Electric Power / Controls

Three-Phase Transformers and AC Machines

Student Manual
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Printed In Canada

Lab-Volt®

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ELECTRIC POWER / CONTROLS

THREE-PHASE TRANSFORMERS AND AC MACHINES

by
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and
the Staff of Lab-Volt Ltd.

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Foreword

Electricity has been used since more than a century and the number of applications requiring electricity is increasing constantly. As a result, the electrical power demand has been rising since the early use of electricity. Many reasons explain why electricity is so popular.

One reason is the great versatility of electricity. We use it every day for cooling, heating, lighting, driving (through electric motors) etc. Furthermore, many apparatuses that are part of our everyday life, such as telephones, televisions, personal computers, etc., require electrical power.

Another reason that explains the constantly rising demand for electricity lies in the fact that it is a highly reliable source of energy.

The Lab-Volt 0.2-kW Electromechanical Training System and related courseware offer a comprehensive program in the field of electrical power technology. It is an ideal tool for preparing the students to the realities of the contemporary job market.

The program was developed by educators to satisfy educational requirements that include industrial applications of electric power technology. The design objective was to develop a low-power educational system with equipment that operates like industrial equipment.

The student manuals explain electrical principles as well as specific industrial applications of the phenomenon discussed in each exercise. Hands-on exercises carried out with the training system reinforce the student's knowledge of the theory being studied.

The method of presentation is unique in its modular concept and places emphasis upon electrical laboratory procedures performed by the individual student.

Symbols and Abbreviations

The user of this Student Manual may find some unfamiliar symbols and abbreviations. In general, Lab-Volt Educational System has adopted the "Letter Symbols for Units" IEEE Standard Number 260/USA Standard Number Y10.19, dated October 18, 1967.

The abbreviations have been adopted by Lab-Volt following a thorough study of available abbreviations and guidelines published by the Institute of Electrical and Electronic Engineers (IEEE) and are consistent in nearly all respects with the recommendations of the International Organization for Standardization (ISO) and with the current work of the International Electrotechnical Commission (IEC).

The symbols and abbreviations used in this manual are listed below. Each symbol derived from a proper name has an initial capital letter. Singular and plural forms are identical.

alternating current	ac
American wire gauge	AWG
ampere	A
ampere-turn	At
applied voltage	V_A
average	avg
British thermal unit	BTU
capacitance	C
capacitive reactance	X_C
clockwise	cw
cosine	cos
coulomb	C
counterclockwise	ccw
counter electromotive force	CEMF
current	I
cycles per second	Hz
decibel	dB
degree Celsius	°C
degree Fahrenheit	°F
degree (plane angle)	...°
direct current	dc
divide	÷,/
effective value (ac)	rms
electromotive force	EMF
farad	F
foot	ft, ′
frequency	f
greater than	>
ground	gnd
henry	H
hertz	Hz
horsepower	hp
hour	h
impedance	Z
inch	in, ″
inductance	L
inductance - capacitance	LC
kilohertz	kHz
kilohm	kΩ
kilovar	kvar
kilovolt	kV
kilovolt-ampere	kVA
kilowatt	kW
kilowatthour	kWh
less than	<
load (resistance)	R_L
logarithm	log
magnetomotive force	MMF
maximum	max.
megahertz	MHz
megavolt	MV
megawatt	MW

Symbols and Abbreviations (cont'd)

megohm	MΩ
microampere	μA
microfarad	μF
microhenry	μH
microsecond	μs
microwatt	μW
mile	mi
milliampere	mA
millifarad	mF
millihenry	mH
milliohm	mΩ
millisecond	ms
millivolt	mV
milliwatt	mW
minimum	min.
minute (time)	min
minus	−
negative	neg, −
ohm	Ω
peak	pk
phase	φ
picofarad	pF
positive	pos, +
potential	E
pound-force	lbf
pound-force inch	lbf·in
pound-force foot	lbf·ft
power (active)	P
power (apparent)	P
power (instantaneous)	S
power (reactive)	Q
power factor	PF
reactance	X
reactance (capacitance)	X_C
reactance (inductance)	X_L
reactive power	var
resistance	R
resistance-capacitance	RC
resistance-inductance	RL
revolutions per minute	r/min
revolutions per second	r/s
root-mean square	rms
second (time)	s
sine	sin
source (current)	I_S
source (voltage)	E_S
tangent	tan
temperature	T
time	t
total current	I_T
total power	P_T
volt	V
voltage (applied)	V_A
volt-ampere	VA
watt	W
watthour	Wh

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To examine the construction of the three-phase squirrel-cage motor. To determine its starting, no-load and full-load characteristics.

Experiment 7 **The Synchronous Motor – Part I** 7-1

To examine the construction of the 3φ synchronous motor. To obtain the starting characteristics of the 3φ synchronous motor.

Experiment 8 **The Synchronous Motor – Part II** 8-1

To observe how a synchronous motor can act as a variable inductance or capacitance. To obtain the DC current vs AC current characteristics curve for the synchronous motor.

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C Performing the Electrical Power Technology Courseware Using the Lab-Volt Data Acquisition and Management System

We Value Your Opinion!

Introduction

The subject matter in this manual, *Three-Phase Transformers and AC Machines*, covers three-phase transformer connections. The operating principles and characteristics of the most common three-phase motors/alternators are also covered.

The student can experiment with a rotary frequency converter and a selsyn remote controller.

The exercises in this manual provide a systematic and realistic means of learning the subject matter. Each exercise contains:

- an OBJECTIVE that clearly defines the objectives of the exercise;
- a DISCUSSION of the theory involved;
- a detailed step-by-step laboratory PROCEDURE in which the student observes and measures important phenomena. Schematic diagrams facilitate connecting the components;
- some REVIEW QUESTIONS to verify that the material has been well assimilated.

The exercises can be carried out using either conventional instruments (AC/DC voltmeters and ammeters, power meters, oscilloscope, etc.), or the Lab-Volt Data Acquisition and Management (LVDAM) System. Appendix C of this manual provides useful guidelines to perform the exercises using the LVDAM system.

As a reference manual, we suggest to consult *Electrical Machines, Drives, and Power Systems* written by Theodore Wildi and published by Prentice Hall.

Note that the highlighted text in the manual only applies to the Imperial system of units.

Experiment 0

Safety and the Power Supply

OBJECTIVE

- To learn the necessary safety rules when working with electricity.
- To learn how to use adequately the AC/DC power supply.

DISCUSSION

TO ALL STUDENTS AND TEACHERS

Be sure to know the location of the first-aid kit in your class or lab at all times. Ensure that all cuts and burns receive immediate care, no matter how minor they may seem to be. Notify your instructor about every accident. He will know what to do.

If students follow the instructions adequately, no serious accident will occur while using the Electro Mechanical Systems. There are many fatal shocks every year caused by ordinary electrical power found at home.

A thorough safety program is a necessity for anyone working with electricity. Electricity can be dangerous and even fatal to those who do not understand and practice the simple rules of safety associated with it. There are many fatal electrical accidents caused by well trained technicians who, either through over-confidence or carelessness, disregard the basic rules of personal safety. The first rule of personal safety is always:

“THINK FIRST”

This rule applies to all industrial work as well as to electrical workers. Develop good work habits. Learn to use your tools correctly and safely. Always study experiments beforehand and carefully think through all of the required procedures and methods. Make sure you know how to use all of your tools, instruments and machines before proceeding with an experiment. Never let yourself be distracted from your work and never distract others around you. Do not joke around near moving machinery and electricity.

There are generally three kinds of accidents which happen frequently to electrical students and technicians: electrical shocks, burns and mechanical injuries. Knowing how to avoid them by observing simple rules will make you a safe person to work with. Observing these precautions could save you from painful experiences (it could even save your life) and prevent expensive damage to the equipment.

Electric shock

Are electric shocks fatal? The physiological effects of electric currents can generally be predicted by the chart shown in Figure 0-1.

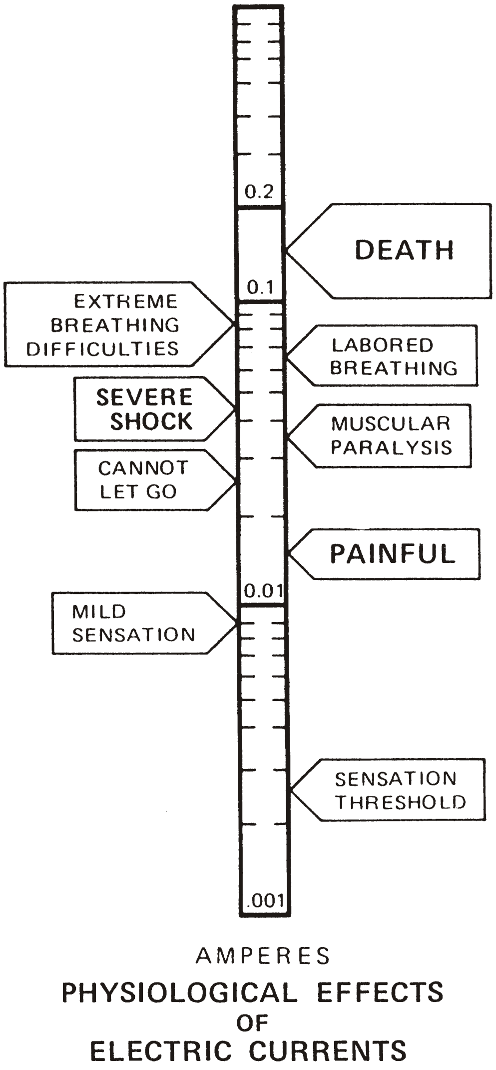


Figure 0-1.

As you can see, it is the current that determines the intensity of an electrical shock. Currents above 100 mA are considered fatal. A person who has received a shock of over 2000 mA is in grave danger and needs immediate medical attention. Currents below 100 mA are still serious and painful. As a safety rule: Do not put yourself in a position where you could receive any kind of shock, no matter how low the current is.

