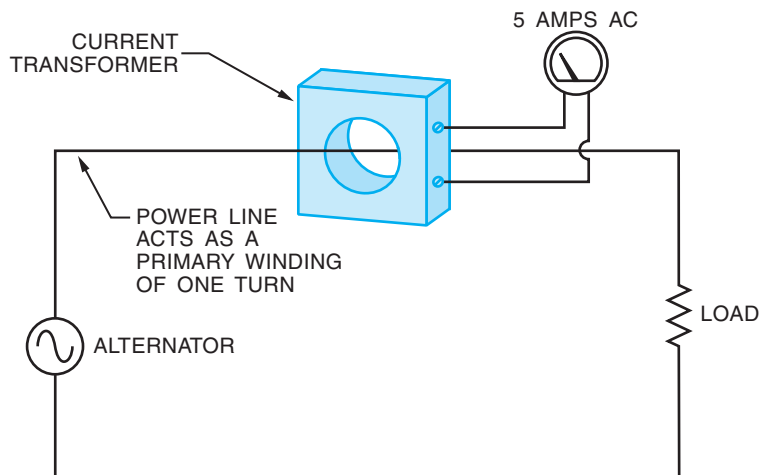
Turns needed for a full scale range of 0.5 ampere.

$$\frac{5}{N_s} = \frac{0.1}{0.5}$$

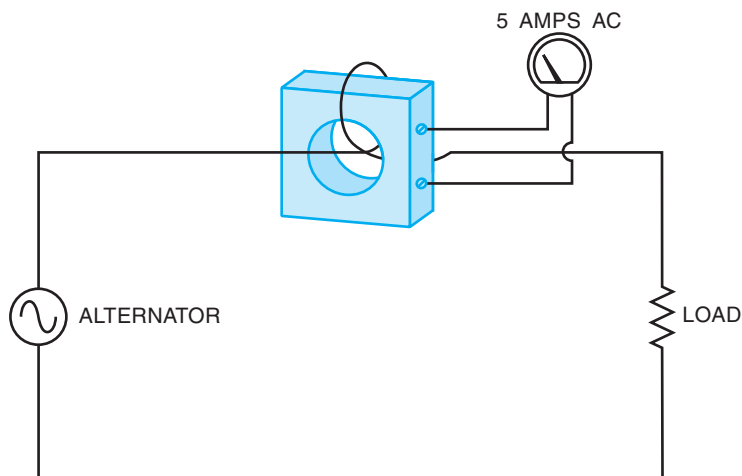
$$0.1N_s = 2.5$$

$$N_s = 25 \text{ turns}$$

When a large amount of AC current must be measured, a different type of current transformer is connected in the power line. These transformers have ratios that start at 100:5 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 amps AC. They are designed to be operated with a 5 amp 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 there is power applied to the primary. This will cause the transformer to produce a step-up in voltage which could be high enough to kill anyone who comes in contact with it.*



► **Figure 21-3**
Current transformer used to
change the scale factor of an
AC ammeter. (Source: Delmar/Cengage
Learning)



► **Figure 21-4**
The primary conductor loops through
the CT to produce a second turn,
changing the turns ratio. (Source: Delmar/
Cengage Learning)

A current transformer of this type is basically a toroid transformer. A toroid transformer is constructed with a hollow core similar to a donut in that it has a hole in the middle. When current transformers are used, the main power line is inserted through the opening in the transformer, Figure 21-3. 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 amps 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 21-4. It now requires 300 amps 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 amps of current flow to deflect the meter full scale.

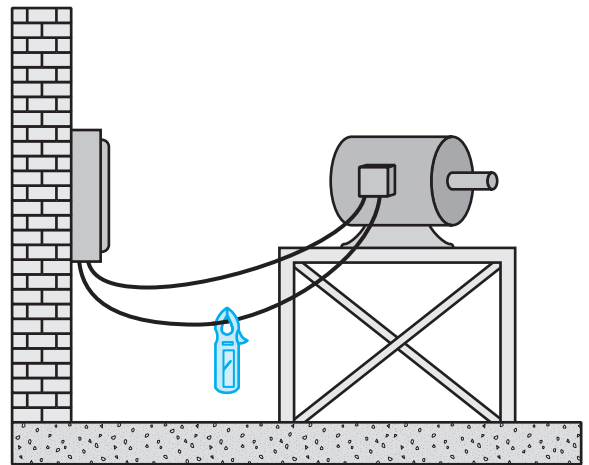
CLAMP-ON AMMETERS

Many service technicians use the clamp-on type of AC ammeter. To use this type of meter, the jaw of the meter is clamped around one of the conductors supplying power to the load, Figure 21–5. 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.

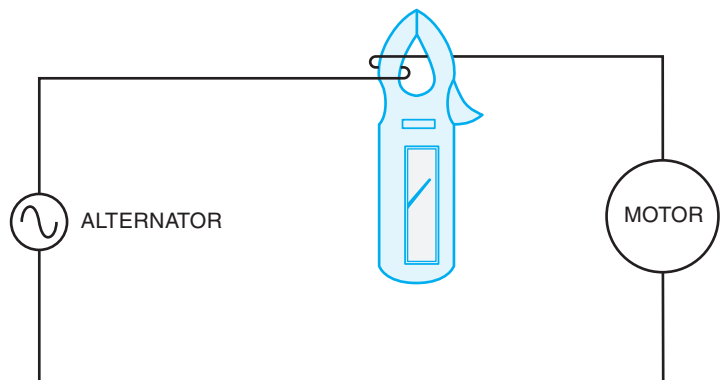
This type of meter uses a current transformer to operate the meter. The jaw of the meter is part of the core material of the transformer. When the meter is connected around the current carrying wire, the changing magnetic field produced by the AC current induces a voltage into the current transformer. The strength of the magnetic field and its frequency determines the amount of voltage induced in the current transformer. Because 60 Hz is a standard frequency throughout the United States and Canada, the amount of induced voltage is proportional to the strength of the magnetic field.

The **clamp-on type ammeter** can have different range settings by changing the turns ratio of the secondary of the transformer just as the in-line ammeter does. The primary of the transformer is the conductor the movable jaw is connected around. If the ammeter is connected around one wire, the primary has one turn of wire as compared to the turns of the secondary. The turn's ratio can be changed in

the same manner as changing the ratio of the CT. If two turns of wire are wrapped around the jaw of the ammeter, Figure 21–6, 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 very useful for measuring low currents.



► **Figure 21–5**
The clamp-on ammeter connects around one conductor.
(Source: Delmar/Cengage Learning)



► **Figure 21–6**
Looping the conductor around the jaw of the ammeter changes the ratio. (Source: Delmar/Cengage Learning)

SUMMARY

- Current transformers have their primary winding connected in series with a load.
- Current transformers are often used to provide multiple scale values for in-line AC ammeters.
- Current transformers are often referred to as CTs.
- CTs are used to measure large amounts of AC current.
- CTs have a standard secondary current value of 5 amperes.
- CTs are designed to be operated with their secondary winding shorted.
- The short circuit connected across the secondary of the CT should never be removed when power is connected to the circuit because the secondary voltage can become very high.
- Many clamp-on AC ammeters operate on the principle of a current transformer.
- The movable jaw of the clamp-on ammeter is the core of the transformer.
- The secondary current value of a current transformer can be changed by changing the turns of wire of the primary.

KEY TERMS

5 amperes
clamp-on ammeter

CTs
current transformers

in-line ammeters

REVIEW QUESTIONS

1. Explain the difference in connection between the primary winding of a voltage transformer and the primary winding of a current transformer.
2. What is the standard current rating for the secondary winding of a CT?
3. Why should the secondary winding of a CT never be disconnected from its load when there is current flow in the primary?
4. A current transformer has a ratio of 600:5. If three loops of wire are wound through the transformer core, how much primary current is required to produce 5 amperes of current in the secondary winding?
5. Assume that a primary current of 75 amperes flows through the windings of the transformer in question 4. How much current will flow in the secondary winding?
6. What type of core is generally used in the construction of a CT?
7. A current transformer has 4 turns of wire in its primary winding. How many turns of wire are needed in the secondary winding to produce a current of 2 amperes when a current of 60 amperes flows in the primary winding?



8. A 1500:5 CT develops a voltage of 3 volts across the primary winding. If the secondary should be disconnected from its load, how much voltage would be developed across the secondary terminals?
9. A CT has a current flow of 80 amperes in its primary winding and a current of 2 amperes in its secondary winding. What is the ratio of the CT?
10. What is the most common use for a CT?



SECTION 5

Control Components

UNIT 22

Overloads

OBJECTIVES

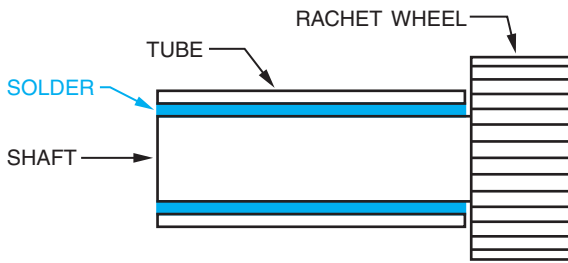
After studying this unit the student should be able to:

- Explain why motors should be protected from an overload condition
- List the different types of overload protectors
- Describe the operation of a solder-melting and bimetal type overload
- Connect an overload relay into a motor circuit
- Perform an ohmmeter test on an overload relay

Overload relays are designed to protect the motor circuit from damage due to **overloads**. Most overload relays are operated by heat. Since the overload unit must be sensitive to motor current, the heater of the overload relay is connected in series with the motor. In this manner, the amount of current that flows through the motor winding also flows through the overload heater. There are two basic types of overload units used in the air conditioning field, the **solder-melting type** and the **bimetal type**.

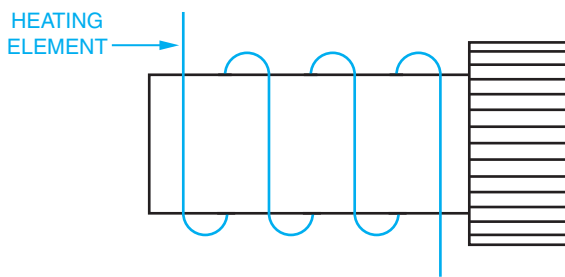
SOLDER-MELTING TYPE OVERLOAD RELAY

The solder-melting type of overload unit is used to a large extent on commercial and industrial air conditioning units. This type of overload unit contains



► **Figure 22-1**
Shaft is held stationary by solder.

(Source: Delmar/Cengage Learning)

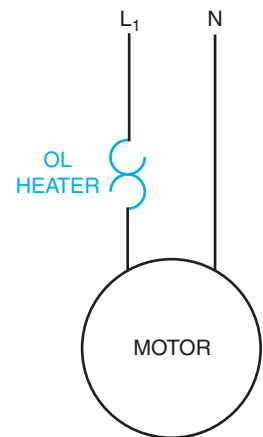


► **Figure 22-2**
An electric heating element is wound around the tube.

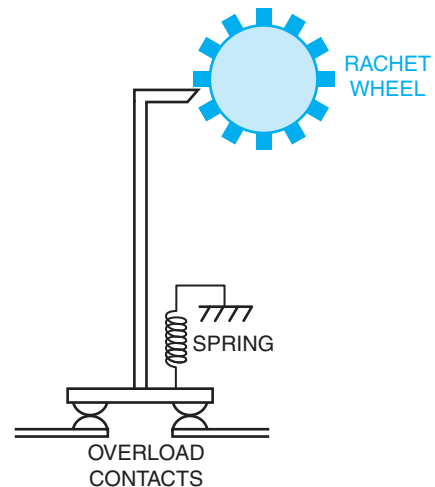
(Source: Delmar/Cengage Learning)

a ratchet wheel that is held stationary by solder. Figure 22-1 illustrates the principle of operation. A serrated wheel is attached to a shaft. The shaft is inserted in a hollow tube. The shaft would be free to rotate inside the tube except for the solder that bonds the two units together.

An electric **heating element** is wound around the tube as shown in Figure 22-2. The heating element is connected in series with the motor, Figure 22-3. The current that flows through the motor windings also flows through the heating element. The heating element is calibrated to produce a certain amount of heat when a predetermined amount of current flows through it. As long as the current flowing through it does not exceed a certain amount, there is not enough heat produced to melt the solder. If the motor should become overloaded, an excessive amount of current will flow through the heater and the solder will melt. When the solder melts, the shaft is free to turn.



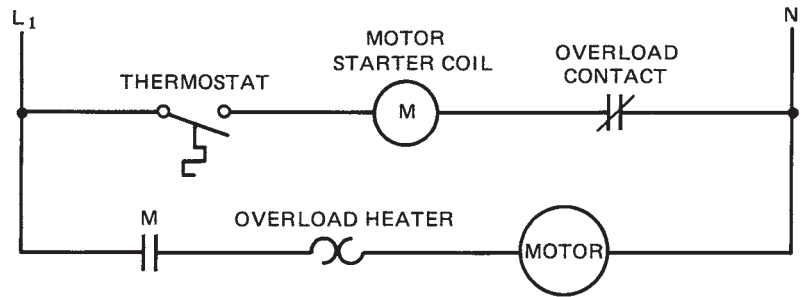
► **Figure 22-3**
The overload heater is connected in series with the motor. (Source: Delmar/Cengage Learning)



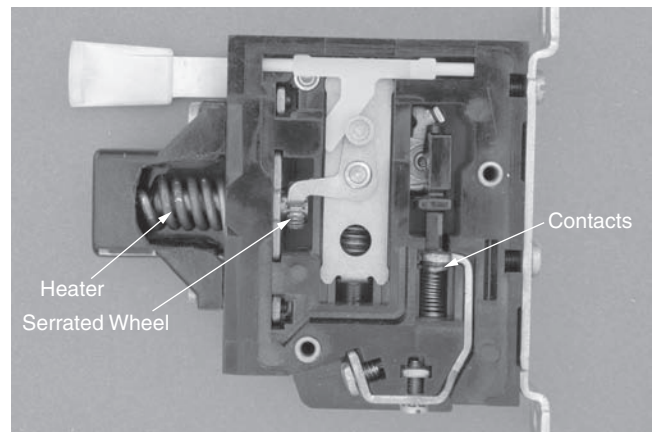
► **Figure 22-4**
The ratchet wheel holds the contacts closed. (Source: Delmar/Cengage Learning)

The ratchet wheel is used to mechanically hold a set of spring-loaded contacts closed as shown in Figure 22-4. When the solder melts, the ratchet wheel is free to turn and the spring causes the contacts to open. The normally closed contacts are connected in series with the coil of the motor starter used to control the motor the overload relay is protecting, Figure 22-5. When the overload contacts open, the motor starter coil deenergizes and disconnects the motor from the line.

Notice that this overload relay has two separate sections, the **heater section** that is connected in series with the motor, and the **contact section**,



► **Figure 22-5**
When the overload contact opens, the motor is disconnected from the line. (Source: Delmar/Cengage Learning)

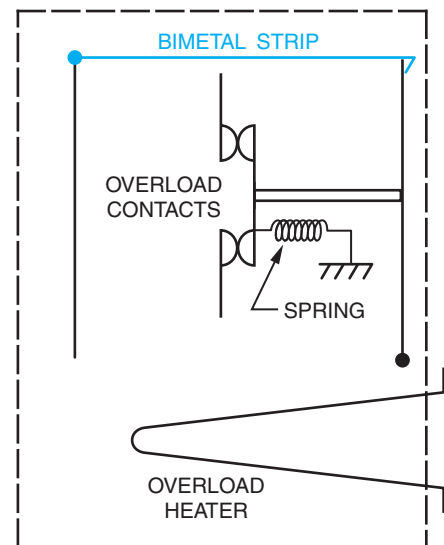


► **Figure 22-6**
Solder-melting type of overload relay. (Source: Delmar/Cengage Learning)

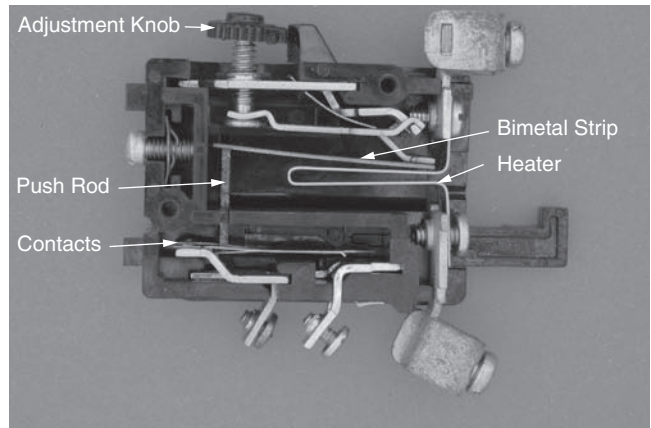
which is connected in series with the coil of the motor starter. Notice also that the overload contacts are not used to disconnect the motor from the line. They are used to disconnect the motor starter coil from the line. This type of overload relay has a set of small auxiliary contacts that are intended to interrupt the current flow in the control circuit only. After the overload has tripped, it must be allowed to cool down enough for the solder to re-harden before it can be reset. This is generally true of any type of thermal overload. Figure 22-6 shows a photograph of this type of overload.

BIMETAL TYPE OF OVERLOAD

The bimetal type of overload operates very similarly to the solder-melting type except a **bimetal strip** is used to cause the contacts to open, Figure 22-7. In this unit, the bimetal strip is used to mechanically



► **Figure 22-7**
Bimetal type of overload. (Source: Delmar/Cengage Learning)



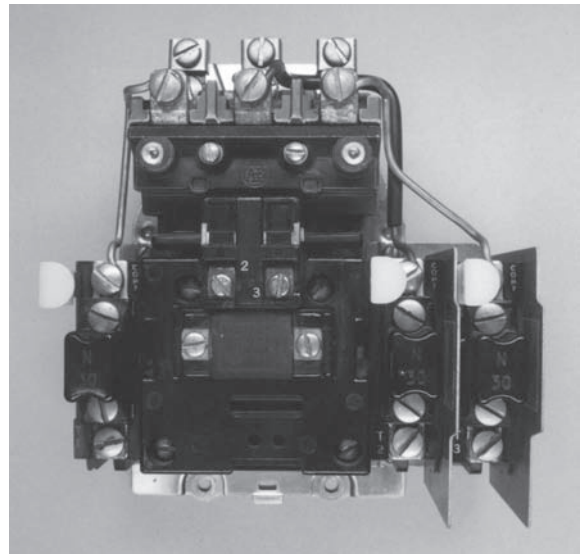
► **Figure 22-8**
Bimetal-type overload relay. (Source: Delmar/Cengage Learning)

hold the spring-loaded contacts closed. If the current flow through the heater becomes excessive, the bimetal strip will warp and permit the spring to open the contacts. After the overload unit has tripped, the bimetal strip must be allowed some time to cool before it can be reset. This type of unit has an advantage over the solder-melting type in that it can be adjusted for manual reset or automatic reset, Figure 22-8. The solder-melting type of overload unit must be manually reset.

PROTECTING THREE-PHASE MOTORS

Each phase of a three-phase motor should be protected by an overload relay. There are two methods employed to provide this protection. One method is to connect a single overload relay like those shown in Figures 22-6 and 22-8 into each phase; see Figure 22-9. When this is done, the three sets of overload contacts are connected in series with each other, as shown in Figure 22-10. Because the overload contacts are connected in series, if any one set of contacts should open, the starter coil will be disconnected, causing the load contacts to open and disconnect the motor from the line.

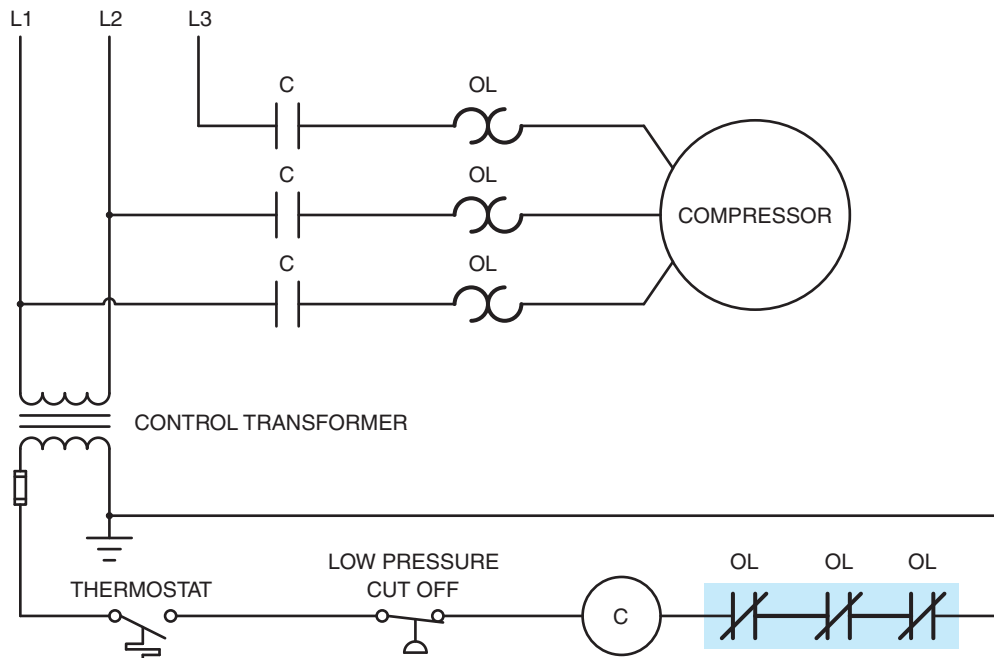
The second method used to protect three-phase motors is with a three-phase overload relay. This overload relay contains three separate heaters but only one set of overload contacts, Figure 22-11. If any one of the heaters should trip, it will open the set of contacts and disconnect the starter coil from the line, Figure 22-12.



► **Figure 22-9**
Three single overload relays are used to protect a three-phase motor. (Source: Delmar/Cengage Learning)

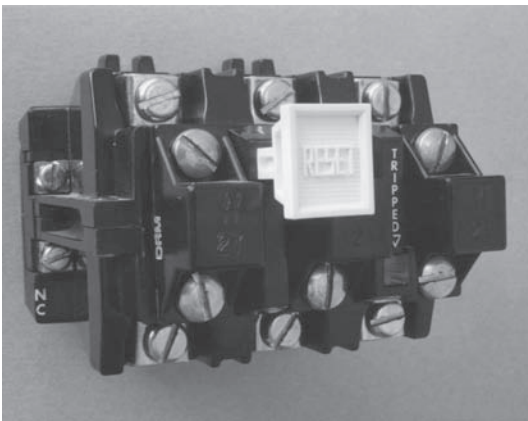
PROTECTING SINGLE-PHASE MOTORS

Single-phase motors are generally protected with a small **automatic reset overload**, Figure 22-13. These units are constructed in one of two ways. One unit has a small heater connected in series with the motor current, Figure 22-14. In this unit the bimetal strip is constructed of a spring metal that provides a snap action when it warps. Notice that the



► **Figure 22-10**

When three single overload relays are employed to protect a three-phase motor, all normally closed overload contacts are connected in series. (Source: Delmar/Cengage Learning)



► **Figure 22-11**

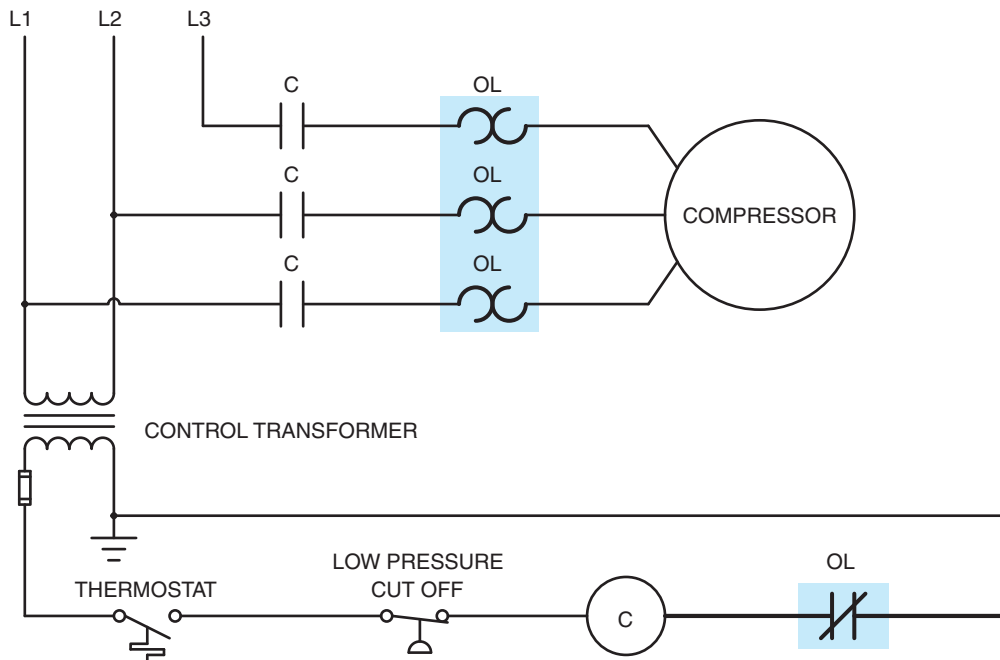
Three-phase overload relay. (Source: Delmar/Cengage Learning)

contacts are connected directly to the bimetal strip. This means that the motor current not only flows through the heating element, but also through the bimetal strip. If the motor current becomes excessive, the heater causes the bimetal strip to snap the

contacts open and disconnect the motor from the line. Notice that the contacts of this unit are used to interrupt the motor current. When the bimetal strip has cooled enough, it snaps back to its original position and recloses the contacts.

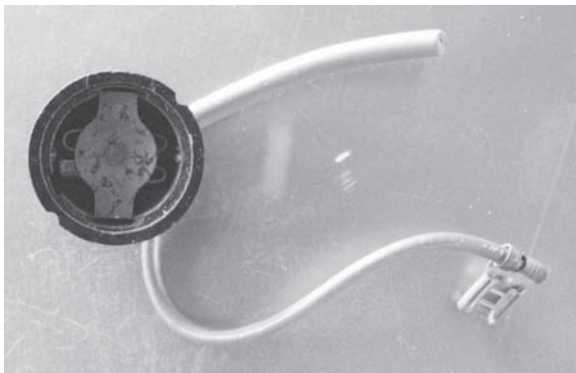
The second type of small overload unit does not contain a heating element, Figure 22-15. In this type of unit, the bimetal strip is used as the heating element. As current flows through the bimetal strip, it begins to heat. If motor current does not become excessive, the bimetal strip does not become heated enough to cause the contacts to open. If the current does become excessive, however, the contacts snap open and disconnect the motor from the line.

These overload units can be tested with an ohmmeter for a complete circuit. If the ohmmeter indicates no continuity through them when they are cool, they are defective and must be replaced. Care must be taken to replace these units with the correct size. Overload units are designed to open their contacts when the motor current reaches 115% to 125% of full-load current. The exact rating is



► **Figure 22-12**

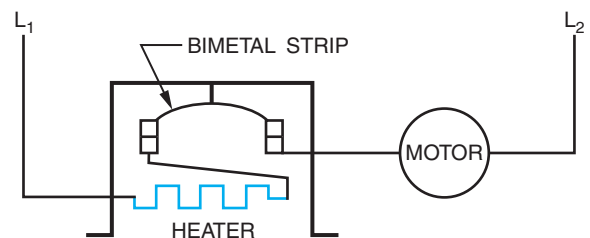
A three-phase overload relay contains three heaters and one set of contacts. (Source: Delmar/Cengage Learning)



► **Figure 22-13**

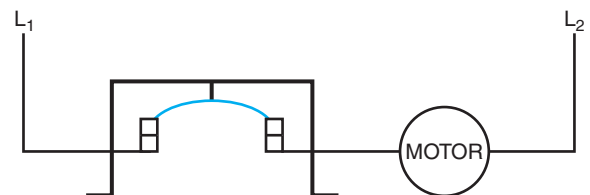
Bimetal overload often used on fractional horsepower single-phase motors. (Source: Delmar/Cengage Learning)

determined by the national electrical code. If an overload unit of too small a rating is installed, it will trip when there is no overload on the motor. If an overload unit of too high a value is used, the motor may be destroyed before the overload contacts open and disconnect the motor.



► **Figure 22-14**

Small overload unit with heater. (Source: Delmar/Cengage Learning)



► **Figure 22-15**

Small overload unit without heater. (Source: Delmar/Cengage Learning)

Notice that all of the overload units discussed are operated by sensing heat. For this reason, a heavy motor overload will cause more heat production and the unit will trip faster than it will under a light overload. Another factor that can affect these units is **ambient air temperature**. Overload relays will trip faster in hot weather than they will in cool weather. In certain parts of the country, it is often necessary to replace the heater elements of industrial-type overload units to match the season. In winter it may be desirable to use a slightly smaller heater element than normal, and in summer it may be necessary to use a slightly larger heater.

PROTECTING LARGE MOTORS

Large horsepower motors often have current draws that are much greater than the rating of any standard overload heating element. When this is the case, current transformers are used to supply

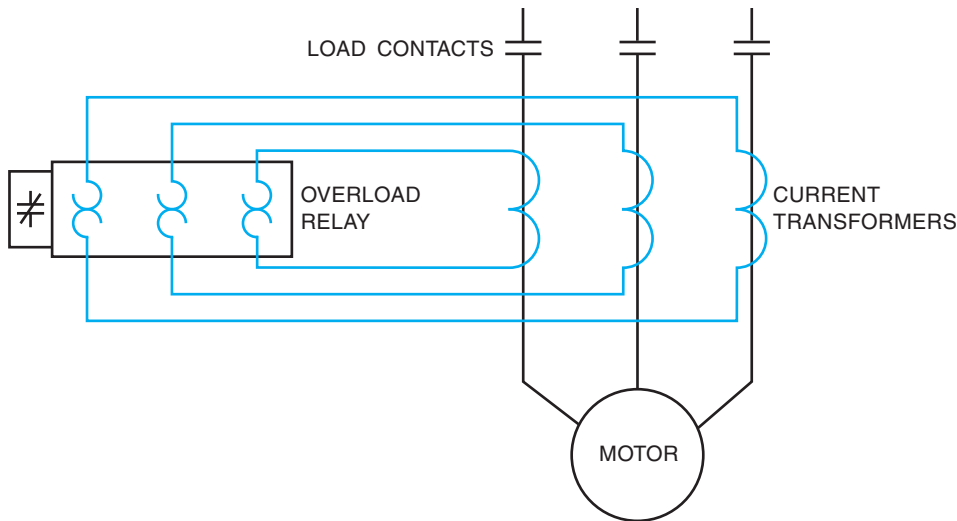
current to the overload heaters, Figure 22-16. Assume that the motor operating a large compressor has a nameplate current of 234 amperes. Now assume that three current transformers with a ratio of 300:5 are to be used to reduce the current to the overload heaters. The current rating of the overload heater can be calculated using the ratio of the current transformer.

$$\frac{300}{5} = \frac{234}{X}$$

$$300 X = 1170$$

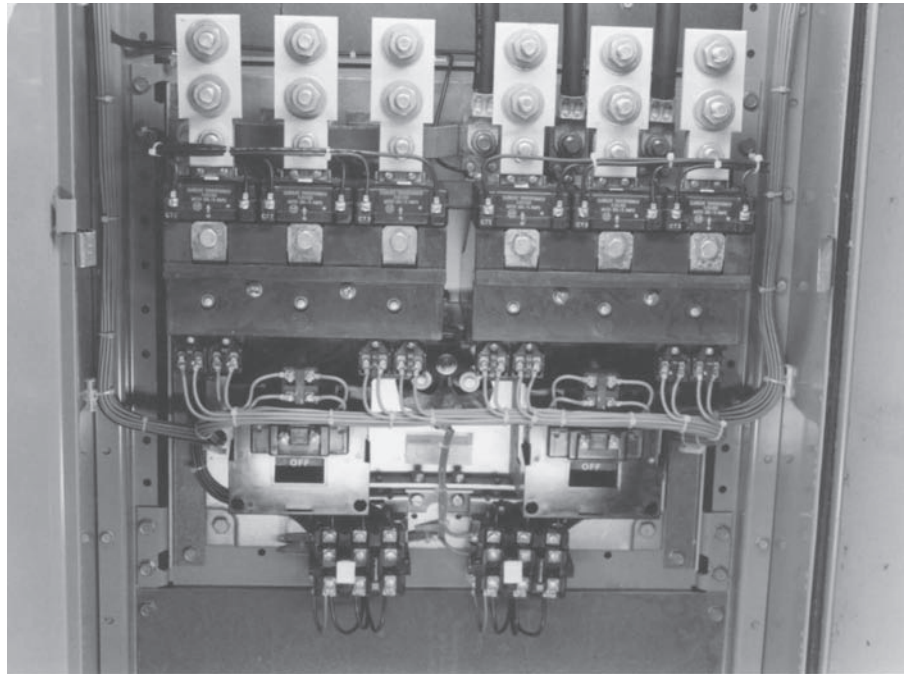
$$X = 3.9 \text{ amps}$$

If the overload heaters are sized for a motor with a running current of 3.9 amperes the motor will be protected. Two NEMA size 5 starters are shown in Figure 22-17. These starters contain current transformers used to reduce the current to the overload heaters.



► **Figure 22-16**

Current transformers reduce the motor current. (Source: Delmar/Cengage Learning)



► **Figure 22-17**
NEMA size 5
starters with current
transformers. (Source:
Delmar/Cengage Learning)

SUMMARY

- Overload relays are designed to protect the motor against an overload condition.
- Most overload relays sense motor current by connecting an electric heater in series with the motor.
- Two basic types of overload relays are:
 - A. Solder-melting type.
 - B. Bimetal strip type.
- Solder-melting type overload relays permit the electric heater to melt solder at a predetermined temperature and open a set of contacts.
- The bimetal strip type of overload relays open a set of contacts when the electric heating element causes a bimetal strip to warp a certain amount.
- Overload relays contain two separate sections, the heater section and the contact section.
- The contacts of an overload relay are connected in series with a motor starter coil.
- Because overload relays operate by sensing heat, they are affected by ambient temperature.

KEY TERMS

ambient air
temperature
automatic reset
overload

bimetal strip
bimetal type
contact section
heater section

heating element
overloads
solder-melting type

REVIEW QUESTIONS

1. What are the two basic types of industrial overload units?
2. What is the advantage of the bimetal type of industrial overload unit?
3. Industrial overload units are divided into two sections. What are they?
4. At what percentage of full-load motor current are overload units generally set to trip?
5. When using an industrial type of overload unit, what are the contacts connected in series with?
6. What is the difference between the two types of small overload units?
7. In the small overload unit that does not contain a heater, what is used to sense the current flow through the motor?

UNIT 23



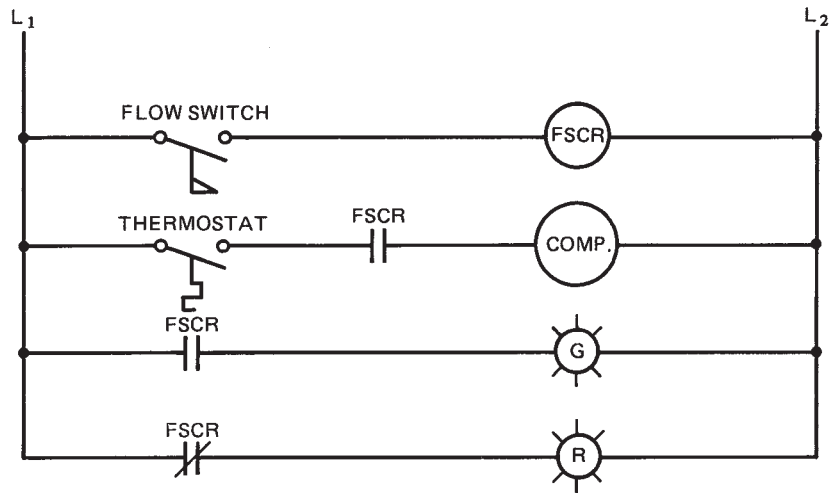
Relays, Contactors, and Motor Starters

OBJECTIVES

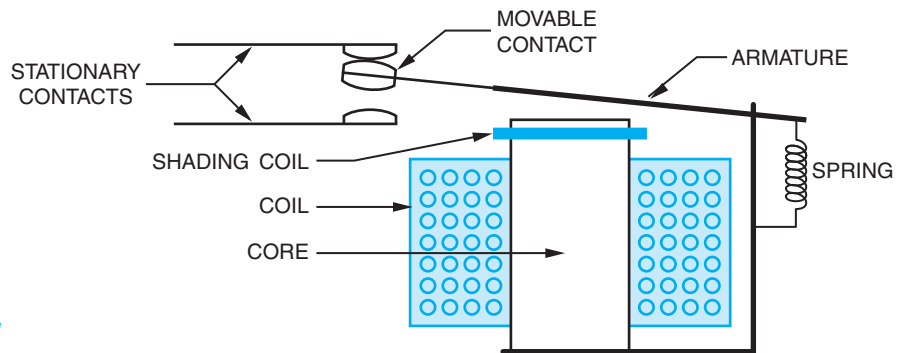
After studying this unit the student should be able to:

- » Describe the construction of a relay
- » Discuss the principle of operation of relays and contactors
- » Discuss different types of relays and contactors
- » Describe the difference between a contactor and a motor starter

The **relay** is a magnetically operated switch. This switch, however, can have multiple sets of contacts, and the contacts can be open or closed. The advantage of the relay is control. A single pilot device can be used to control the input or coil of the relay, and the output or contacts can control several different devices. An example of this is shown in the circuit of Figure 23–1. A flow switch is used to control the coil of a magnetic relay. When the flow switch closes, the coil of relay **FSCR (flow switch control relay)** is connected to the line. When current flows through the coil, the relay is energized, and all FSCR contacts change position. Notice that one FSCR contact is connected in series with the compressor motor. This contact does not actually start the motor, but it permits the thermostat to control the motor. This particular type of control is known as **interlocking**. Interlocking is used to prevent



► **Figure 23-1**
One relay controls several de-
vices. (Source: Delmar/Cengage Learning)



► **Figure 23-2**
Simple relay. (Source: Delmar/Cengage
Learning)

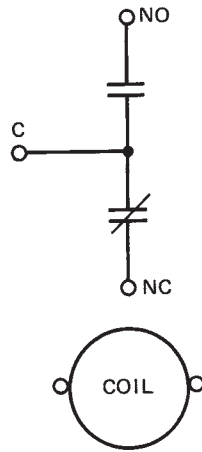
some function from happening until some other function has occurred. In this case, the thermostat cannot start the compressor until there is airflow in the system.

The second FSCR contact is normally open. When the FSCR coil energizes, this contact closes and turns on a green pilot light to indicate there is airflow in the system. The third FSCR contact is normally closed. It is used to turn off a red pilot light, which indicates there is no airflow in the system.

PRINCIPLE OF OPERATION

The relay operates on the **solenoid** principle. A solenoid is an electrical device that converts electrical energy to linear motion. This principle is

illustrated in Figure 23-2. A coil of wire is wound around an iron core. When current flows through the coil, a magnetic field is developed in the iron core. The magnetic field of the iron core attracts the movable arm, known as the **armature**, and overcomes the strength of the spring holding the arm away from the iron core. Notice that a movable contact is connected to the armature. In its present position, the movable contact makes connection with a stationary contact. This contact set is normally closed. When the armature is attracted to the iron core, the movable contact breaks connection with one stationary contact and makes connection with another. This relay has both a normally open and normally closed set of contacts. Notice that the movable contact is common to both of the



► **Figure 23-3**
Schematic of a simple
relay. (Source: Delmar/
Cengage Learning)

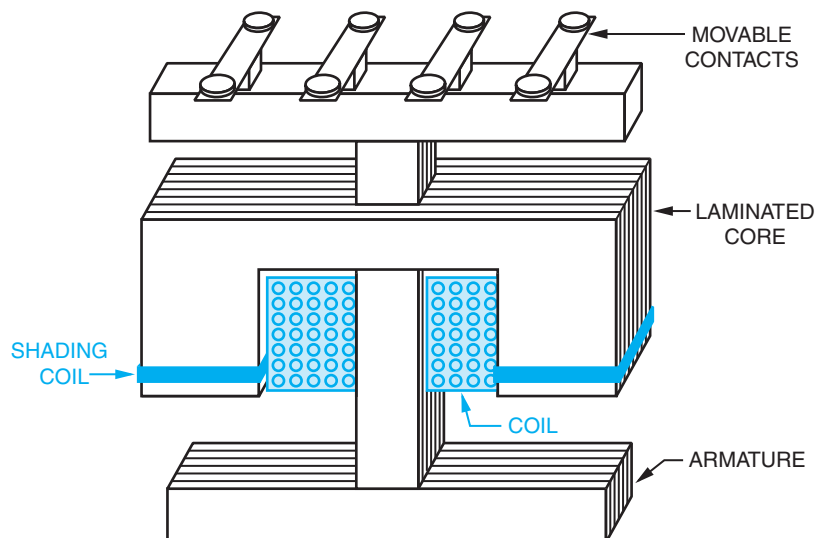
stationary contacts. The movable contact would be the common and the stationary contacts would be labeled normally open and normally closed. A schematic of this type of relay is shown in Figure 23-3. This illustration shows a relay with only one set of contacts. In practice, it is common to find this type of relay with several sets of contacts.

Notice in Figure 23-2 that a shading coil has been added to the iron core. The shading coil is used with AC relays to prevent contact chatter and hum. The shading coil operates in the same way it does in the shaded-pole motor. It opposes a change of magnetic flux. The shading coil is used to provide

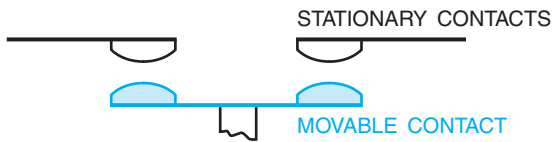
a continuous magnetic flow to the armature when the voltage of the AC waveform is zero. DC-operated relays do not contain a shading coil since the magnetic flux is constant.