What about VOLTAGE?

Current depends upon voltage and resistance. We will now measure the resistance of your body. Using your ohmmeter, measure your body resistance between these points:

From right to left hand ______ Ω

From hand to foot ______ Ω

Now wet your fingers and repeat the measurements:

From right to left hand ______ Ω

From hand to foot ______ Ω

As you can see, the actual resistance of your body varies greatly depending on the points of contact, the condition of your skin, and the contact area. Notice how your resistance varies as you squeeze the probes more or less tightly. Skin resistance may vary between 250 Ω for wet skin and large contact areas, to 500 000 Ω for dry skin. Using the measured resistance of your body and considering 100 mA as a fatal current, calculate what voltages could be fatal to you:

Use the formula: Volts = .1 x ohms.

Contact between two hands (dry): ______ V

Contact between one hand and one foot (dry): ______ V

Contact between two hands (wet): ______ V

Contact between one hand and one foot (wet): ______ V

DO NOT ATTEMPT TO PROVE THIS!

Here are nine rules to avoid electric shocks:

1. Be sure to check the condition of your equipment and the possible dangers before working on a piece of equipment. The same way someone can be accidentally killed by a supposedly unloaded gun, an electrical technician can receive shocks from a circuit that is supposedly turned off.

2. Never rely on safety devices such as fuses, relays and interlock systems to protect you. They may not be working correctly and may fail to protect you when most needed.

3. Never remove the grounding prong of a three wire input plug. Without ground, electrical equipments become much more dangerous shock hazards.

4. Do not work on a cluttered desk. A disorganized working area full of connecting leads, components and tools leads to careless thinking, short circuits, shocks and accidents. Develop systemized and organized work habits.

5. Do not work on a wet floor. This would greatly reduce your contact resistance to the ground. Work on a rubber mat or an insulated floor.

6. Do not work alone. It's an additional safety measure to have someone around to shut off the power, give artificial respiration or make an emergency call in case of need.

7. Work with one hand behind you or in your pocket. A current between one hand to the other would pass through your heart and is thus more lethal than a current from hand to foot.

8. Never talk to anyone while working. Do not let yourself be distracted by your surroundings. Similarly, do not talk to someone working on dangerous equipment.

9. Always move slowly when working around electrical circuits. Fast and careless movements lead to accidental shocks and short circuits.

Burns

Accidents resulting in burns, although usually not fatal, can be painful and serious. They are generally caused by the production of heat due to electrical energy dissipation. Here are four rules to avoid electrical burns:

1. Resistors may get very hot, especially those that carry high currents. Watch out especially for five and ten watt resistors. They can severely burn your skin. Do not touch them until they cool off.

2. Be wary of capacitors: they may still retain a charge. Not only would you receive a dangerous and sometimes fatal shock, you could also be burned from the electrical discharge. If the rated voltage of electrolytic capacitors is exceeded or their polarities reversed, they may get very hot and actually burst.

3. Watch out for hot soldering irons or guns. Do not leave one where your arm might accidentally touch it. Never store a soldering iron away while it is still hot. Unknowing students could be burned by picking it up.

4. Hot solder can be painful when put in contact with naked skin. Wait for soldered joints to cool off. When desoldering joints, do not shake hot solder off. You or a neighbor could receive hot solder in the eye or on his body.

Mechanical injuries

This third class of safety rules concerns all students who work with tools and machinery. Here are five rules to avoid mechanical injury:

1. Metal corners and sharp edges on chassis and panels can cut and scratch. File them until they are smooth.

2. Improper tool selection for a job can result in damage to the equipment and personal injuries.

3. Use proper eye protection when grinding, chipping or working with hot metals which might splatter.

4. Protect your hands and clothes when working with battery acids, etchants, and finishing fluids. These liquids can cause severe burns.

5. If you are unsure about something, ask your instructor.

The Power Supply

The Power Supply provides all of the necessary AC/DC power, both fixed and variable, single phase and three-phase, to perform all of the experiments presented in this manual.

The module must be connected to a three-phase, 240 /415 V, four wire (with fifth wire ground) system. Power is brought in through a five prong, twist-lock connector located at the rear of the module. An input power cable with mating connector is provided for this purpose.

The power supply provides the following outputs:

1. Fixed 24 V ac is made available for the use of accessory equipments such as meters.

2. Fixed 120 /208 V, 3φ power is brought out to four terminals, labeled 1, 2, 3 and N. Fixed 208 V 3φ may be obtained from terminals 1, 2 and 3. Fixed 208 V ac may be obtained between terminals 1 and 2, 2 and 3 or 1 and 3. Fixed 120 V ac may be obtained between any one of the 1, 2 or 3 terminals and the N terminal. The current rating of this supply is 15 A per phase.

3. Variable 120 /208 V, 3φ power is brought out to four terminals, labeled 4, 5, 6 and N. Variable 3φ 0-208 V may be obtained from terminals 4, 5 and 6. Variable 0-208 V ac may be obtained between terminals 4 ans 5, 5 and 6 or 4 and 6.Variable 0-120 V ac may be obtained between any one of the 4, 5 or 6 terminals and the N terminal. The current rating of this supply is 5 A per phase.

4. Fixed 120 V dc is brought out to terminals labeled 8 and N. The current rating of this supply is 2 A.

5. Variable 0-120 V dc is brought out to terminals labeled 7 and N. The current rating of this supply is 8 A.

The full current rating of the various outputs cannot be used simultaneously. If more than one output is used at a time, reduced current must be drawn. The neutral N terminals are all connected together and joined to the neutral wire of the AC power line. All power is removed from the outputs when the on-off breaker is in the off position (breaker handle down).

CAUTION!

Power is still available behind the module face with the breaker off! Never remove the power supply from the console without first removing the input power cable from the rear of the module.

The variable AC and DC outputs are controlled by the single control knob on the front of the module. The built-in voltmeter will indicate all the variable AC and the variable and fixed DC output voltages according to the position of the voltmeter selector switch. The power supply is fully protected against overload or short circuit. Besides the main 15 A 3φ on-off circuit breaker on the front panel, all of the outputs have their own circuit breakers. They can be reset by a common button located on the front panel.

The rated current output may be exceeded considerably for short periods of time without harming the supply or tripping the breakers. This feature is particularly useful in the study of DC motors under overload or starting conditions where high currents may be drawn.

All of the power sources can be used simultaneously, providing that the total current drawn does not exceed the 15 A per phase input breaker rating. Your power supply, if handled properly, will provide years of reliable operation and will present no danger to you.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are used in this Experiment! Do not make or modify any banana jack connections with the power on unless otherwise specified!

☐ 1. Examine the construction of the Power Supply. On the front panel of the module, identify the following elements:

   a. The three-pole circuit breaker on-off switch.

   b. The three lamps indicating the operation of each phase.

   c. The AC/DC voltmeter.

   d. The AC/DC voltmeter selector switch.

   e. The variable output control knob.

   f. The fixed 24 V ac receptacle.

   g. The fixed 120 /208 V output terminals (labeled 1, 2, 3 and N).

   h. The variable 0-120 /208 V output terminals (labeled 4, 5, 6 and N).

   i. The fixed DC output terminals (labeled 8 and N).

   j. The variable DC output terminals (labeled 7 and N).

   k. The common reset button.

☐ 2. State the AC or DC voltage and the rated current available from each of the following terminals:

a. Terminals 1 and N = ______ V ______ A ______

b. Terminals 2 and N = ______ V ______ A ______

c. Terminals 3 and N = ______ V ______ A ______

d. Terminals 4 and N = ______ V ______ A ______

e. Terminals 5 and N = ______ V ______ A ______

f. Terminals 6 and N = ______ V ______ A ______

g. Terminals 7 and N = ______ V ______ A ______

h. Terminals 8 and N = ______ V ______ A ______

i. Terminals 1, 2 & 3 = ______ V ______ A ______

j. Terminals 4, 5 & 6 = ______ V ______ A ______

k. The low power connector = ______ V ______ A ______

☐ 3. Examine the interior construction of the module. Identify the following items:

a. The 3φ variable autotransformer.
b. The filter capacitors.
c. The thermal-magnetic circuit breakers.
d. The solid state rectifier diodes.
e. The five prong twist lock connector.

☐ 4. Insert the Power Supply into the console. Make sure that the on-off switch is in the off position and that the output control knob is turned fully counterclockwise for minimum output. Insert the power cable through the clearance hole in the rear of the console and into the twist-lock module connector. Connect the other end of the power cable into a source of 3φ 120 /208 V.

☐ 5. a. Set the voltmeter selector switch to its 7-N position and turn the power supply on by placing the on-off breaker switch in its “up” position.

b. Turn the control knob of the 3φ autotransformer and note that the DC voltage increases. Measure and record the minimum and maximum DC output voltage as indicated by the built-in voltmeter.

$V\ dc_{minimum}$ = ______ $V\ dc_{maximum}$ = ______

c. Return the voltage to zero by turning the control knob to its full ccw position.

☐ 6. a. Place the voltmeter selector switch into its 4-N position.

b. Turn the control knob and note that the AC voltage increases. Measure and record the minimum and maximum AC output voltage as indicated by the built- voltmeter.

V $\text{ac}_{\text{minimum}}$ = ______ V $\text{ac}_{\text{maximum}}$ = ______

c. Return the voltage to zero and turn off the power supply by placing the on-off breaker switch in its “down” position.

☐ 7. What other AC voltages are affected by turning the control knob?

Terminals ______ and ______ = ______ V ac

Terminals ______ and ______ = ______ V ac

Terminals ______ and ______ and ______ = ______ V ac

☐ 8. For each of the following conditions:

a. Connect the 250 V ac meter across the specified terminals.
b. Turn on the power supply.
c. Measure and record the voltage.
d. Turn off the power supply.