Another type of relay is shown in Figure 23-4. This relay uses a **plunger-type** of solenoid. Notice that the coil is surrounded by the iron core. There is an opening in the iron core through which the shaft of the armature can pass. When the coil is energized, the armature is attracted to both ends of the core. This creates a stronger magnetic field than the relay discussed in Figure 23-2. Notice the shading coils around both ends of the core. Notice also that the core and armature are constructed of laminated sheets. The core and armature are laminated to help prevent the induction of **eddy currents** into the core. Eddy currents are currents induced in the core material by the magnetic field of the coil. Eddy currents are generally unwanted because they heat the core and cause a power loss.

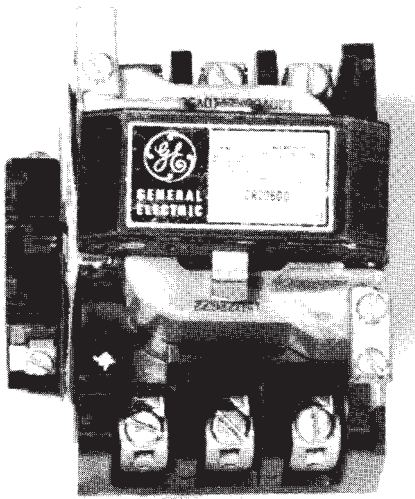
The plunger-type of solenoid is generally used with relays that use double-break contacts. A **double-break contact** is one that breaks connection at two points as shown in Figure 23-5. Notice there are two stationary contacts and one movable contact. The movable contact is used to bridge the gap between the two stationary contacts. This type of contact arrangement is preferred for relays that must control high voltage and current.



► **Figure 23-4**
Plunger type of solenoid. (Source:
Delmar/Cengage Learning)



► **Figure 23-5**
A set of double-beak contacts. (Source: Delmar/Cengage Learning)

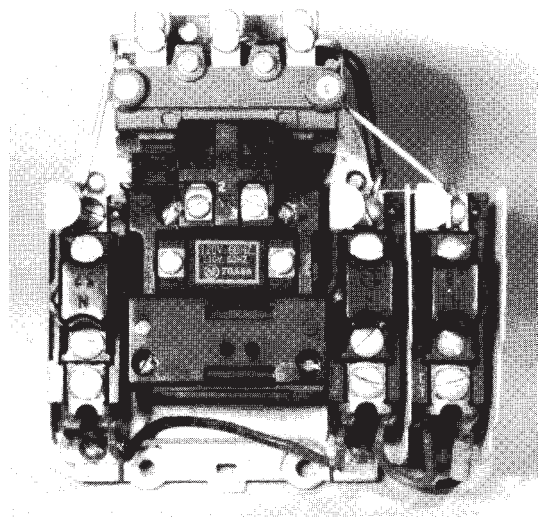


► **Figure 23-6**
Contactor. (Source: Delmar/Cengage Learning)

Notice that the surface of the contact is curved. This curved surface provides a wiping action when the contacts make connection. The wiping action helps to keep contact surfaces clean. Contact surfaces should never be filed flat. This would permit oil and dirt to collect on the surface of the contact and cause poor connection.

CONTACTORS AND MOTOR STARTERS

The term *relay* is often used to describe any type of magnetically operated switch. A relay is actually a control device that contains small auxiliary contacts designed to operate only low-current loads.



► **Figure 23-7**
Motor starter with overload relays. (Source: Delmar/Cengage Learning)

A **contactor** is very similar to a relay except that a contactor contains large-load contacts designed to control large amounts of current. In the heating and airconditioning field, contactors are often used to connect power to resistance heater banks. A photograph of a contactor is shown in Figure 23-6. Contactors may contain auxiliary contacts as well as load contacts.

Motor starters are basically contactors with the addition of overload relays. Motor starters generally contain auxiliary contacts as well as load contacts. The auxiliary contacts are used as part of the control circuit, and the load contacts are used to connect the motor to the line. A photograph of a motor starter is shown in Figure 23-7.

SUMMARY

- ▶ A relay is a magnetically operated switch.
- ▶ A relay is a single-input multi-output device.
- ▶ Relays can have contacts that are normally open or normally closed.
- ▶ On a schematic diagram, the contacts of a relay are always shown in the deenergized condition.
- ▶ Interlocking is used to prevent some function from happening until some other function has occurred.
- ▶ Most relays are basically electric solenoids with a set of contacts attached.
- ▶ A solenoid is a device that converts electrical energy into linear motion.
- ▶ AC relays used shading coils on the iron core to prevent contact chatter.
- ▶ Contact surfaces are generally curved to provide a wiping action.
- ▶ A relay is actually a control device that has only small auxiliary contacts that are used as part of the control circuit or to operate low current devices.
- ▶ Contactors contain large load contacts intended to connect the load to the line.
- ▶ Motor starters are contactors with the addition of overload relays.

KEY TERMS

armature
contactor
double-break contact
eddy currents

FSCR (flow switch
control relay)
interlocking
motor starters

plunger-type
relay
solenoid

REVIEW QUESTIONS

1. What is a solenoid?
2. What type of relays contains a shading coil?
3. What purpose does the shading coil serve?
4. What is the movable part of a relay called?
5. Why is the core material of a relay laminated?
6. What are eddy currents?
7. What effect do eddy currents have on a relay?
8. Why are contact surfaces curved?
9. What is the difference between a relay and a contactor?
10. What is the difference between a contactor and a motor starter?

UNIT 24

The Solid-State Relay

OBJECTIVES

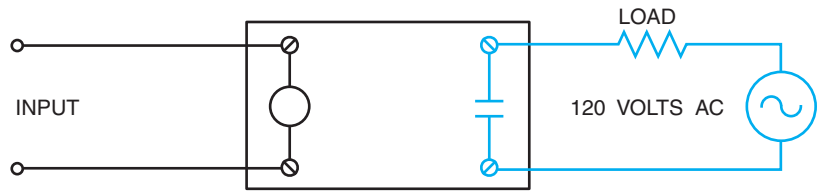
After studying this unit the student should be able to:

- Describe the construction of a solid-state relay
- Discuss the principle of opto-isolation
- Describe the internal devices used for a relay intended to control a DC and an AC load
- Describe zero switching
- Connect a solid-state relay in a circuit

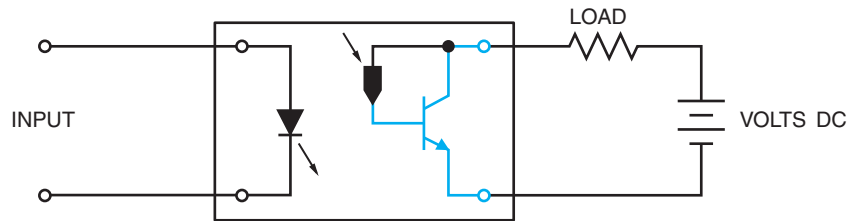
The **solid-state relay** is a device that has become increasingly popular for switching applications. The solid-state relay has no moving parts, it is resistant to shock and vibration, and is sealed against dirt and moisture. The greatest advantage of the solid-state relay, however, is the fact that the control input voltage is isolated from the line device the relay is intended to control. Refer to Figure 24–1.

Solid-state relays can be used to control either a DC load or an AC load. If the relay is designed to control a DC load, a **power transistor** is used to connect the load to the line as shown in Figure 24–2. The relay shown in Figure 24–2 has a **light-emitting diode (LED)** connected to the input or control voltage. When the input voltage turns the LED on, a photo detector connected to the base of the transistor turns the transistor on and connects

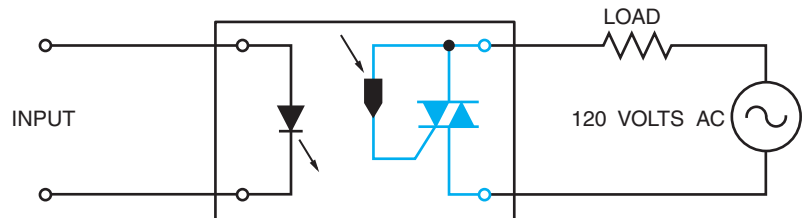
► **Figure 24-1**
Solid-state relay. (Source: Delmar/
Cengage Learning)



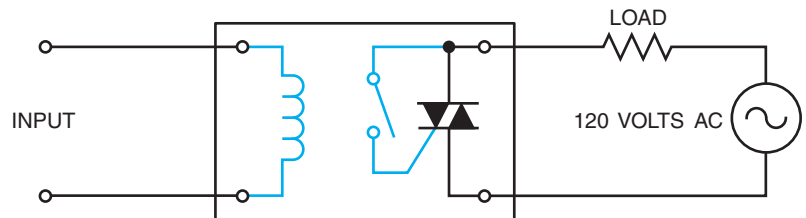
► **Figure 24-2**
Power transistor used to
control DC load. (Source: Delmar/
Cengage Learning)



► **Figure 24-3**
Triac used to control an AC load.
(Source: Delmar/Cengage Learning)



► **Figure 24-4**
Reed relay controls the output.
(Source: Delmar/Cengage Learning)



the load to the line. This optical coupling is a very common method used with solid-state relays. The relays that use this method of coupling are referred to as being **opto-isolated**, which means the load side of the relay is optically isolated from the control side of the relay. Because a light beam is used as the control medium, no voltage spikes or electrical noise produced on the load side of the relay can be transmitted to the control side of the relay.

Solid-state relays intended for use as AC controllers have a **triac** connected to the load circuit in place of a power transistor. Refer to Figure 24-3. In

this example, an LED is used as the control device just as it was in the previous example. When the photo detector “sees” the LED, it triggers the gate of the triac and connects the load to the line.

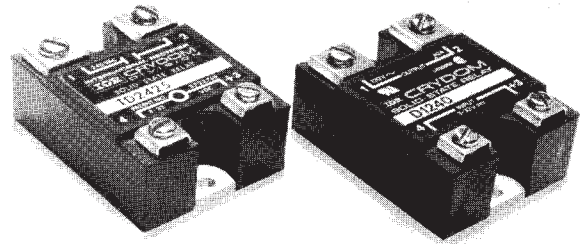
Although opto-isolation is probably the most common method used for the control of a solid-state relay, it is not the only method used. Some relays use a small **reed relay** to control the output. Refer to Figure 24-4. A small set of reed contacts are connected to the gate of the triac. The control circuit is connected to the coil of the reed relay. When the control voltage causes a current to flow through the

coil, a magnetic field is produced around the coil of the relay. This magnetic field closes the reed contacts, which causes the triac to turn on. In this type of solid-state relay, a magnetic field is used to isolate the control circuit from the load circuit instead of a light beam.

The control voltage for most solid-state relays ranges from about 3 to 32 volts and can be DC or AC. If a triac is used as the control device, load voltage ratings of 120 to 240 VAC are common and current ratings can range from 5 to 25 amps. Many solid-state relays have a feature known as **zero switching**. Zero switching means that if the relay is told to turn off when the AC voltage is in the middle of a cycle, it will continue to conduct until the AC voltage drops to a zero level and then turn off. For example, assume the AC voltage is at its positive peak value when the gate tells the triac to turn off. The triac will continue to conduct until the AC voltage drops to a zero level before actually turning off. Zero switching can be a great advantage when used with some inductive loads such as transformers. The core material of a transformer can be left saturated on one end of the flux swing if power is removed from the primary winding when the AC

voltage is at its positive or negative peak. This can cause inrush currents of up to 600% of the normal operating current when power is restored to the primary.

Solid-state relays are available in different case styles and power ratings. Figure 24–5 shows a typical solid-state relay. Some solid-state relays are designed to be used as time-delay relays. One of the most common uses for the solid-state relay is the I/O (eye-oh) track of a programmable controller, which is to be covered in a later unit.



► **Figure 24–5**
Solid-state relays. (Courtesy of International Rectifier).

SUMMARY

- Solid-state relays have no moving parts.
- Solid-state relays are sealed against dirt and moisture and are resistant to mechanical shock and vibration.
- The control side of a solid-state relay is totally isolated from the load side.
- Solid-state relays used to control AC loads use a triac connected in series with the load.
- Solid-state relays used to control DC loads use a power transistor connected in series with the load.
- Many solid-state relays use a light-emitting diode (LED) as the control device.
- Opto-isolation is used to separate the load side of the circuit from the control side. This prevents any electrical noise from being transferred from the load side to the control side of the circuit.
- Solid-state relays are generally used in the I/O track of programmable controllers.

KEY TERMS

light-emitting
diode (LED)
opto-isolated

power transistor
reed relay
solid-state relay

triac
zero switching

REVIEW QUESTIONS

1. What electronic component is used to control the output of a solid-state relay used to control a DC voltage?
2. What electronic component is used to control the output of a solid-state relay used to control an AC voltage?
3. Explain opto-isolation.
4. Explain magnetic isolation.
5. What is meant by zero switching?

UNIT 25



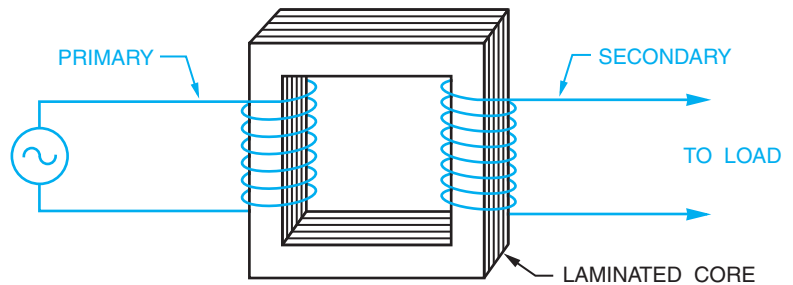
The Control Transformer

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the principle of operation of a transformer
- Define mutual induction
- Discuss the voltage and current relationships in a transformer
- Find values of voltage, current, and turns of wire using transformer formulas and Ohm's law
- Connect an industrial control transformer for operation on low and high voltage
- Perform an ohmmeter test on a control transformer

The **transformer** is a device that has the ability to change the value of AC voltage and current without a change of frequency. Most of the transformers used in the air conditioning and refrigeration field are known as **isolation transformers**. This means that the primary and secondary windings are magnetically coupled but electrically isolated from each other. Figure 25–1 illustrates the basic principle of operation of a transformer. This transformer contains two separate windings, the primary and the secondary. The primary is the winding that is connected to the power source and brings power to the transformer. The secondary winding is used to supply power to the load. Notice that there is no electrical connection between the two windings. If one lead of an ohmmeter is connected to one of the primary leads and the other ohmmeter lead is connected to one of the secondary leads, the ohmmeter



► **Figure 25-1**
A basic transformer.
(Source: Delmar/Cengage Learning)

should indicate no continuity between the two windings.

PRINCIPLE OF OPERATION

The transformer operates by magnetic induction. When current flows through the primary winding, a magnetic field is created in the winding. Because the secondary winding is wound on the same core as the primary, the magnetic field of the primary induces a voltage into the secondary. This action is known as **mutual induction**. The amount of voltage induced into the secondary is determined by the ratio of the number of turns of wire in the primary as compared with the number of turns of wire in the secondary. For example, assume that the primary winding shown in Figure 25-1 contains 120 turns of wire and is connected to 120 volts AC. This means that each turn of the primary has a voltage drop of 1 volt. If the secondary winding also has 120 turns of wire, and 1 volt is induced into each turn, then the output voltage of the secondary is 120 volts also. This transformer has a turns ratio of 1:1, which is to say that the primary contains 1 turn of wire for each turn of wire in the secondary.

Now assume that the number of turns of wire in the secondary has been changed to 60. If the number of turns in the primary has not been changed, there

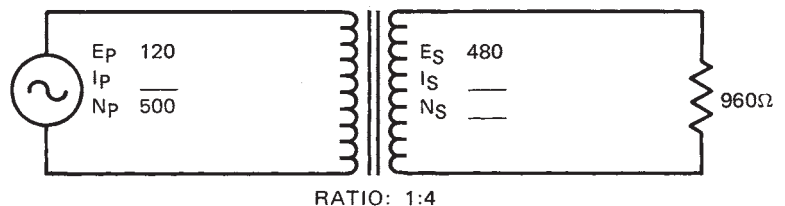
is still 1 volt for each turn of wire. This will produce a secondary voltage of 60 volts ($60 \times 1 = 60$).

If the number of turns of wire on the secondary is changed to 240, the output voltage of the secondary will be 240 volts ($240 \times 1 = 240$). Notice that the transformer has the ability to increase or decrease the amount of the secondary voltage. If the voltage of the secondary is less than the primary voltage, the transformer is known as a step-down transformer. If the secondary voltage is greater than the primary voltage, it is known as a step-up transformer.

VOLTAGE AND CURRENT RELATIONSHIPS

It would first appear that the transformer has the ability to give more than it receives. This is not the case, however. Transformers are extremely efficient devices; they generally operate at 95% to 98% efficiency. For this reason, when working with transformers it is generally assumed that the power out of the transformer is equal to the power being put into the transformer.

Figure 25-2 shows the schematic symbol for a transformer. The primary has been connected to 120 volts. The secondary has a voltage of 480 volts and is connected to a load resistor of 960 ohms.



► **Figure 25-2**
Schematic for transformer.
(Source: Delmar/Cengage Learning)

This transformer has a turns ratio of 1:4, which is to say that there is 1 turn of wire in the primary for every 4 turns of wire in the secondary. The amount of current in the secondary (I_s) can be computed by using Ohm's law.

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

$$I = \frac{480}{960}$$

$$I = .5 \text{ amp}$$

Question: If the secondary of this transformer has a current flow of .5 amp, how much current is required in the primary? There are actually several methods that can be used to solve this problem. The most accepted method is to use the formulas shown in Figure 25-3. Because both the primary and secondary voltages are known, the formula that contains voltage and current will be used to solve the problem.

$$\frac{E_p}{E_s} = \frac{I_s}{I_p}$$

$$\frac{120}{480} = \frac{.5}{I_p}$$

$$120 I_p = 240$$

$$I_p = 2$$

Notice that the transformer must have a current draw of 2 amps on the primary to supply a current of .5 amps at the secondary. If the power (volts $\times$ amps) is computed for both the primary and the secondary, it will be seen that they are equal.

$\frac{E_p}{E_s} = \frac{N_p}{N_s}$	$\frac{E_p}{E_s} = \frac{I_p}{I_s}$	$\frac{N_p}{N_s} = \frac{I_s}{I_p}$
E_p — Voltage of the primary		
E_s — Voltage of the secondary		
N_p — Number of turns of wire in the primary		
N_s — Number of turns of wire in the secondary		
I_p — Current flow in the primary		
I_s — Current flow in the secondary		

Figure 25-3
Transformer formulas. (Source: Delmar/Cengage Learning)

Primary

$$120 \times 2 = 240$$

Secondary

$$480 \times .5 = 240$$

The number of turns of wire can now be computed.

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$\frac{120}{480} = \frac{500}{N_s}$$

$$120 N_s = 240,000$$

$$N_s = 2000$$

Notice that the secondary has 2000 turns of wire compared to 500 turns in the primary. This is consistent with the turns ratio, which states there is 1 turn of wire in the primary for every 4 turns in the secondary.

The transformer shown in Figure 25-4 is a step-down transformer that has a primary voltage of 120 volts and a secondary voltage of 24 volts. The secondary is connected to a load resistance of 6 ohms. The current flow in the secondary winding is:

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

$$I = \frac{24}{6}$$

$$I = 4 \text{ amps}$$

Now that the secondary current is known, the amount of primary current can be computed.

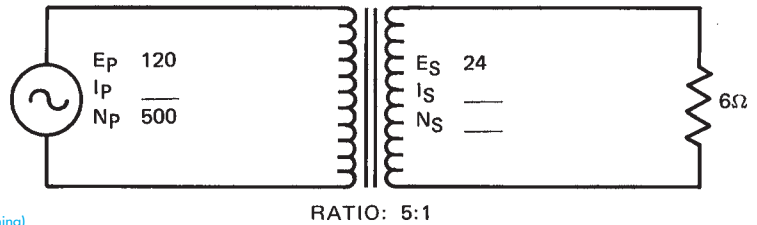
$$\frac{E_p}{E_s} = \frac{I_s}{I_p}$$

$$\frac{120}{24} = \frac{4}{I_p}$$

$$120 I_p = 96$$

$$I_p = .8 \text{ amp}$$

If the amount of power for the primary and that for the secondary are computed, it will be seen that they are the same.



► **Figure 25-4**
Step-down transformer. (Source: Delmar/Cengage Learning)

Primary

$$120 \times .8 = 96$$

Secondary

$$24 \times 4 = 96$$

The number of turns of wire in the secondary can now be computed.