Terminals 1 and 2 = ______ V ac

Terminals 2 and 3 = ______ V ac

Terminals 3 and 1 = ______ V ac

Terminals 1 and N = ______ V ac

Terminals 2 and N = ______ V ac

Terminals 3 and N = ______ V ac

e. Are any of these voltages affected by turning the control knob?

☐ Yes ☐ No

☐ 9. a. Set the voltmeter selector switch to its 8-N position.

b. Turn on the power supply.

c. Measure and record the voltage

Terminals 8 and N = ______ V dc

d. Is this voltage affected by turning the control knob?

☐ Yes ☐ No

e. Turn off the power supply.

☐ 10. For each of the following positions of the voltmeter selector switch:

a. Turn on the power supply and rotate the control knob to its full cw position.
b. Measure and record the voltage.
c. Return the voltage to zero and turn off the power supply.

Terminals 4 and 5 = ______ V ac

Terminals 5 and 6 = ______ V ac

Terminals 6 and 4 = ______ V ac

Terminals 4 and N = ______ V ac

Terminals 5 and N = ______ V ac

Terminals 6 and N = ______ V ac

Experiment 1

Three-Phase Transformer Connections

OBJECTIVE

- To connect transformers in delta and wye configurations.
- To study the current and voltage relationships.

DISCUSSION

The three-phase transformer may be a single transformer or three separate single-phase transformers connected in delta or wye. Sometimes only two transformers are used.

Commercial three-phase voltage from the power lines is generally 208 V, and the standard values of single-phase voltage (120 V) can be supplied from the line as shown in Figure 1-1.

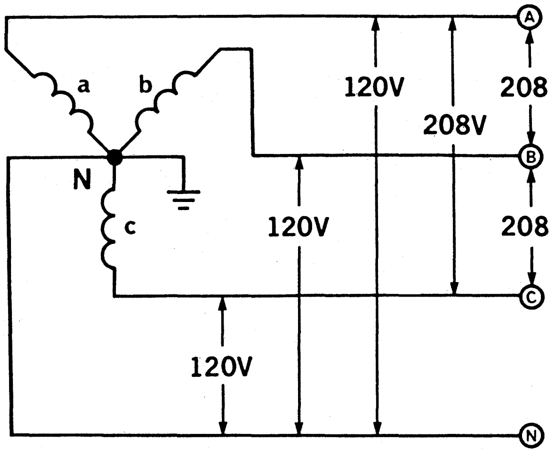


Figure 1-1.

The windings a, b and c, represent the three wye-connected transformer secondaries. The three-phase lines are designated A, B and C, and the single-phase connections are from A, B or C to neutral (ground). Three-phase transformers must be properly connected to these lines in order to operate. Four of the most widely used transformer connections (see Figure 1-2) are:

a) Primary windings in delta, secondary windings in delta, or delta-delta (Δ - Δ)

b) Primary windings in wye, secondary windings in wye, or wye-wye (Y - Y)

c) Primary windings in wye, secondary windings in delta, or wye-delta (Y - Δ)

d) Primary windings in delta, secondary windings in wye, or delta-wye (Δ - Y)

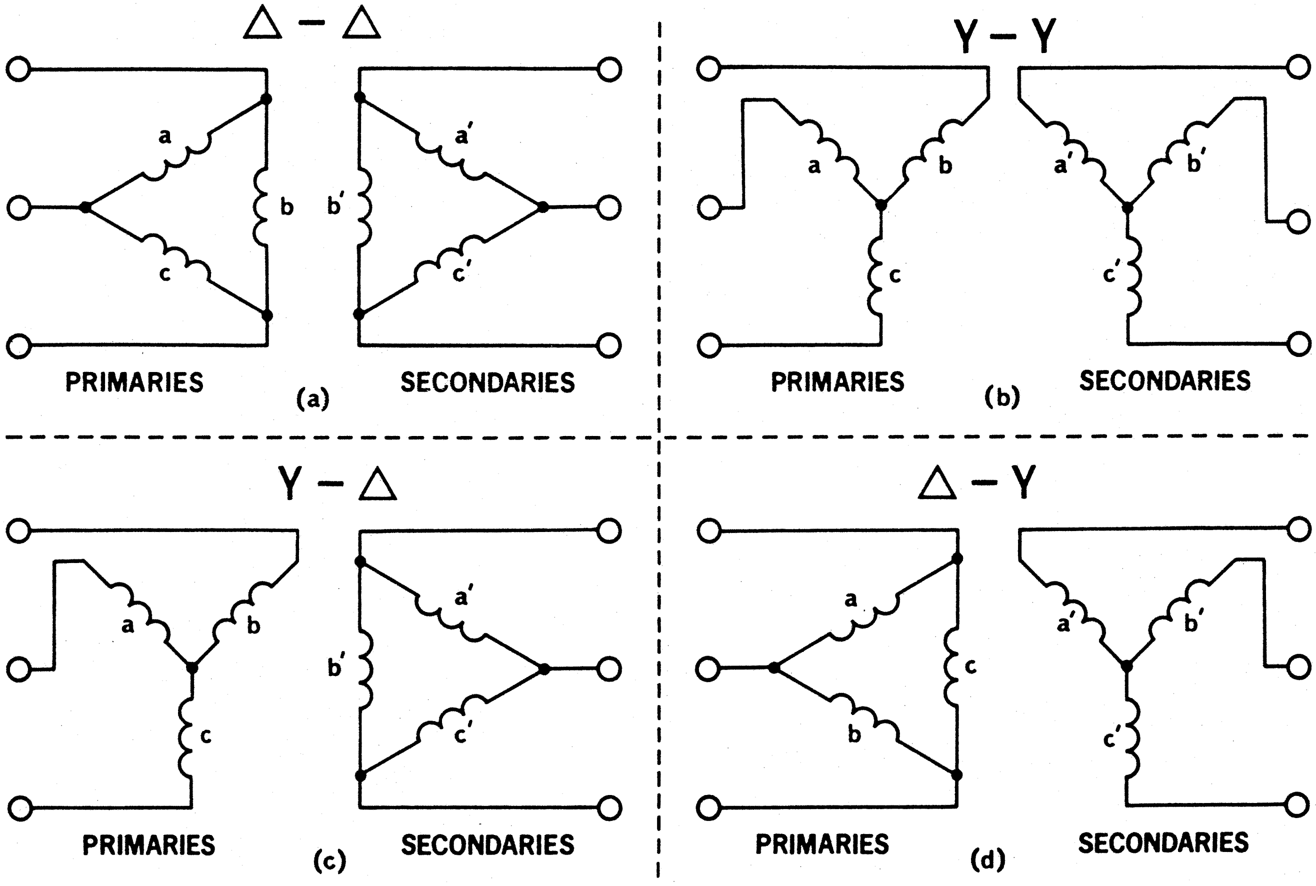


Figure 1-2.

Of these four combinations, the one used most extensively is the last one listed, the delta-wye.

Regardless of what method of connection is used, the windings must be connected in the proper phase relationships. To determine these in a wye-connected secondary, the voltage is measured across two windings as shown in Figure 1-3 (a). The voltage A to B should be equal to $\sqrt{3}$ times the voltage across either winding. If the voltage is equal to that across either winding, then one of the windings must be reversed. The third winding c is then connected as shown in Figure 1-3 (b), and the voltage C to A or B should also equal $\sqrt{3}$ times the voltage across any one winding. If not, the winding c must be reversed.

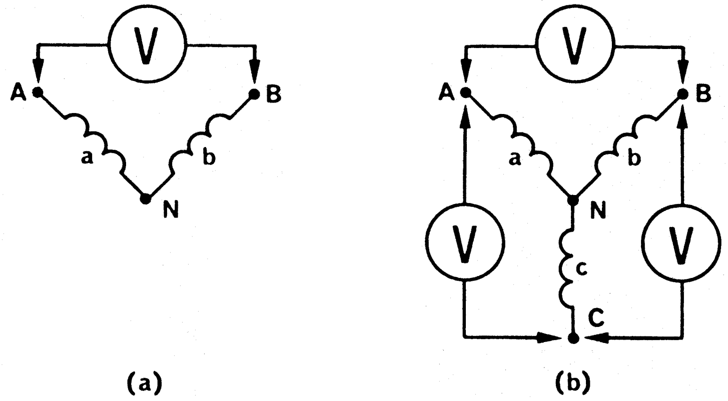


Figure 1-3.

To determine the proper phase relationships in a delta-connected secondary, the voltage is measured across two windings as shown in Figure 1-4 (a). The voltage A to C should equal the voltage across either winding. If not, one of the windings must be reversed. The winding c is then connected as shown in Figure 1-4 (b), and the voltage across the three windings C^1 to C should equal zero. If not, winding c must be reversed. The open ends (C^1 & C) are then joined and the transformer has the proper phase relationships for delta connection as shown in Figure 1-4 (c).

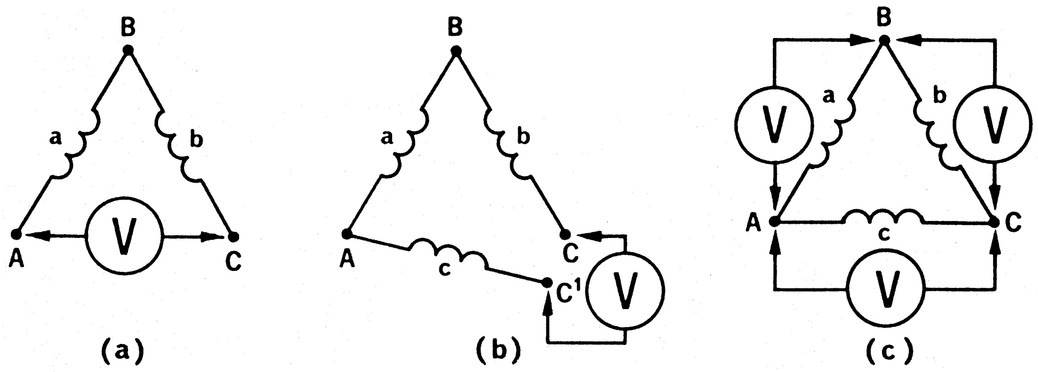


Figure 1-4.

CAUTION!

The delta should never be closed until a test is first made to determine that the voltage within the delta is zero. If not, and the delta is closed on itself, the resulting current will be of short-circuit magnitude, with resulting damage to the transformers.

The wye-wye connection has the same volts per turn ratio between primary and secondary windings as that of an individual single-phase transformer. The voltage output of the delta-delta is also dependent on the turn ratio of the primary and secondary windings. The delta-wye connection has a higher 3φ voltage ratio than either the delta-delta or wye-wye connection. This is because the voltage across any two windings of the wye secondary is equal to $\sqrt{3}$ times the 3φ primary line voltage. The wye-delta connection is the opposite of the delta-wye connection.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. a. The circuit shown in Figure 1-5 has three transformers connected in a ______ ______ configuration.

b. Calculate the expected voltages and record the values in the spaces provided.

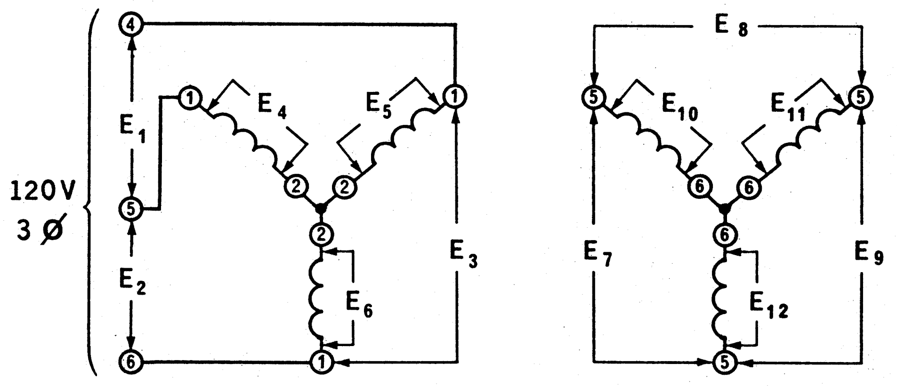
c. Connect the circuit as shown.

> **Note:** *When connecting the primary windings in a wye configuration, the neutral point of the windings must be connected to the neutral terminal of the Power Supply to maintain the neutral point voltage to zero.*

d. Turn on the power supply and slowly increase the output for a line-to-line voltage of 120 V ac.

e. Measure the indicated voltages and record the values in the spaces provided.

f. Return the voltage to zero and turn off the power supply. Repeat (d), (e) and (f) until all of the listed voltages have been measured.



PRIMARY (120V) WINDINGS

SECONDARY (120V) WINDINGS

Figure 1-5.

CALCULATED VALUES			MEASURED VALUES		
E_1 = ______ V,	E_2 = ______ V,	E_3 = ______ V	E_1 = ______ V,	E_2 = ______ V,	E_3 = ______ V
E_4 = ______ V,	E_5 = ______ V,	E_6 = ______ V	E_4 = ______ V,	E_5 = ______ V,	E_6 = ______ V
E_7 = ______ V,	E_8 = ______ V,	E_9 = ______ V	E_7 = ______ V,	E_8 = ______ V,	E_9 = ______ V
E_{10} = ______ V,	E_{11} = ______ V,	E_{12} = ______ V	E_{10} = ______ V,	E_{11} = ______ V,	E_{12} = ______ V

☐ 2. a. The circuit shown in Figure 1-6 has three transformers connected in a ______ ______ configuration.

b. Calculate the expected voltages and record the values in the spaces provided.

c. Connect the circuit as shown.

d. Turn on the power supply and slowly increase the output for a line-to-line voltage of 90 V ac.

e. Measure the indicated voltages and record the values in the spaces provided.

f. Return the voltage to zero and turn off the power supply. Repeat (d), (e) and (f) until all of the listed voltages have been measured.

Three-Phase Transformer Connections

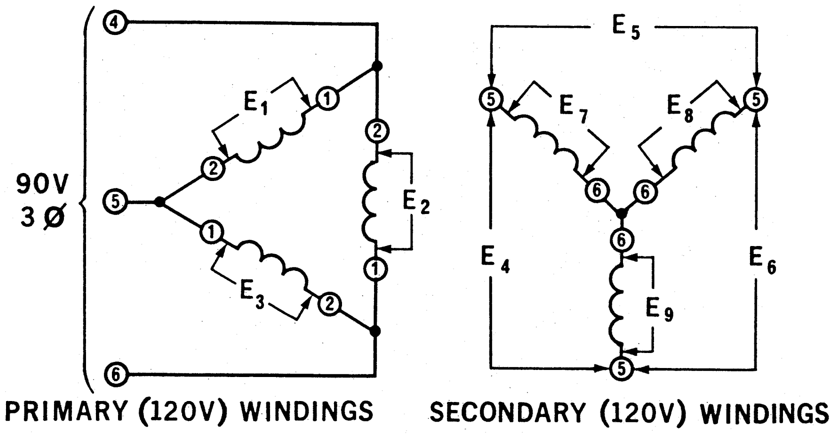


Figure 1-6.

CALCULATED VALUES	MEASURED VALUES
E_1 = ______ V, E_2 = ______ V, E_3 = ______ V	E_1 = ______ V, E_2 = ______ V, E_3 = ______ V
E_4 = ______ V, E_5 = ______ V, E_6 = ______ V	E_4 = ______ V, E_5 = ______ V, E_6 = ______ V
E_7 = ______ V, E_8 = ______ V, E_9 = ______ V	E_7 = ______ V, E_8 = ______ V, E_9 = ______ V

☐ 3. a. The circuit shown in Figure 1-7 has three transformers connected in a ______ ______ configuration.

b. Calculate the expected voltages and record the values in the spaced provided.

c. Connect the circuit as shown. Open the delta connected secondary at point "A" and place a voltmeter across the opened loop.

> **Note:** *When connecting the primary windings in a wye configuration, the neutral point of the windings must be connected to the neutral terminal of the Power Supply to maintain the neutral point voltage to zero.*

d. Turn on the power supply and slowly increase the output voltage. The voltmeter across the open delta, at point "A", should not indicate any appreciable voltage if your delta connections are phased properly. Some small voltage will be present because the normal 3φ supply does not have all 3φ voltages equal and the three transformers also have small differences.

e. Return the voltage to zero and turn off the power supply.

f. Remove the voltmeter and close the delta loop at point "A".

g. Turn on the power supply and slowly increase the output for a line-to-line voltage of 120 V ac.

h. Measure the indicated voltages and record the values in the spaces provided.

i. Return the voltage to zero and turn off the power supply. Repeat (g), (h) and (I) until all of the listed voltages have been measured.

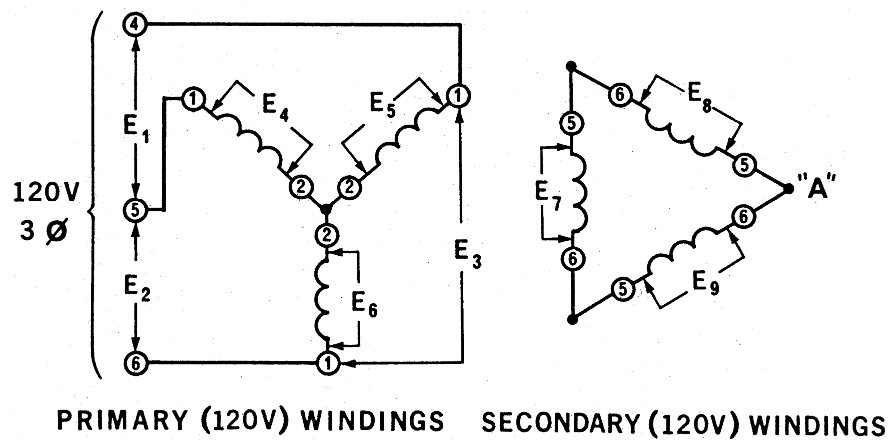


Figure 1-7.

CALCULATED VALUES			MEASURED VALUES		
E_1 = ______ V,	E_2 = ______ V,	E_3 = ______ V	E_1 = ______ V,	E_2 = ______ V,	E_3 = ______ V
E_4 = ______ V,	E_5 = ______ V,	E_6 = ______ V	E_4 = ______ V,	E_5 = ______ V,	E_6 = ______ V
E_7 = ______ V,	E_8 = ______ V,	E_9 = ______ V	E_7 = ______ V,	E_8 = ______ V,	E_9 = ______ V

☐ 4. a. The circuit shown in Figure 1-8 has three transformers connected in a ______ ______ configuration.

b. Calculate the expected voltages and record the values in the spaced provided.

c. Connect the circuit as shown. Open the delta connected secondary at point “A” and place a voltmeter across the opened loop.

d. Turn on the power supply and slowly increase the output voltage. The voltmeter across the open delta, at point “A”, should not indicate any appreciable voltage if your delta connections are phased properly.

e. Return the voltage to zero and turn off the power supply.

f. Remove the voltmeter and close the delta loop at point “A”.

g. Turn on the power supply and slowly increase the output for a line-to-line voltage of 120 V ac.

h. Measure the indicated voltages and record the values in the spaces provided.

i. Return the voltage to zero and turn off the power supply. Repeat (g), (h) and (I) until all of the listed voltages have been measured.

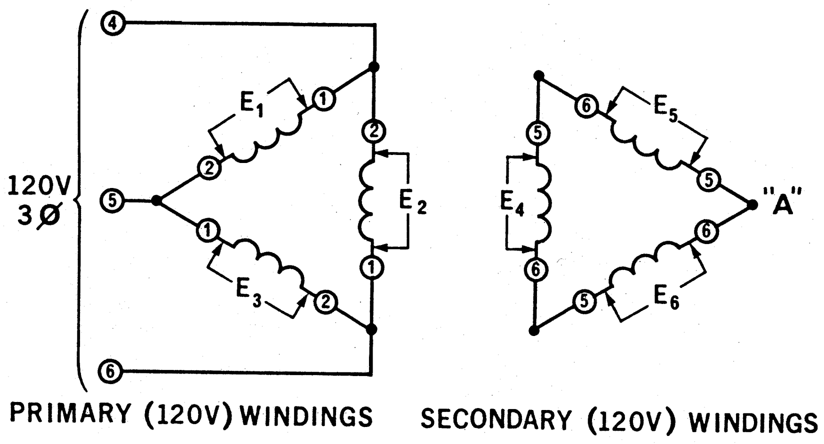


Figure 1-8.