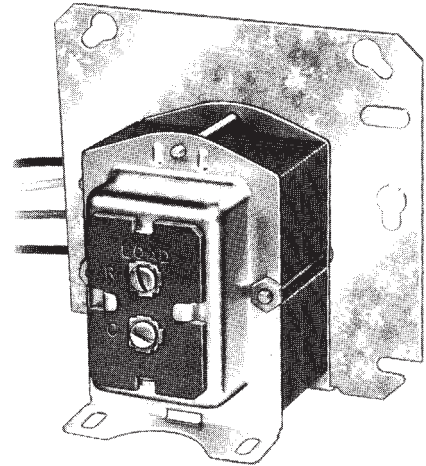
$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$\frac{120}{24} = \frac{500}{N_s}$$

$$120 N_s = 12000$$

$$N_s = 100$$

Notice that the number of turns of wire in the secondary, 100, as compared with the turns of wire in the primary, 500, is consistent with the turns ratio of 5:1.



► **Figure 25-5**
A 24-volt transformer. (Courtesy of Honeywell Inc.).

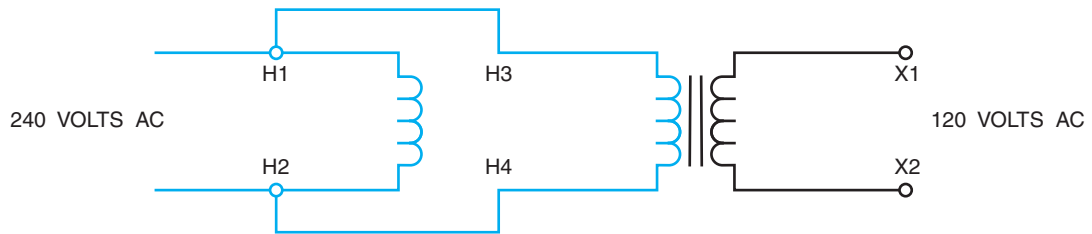
RESIDENTIAL CONTROL TRANSFORMERS

Control transformers are used to change the value of line voltage to the value needed for the control circuit. Most residential air conditioning systems operate on a control voltage of 24 volts AC. The amount of current needed will vary from one system to another, but it is generally less than 1 amp. The primary voltage for residential control transformers is 120 or 240 volts. A photograph of a control transformer used in residential applications is shown in Figure 25-5. The primary lead wires for most of these transformers will be black in color. The color of the secondary leads will vary from one manufacturer to another.

INDUSTRIAL CONTROL TRANSFORMERS

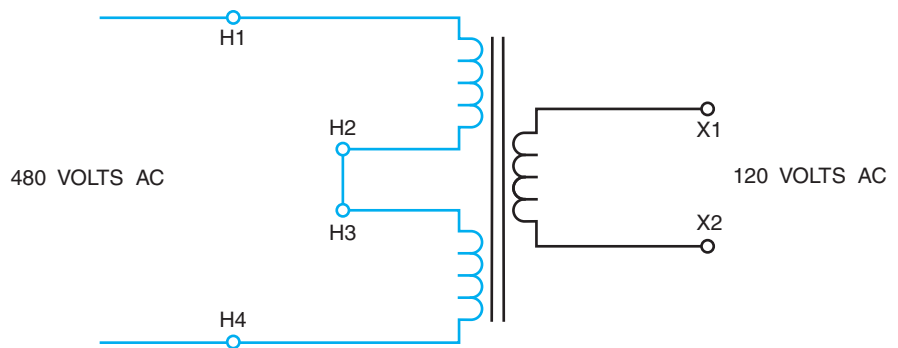
Most industrial and commercial air conditioning systems operate on 240 or 480 volts. The control voltage for most of these units is 120 or 24 volts AC. Most industrial control transformers contain two primary windings and one or two secondary windings. In the following explanation, it will be assumed that the transformer has two primary windings and one secondary winding. In this type of transformer, each primary winding has a voltage rating of 240 volts, and the secondary winding has a voltage rating of 120 volts. There is a turns ratio of 2:1 between each of the primary windings and the secondary winding.

There is a standard for marking the terminals of control transformers. One of the primary windings



► **Figure 25-6**
Primaries connected in parallel for 240-volt operation.

(Source: Delmar/Cengage Learning)



► **Figure 25-7**
Primaries connected in series for 480-volt operation.

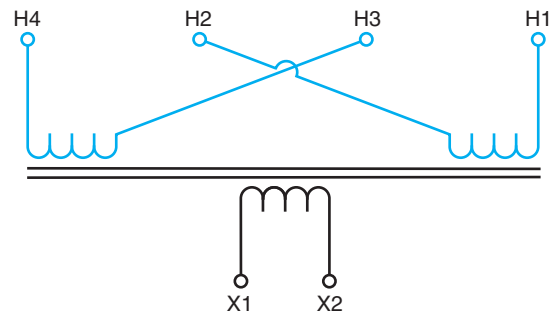
(Source: Delmar/Cengage Learning)

will be identified with terminal markings of H1 and H2. The other primary winding will be identified with terminal markings of H3 and H4. The secondary winding will be identified with terminal markings of X1 and X2.

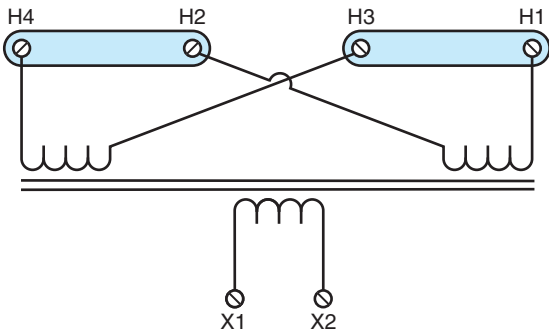
If the transformer is to be used to change a primary voltage of 240 volts into 120 volts, the two primary windings will be connected in parallel as shown in Figure 25-6. Because the two primary windings are connected in parallel, each will receive the same voltage. This will produce a turns ratio of 2:1 between the primary windings and the secondary windings. If 240 volts is connected to the primary of a 2:1 ratio transformer, the secondary voltage will be 120 volts.

If the transformer is to be used to change 480 volts to 120 volts, the primary windings will be connected in series as shown in Figure 25-7. In this connection, H2 of one primary winding is connected to H3 of the other primary winding. This series connection of the two windings produces a turns ratio of 4:1. When 480 volts is connected to the primary, 120 volts will be produced in the secondary.

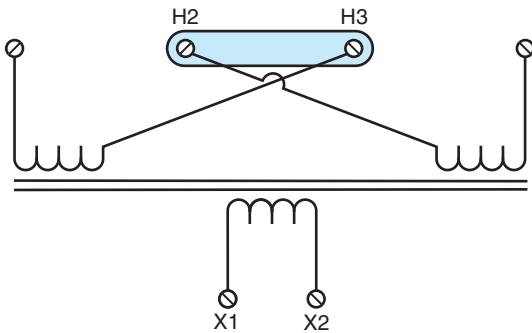
The primary windings of most control transformers have leads H2 and H3 crossed as shown in Figure 25-8. This is done to aid in the connection of the primary. For example, if it is desired to operate the transformer with the primary windings connected in parallel, a metal link is used to connect leads H1 and H3 together. Another metal link is used to connect leads H2 and H4 together,



► **Figure 25-8**
Primary leads are crossed. (Source: Delmar/Cengage Learning)



► **Figure 25-9**
Metal links used to make a 240-volt connection.
(Source: Delmar/Cengage Learning)



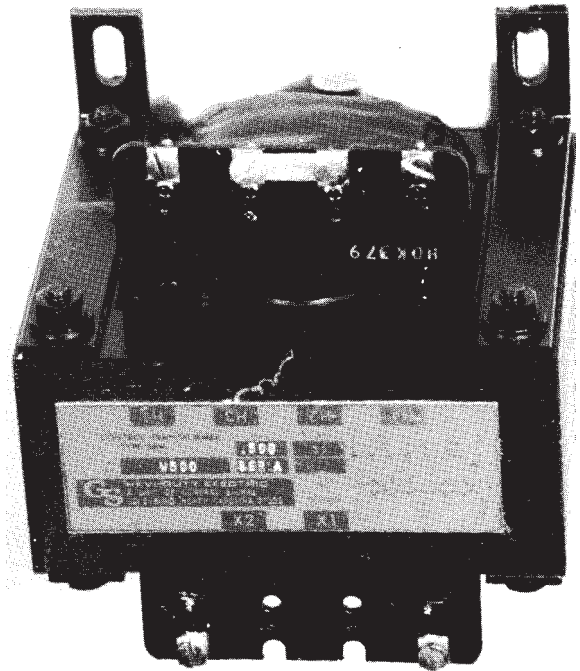
► **Figure 25-10**
Metal link used to make a 480-volt connection.
(Source: Delmar/Cengage Learning)

Figure 25-9. Compare this lead connection with the schematic shown in Figure 25-6.

If it is desired to connect the primary windings for operation on 480 volts, terminals H2 and H3 are joined together with a metal link, Figure 25-10. Compare this connection with the schematic shown in Figure 25-7. A photograph of an industrial control transformer is shown in Figure 25-11.

TESTING THE TRANSFORMER

An ohmmeter is generally used to test the windings of the transformer. To test the transformer, check for continuity through each set of windings. For example, there should be continuity between leads H1 and H2; H3 and H4; and X1 and X2. There should be no continuity between any of the windings such as H1 and H3, or H1 and X1. Also check



► **Figure 25-11**
Industrial control transformer. (Source: Delmar/Cengage Learning)

for a grounded winding by testing to be sure there is no continuity between any of the windings and the case of the transformer.

The output voltage of the transformer should be tested with an AC voltmeter. If the output voltage is not close to the rated voltage, the transformer is probably defective. If the transformer is tested without a load connected to the secondary, it is normal for the secondary voltage to be slightly higher than the rated voltage. For example, a 24-volt transformer may have an output voltage as high as 28 volts without load connected to it. The voltage rating of the transformer assumes it is supplying full-rated current to the load. If the voltage is tested when the transformer is under full load, the rated voltage should be seen. Notice the use of the control transformer in the schematic shown in Figure 25-12.

LEGEND	
CMT	CONDENSER MOTOR THERMOSTAT
CAP	CAPACITOR
CC	COMPRESSOR CONTACTOR
CCH	CRANKCASE HEATER
CFM	CONDENSER FAN MOTOR
COMP	COMPRESSOR
EFC	EVAPORATOR FAN CONTACTOR
F	FUSE
RR	RESET RELAY
T	TRANSFORMER
TB	TERMINAL BLOCK
TOP	TERMINAL OVERLOAD PROTECTOR
TS	TERMINAL STRIP
EFM	EVAPORATOR FAN MOTOR
LPC	LOW PRESSURE CONTROL
HPC	HIGH PRESSURE CONTROL
OL	OVERLOAD PROTECTOR

WARNING
DISCONNECT ELECTRICAL POWER
SOURCE TO PREVENT INJURY OR
DEATH FROM ELECTRICAL SHOCK

CAUTION
USE COPPER CONDUCTORS ONLY
TO PREVENT EQUIPMENT DAMAGE

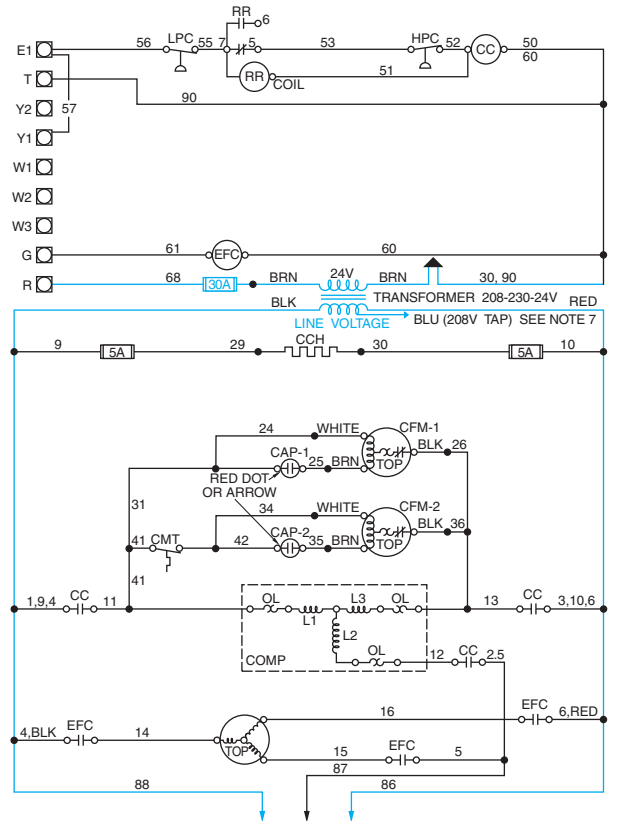


Figure 25-12
Control transformer used to provide low voltage for the control circuit. (Schematic courtesy of Trane Corp.).

SUMMARY

- ▶ A transformer is a device that can change values of AC voltage and current without a change of frequency.
- ▶ Isolation transformers have their primary and secondary sides physically and electrically separated from each other.
- ▶ Isolation transformers operate on the principle of mutual induction.
- ▶ The primary is the winding of the transformer that is connected to the incoming power line.
- ▶ The secondary is the winding that is connected to the load.
- ▶ All values of voltage and current in a transformer are proportional to the turns ratio.
- ▶ A step-up transformer will have a higher secondary voltage than primary voltage.
- ▶ A step-down transformer will have a lower secondary voltage than primary voltage.

KEY TERMS

control transformers
isolation transformers
mutual induction
transformer

REVIEW QUESTIONS

1. What is an isolation transformer?
2. Define a step-up transformer.
3. Define a step-down transformer.
4. The primary of a transformer is connected to 120 volts AC. The secondary has a voltage of 30 volts and is connected to a resistance of 5 ohms. How much current will flow in the primary of the transformer?
5. What is the amount of control voltage used in most residential air conditioning systems?
6. What is the amount of control voltage used in most industrial air conditioning systems?
7. What is the color of the primary leads of most control transformers used for residential service?
8. How many primary windings are generally contained in an industrial control transformer?
9. What is the turns ratio of each of these primary windings as compared with the secondary winding?
10. When an industrial control transformer is to be operated on 480 volts, are the primary windings connected in parallel or in series?

UNIT 26



Starting Relays

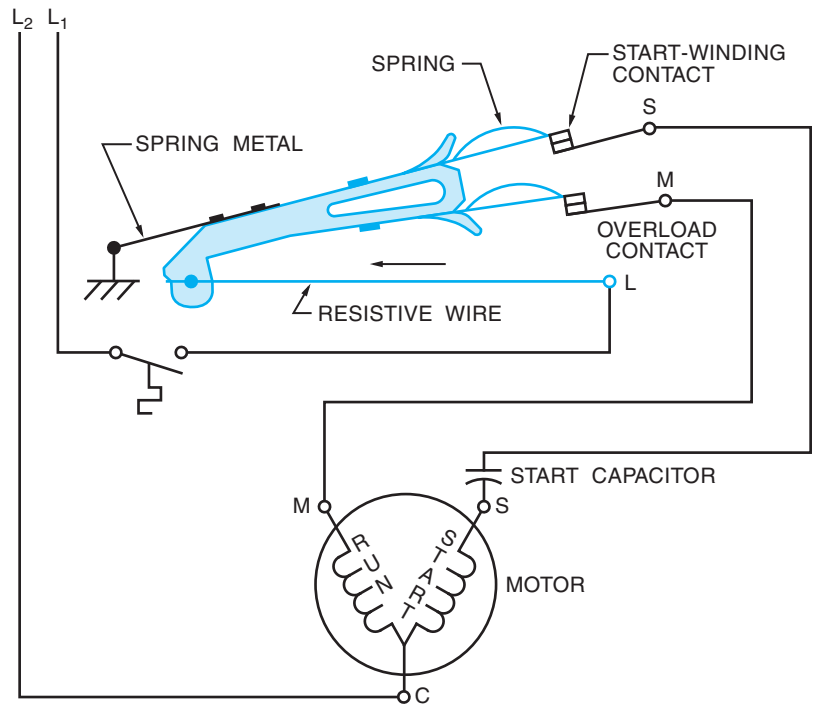
OBJECTIVES

After studying this unit the student should be able to:

- List the common types of starting relays
- Describe the operation of a hot-wire relay
- Connect a hot-wire relay in a circuit
- Describe the operation of a current relay
- Connect a current relay in a circuit
- Describe the operation of a potential relay
- Connect a potential relay in a circuit
- Describe the operation of a solid-state starting relay
- Connect a solid-state starting relay in a circuit
- Describe the operation, construction, and connection of a solid-state hard starting kit

When a split-phase motor is started, it is often necessary to disconnect the start windings when the motor reaches about 75% of full speed. In an open case motor, this job is generally done by the centrifugal switch. Some single-phase motors are hermetically sealed, however, and a centrifugal switch cannot be used. When this is the case, a **starting relay** must be used. A starting relay is located away from the motor and is used to disconnect the start windings when the motor has reached about 75% of its full speed. There are four basic types of starting relays in general use:

1. The **hot-wire relay**.
2. The **current relay**.
3. The **potential relay**.
4. The **solid-state relay**.

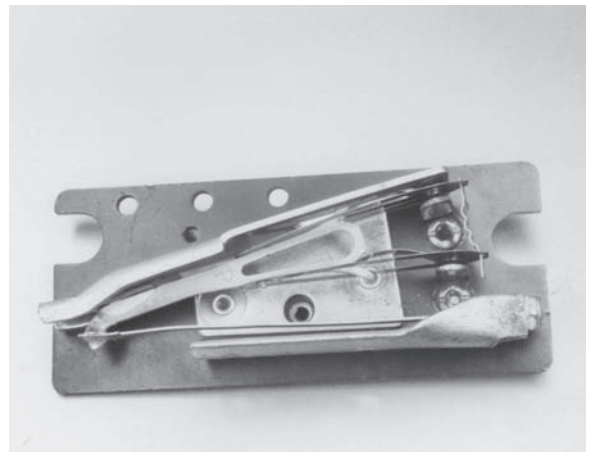


► **Figure 26-1**
Hot-wire relay connection.

(Source: Delmar/Cengage Learning)

THE HOT-WIRE RELAY

The **hot-wire relay** is so named because it uses a length of resistive wire connected in series with the motor to sense motor current. A diagram of this type of relay is shown in Figure 26-1. When the thermostat contact closes, current can flow from line 1 to terminal L of the relay. Current then flows through the resistive wire, the movable arm, and the normally closed contacts to the run and start windings. When current flows through the resistive wire, its temperature increases. This increase of temperature causes the wire to expand in length. When the length of the resistive wire increases, the movable arm is forced to move down. As the arm moves down, tension is applied to the springs of both contacts. The relay is so designed that the start contact will snap open first. When the start winding is disconnected, the current flow to the motor will decrease. If the motor current is not excessive, the resistive wire will not expand enough to cause the run contact to open. If the current flow is excessive, however, the wire will continue to expand and the contact connected in series with the run winding will open.



► **Figure 26-2**
Hot-wire type of starting relay. (Source: Delmar/Cengage Learning)

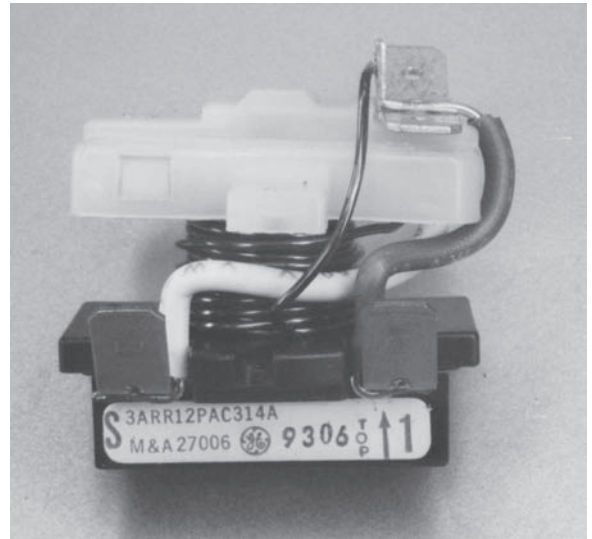
Notice that this type of relay is used as both a starting relay and an overload relay. One disadvantage of the hot-wire relay is that it must be permitted to cool after each operation. A motor using this type of starting relay cannot be started in rapid succession. Figure 26-2 shows a photograph of the hot-wire type of starting relay.

Testing this relay is difficult. An ohmmeter can be used to check for continuity between the L terminal and the start and main winding terminals. To properly test this relay, an ammeter should be used to make certain the start contact opens and disconnects the start winding. If the relay is opening on overload, the ammeter can be used to check the current draw of the motor. This will determine if the motor is actually overloaded, or if the relay is opening when it should not. A good rule to follow concerning starting relays is to always test them if the motor has been damaged. It makes poor business sense to damage a new motor because of not checking the starting relay.

When replacing this relay, it is necessary to use the correct replacement. Because the relay is operated by motor current, it has been designed to open its contacts when a specific amount of current flows through the circuit. The relay must, therefore, be matched to the characteristics of the motor it is intended to control.

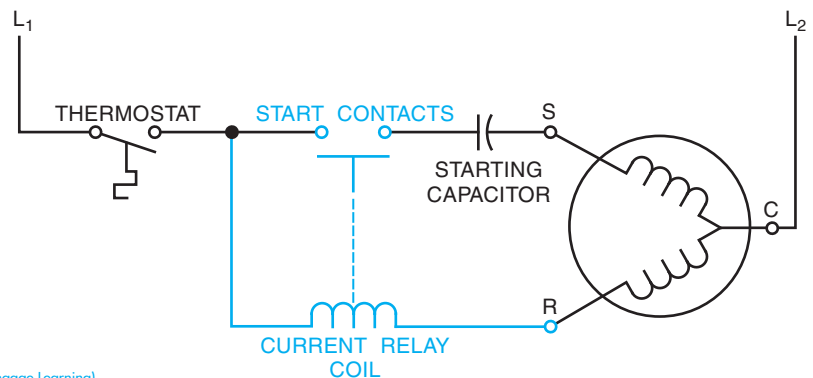
THE CURRENT RELAY

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 of a few turns of large wire, and a set of normally open contacts, Figure 26–3. The coil of the relay is connected in series with the run winding of the motor as shown in Figure 26–4. The contacts are connected in series with the start winding. When the thermostat contact closes and connects



► **Figure 26–3**
Current type of starting relay. (Source: Delmar/Cengage Learning)

power to the motor, the starting contacts of the relay are open. Because no power is applied to the start winding, the motor cannot start. This causes a current of about three times the normal full-load current to flow in the run winding. The high current flow through the coil of the start relay produces a strong magnetic field. The magnetic field is strong enough to cause the solenoid to close the starting contacts. When the starting contacts close, power is applied to the start winding and the motor begins to turn. As the motor accelerates, the current flow through the run winding decreases rapidly. When the current flow through the relay coil decreases,



► **Figure 26–4**
Current relay connection. (Source: Delmar/Cengage Learning)

the strength of the magnetic field becomes weaker. When the motor has reached about 75% of full speed, the magnetic field is weak enough to permit the solenoid to reopen the starting contacts. This disconnects the start winding from the circuit and the motor continues to operate normally.

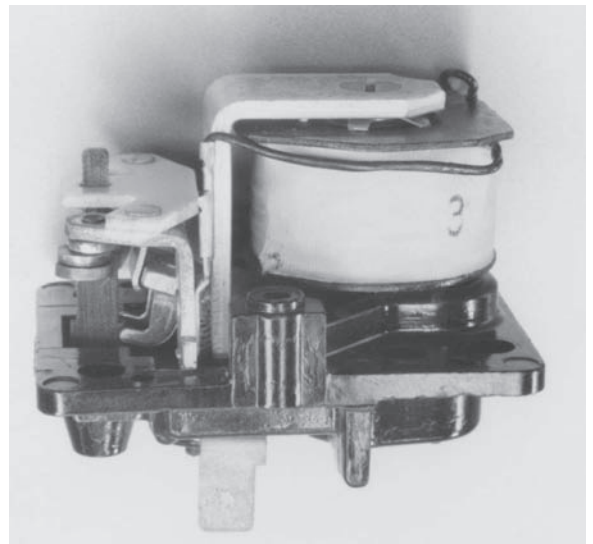
Notice that the current relay is used to disconnect the start windings only and does not provide overload protection. A motor using this type of starting relay must be provided with separate overload protection.

If it is necessary to replace this type of relay, the correct size must be used. The current relay is matched to the characteristics of the motor it is designed to be used with. This type of relay is also sensitive to the position it is mounted in. The current relay generally uses the force of gravity to open the starting contacts. When installing a new relay, it must be mounted in the correct position. If it is installed upside down, the starting contacts will be closed instead of open.

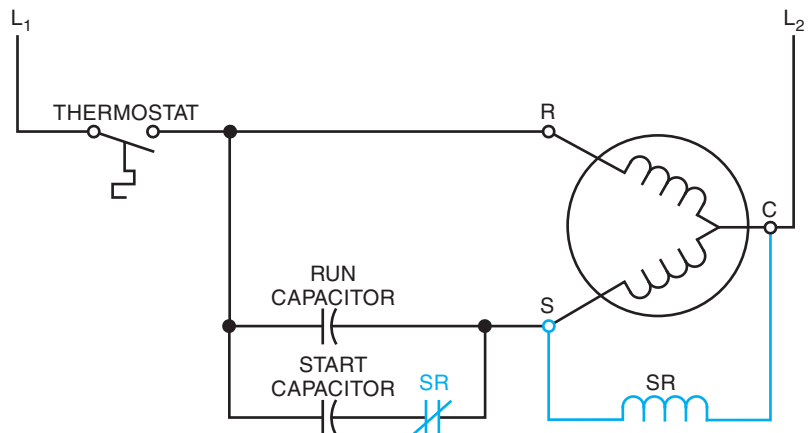
When testing this type of relay, an ohmmeter can be used to check the continuity of the contacts. When the relay is held in the correct position, the ohmmeter should show an open circuit across the contacts. If it does not, the contacts are shorted. If the relay is held upside down, the contacts should indicate continuity. The coil of the relay is generally exposed and a visual inspection will reveal shorted windings. The best method of testing the relay is with an ammeter. If the ammeter is used to measure the current flow to the start winding, it can be seen if the motor starts and the relay contacts disconnect the start winding.

THE POTENTIAL RELAY

The **potential** (voltage) **relay** operates by sensing an increase in the voltage developed in the start winding when the motor is operating. A potential relay is shown in Figure 26–5. A schematic diagram for a potential starting relay circuit is shown in Figure 26–6. In this circuit, the potential relay is used to disconnect the starting capacitor from the circuit when the motor reaches about 75% of its full speed. SR (starting relay) coil is connected in



► **Figure 26–5**
Potential starting relay. (Source: Delmar/Cengage Learning)



► **Figure 26–6**
Potential relay connection.
(Source: Delmar/Cengage Learning)

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 of the motor. Notice that both the run capacitor and the start capacitor are in the circuit at this time.

The rotating magnetic field of the stator cuts through the bars of the squirrel-cage rotor and induces a current into them. The current flow in the rotor produces a magnetic field around the rotor. As the rotor begins to turn, its magnetic field cuts through the start winding and induces a voltage into it. The induced voltage causes the total voltage across the start winding to be higher than the voltage applied by the line. When the motor has accelerated to about 75% of full speed, the induced voltage in the start winding is high enough to energize SR coil. When SR coil energizes, SR contact opens and disconnects the start capacitor from the circuit, Figure 26-7.

Notice that this type of relay depends on the induced voltage created in the start winding by the magnetic field of the rotor and the run winding. The start winding acts like the secondary winding of a transformer and produces a step-up in voltage. For this reason, the amount of voltage necessary to energize the coil of a potential relay is greater than line voltage. Once the relay has been energized it can be held in by less voltage than that required to energize it. The potential relay is primarily used to disconnect the starting capacitor of a permanent-split capacitor motor, as shown in Figure 26-6. Although the potential relay is still in use, it is being replaced by the solid-state relay.

The potential type of starting relay is often used with compressors that use the permanent-split capacitor start motor. The coil of the relay can be tested for an open circuit with an ohmmeter. When the ohmmeter is connected across the coil, it should indicate continuity. The actual amount of resistance can vary from one type of relay to another. The best method for testing the starting relay is with an ammeter. If an ammeter is connected to the start capacitor, it can be seen if the capacitor is energized when the motor is started, and if the relay disconnects it from the circuit.

AUTHOR'S NOTE: A couple of things need to be pointed out concerning the schematic in Figure 26-7. One is that there is a mistake in the terminal numbers of the potential relay. Terminal numbers 1 and 2 should be switched. The terminal shown as 2 is actually terminal 1, and the terminal shown as 1 is actually terminal 2. The second is not a mistake, but due to how the schematic was drawn it could cause confusion. Notice that the low-pressure switch has been drawn upside down. The switch appears to be a normally closed switch. In reality, it is a normally open held-closed switch. If the switch were drawn properly, it would be apparent that the switch is actually a normally open held-closed switch. Although this schematic does contain a mistake and a component not drawn properly, I chose to retain it in the text. This is an excellent example of problems that occur in the field. The service technician must be aware that mistakes like this do happen.

SOLID-STATE STARTING RELAYS

Another type of starting relay is known as the **solid-state starting relay**, Figure 26-8. This relay is intended to replace the current-type starting relay and has several advantages over the current relay. Some of these advantages are:

1. The solid-state relay contains no moving parts and no contacts, which can become burned or pitted.
2. The solid-state relay can be used to replace almost any current relay. This interchangeability makes it possible for the service technician to stock only a few solid-state relays instead of a large number of current relays.

The solid-state starting relay is actually an electronic component known as a **thermistor**. A thermistor is a device that exhibits a change of resistance with a change of temperature. This particular thermistor has a positive coefficient of resistance, which means that the resistance of the device will increase with an increase of temperature.

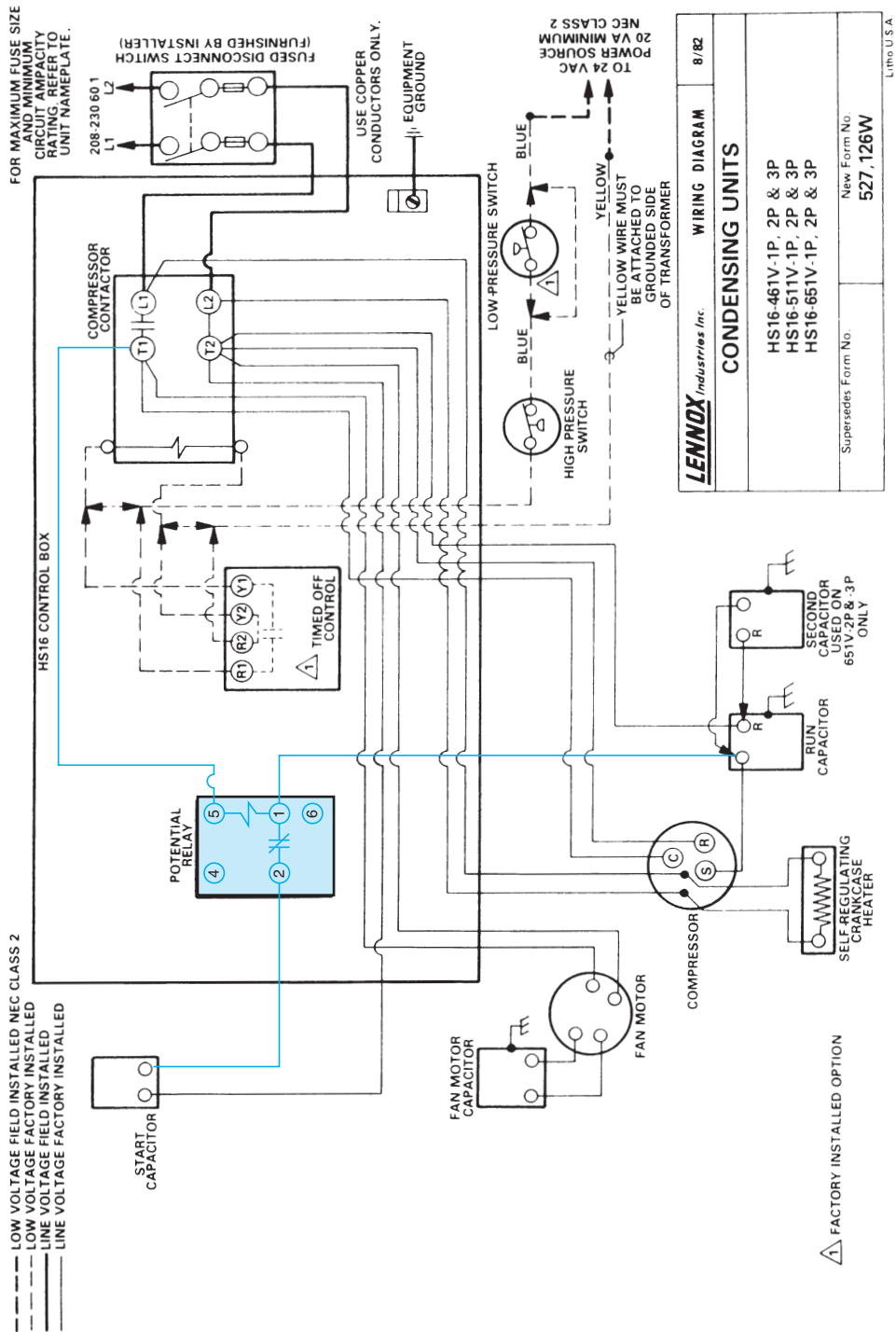
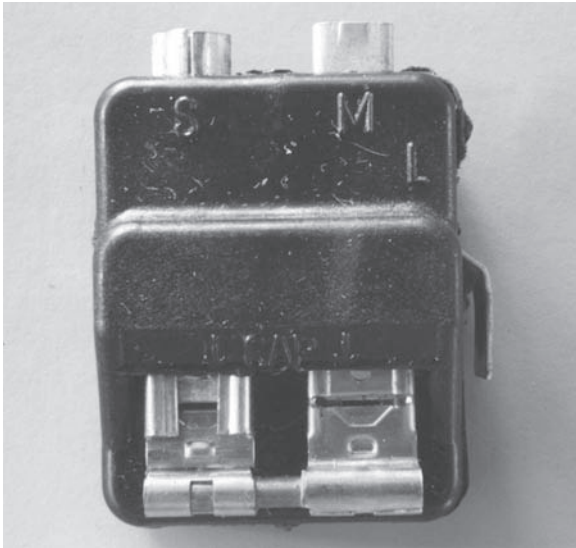


Figure 26-7

A potential relay is used to disconnect the start windings of the compressor when the motor reaches about 75% of full speed. (Courtesy of Lennox Industries Inc.)

The schematic diagram in Figure 26–9 illustrates the connection for a solid-state starting relay. Notice that this is the same basic connection used for the connection of a current starting relay, Figure 26–4. The solid-state relay, however, does not contain a coil or contacts. When the solid-state relay is used, a current path exists between the line connection terminal and the terminal marked M for MAIN winding. The thermistor is connected between the line connection and the terminal marked S for START winding.

When power is first applied to the circuit, the thermistor has a relatively low resistance. This permits current to flow through both the start and run windings of the motor. The temperature of the thermistor increases because of the current flowing through it. The increase of temperature causes the



► **Figure 26–8**
Solid-state starting relay. (Source: Delmar/Cengage Learning)

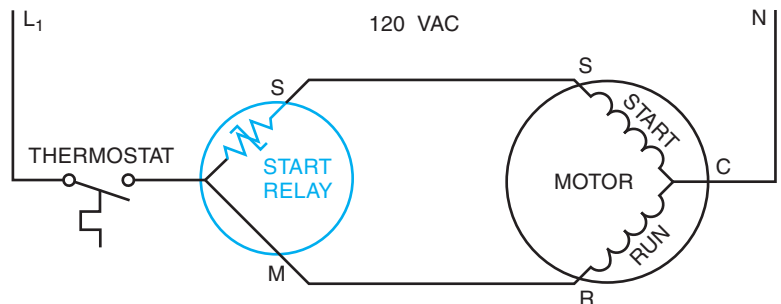
resistance to change from a very low value of 3 or 4 ohms to several thousand ohms. This increase of resistance is very sudden and has the effect of opening a set of contacts connected in series with the start winding. Although the start winding is never completely disconnected from the power line, the amount of current flow through it is very small, typically 0.03 to 0.05 amps, and does not affect the operation of the motor. This small amount of **leakage current** maintains the temperature of the thermistor and prevents it from returning to a low resistance. After power has been disconnected from the motor, a cool-down period of about 2 minutes should be allowed before restarting. This cool-down period is needed for the thermistor to return to a low value of resistance.

TESTING THE SOLID-STATE STARTING RELAY

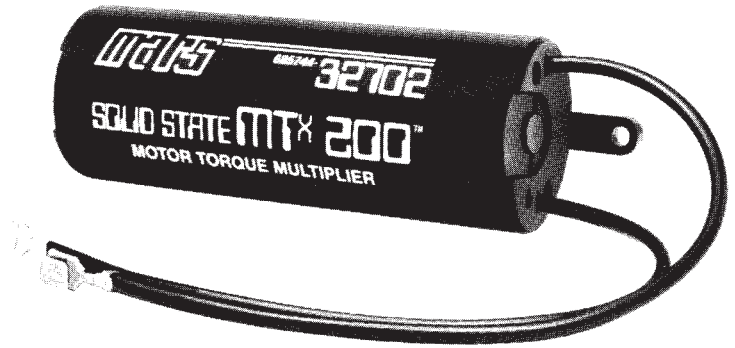
A continuity test can be made with an ohmmeter. If the probes of an ohmmeter are connected to the M and S terminals of the relay, a low value of resistance, typically 2 to 5 ohms, should be seen. The most accurate test is made by connecting the relay in the motor circuit. A clamp-on ammeter set to its lowest scale can be used to measure the current in the start winding. After the motor has been started, the ammeter should give an indication very close to zero amps.

SOLID-STATE HARD STARTING KIT

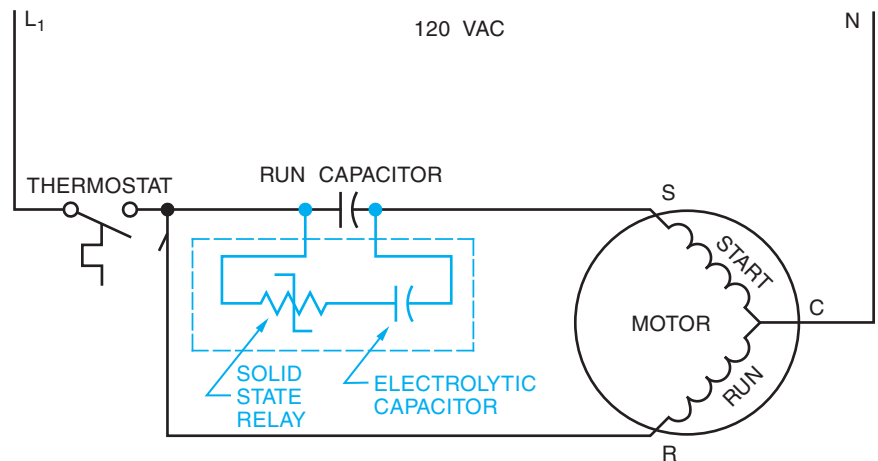
Another device that uses a solid-state relay, the **solid-state hard starting kit**, is shown in Figure 26–10. This device is intended to increase



► **Figure 26–9**
Solid-state starting relay connection.
(Source: Delmar/Cengage Learning)



► **Figure 26-10**
Hard starting kit increases starting torque of permanent-split capacitor motors. (Courtesy of Motors & Armatures, Inc.)



► **Figure 26-11**
Hard starting kit.
(Source: Delmar/Cengage Learning)

the starting torque of a permanent-split capacitor motor. The kit contains a solid-state relay and an AC electrolytic capacitor similar to those used as the starting capacitor for a capacitor-start induction run motor. The kit connects directly across the terminals of the existing run capacitor as shown in Figure 26-11. When the thermostat contact closes and connects power to the motor circuit, the resistance of the solid-state relay is very low. A current path exists through the run winding, run capacitor, solid-state relay, electrolytic capacitor, and start winding. Because the run capacitor and electrolytic capacitor are connected in parallel, their values of capacitance add, providing extra capacitance to

the motor during the starting period. The current flowing through the solid-state relay and electrolytic capacitor causes the temperature of the relay to increase, resulting in an increase in resistance. The increased resistance reduces the current flow through the electrolytic capacitor to a very low value. This has the effect of disconnecting the electrolytic capacitor from the circuit. The leakage current through the relay and electrolytic capacitor prevents the relay from returning to a low value of resistance. After power has been disconnected from the motor circuit, a cool down period of 2 to 3 minutes should be given to permit the solid-state relay to return to a low value of resistance.

SUMMARY

- Ⓢ Starting relays are used to disconnect the start winding of a hermetically sealed split-phase motor.
- Ⓢ The four basic types of starting relays are:
 - A. The hot-wire relay.
 - B. The current relay.
 - C. The potential relay.
 - D. The solid-state relay.
- Ⓢ The hot-wire relay senses motor current by connecting a piece of resistive wire in series with the motor. The motor current heats the wire, causing it to expand and open a set of contacts.
- Ⓢ Hot-wire relays can also provide overload protection for the motor.
- Ⓢ Current relays use a coil connected in series with the motor run winding. The magnetic field of the coil is used to close a set of contacts connected in series with the start winding.
- Ⓢ The potential relay is used primarily with permanent-split capacitor motors.
- Ⓢ The coil of the potential relay is connected in parallel with the motor start winding.
- Ⓢ The contact of the potential relay is connected in series with the starting capacitor.
- Ⓢ Solid-state starting relays are generally used to replace current starting relays.
- Ⓢ Solid-state starting relays use a thermistor, which rapidly changes its resistance when heated.
- Ⓢ Solid-state hard starting kits generally consist of an AC electrolytic capacitor and a solid-state starting relay that connect in parallel with the existing run capacitor.

KEY TERMS

current relay
hot-wire relay
leakage current

potential relay
solid-state hard starting kit
solid-state starting relay

starting relay
thermistor

REVIEW QUESTIONS

1. What are the four types of starting relays?
2. On what type of motor is it necessary to use a starting relay?
3. What principle is used to operate the hot-wire relay?
4. What principle is used to operate the current relay?
5. What type of starting relay does not sense motor current to operate?
6. What type of starting relay can be used for overload protection for the motor?
7. What type of motor can the potential relay be used with?