CALCULATED VALUES

E_1 = ______ V, E_2 = ______ V, E_3 = ______ V

E_4 = ______ V, E_5 = ______ V, E_6 = ______ V

MEASURED VALUES

E_1 = ______ V, E_2 = ______ V, E_3 = ______ V

E_4 = ______ V, E_5 = ______ V, E_6 = ______ V

☐ 5. a. The circuit shown in Figure 1-9 has two transformers connected in a open-delta configuration.

b. Calculate the expected voltages and record the values in the spaces provided.

c. Connect the circuit as shown.

d. Turn on the power supply and slowly increase the output for a line-to-line voltage of 120 V ac.

e. Measure the indicated voltages and record the values in the spaces provided.

f. Return the voltage to zero and turn off the power supply. Repeat (d), (e) and (f) until all of the listed voltages have been measured.

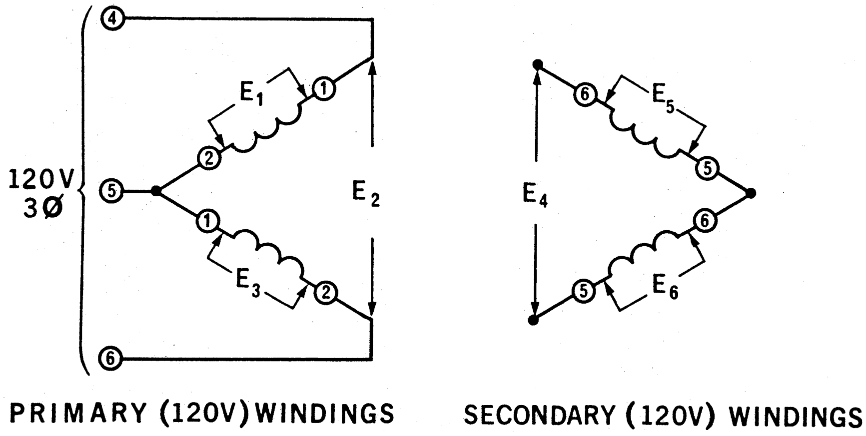


Figure 1-9.

CALCULATED VALUES			MEASURED VALUES		
E_1 = ______ V,	E_2 = ______ V,	E_3 = ______ V	E_1 = ______ V,	E_2 = ______ V,	E_3 = ______ V
E_4 = ______ V,	E_5 = ______ V,	E_6 = ______ V	E_4 = ______ V,	E_5 = ______ V,	E_6 = ______ V

REVIEW QUESTIONS

1. Compare the results of procedure 4 and 5.

   a) Is there a voltage difference in a delta-delta vs open-delta configuration?

      ☐ Yes ☐ No

   b) Is the VA rating of the delta-delta configuration the same as for the open-delta configuration? Explain.

      ☐ Yes ☐ No

      ____

      ____

   c) If the current ratings for each winding were increased, could the open-delta configuration work as well as the delta-delta configuration? Explain.

      ☐ Yes ☐ No

      ____

      ____

      ____

2. If each transformer has a capacity of 60 kVA what total 3φ power can be obtained in each of the five types of configurations.

   a) wye-wye ____

   ____

   ____

   ______________________________ = ____________ kVA

   b) wye-delta ____

   ____

   ____

   ______________________________ = ____________ kVA

   c) delta-wye ____

   ____

   ____

   ______________________________ = ____________ kVA

   d) delta-delta ____

   ____

   ____

   ______________________________ = ____________ kVA

   e) open-delta ____

   ____

   ____

   ______________________________ = ____________ kVA

3. If one of the secondary winding polarities were reversed, in procedure 1:

   a) Would there be a dead short?

   ☐ Yes ☐ No

   b) Would the transformer heat up?

   ☐ Yes ☐ No

c) Would the primary voltages become unbalanced?

☐ Yes ☐ No

d) Would the secondary voltages become unbalanced?

☐ Yes ☐ No

4. If one of the secondary winding polarities were reversed in procedure 4:

a) Would there be a dead short?

☐ Yes ☐ No

b) Would the transformer heat up?

☐ Yes ☐ No

c) Would the primary voltages become unbalanced?

☐ Yes ☐ No

d) Would the secondary voltages become unbalanced?

☐ Yes ☐ No

Experiment 2

Prime Mover and Torque Measurement

OBJECTIVE

- To learn how to connect a direct current shunt motor.
- To learn how to connect the Electrodynamometer.
- To learn how to use the Prony Brake.

DISCUSSION

The DC motor is a very useful machine in applications where the running speed must be adjustable. By means of a simple control rheostat placed in series with its shunt field winding, the speed of a DC motor can be varied over a wide range.

In this Experiment, you will learn how to use the DC motor as a prime mover for the study of torque measuring devices.

The load imposed on a motor can be measured by two different means; these two torque measuring devices are the Prony Brake and the Electrodynamometer. The Prony Brake is an entirely passive device (no electrical power is required) while the Electrodynamometer requires external power.

The Prony Brake is a friction brake which is used to act as a load for any type of motor and to measure the torque developed by these motors. This brake is entirely mechanical, and consist of a spring balance mounted in a standard full size module. It is built to accurately measure the torque developed by any rotating machine placed on its left-hand side.

A self-cooling friction wheel is slipped over the shaft of the machine under test, and attached to its output pulley by means of two screws. The friction belt of the Prony Brake is then removed from inside the module and slipped over the friction wheel. The braking torque applied to the machine can be varied by turning the knurled wheel (LOAD) in the upper left corner of the module. A second knurled wheel (TORQUE PRESET) in the upper center allows the spring balance to be brought back into equilibrium by aligning the red line in the right-hand window (ZERO) with the black line; the torque can then be read directly on the 0-3.4 N·m [0-30 lbf·in], 360° circular scale, in steps of 0.02 N·m [0.2 lbf·in].

The accuracy is better than 2% and the torque is continuously adjustable over the full range from no load to locked rotor. When one wants to apply a known torque to the machine, the TORQUE PRESET wheel must first be set to that the calibrated circular scale reads exactly the desired torque value and the LOAD wheel must then be turned in such a way that the red line in the ZERO window is aligned with the black line.

The Electrodynamometer is a device used to accurately measure the torque developed by motors of all kinds. It is actually an electrical brake in which the braking force can be varied electrically rather than by mechanical friction. The Electrodynamometer is a more stable, easier to adjust, device than the mechanical friction brakes.

The Electrodynamometer consists of a stator and a squirrel-cage rotor. The stator, unlike other Electromechanical devices, is free to turn, but its motion is restricted by a helical spring.

In normal operation, DC current is applied to the stator winding. This sets up a magnetic field which passes through both the stator and the rotor. As the rotor turns (being belt-coupled to the driving motor), a voltage is induced in the rotor bars, and the resulting eddy currents react with the magnetic field causing the stator to turn in the same direction as the rotor.

The stator rotation is limited by the helical spring and the amount that it turns is marked off on a scale attached to the external stator housing.

The Electrodynamometer is calibrated from −0.3 to 3 N·m [−3 to 27 pound-force-inches (lbf·in)] which is more than adequate for the testing of 0.2 kW [¼ hp] motors even when they are tested at overload conditions.

The power output of a motor depends upon its speed and the torque it develops. This relationship is given by the following equation:

$$P_{out}\ (W) = \frac{2\pi \times N \times T}{60}$$

where P_{out} = Mechanical Output Power in watts (W)
N = Speed in revolution per minute (r/min)
T = Torque in Newton·meter (N·m)

$$P_{out}\ (hp) = \frac{1.59 \times N \times T}{100\ 000}$$

where P_{out} = Mechanical Output Power in horse power (hp)
N = Speed in revolution per minute (r/min)
T = Torque in pound-force·inches (lbf·in)

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

DC Motor

☐ 1. Using your Power Supply, DC Motor/Generator, DC Voltmeter/Ammeter and Electrodynamometer, connect the circuit shown in Figure 2-1.

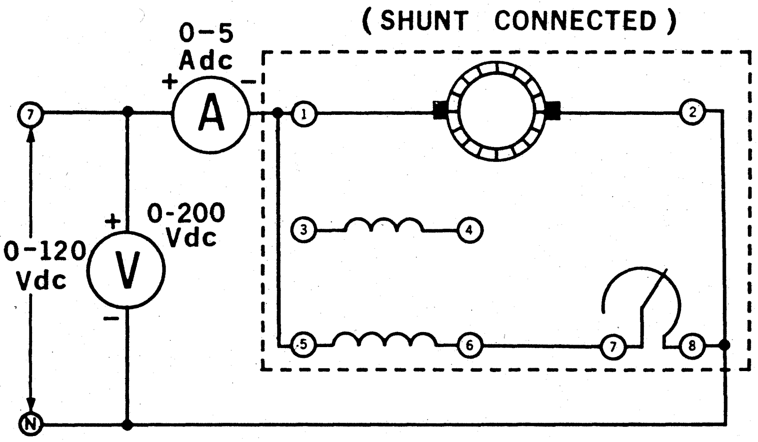


Figure 2-1.

DO NOT APPLY POWER AT THIS TIME!

Notice that the motor is wired for shunt operation (the shunt field winding, in series with the field rheostat, is connected in parallel with the armature), and is connected to the variable DC output of the power supply (terminals 7 and N).