8. Is the start contact of a hot-wire relay open or closed when power is first applied to the motor?
9. Is the start contact of a current relay open or closed when power is first applied to the motor?
10. Refer to the circuit shown in Figure 26–4. What would happen if the coil of the current relay were open when the thermostat connected power to the motor circuit?

▶ TROUBLESHOOTING QUESTIONS

Refer to the schematic shown in Figure 26–7 to answer the following questions.

NOTE: The “TIMED OFF CONTROL” shown in the schematic is a short-cycle timer, which will be discussed in Unit 36.

1. What voltage is used to operate the coil of the compressor contactor?
 - A. 208 VAC
 - B. 230 VAC
 - C. 60 VAC
 - D. 24 VAC
2. This schematic does not show the thermostat connection, which is relatively common with air conditioning schematics. In which wire would the thermostat contact normally be connected?
 - A. L1
 - B. L2
 - C. The blue wire
 - D. The yellow wire
3. Which of the following components is not controlled by the operation of the compressor contactor?
 - A. Self-regulating crankcase heater
 - B. The fan motor
 - C. The compressor
 - D. All circuit components are controlled by the compressor contactor.
4. To which line is the common of the compressor connected?
 - A. The blue wire of the 24-volt circuit.
 - B. The yellow wire of the 24-volt circuit.
 - C. Line 1 of the main power.
 - D. Line 2 of the main power.
5. Assume that this unit is a model 651V-3P. How many capacitors are connected to the compressor start winding during the initial starting period?
 - A. 1
 - B. 2
 - C. 3
 - D. None

UNIT 27

Variable-Speed Motor Control

OBJECTIVES

After studying this unit the student should be able to:

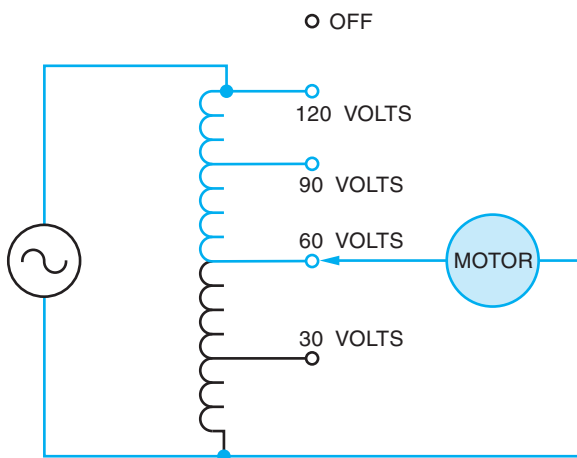
- Describe different types of variable-speed motors
- Discuss autotransformer control
- Connect an autotransformer speed controller in a circuit
- Discuss the use of a triac to control motor speed
- Connect a triac speed controller in a circuit
- Discuss the operation of a series impedance speed control
- Connect a series impedance speed controller in a circuit

The use of small **variable-speed motors** has increased greatly in the last few years. These motors are commonly used to operate light loads such as ceiling fans and blower motors. There are two types of motors used for these applications, the shaded-pole and the permanent-split capacitor motor. These motors are used because they operate without having to disconnect a set of start windings with a centrifugal switch or starting relay. Motors intended to be used in this manner are wound with high-impedance stator windings. The high impedance of the stator limits the current flow through the motor when the speed of the rotor is decreased. Speed control for these motors is accomplished by controlling the amount of voltage applied to the motor, or by inserting impedance in series with the stator winding.

VARIABLE-VOLTAGE CONTROL

The amount of voltage applied to the motor can be controlled by several methods. One method is to use an **autotransformer** with several taps, Figure 27-1. This type of controller has several steps of speed control. Notice that the applied voltage, 120 volts in this illustration, is connected across the entire transformer winding. When the rotary switch is moved to the first tap, 30 volts is applied to the motor. This produces the lowest motor speed for this controller. When the rotary switch is moved to the second tap, 60 volts is applied to the motor. This provides an increase in motor speed. When the switch has been moved to the last position, the full 120 volts is applied to the motor operating it at the highest speed.

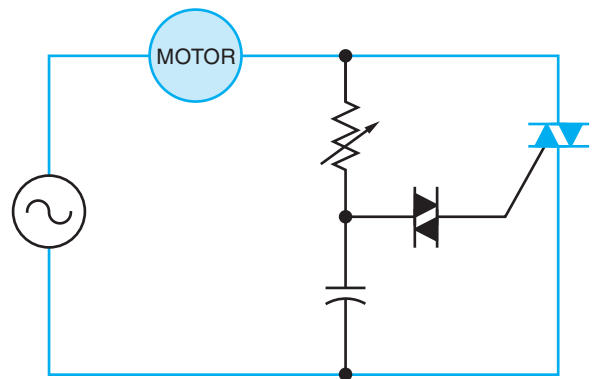
Another type of variable-voltage control uses a triac to control the amount of voltage applied to the motor, Figure 27-2. This type of speed control provides a more linear control since the voltage can be adjusted from 0 to the full applied voltage. At first appearance, many people assume this controller to be a **variable resistor** connected in series with the motor. A variable resistor large enough to control even a small motor would produce several hundred watts of heat and could never be mounted in a switch box. The variable resistor in this circuit



► **Figure 27-1**
Autotransformer controls motor voltage. (Source: Delmar/
Cengage Learning)

is used to control the amount of phase shift for the triac. The triac controls the amount of voltage applied to the motor by turning on at different times during the AC cycle.

A triac speed control is very similar to a triac light dimmer used in many homes. A light dimmer, however, should never be used as a motor speed controller. Triac light dimmers are intended to be used with resistive loads such as incandescent lamps. Light dimmer circuits will sometimes permit one half of the triac to start conducting before the other half. The wave form shown in Figure 27-3 illustrates this condition. Notice that only part of the positive half of the waveform is being conducted to the load. Since only positive voltage is being applied to the load, it is DC. Operating a resistive load, such as an incandescent lamp with DC, will do no damage. Operating an inductive load such as the winding of a motor can do a great deal of damage, however. When direct current is applied to a motor winding, there is no inductive reactance to limit the current. The actual wire resistance of the stator is the only current limiting factor. The motor winding or the



► **Figure 27-2**
Triac used to control motor speed.
(Source: Delmar/Cengage Learning)

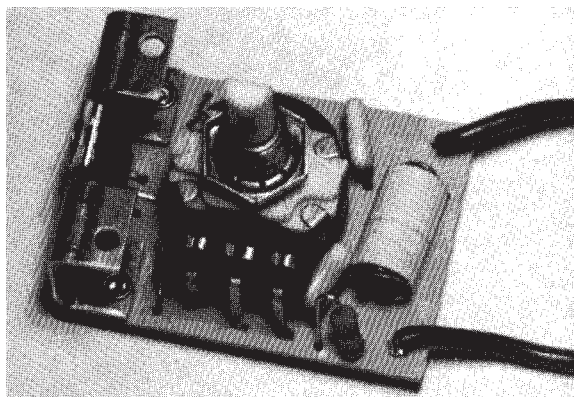


► **Figure 27-3**
Triac conducts only the positive half of the waveform.
(Source: Delmar/Cengage Learning)

controller can easily be destroyed if direct current is applied to the motor. For this reason only triac controllers designed for use with inductive loads should be used for motor control. A photograph of a triac speed controller is shown in Figure 27-4.

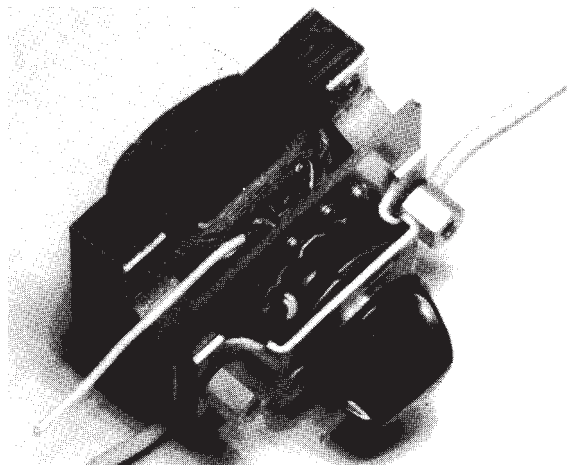
SERIES IMPEDANCE CONTROL

Another common method of controlling the speed of small AC motors is to connect impedance in series with the stator winding. This is the same basic method of control used with multi-speed fan motors.

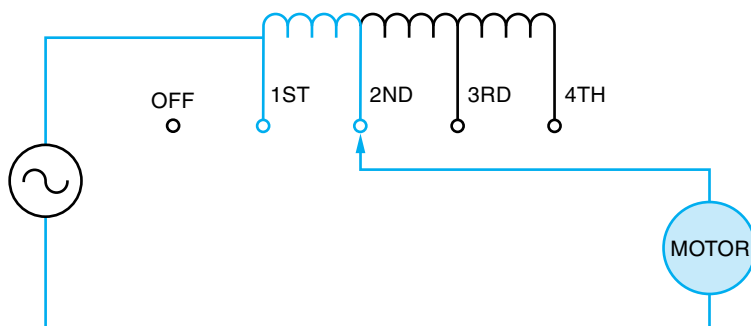


► **Figure 27-4**
Triac speed control. (Source: Delmar/Cengage Learning)

The circuit in Figure 27-5 shows a tapped inductor connected in series with the motor. When the motor is first started, it is connected directly to the full voltage of the circuit. As the rotary switch is moved from one position to another, steps of inductance are connected in series with the motor. As more inductance is connected in series with the stator, the amount of current flow decreases. This produces a weaker magnetic field in the stator. **Rotor slip** increases because of the weaker magnetic field and causes the motor speed to decrease. A photograph of this type of controller is shown in Figure 27-6.



► **Figure 27-6**
Fan speed control using a tapped inductor connected in series with the motor. (Source: Delmar/Cengage Learning)



► **Figure 27-5**
Series inductor changes impedance of circuit. (Source: Delmar/Cengage Learning)

SUMMARY

- ▶ The two main types of single-phase AC motors used for variable-speed control are the permanent-split capacitor motor and the shaded-pole motor.
- ▶ Permanent-split capacitor motors and shaded-pole motors are generally used for variable-speed control because they do not have to disconnect the start windings when the motor reaches a certain speed.
- ▶ Variable-speed control for small motors is accomplished by controlling the amount of voltage applied to the motor or by inserting impedance in series with the motor.
- ▶ Two common methods used to control the voltage applied to the motor are autotransformer control and triac control.
- ▶ Only triac controllers designed for use as motor speed controllers should be used for motor speed control.
- ▶ Series impedance control is accomplished by connecting a tapped inductor in series with the motor.

KEY TERMS

autotransformer
rotor slip

variable resistor
variable-speed motors

REVIEW QUESTIONS

1. What two types of small AC motors are used with variable-voltage speed control?
2. Why are these two types of motors used?
3. Name two methods of variable-voltage control for small AC motors.
4. What solid-state device is used to control the voltage applied to the motor?
5. Why is it necessary to use only controllers designed for use with inductive loads?
6. Name a method other than variable voltage used to control the speed of small AC motors.

UNIT 28



The Defrost Timer

OBJECTIVES

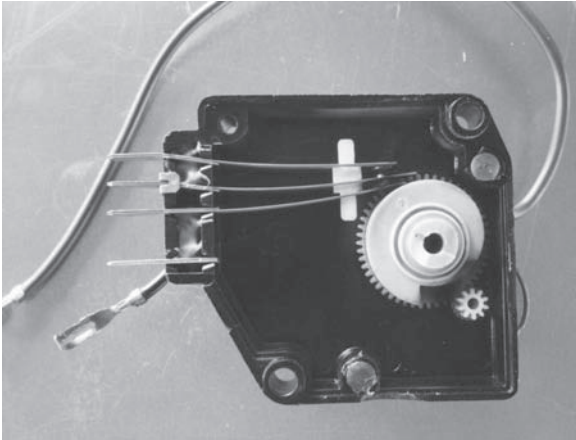
After studying this unit the student should be able to:

- ▶ Describe the construction of a defrost timer
- ▶ Discuss the operation of a continuous run and cumulative compressor run timer
- ▶ Connect a defrost timer for continuous run
- ▶ Connect a defrost timer for cumulative compressor run
- ▶ Discuss the operation of commercial defrost timers
- ▶ Perform an ohmmeter test on a defrost timer

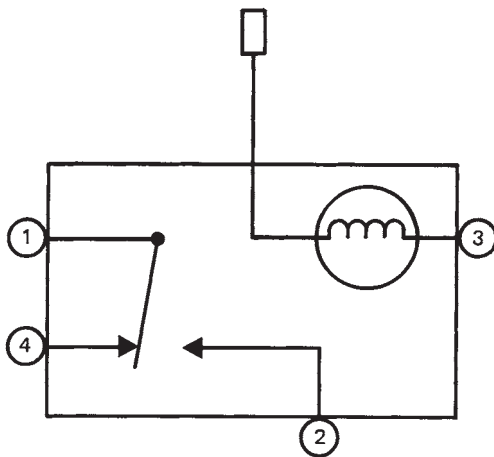
Many of the refrigeration appliances used in the home are “frost-free.” The frost-free appliance could more accurately be termed “automatic defrost.” The brain of the frost-free appliance is the **defrost timer**. The job of this timer is to disconnect the compressor circuit and connect a **resistive heating element** located near the **evaporator** at regular time intervals. The defrost heater is thermostatically controlled and is used to melt any frost formation on the evaporator. The defrost heater is permitted to operate for some length of time before the timer disconnects it from the circuit and permits the compressor to operate again.

TIMER CONSTRUCTION

The defrost timer is operated by a single-phase synchronous motor like those used to operate electric wall clocks, Figure 28–1. The contacts are operated



► **Figure 28-1**
Defrost timer. (Source: Delmar/Cengage Learning)



► **Figure 28-2**
Schematic of a defrost timer. (Source: Delmar/Cengage Learning)

by a **cam** that is gear driven by the clock motor. A schematic drawing of the timer is shown in Figure 28-2. Notice that terminal 1 is connected to the common of a single-pole double-throw switch. Terminals 2 and 4 are connected to stationary contacts of the switch. In the normal operating mode, the switch makes connection between contacts 1 and 4. When the defrost cycle is activated, the contact will change position and make connection between terminals 1 and 2. Terminal 3 is connected to one lead of the motor. The other motor lead is

brought outside the case. This permits the timer to be connected in one of two ways, which are:

1. The **continuous run timer**.
2. The **cumulative compressor run timer**.

It should be noted that the schematic drawing can be a little misleading. In the schematic shown, the timer contact can only make connection between terminals 1 and 4, or terminals 1 and 2. In actual practice, a common problem with this timer is that the movable contact becomes stuck between terminals 4 and 2. This causes the compressor and defrost heater to operate at the same time.

THE CONTINUOUS RUN TIMER

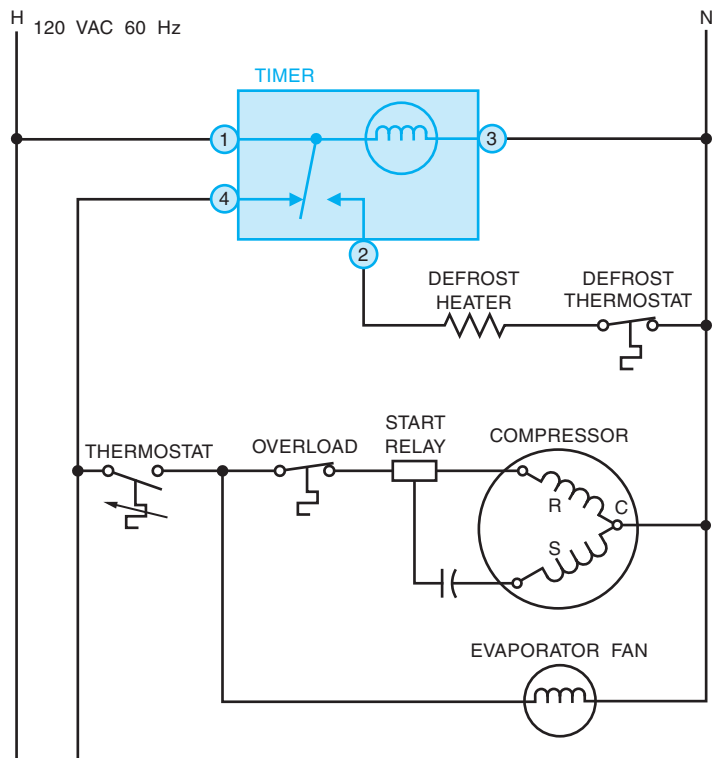
The schematic for the continuous run timer is shown in Figure 28-3. Notice in this circuit that the pigtail lead of the motor has been connected to terminal 1, and that terminal 1 is connected directly to the power source. Terminal 3 is connected directly to the neutral. This places the timer motor directly across the power source, which permits the motor to operate on a continuous basis.

Figure 28-4 shows the operation of the timer in the compressor run cycle. Notice there is a current path through the timer motor and a path through the timer contact to the thermostat. This permits power to be applied to the compressor and evaporator motor when the thermostat closes.

Figure 28-5 shows the operation of the circuit when the timer changes the contact and activates the defrost cycle. Notice there is still a complete circuit through the timer motor. When the timer contact changes position, the circuit to the thermostat is open and the circuit to the defrost heater is closed. The heater can now melt any frost accumulation on the evaporator. At the end of the defrost cycle, the timer contact returns to its normal position and permits the compressor to be operated by the thermostat.

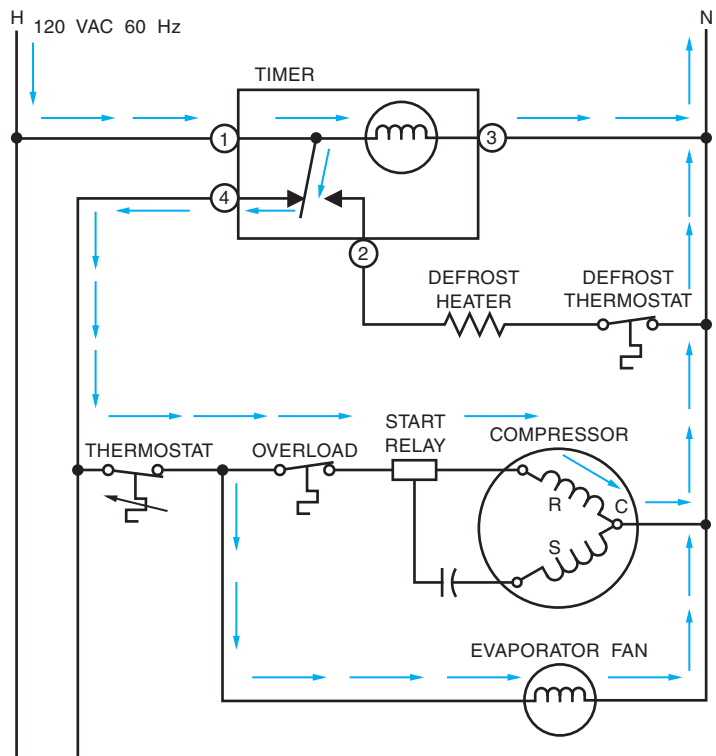
THE CUMULATIVE COMPRESSOR RUN TIMER

The cumulative compressor run timer circuit gets its name from the fact that the timer motor is permitted to operate only when the compressor is in operation and the thermostat is closed. The schematic for this circuit is shown in Figure 28-6. Notice that the



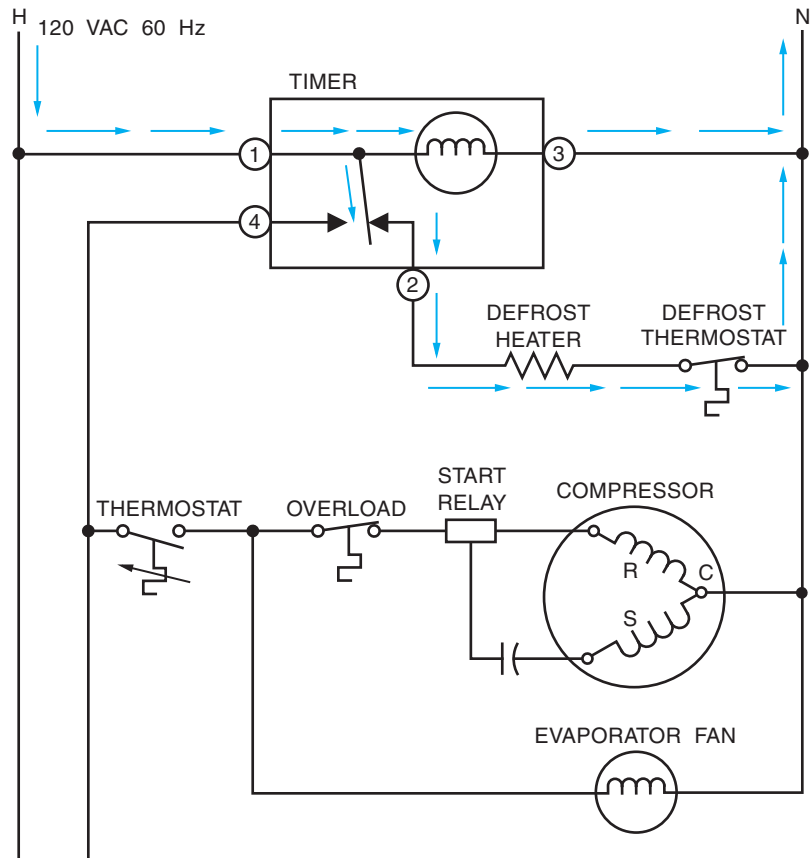
► **Figure 28-3**
Schematic of a defrost timer used in a
continuous run circuit.