☐ 2. Set the shunt field rheostat control knob at its full cw position (for maximum shunt field excitation and maximum starting torque). Make sure the brushes are in their neutral position; in case of difficulty, ask your instructor how to set the brushes in the neutral position.

☐ 3. a. Turn on the power supply and slowly increase the output voltage to 120 V dc. The motor should be running. Note the direction of rotation; if it is not clockwise, turn the power supply and interchange the shunt field connections.

b. Using your hand tachometer, measure the motor speed in revolutions per minute.

Speed = ______ r/min

c. Turn the shunt field rheostat control knob ccw by steps, and measure the motor speed. Adjust the rheostat for a no-load motor speed of 1800 r/min. Make sure that the voltmeter, connected across the input of your circuit, indicates exactly 120 V dc.

d. Measure the line current, as indicated by the ammeter, for a motor speed of 1800 r/min.

I = ______ A dc

e. Return the voltage to zero and turn off the power supply.

f. Disconnect the DC motor.

Electrodynamometer

Note: *If your list of equipment does not include an electrodynamometer, proceed to procedure 10.*

☐ 4. a. Examine the construction of the Electrodynamometer.

b. Note the cradle construction for the electrodynamometer housing. (This is also called trunnion mounting.)

c. Note the helical spring at the rear of the machine. This spring has been accurately calibrated against the graduations marked on the front of the housing.

d. Note the mechanical stops that limit the rotational travel of the stator housing.

e. Identify the stator winding that is attached to the inside of the housing. (This winding carries DC current.)

f. Identify the two wire leads that carry DC current to the stator winding. (They enter the housing through the center of the helical spring.)

g. Identify the bridge rectifier located at the rear of the module. (This bridge furnishes DC power for the stator magnetic field.)

h. Identify the variable autotransformer mounted on the front face of the module. The braking effect of the electrodynamometer is controlled by the strength of the stator magnetic field, which is proportional to the DC output of the bridge rectifier, which is varied by the variable autotransformer.

i. Identify the two AC connections terminals mounted on the module face.

☐ 5. a. Connect the electrodynamometer to the fixed AC output of the power source by connecting the two input terminals of the electrodynamometer to terminals 1 and N of the power source.

DO NOT APPLY POWER AT THIS TIME!

b. Set the electrodynamometer variable transformer control knob to its mid-position.

c. Lower the front face of the module so that you may turn the pulley by hand.

☐ 6. a. Turn on the power supply.

b. Keeping one hand in your pocket, for safety reasons, carefully reach in and try to turn the pulley. Caution is advised because there are several live terminals exposed when the front panel is dropped.

Do you feel a drag when you turn the pulley?

☐ Yes ☐ No

Does the stator housing tend to turn in the same direction as the pulley?

☐ Yes ☐ No

☐ 7. a. Remove your hand from the inside of the module and advance the control knob, thereby increasing the magnetic stator field.

b. Carefully reach in and turn the pulley. Did the drag increase?

☐ Yes ☐ No

c. Repeat (a) but this time reduce the stator magnetic field.

d. Carefully reach in and turn the pulley. Did the drag increase?

☐ Yes ☐ No

e. Turn off the power supply.

☐ 8. a. Couple the DC Motor/Generator and the electrodynamometer with the timing belt.

b. Connect the motor as shown in Figure 2-1.

c. Set the electrodynamometer control knob at its full ccw position (to provide minimum starting load for the motor).

d. Set the shunt field rheostat at its full cw position (to provide maximum starting torque for the motor).

e. Turn on the power supply and adjust for an output of 120 V dc. Note the direction of rotation. If it is not cw, proceed as indicated in procedure 3 (a). (The electrodynamometer torque can only be measured for cw rotation.)

f. Adjust the shunt field rheostat for a no-load motor speed of 1800 r/min, as indicated on your hand tachometer. Make sure that the input voltage is maintained exactly at 120 V dc. Leave the shunt field rheostat in this position for the remainder of this experiment.

☐ 9. a. Apply a load to your DC motor by varying the electrodynamometer control knob until the scale marked on the stator housing indicates 1 N·m [9 lbf·in] (the numeral 1 [9] should be directly beneath the red vertical line beneath the pulley). Readjust the power supply, if necessary, to maintain exactly 120 V dc.

b. Measure and record the line current and motor speed.

I = ______ A dc Speed = ______ r/min

c. Return the voltage to zero and turn off the power supply.

Prony Brake

Note: *If your list of equipment does not include a Prony brake, proceed to REVIEW QUESTIONS.*

CAUTION!

The friction wheel may become very hot during this experiment.

☐ 10. a. Examine the construction of the Prony Brake.

b. Remove the friction wheel from inside the module and note the holes in the web of the pulley; they are for cooling purposes. Slip the friction wheel over the synchronous motor shaft and secure it firmly to the motor pulley by tightening the two screws in the grooves of the motor pulley.

c. Note the floating plate inside the module. In operation, this plate is pulled in one direction by the friction belt and in the other direction by a spring which is connected to the fixed frame by means of a rack gear. A pinion gear, driven by the rack, turns the front plastic disc which has a red line to read the torque. The TORQUE PRESET wheel effectively increases the spring tension and so, the force which tends to turn the floating plate.

d. The LOAD wheel effectively increases the tension on the friction belt, and tends to turn the floating plate in the opposite direction.

e. Note the friction belt attached at one end to the floating plate and at the other end to the LOAD wheel screw.

f. The complete system constitutes a spring balance.

☐ 11. a. Turn the LOAD wheel downwards to release the tension on the friction belt and slip the belt over the friction wheel mounted on the DC motor shaft. Leave the belt loose.

b. Connect your circuit as shown in Figure 2-1.

DO NOT APPLY POWER AT THIS TIME!

Notice that the motor is wired for shunt operation (the shunt field winding, in series with the field rheostat, is connected in parallel with the armature) and is connected to the variable DC output of the power supply (terminals 7 and N).

c. Set the field rheostat for minimum resistance at its full cw position (to provide maximum starting torque for the DC motor).

d. Turn on the power supply and adjust for an output of 120 V dc. Note the direction of rotation. If it is not cw, proceed as indicated in procedure 3 (a). (The Prony brake torque can only be measured for cw rotation).

e. Adjust the shunt field rheostat for a no-load speed of 1800 r/min as indicated on your hand tachometer. Make sure that the input voltage is maintained exactly at 120 V dc. Leave the shunt field rheostat in this position for the remainder of this experiment.

☐ 12. a. Vary the LOAD PRESET wheel of the Prony brake until the circular scale indicates 1 N·m [9 lbf·in]. This does not impose any torque on the motor and the current or speed should not change. You have just preset the balance to this torque.

b. Turn the LOAD wheel upwards slowly to tighten the belt over the fiction pulley. Note a gradual increase of the current. Keep turning the LOAD wheel until the hairlines in the right-hand window are aligned. The balance is now in equilibrium and is imposing a torque of 1 N·m [9 lbf·in] on the motor. (Readjust the power supply, if necessary, to maintain exactly 120 V dc).

c. Measure and record the line current and motor speed.

I = ______ A dc   Speed = ______ r/min

d. Return the voltage to zero and turn off the power supply.

REVIEW QUESTIONS

1. How can you reverse the direction of rotation of a shunt-wound DC motor?

____

____

2. Calculate the developed motor power P [horsepower] in procedure 9 (b) or 12 (c).

____

P = ______ W [hp]

3. Which torque measuring device is easier to use, the electrodynamometer of the Prony brake?

____

____

4. Where is the power (heat) dissipated in the electrodynamometer?

____

____

5. Where is the power (heat) dissipated in the Prony brake?

____

____

Experiment 3

The Wound-Rotor Induction Motor – Part I

OBJECTIVE

- To examine the construction of the three-phase wound-rotor induction motor.
- To understand exciting current, synchronous speed and slip in a three-phase induction motor.
- To observe the effect of the revolving field and rotor speed upon the voltage induced in the rotor.

DISCUSSION

You have, so far, been introduced to rotating stator fields produced by single-phase power. electric power companies normally generate and transmit three-phase power. Single-phase power for the individual home is obtained from one phase of the three-phase power lines. Three-phase (polyphase) motors are commonly used in industry and electric power companies normally supply three-phase power to industrial users.

The creation of a rotating stator field using three-phase power is similar to the principle of the split-phase or two-phase (capacitor-run) system. In the three-phase system, a rotating magnetic field is generated in three phases instead of two. When the stator of a three-phase motor is connected to a three-phase power source, courrents flow in the three stator windings and a revolving magnetic field is established. These three exciting currents supply the reactive power to establish the rotating magnetic field. They also supply the power consumed by the copper and iron losses in the motor.

The speed of the rotating magnetic field is entirely determined by the frequency of the three-phase power source, and is known as the synchronous speed. The frequency of electric power systems is accurately maintained by the electric power companies, therefore, the synchronous speed of the stator field (in r/min) remains constant. (It is, in fact, used to operate electric clocks).

The wound-rotor consists of a rotor core with the three windings in place of the conducting bars of the squirrel-cage rotor. in this case, currents are induced in the windings just as they would be in shorted turns. However, the advantage of using windings is that the wires can be brought out through slip rings so that resistance, and, therefore, the current through the windings, can be controlled.

The rotating stator field induces an alternating voltage in each winding of the rotor. When the rotor is at standstill the frequency of the induced rotor voltage is equal to that of the power source. If the rotor is now rotated by some external means, in the same direction as the rotating stator field, the rate at which the magnetic flux cuts the rotor windings will diminish. The induced voltage and its frequency will drop. When the rotor revolves at the same speed and in the same direction as the rotating stator field, the induced voltage, as well as its frequency, will drop to zero. (The rotor is now at synchronous speed.) Conversely, if the rotor is driven at synchronous speed, but in the opposite direction to the rotating stator field, the induced voltage, as well as its frequency, will be twice the value as when the rotor was at standstill.

Although the rotor will be driven by an external motor in this Experiment, it should be noted that for a given rotor speed the induced voltage value and its frequency will be the same even if the rotor were turning by itself.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

⚠ **High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!**

☐ 1. Examine the construction of the Three-Phase Wound-Rotor Induction Motor, paying particular attention to the motor, slip rings, connection terminals and the wiring.

☐ 2. Viewing the motor from the rear of the module:

   a. Identify the three rotor slip rings and brushes.

   b. Can the brushes be moved?

      ☐ Yes ☐ No

   c. Note that the three rotor windings are brought out to the three slip rings via a slot in the rotor shaft.

   d. Identify the stator windings. Note that they consist of many turns of small diameter wire evenly spaced around the stator.

   e. Identify the rotor windings. Note that they consist of many turns of slightly larger diameter wire evenly spaced around the rotor.

   f. Note the spacing of the air gap between the rotor and the stator.

☐ 3. Viewing the front face of the module:

   a. The three separate stator windings are connected to terminals _____ and _____, _____ and _____, _____ and _____.

b. What is the rated current of the stator windings? ______

c. What is the rated voltage of the stator windings? ______

d. The three rotor windings are (wye, delta) ______ connected.

e. They are connected to terminals ______, ______ and ______.

f. What is the rated voltage of the rotor windings? ______

g. What is the rated current of the rotor windings? ______

h. What is the rated speed and mechanical output power of the rotor?

Speed = ______ r/min

Power = ______ W

☐ 4. Using your DC Motor/Generator, Three-Phase Wound-Rotor Induction Motor, Three-Phase Wattmeter, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 3-1.

☐ 5. a. Note that the DC motor/generator is connected with fixed shunt field excitation to power supply terminals 8 and N, (120 V dc). The field rheostat should be turned to its full cw position (for minimum resistance).

b. Note that the armature is connected to the variable DC output of the power supply, terminals 7 and N, (0-120 V dc).

c. Note that the stator of the wound-rotor motor is wye connected, in series with three ammeters and the wattmeter to the fixed 208 V, 3φ output of the power supply, terminals 1, 2 and 3.

d. Note that the 3φ input voltage is measured by V_1 and that the 3φ rotor output voltage is measured by V_2.

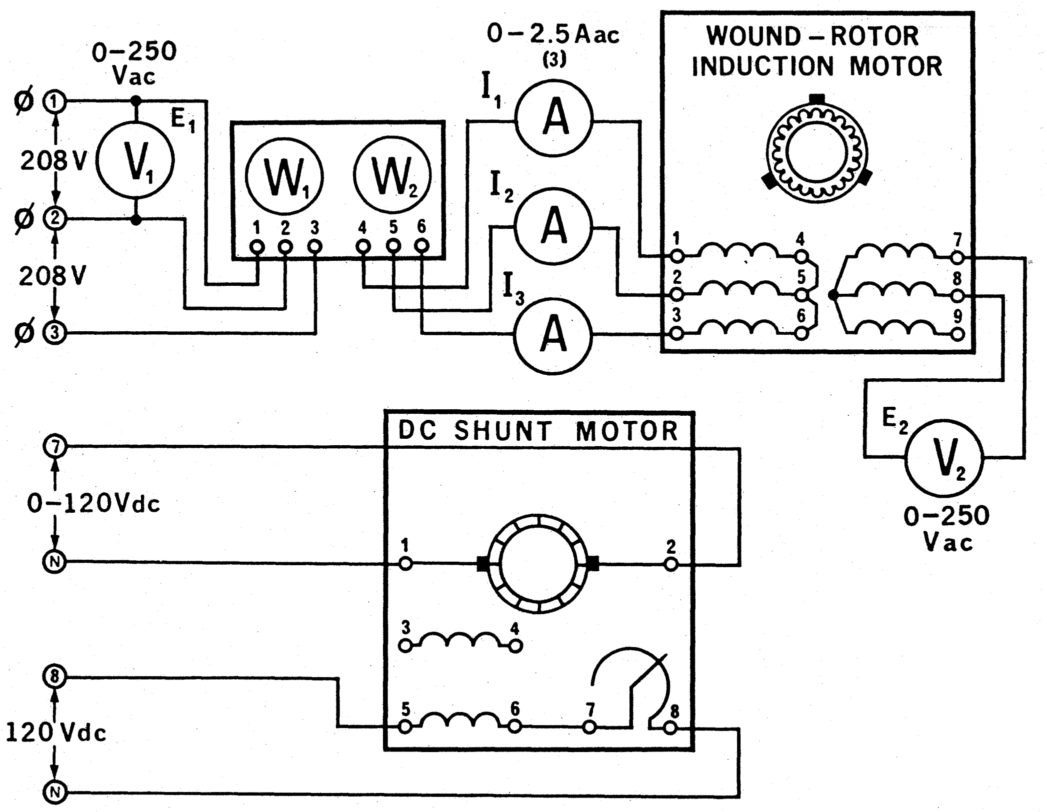


Figure 3-1.

☐ 6. a. Couple the DC motor/generator to the wound-rotor motor with the timing belt.

b. Turn on the power supply. Keep the variable output voltage control at zero (the DC motor should not be turning).

c. Measure and record the following:

E_1 = ______ V ac, W_1 = ______ W, W_2 = ______W

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

E_2 = ______ V ac

d. Turn off the power supply.

☐ 7. Calculate the following:

a. Apparent power

____

______________________________ = ______________ VA

b. Active power

____

______________________________ = ______________ W

c. Power factor

____

______________________________ = ______________

d. Reactive power

____

______________________________ = ______________ var

☐ 8. a. Turn on the power supply and adjust the variable DC output voltage for a motor speed of exactly 900 r/min.

b. Measure and record the following:

Note: *If the value of E_2 is less than in procedure 6, turn off the power supply and interchange any two of the three stator leads.*

E_1 = ______ V ac, W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

E_2 = ______ V ac

c. Is the active power approximately the same as before?

☐ Yes ☐ No

☐ 9. a. Increase the variable DC output voltage to 120 V dc and adjust the field rheostat for a motor speed of exactly 1800 r/min.

b. Measure and record the following:

E_1 = ______ V ac, W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

E_2 = ______ V ac

c. Return the voltage to zero and turn off the power supply.

d. In procedures 8 and 9 is the rotor being turned with or against the rotating stator field? Explain.

____

____

____

☐ 10. a. Interchange your DC armature connections in order to reverse the motor direction. Turn the field rheostat to its full cw position.

b. Turn on the power supply and adjust the DC output voltage for a motor speed of 900 r/min.

c. Measure and record the following:

E_1 = ______ V ac, W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

E_2 = ______ V ac

☐ 11. a. Increase the variable DC output voltage to 120 V dc and adjust the field rheostat for a motor speed of 1800 r/min.

b. Measure and record the following:

E_1 = ______ V ac, W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

E_2 = ______ V ac

c. Return the voltage the zero and turn off the power supply.

d. In procedures 10 and 11 is the rotor being turned with or against the rotating stator field? Explain.

____

____

____

REVIEW QUESTIONS

1. Knowing that the voltage induced in the rotor winding is zero when it is turning at synchronous speed, what is the synchronous speed of your motor?

Synchronous speed = ______ r/min

2. Knowing that the equation for synchronous speed is:

$N_s = 120f/P$

where: N_S = synchronous speed (r/min)
f = power line frequency (Hz)
P = number of stator poles

determine the number of poles in your motor.

____

____

____

____

____

______________________________________ = ____________ poles

3. Calculate the rotor slip (in r/min) in procedures 6, 8, 9, 10 and 11. (Slip in r/min = sync speed-rotor speed).

slip (6) = ______ r/min, slip (8) = ______ r/min

slip (9) = ______ r/min, slip (10) = ______ r/min

slip (11) = ______ r/min

4. Calculate the percent slip in procedures 6, 8, 9, 10 and 11.

slip (6) = ______ %, slip (8) = ______ %

slip (9) = ______ %, slip (10) = ______ %

slip (11) = ______ %

5. Does the value of the exciting current of your 3φ motor depend upon the rotor speed?

☐ Yes ☐ No

6. How much power is needed to produce the magnetic field in your motor?

____

____

____________________________ = ____________ var

7. How much power is needed to supply the losses associated with the production of the magnetic field?

____

____________________________ = ____________ W

8. Plot the rotor speed vs rotor voltage on the graph of Figure 3-2. Should it be a straight line?

☐ Yes ☐ No

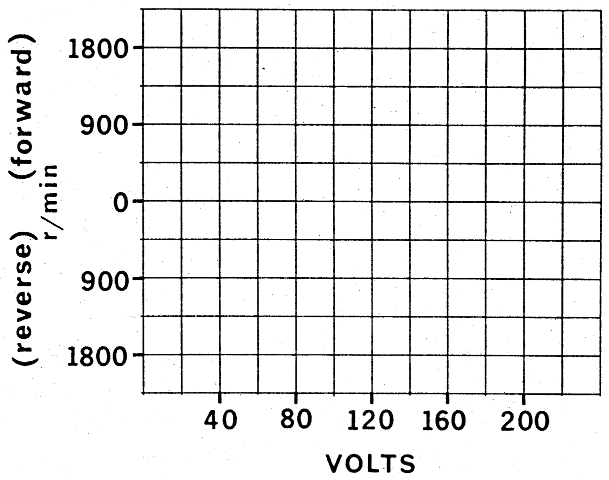


Figure 3-2.

Experiment 4

The Wound-Rotor Induction Motor – Part II

OBJECTIVE

- To determine the starting characteristics of the wound-rotor induction motor.
- To observe the rotor and stator currents at different motor speeds.

DISCUSSION

In the previous Experiment we saw that a considerable voltage appears across the rotor windings on open circuit, and that this voltage varies linearly with rotor slip in r/min, becoming zero at synchronous speed.