(Source: Delmar/Cengage Learning)

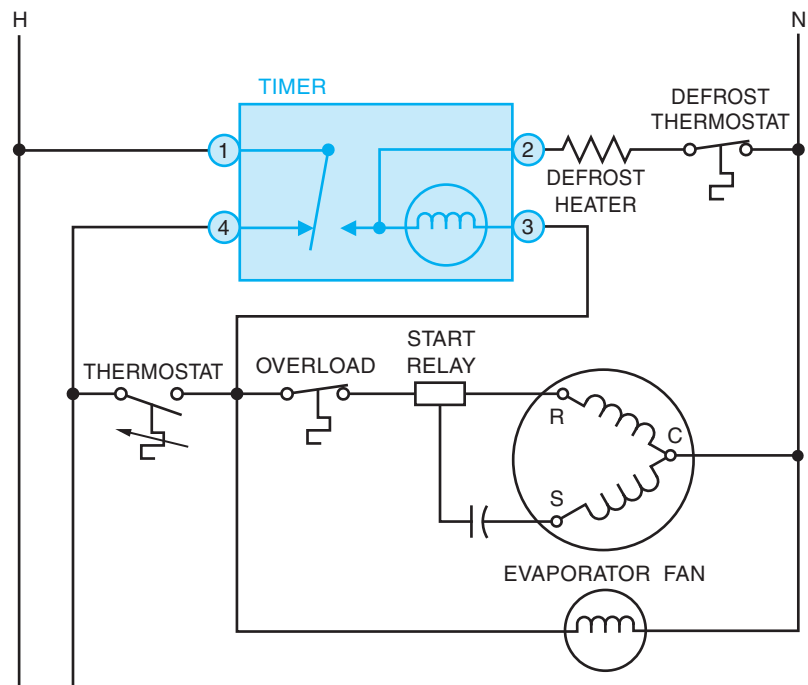


► **Figure 28-4**
Current path during cooling operation.

(Source: Delmar/Cengage Learning)



► **Figure 28-5**
Current path during defrost
operation. (Source: Delmar/Cengage Learning)



► **Figure 28-6**
Defrost timer connected in
a cumulative compressor run circuit.
(Source: Delmar/Cengage Learning)

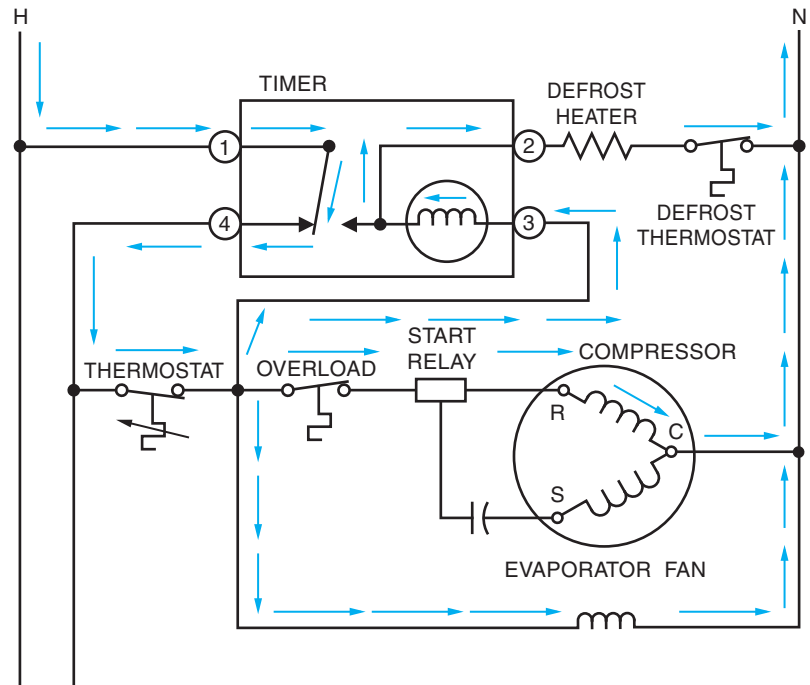


Figure 28-7
Current path during the cooling cycle.

(Source: Delmar/Cengage Learning)

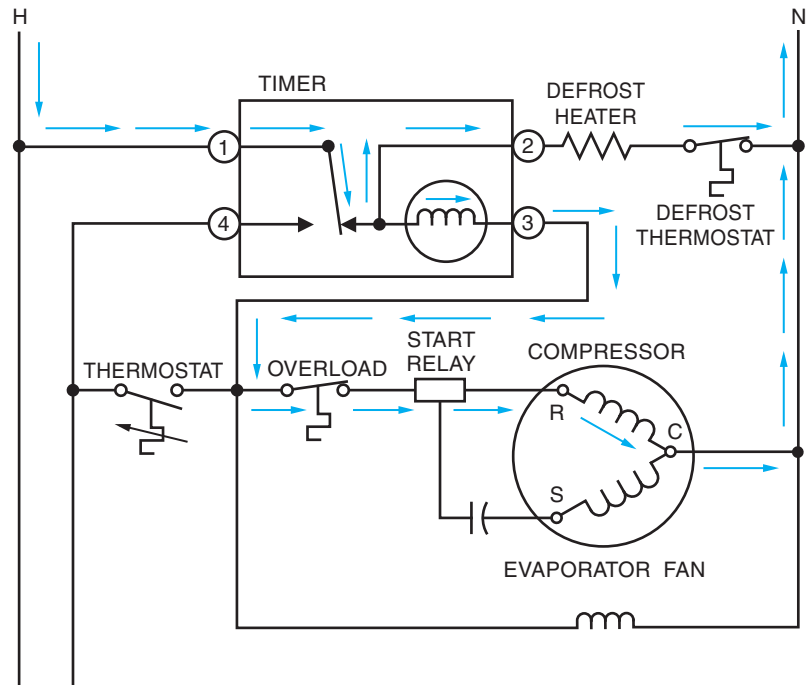
pigtail lead of the clock motor has been connected to terminal 2 instead of terminal 1. Figure 28-7 shows the current path during compressor operation. The timer contact is making connection between terminals 1 and 4. This permits power to be applied to the thermostat. When the thermostat contact closes, current is permitted to flow through the compressor motor, the evaporator fan motor, and the defrost timer motor. In this circuit, the timer motor is connected in series with the defrost heater. The operation of the timer motor is not affected, however, because the impedance of the timer motor is much greater than the resistance of the heater. For this reason almost all the voltage of this circuit is dropped across the timer motor. The impedance of the timer motor also limits the current flow through the defrost heater to such an extent that it does not become warm.

Figure 28-8 shows the current path through the circuit when the defrost cycle has been activated. Notice in this circuit that the defrost heater is connected directly to the power line. This permits the

heater to operate at full power and melt any frost accumulation on the evaporator. There is also a current path through the timer motor and run winding of the compressor motor. In this circuit, the timer motor is connected in series with the run winding of the compressor. As before, the impedance of the timer motor is much greater than the impedance of the run winding of the compressor. This permits almost all the voltage in this circuit to be applied across the timer motor. At the end of the defrost cycle, the timer contact returns to its normal position and the compressor is permitted to operate.

TESTING THE TIMER

An ohmmeter can be used to check the continuity of the contacts and the motor winding. However, to really test the timer for operation takes time. The cam can be manually turned to the position so that the defrost cycle is turned on. This can be checked with a voltmeter to determine when full circuit voltage is applied to terminal 2. It is then necessary to



► **Figure 28-8**
Current path during the defrost cycle.
(Source: Delmar/Cengage Learning)

wait long enough for the timer to open the contact to the defrost heater and reconnect the compressor circuit. If the thermostat is closed, the compressor will start when the timer contact changes position. This test shows that the timer motor is operating and that the contact does change position.

COMMERCIAL DEFROST TIMERS

Many large commercial refrigeration units often use a separate **timer clock** to control the defrost cycle. This has several advantages over the previously discussed defrost timer. When this method is used, the timer clock is connected directly across the power line as shown in Figure 28-9. This separates the operation of the timer from the operation of the compressor. In this way, the defrost cycle can be started during periods when the unit is in minimum use.

Timers of this type, Figure 28-10, generally have two timed settings. One determines the time of day or night the timer turns on. The second setting determines how long the timer is permitted to remain on. The timer shown in this example can be started on even numbered hours of the day or night. The center knob sets how long the contacts are energized before they return to their normal position. Once turned on, the contacts can be set to remain in their energized position for a minimum of two minutes to a maximum of 120 minutes.

This timer has a separate timer release solenoid incorporated into its design. When the timer release solenoid is energized, it causes the contacts to return to their normal reenergized position immediately. This permits the action of some type of external limit switch, such as a temperature or pressure switch, to terminate the defrost cycle.

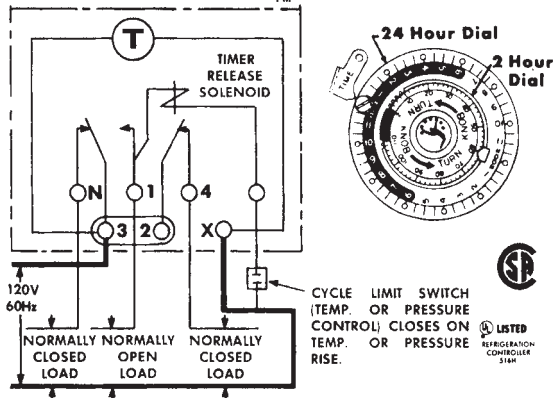
MODEL 8141-00

D-FROST-O-MATIC TIME CONTROL

A-345-00

PRINTED 6-1-73

C-2675

**INSTALLING AND OPERATING DIRECTIONS:**

Place start pins in outer (24 Hour) dial at the time of day that switch contacts are to be reverse from shown above when dial pins are opposite time pointer. **CAUTION:** (Leave at least 1 hole between each adjacent pin).

TO SET BACK-UP DEFROST TERMINATION: Push down and rotate pointer on inside (2 Hour) dial until it is opposite desired time.

TO SET TIME OF DAY: Grasp knob in the center of the inner (2 Hour) dial and rotate it in a counter-clockwise direction. This will revolve the outer dial. Line up the correct time of day on the outer dial with the time pointer. Do not try to set the time control by grasping the outer dial. Rotate the inner dial only.

FOR REPLACEMENT of this control contact refrigerator manufacturer.

FOR REPAIR contact nearest Paragon service station.

MAXIMUM CONTACT RATING		
40A	Non Inductive	120Vac
2hp		120Vac
690VA	Pilot Duty	120Vac

Timing Motor: 120V 60Hz

Made in the U.S.A.

606 Parkway Blvd., P.O. Box 28, Two Rivers, WI 54241 U.S.A.

EXPORT SALES OFFICE: Two Rivers, Wisconsin 54241 U.S.A.

Cable: PECO Telex 26-3450 PARAGON TWOR

IN CANADA: PARAGON ELECTRIC P.O. Box 1030 Guelph, Ontario
Division of AMF CANADA LIMITED**Paragon**

Printed in U.S.A.

► **Figure 28-9**

Schematic diagram of a commercial defrost timer.

(Courtesy of Paragon Electric Company, Inc.).

► **Figure 28-10**

Commercial defrost timer. (Courtesy of Paragon Electric Company, Inc.).

SUMMARY

- ④ Frost-free appliances use a defrost timer to control the operation of the defrost cycle.
- ④ The function of the defrost timer is to disconnect the compressor from the circuit and connect a resistive heater located near the evaporator at regular intervals.
- ④ The defrost timer is a cam-operated timer powered by a small single-phase synchronous motor similar to an electric clock motor.
- ④ Two basic connections for a defrost timer are:
 - A. The continuous run timer.
 - B. The cumulative compressor run timer.
- ④ The motor of the continuous run timer is connected directly to the power line and runs at all times.
- ④ The motor of the cumulative compressor run timer is connected in such a manner that it runs only during the time the compressor motor is in operation.
- ④ Commercial defrost timers often use a separate time clock to control the defrost cycle.

KEY TERMS

cam
continuous run timer
cumulative compressor
run timer

defrost timer
evaporator
resistive heating element
timer clock

QUESTIONS

1. What type of motor is used to operate the timer?
2. Why is one of the motor leads brought outside the timer?
3. Name two ways of connecting the defrost timer.
4. What function does the defrost heater perform?
5. To which terminal is the pigtail lead of the timer motor connected if the timer is to operate continuously?

UNIT 29



The Thermostat

OBJECTIVES

After studying this unit the student should be able to:

- Define a thermostat
- Describe the operation of bimetal thermostats
- Discuss the operation of a contact-type and mercury-contact thermostat
- Discuss the operation of heating and cooling thermostats
- Describe the operation of the fan switch
- Discuss the operation of the heat anticipator and cooling anticipator
- Discuss the operation of line voltage, programmable, staging, and differential thermostats
- Connect a thermostat in a circuit

Thermostats are temperature-sensitive switches. They use a variety of methods to sense temperature, and can be found with different **contact** arrangements. Some thermostats are designed to be used with low-voltage systems, generally 24 volts; and others are designed to be connected directly to line voltage and operate motors and heating units. The advantage of low-voltage thermostats is that they are more economical and safer to use inside the home.

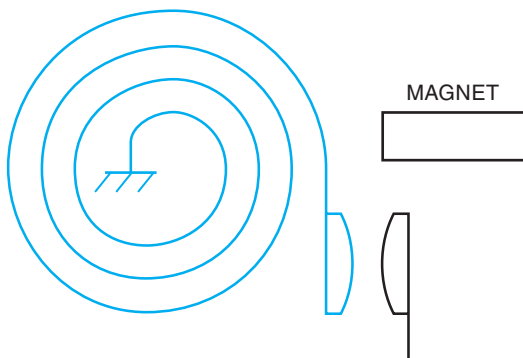
BIMETAL THERMOSTATS

One of the most common methods of sensing temperature is with a bimetal strip. When used as the temperature sensing element of a thermostat, the bimetal strip is generally bent in a spiral that

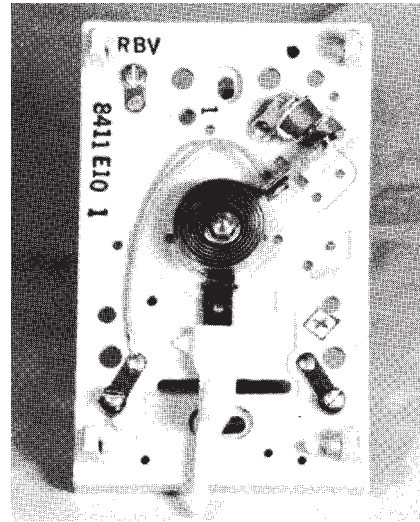
resembles a clock spring. If a contact is attached to the end of the strip and another contact is held stationary, a thermostat is formed, Figure 29-1. A small permanent magnet is used to provide a snap action for the contacts.

This type of thermostat is inexpensive and has the advantage of not having to be mounted in a level position. The greatest enemy of an open-contact thermostat is dirt. This is especially true for thermostats designed for low-voltage operation. If poor thermostat contact is suspected, the contacts should be cleaned. This can be done with a strip of hard paper, such as typing paper, and alcohol. Soak a strip of hard paper in alcohol and place the strip between the contacts. Close the contacts and draw the strip through the closed contacts. This will generally remove any accumulation of dirt and oil. After cleaning, the contacts should be buffed to remove any alcohol residue. This can be done by drawing a piece of dry hard paper through the contacts several times. This type of thermostat is shown in Figure 29-2.

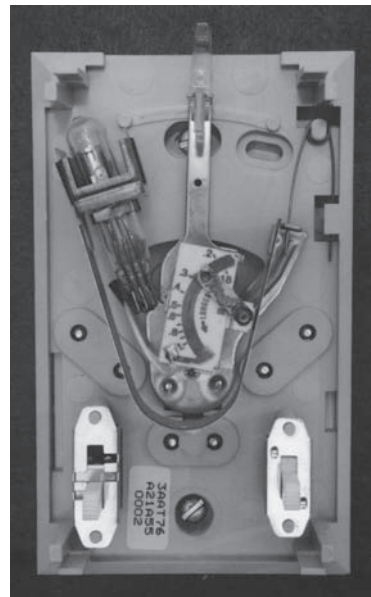
To avoid the problem of dirty contacts, the contacts of some thermostats are enclosed inside a glass tube, Figure 29-3. Because the contacts are enclosed in glass, they are stationary. The bimetal strip is attached to a permanent magnet instead of a contact. In the case of a double acting thermostat, there are two magnets attached to the bimetal strip. When the magnet is close enough to the glass tube, it is attracted to the metal contacts and causes the contacts to close with a snap action.



► **Figure 29-1**
Contacts operated by a bimetal strip. (Source: Delmar/Cengage Learning)



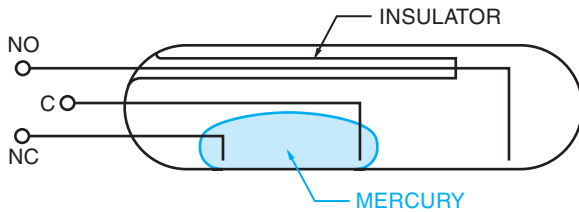
► **Figure 29-2**
Open-contact thermostat. (Source: Delmar/Cengage Learning)



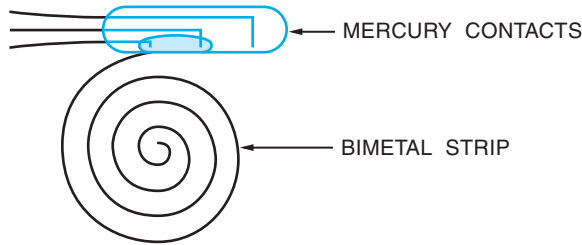
► **Figure 29-3**
Contacts are enclosed inside a glass tube. (Source: Delmar/Cengage Learning)

MERCURY CONTACT THERMOSTAT

Another type of contact used with the bimetal type of thermostat is the mercury contact. In this type of thermostat, a small pool of mercury is sealed inside



► **Figure 29-4**
Mercury contacts. (Source: Delmar/Cengage Learning)



► **Figure 29-5**
Mercury-type thermostat. (Source: Delmar/Cengage Learning)

a glass container. A set of contacts is also sealed in the glass. Most mercury-type contacts are made to be single-pole double-throw, which means there are a common terminal, a normally open terminal, and a normally closed terminal. Figure 29-4 illustrates this type of contact. Notice in this example that the pool of mercury makes connection with the common terminal, located in the center, and the normally closed terminal. If the glass bulb is tilted in the other direction, the mercury will flow to the opposite end and make connection between the common terminal and the normally open contact.

The mercury contact has the advantage of being sealed in glass and not subjected to dirt and oil. When this type of contact is used with a bimetal strip, it is generally mounted as shown in Figure 29-5. This type of thermostat uses the weight of the mercury to provide a snap action for the contact instead of a magnet. When the bimetal strip has turned far enough to permit the mercury to flow from one end of the glass bulb to the other, the weight of the mercury prevents any spring action of the bimetal strip from snapping the contact open. A mercury thermostat, however, must be mounted in a level position if it is to operate properly. This



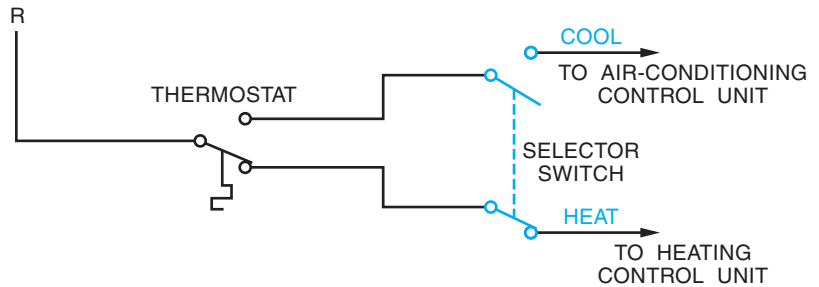
► **Figure 29-6**
Mercury thermostat. (Source: Delmar/Cengage Learning)

can sometimes be a problem in homes that do not remain level. A mercury type thermostat is shown in Figure 29-6.

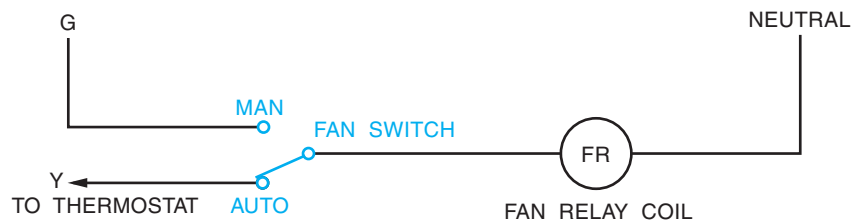
Mercury type thermostats are particularly sensitive to the way they are mounted. If they are to operate correctly, they must be mounted level. The manufacturer's instructions will generally show how the thermostat should be checked with a leveling device.

HEATING AND COOLING THERMOSTATS

Many thermostats are designed to be used for both heating and cooling applications. This can be done with thermostats that contain both a normally open and normally closed contact. A simple schematic diagram of this type of thermostat is shown in Figure 29-7. Notice the thermostat contact is a single-pole double-throw type. The selector switch is a double-pole type. The dashed line indicates mechanical intertie. With the selector switch in the position shown, the thermostat is being used for heating. If the selector switch is changed, the



► **Figure 29-7**
Dual operation of a thermostat.
(Source: Delmar/Cengage Learning)



► **Figure 29-8**
Fan switch. (Source: Delmar/
Cengage Learning)

bottom movable contact will break connection with its stationary contact, and the top movable contact will make connection with its stationary contact. Notice that changing this switch will also change the sense of the thermostat. In the heating position, the thermostat activates the heating unit when the contact closes because of a decrease in temperature. In the cooling position, the thermostat activates the air conditioning unit when the contact makes connection because of an increase in temperature.

THE FAN SWITCH

Many thermostats are designed to permit manual control of the blower fan. This is done to permit the blower fan to be operated separately. Some people find it desirable to operate the blower fan continuously to provide circulation of air throughout the building. This is especially true for buildings equipped with electronic air cleaners (precipitators) or for buildings that must remove undesirable elements such as smoke in an office building or night club. A schematic diagram of this type of circuit is shown in Figure 29-8. The **fan switch** is a single-pole double-throw switch. When the switch is in one position, it permits the fan relay to be

controlled by the thermostat. If the switch is thrown in the opposite direction, the fan relay is connected directly to the control voltage.

THE HEAT ANTICIPATOR

The **heat anticipator** is a small resistance heater located near the bimetal strip. The function of this heater is to slightly preheat the bimetal strip and prevent overrun of the heating system. For example, many heating systems, such as fuel oil or gas, operate by heating a metal container called a heat exchanger. When the temperature of the heat exchanger reaches a high enough level, a thermostatically controlled switch causes the blower to turn on and blow air across the heat exchanger. The moving air causes heat to be removed from the heat exchanger to the living area. When the thermostat is satisfied, the heating unit is turned off. The blower will continue to operate, however, until the excess heat has been removed from the heat exchanger.

Now assume that the thermostat has been set for a temperature of 75 degrees. If the heating unit is permitted to operate until the temperature reaches 75 degrees, the final temperature of the living area may be from 3 to 5 degrees higher than

the thermostat setting by the time enough heat has been removed from the heat exchanger to cause the blower to turn off.

If the heat anticipator has been properly set, however, it will cause the thermostat to turn off several degrees before the room temperature has reached the thermostat setting. This permits the excess heat of the heat exchanger to raise the temperature to the desired level without overrunning the thermostat setting.

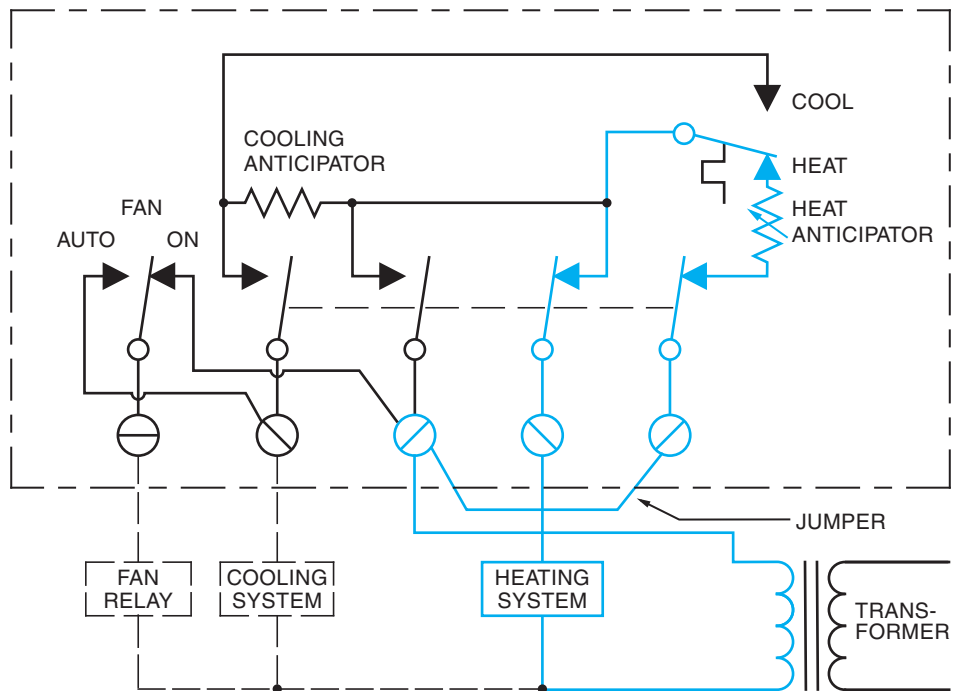
The setting of the heat anticipator is controlled by a sliding contact. There are markings such as .2, .25, .3, .35, and .4. The sliding contact is generally set at the number that corresponds to the current rating of the control system. The current rating can generally be located in the service information or on the control unit itself. The heat anticipator does not have to be set at that position, however. The service technician should set it to operate the unit for longer or shorter periods depending on the desires of the customer.

THE COOLING ANTICIPATOR

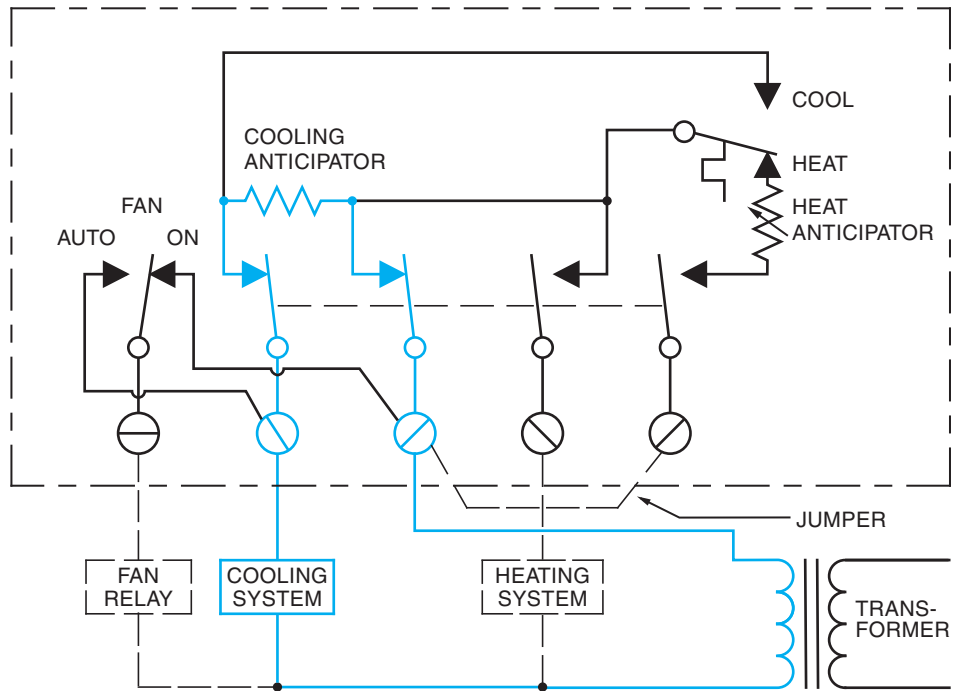
A device that operates in a similar manner to the heat anticipator is the **cooling anticipator**. The cooling anticipator is a resistive heating element that operates in an opposite sense to the heat anticipator. The cooling anticipator operates while the thermostat contacts are open and the air conditioning unit is not running. The cooling anticipator heats the thermostat slightly and causes it to close its contacts before the ambient temperature increases enough to close them.

The circuit shown in Figure 29–9 displays the current path of the heat anticipator for a heating and cooling thermostat during the heating cycle. In this mode of operation, current flows through the heat anticipator while the thermostat contact is closed and the heating unit is in operation.

In Figure 29–10, the thermostat has been switched to the cooling mode. Notice that a current path exists through the cooling anticipator when



► **Figure 29–9**
Current path for heat
anticipator. (Source:
Delmar/Cengage Learning)



► **Figure 29-10**
Current path for
cooling anticipator.

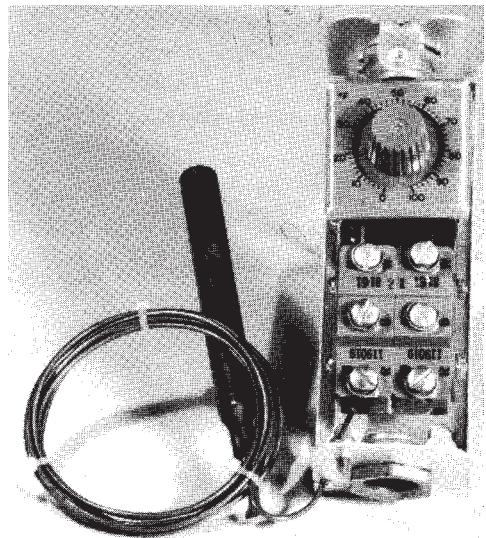
(Source: Delmar/Cengage
Learning)

the thermostat contact is open and the air conditioning unit is not in operation. When the thermostat contact closes, a low resistance path exists around the cooling anticipator. This stops the flow of current through it while the air conditioning unit is in operation.

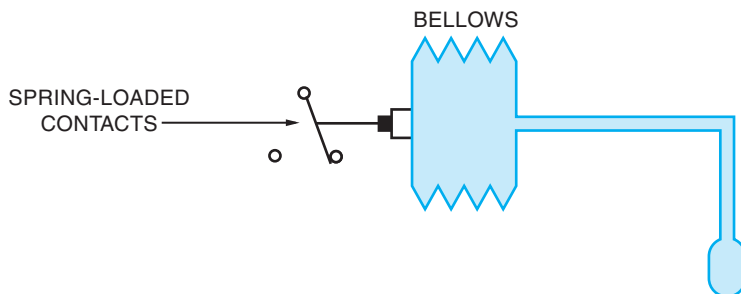
LINE VOLTAGE THERMOSTATS

Line voltage thermostats are generally used to control loads such as blower fans and heating elements. This means that the thermostat must contain contacts that are capable of handling the current needed to operate these loads without an intervening relay. This type of thermostat is shown in Figure 29-11. Many of these thermostats use the pressure of refrigerant in a sealed system to sense temperature, Figure 29-12. When the temperature increases, the pressure in the system increases also. The increase in pressure causes the bellows to expand. When the bellows expands far enough, it activates a set of spring-loaded contacts.

Although line voltage thermostats can be used for many applications, they do not contain a heat anticipator and are not as accurate as low voltage thermostats.



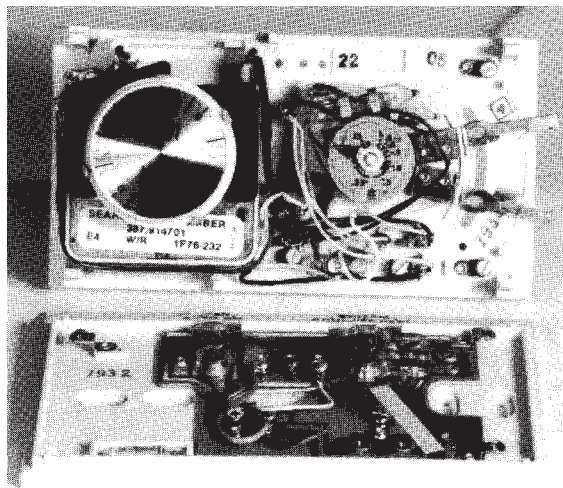
► **Figure 29-11**
Line voltage thermostat. (Source: Delmar/Cengage Learning)



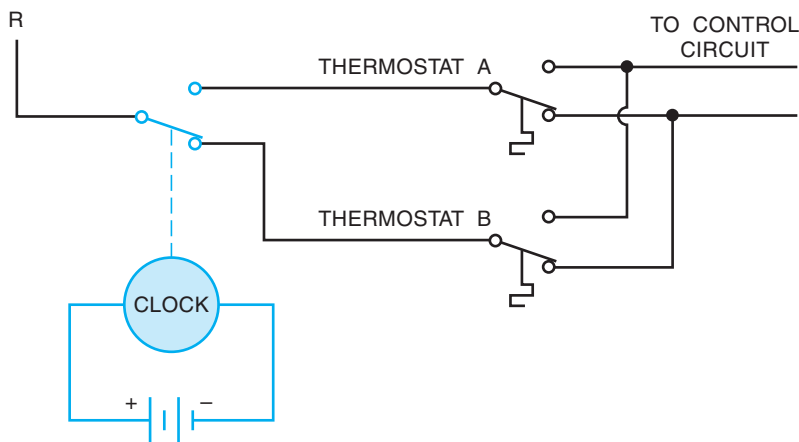
► **Figure 29-12**
Thermostat contacts are operated by pressure. (Source: Delmar/Cengage Learning)

PROGRAMMABLE THERMOSTATS

The term *programmable* is a catch word that has taken on many meanings. In the case of thermostats, the term *programmable* generally means that a thermostat can be set to operate at different temperature settings at different times. **Programmable thermostats** range in complexity from units that use a simple time clock to units that are operated by integrated circuits (ICS) and permit the temperature to be set to any desired level at any desired time. A programmable thermostat is shown in Figure 29-13. This thermostat uses a quartz-operated time clock and two separate thermostat units. The time clock is used to operate a switch. The setting of the clock determines the position of the switch at any particular time. A schematic for this type of circuit is shown in Figure 29-14. Notice that



► **Figure 29-13**
Programmable thermostat. (Source: Delmar/Cengage Learning)



► **Figure 29-14**
Schematic for a programmable thermostat. (Source: Delmar/Cengage Learning)

the position of the clock-operated switch determines which thermostat is used to control the system. To understand the operation of this system, assume that thermostat A has been set for a temperature of 95 degrees, and thermostat B is set for 75 degrees. The time clock has been set to permit thermostat A to control the air conditioning system when there is no one in the residence. One hour before people are to return home, the time clock changes the contact and thermostat B is used to control the system. Because thermostat B has been set for 75 degrees, the residence will have been cooled to that temperature when the people arrive.

The programmable thermostat can reduce energy consumption by maintaining a desired temperature only during the hours the dwelling is occupied. The temperature can be maintained at an uncomfortable level the rest of the time, which permits the air conditioning unit to operate much less.

Electronic Programmable Thermostats

Many programmable thermostats are solid state and do not contain mechanical contacts. These units generally employ electronic devices such as thermistors to sense temperature. They can be programmed

for several different conditions or events. Many permit the thermostat to be programmed differently for each day. The temperature can be set differently for different times of the day. Most electronic thermostats provide a variety of functions and options that are set by the homeowner. An electronic thermostat is shown in Figure 29–15.

STAGING THERMOSTATS

Staging thermostats are similar to programmable thermostats in that they contain two separate sets of contacts. Unlike the programmable thermostat, however, the staging thermostat contains only one bimetal strip, which is used to control the action of both sets of contacts. One set of contacts is designed to operate slightly behind the other set. A good example of how a staging thermostat is used can be found in a heat-pump system. Assume that the first contact is used to operate the compressor relay, and the second contact is used to operate the contactor, which controls the electric resistance heating strips. When the temperature decreases, the first thermostat contact closes and connects the compressor to the line. If the compressor is able to provide enough heat to the dwelling, the second contact will never make connection. If, however,

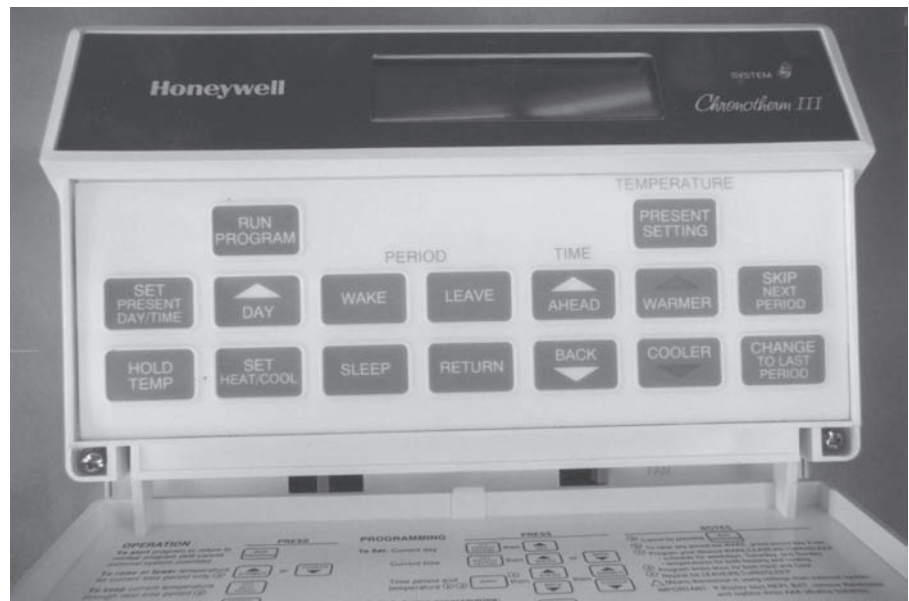


Figure 29–15
Electronic thermostat.
(Source: Delmar/Cengage Learning)

the outside temperature is low enough that the heat pump cannot provide enough heat, the second thermostat contact will close and permit the electric heat strip to operate.

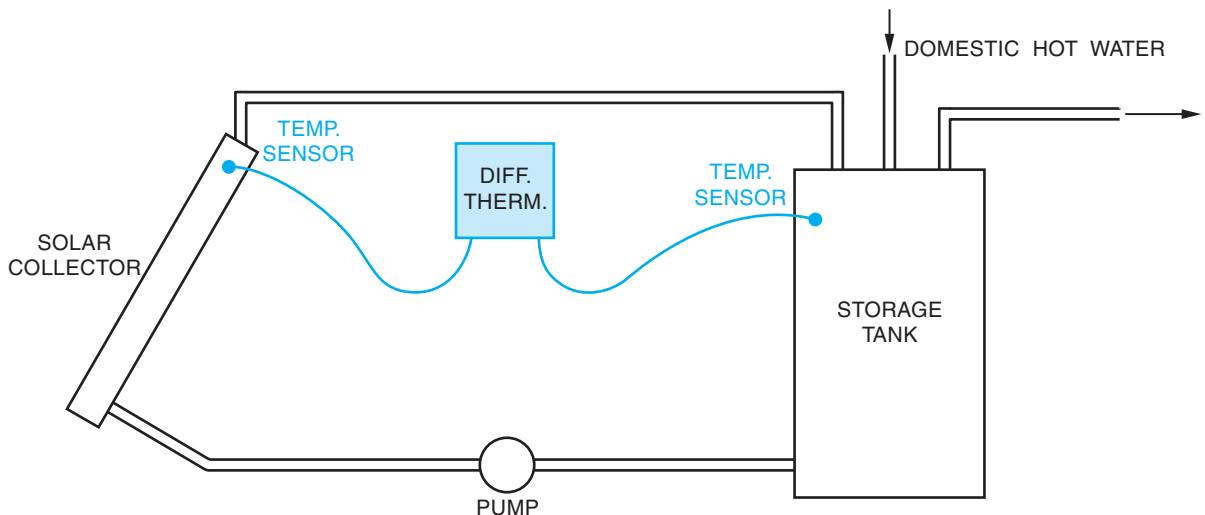
THE DIFFERENTIAL THERMOSTAT

The **differential thermostat** is used primarily with solar-powered heating systems. A differential thermostat is shown in Figure 29-16. This thermostat uses two separate temperature sensors and is activated by the difference of temperature between them. A solar hot-water system is shown in Figure 29-17. A solar collector is used to heat the water. A storage tank stores the heated water and acts as a heat exchanger for the domestic hot water for the home. The system is controlled by the differential thermostat. When the temperature of the collector becomes greater than the temperature of the water in the storage tank by so many degrees, the thermostat activates the pump motor. The pump motor circulates water from the storage tank to the collector, and from the collector back to the tank. When the temperature of the collector is within a certain amount of the water temperature, the thermostat turns the pump off. In this way, water is circulated through the collector only when the collector is at a higher temperature than the stored water.

A common setting for the differential thermostat is 20 and 5. This means that the thermostat will turn the pump on when the collector is 20 degrees hotter than the stored water, and turn the pump off when the collector is only 5 degrees hotter than the stored water.



► **Figure 29-16**
Differential thermostat. (Courtesy of Independent Energy Corp.)



► **Figure 29-17**
Solar hot-water system controlled by a differential thermostat. (Source: Delmar/Cengage Learning)