If the rotor windings are short-circuited, the induced voltage will cause large circulating currents in the windings. To supply this rotor current, the stator current must increase in value above its ordinary exciting current level. The power consumed (VA) in the rotor windings (and associated circuitry) must be supplied by the stator windings. Therefore, we should expect the following:

a) At standstill, or at low speed, the rotor currents, stator currents and torque will be high.

b) At synchronous speed, the rotor current and torque will be zero, and the stator will only carry the exciting current.

c) At any other motor speed, the currents and the developed torque will be between the above extremes.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Wound-Rotor Induction Motor, Electrodynamometer, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 4-1. Note that the three stator windings are connected to the variable 3φ output of the power supply, terminals 4, 5 and 6.

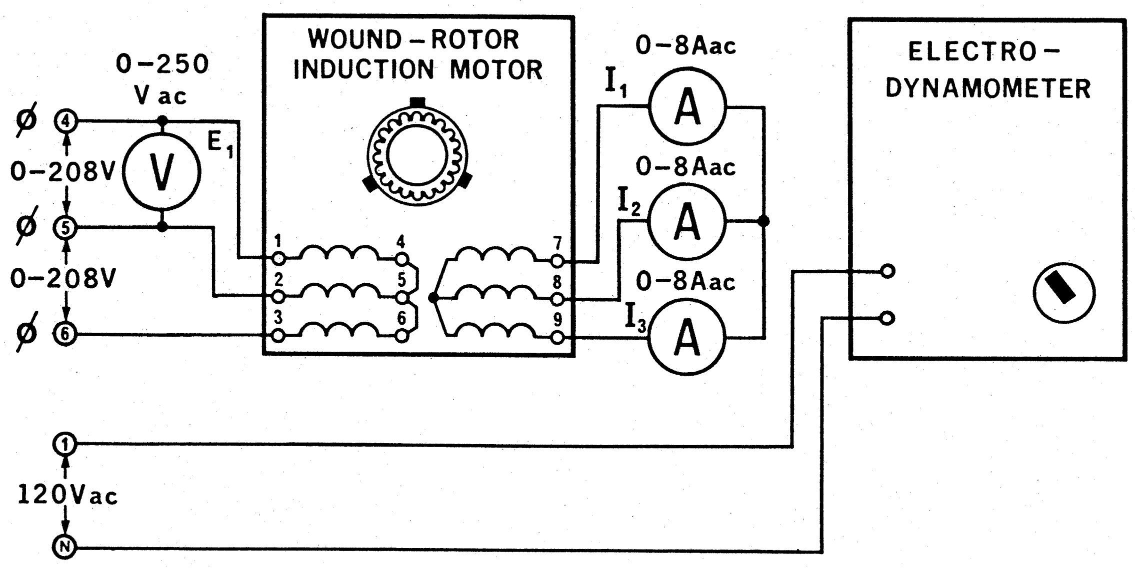


Figure 4-1.

☐ 2. a. Couple the electrodynamometer to the motor with the timing belt.

b. Connect the input terminals of the electrodynamometer to the fixed 120 V ac output of the power supply, terminals 1 and N.

c. Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the rotor).

☐ 3. a. Turn on the power supply and adjust for an E_1 of 100 V ac. The motor should be turning slowly.

b. Measure and record the three rotor currents and the developed torque.

I_1 = ______ A ac, I_2 = ______ A ac

I_3 = ______ A ac, Torque = ______ N·m [lbf·in]

c. Are the three rotor currents approximately equal?

☐ Yes ☐ No

☐ 4. a. Gradually reduce the load on the motor by slowly adjusting the dynamometer control knob. As the load is reduced the motor speed will increase.

b. Do the three rotor currents decrease as the motor speeds up?

☐ Yes ☐ No

c. Measure and record the rotor currents at a torque of 0.2 N·m [1.8 lbf·in].

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

d. Return the voltage to zero and turn off the power supply.

☐ 5. a. Connect the circuit shown in Figure 4-2. Note that the fixed 3φ output of the power supply, terminals 1, 2 and 3 are now being used.

b. Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor).

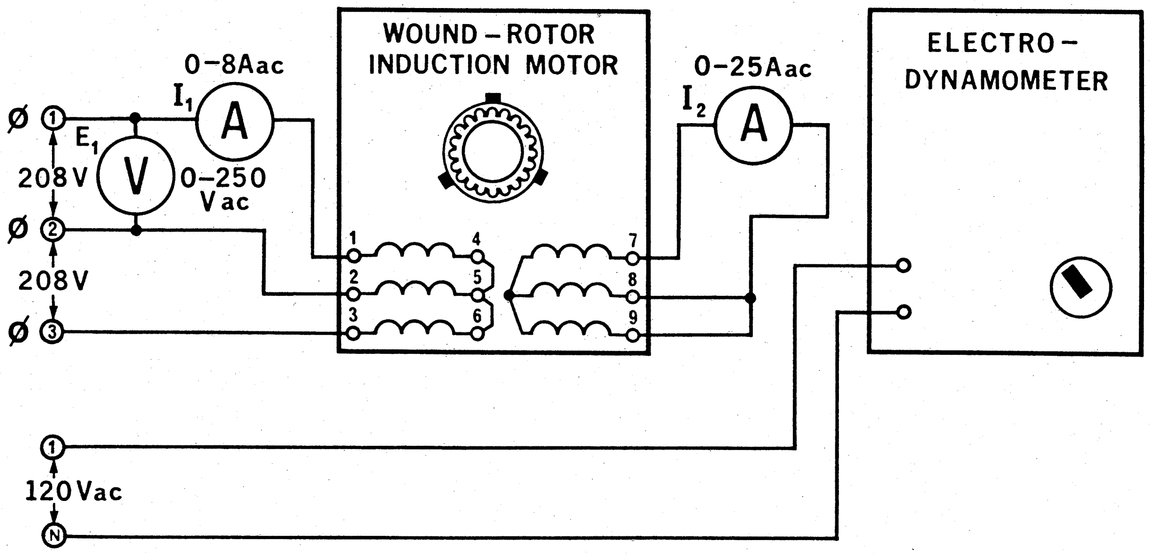


Figure 4-2.

☐ 6. a. Turn on the power supply and quickly measure E_1, I_1, I_2 and the developed starting torque. Turn off the power supply.

I_1 = ______ A ac I_2 = ______ A ac

E_1 = ______ V ac, Torque = ______ N·m [lbf·in]

b. Calculate the apparent power to the motor at starting torque.

Apparent power = ______ VA

REVIEW QUESTIONS

1. Assuming the full load 175 W [¼ hp] motor speed is 1500 r/min, calculate the value of the full load torque using the formula for output power:

$$P_{out}\ (W) = \frac{2\pi \times N \times T}{60}$$

where P_{out} = Mechanical Output Power in watts (W)
N = Speed in revolution per minute (r/min)
T = Torque in Newton·meter (N·m)

____

____

________________________________ = __________ N·m [lbf·in]

$$P_{out}\ (hp) = \frac{1.59 \times N \times T}{100\ 000}$$

where P_{out} = Mechanical Output Power in horse power (hp)
N = Speed in revolution per minute (r/min)
T = Torque in pound-force·inches (lbf·in)

2. Calculate the ratio of starting torque to full load torque:

____

____

_________________________ Torque ratio = __________________

3. Assuming that the full load stator current is 1.2 A per phase, calculate the ratio of starting current to full load operating current.

____

____

_________________________ Current ratio = __________________

4. If the stator voltage of a wound-rotor motor is reduced by approximately 50% of the rated value:

   a) By how much is the starting current reduced?

   ____

   ____

   ______________________________ = ____________ %

b) By how much is the apparent power reduced?

____

____

____ = ________________ %

c) By how much is the starting torque reduced?

____

____

____ = ________________ %

Experiment 5

The Wound-Rotor Induction Motor – Part III

OBJECTIVE

- To observe the characteristics of the wound-rotor induction motor at no-load and full-load.

- To observe speed control using an external variable resistance.

DISCUSSION

The three ends of the three-phase rotor windings are brought out to three slip rings mounted on the rotor shaft. The brushes bearing on the slip rings play an important role in realizing maximum advantage from the wound-rotor motor. By connecting the brushes through rheostats, it becomes possible to develop a higher starting torque than is possible with a squirrel-cage motor. On starting, the full resistance of the rheostats is maintained in the rotor circuit, thus providing the very maximum starting torque.

As the motor approaches normal operating speed, the rheostat resistance is gradually reduced until it is out of the circuit entirely at full speed. Although the starting torque of the wound-rotor motor is higher, it is not as efficient as the squirrel cage motor at full speed, because the resistance of the rotor windings is always more than that of a squirrel cage motor.

A special feature of the wound-rotor motor is its variable speed capability. By varying the rheostat resistance, it is possible to vary the percentage of slip and thus, vary the motor speed. In such cases, below full speed operation means the motor is running at reduced efficiency and mechanical output power. In addition, because of a high rotor resistance, the motor is made more susceptible to variation in speed as the load changes.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. a. Examine the construction of the Three-Phase Rheostat, paying particular attention to the circuit schematic diagramed on the face of the module.

b. Note that the arms of the three rheostats are separately brought out to terminals 1, 2 and 3. The remaining ends of the rheostats are wired together internally and brought out to the N terminal.

c. Note that the three rheostats are ganged together and that their individual resistances ca be varied simultaneously by turning the single control knob.

d. When the control knob is fully ccw the resistance of each rheostat is 0 Ω. When the control knob is fully cw the resistance of each rheostat is 16 Ω.

☐ 2. Using your Three-Phase Wound-Rotor Induction Motor, Electrodynamometer, Single-Phase Wattmeter, Three-Phase Rheostat, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 5-1. Do not couple the motor to the electrodynamometer at this time!

☐ 3. a. Set the speed control rheostat knob at its full ccw position for zero resistance.

b. Turn on the power supply and adjust E_1 to 208 V ac. The motor should be running.

c. Measure and record in Table 5-1, the three line currents, the two wattmeter indications (remember, to observe the polarities) and the motor speed.

d. Return the voltage to zero and turn off the power supply.

The Wound-Rotor Induction Motor – Part III

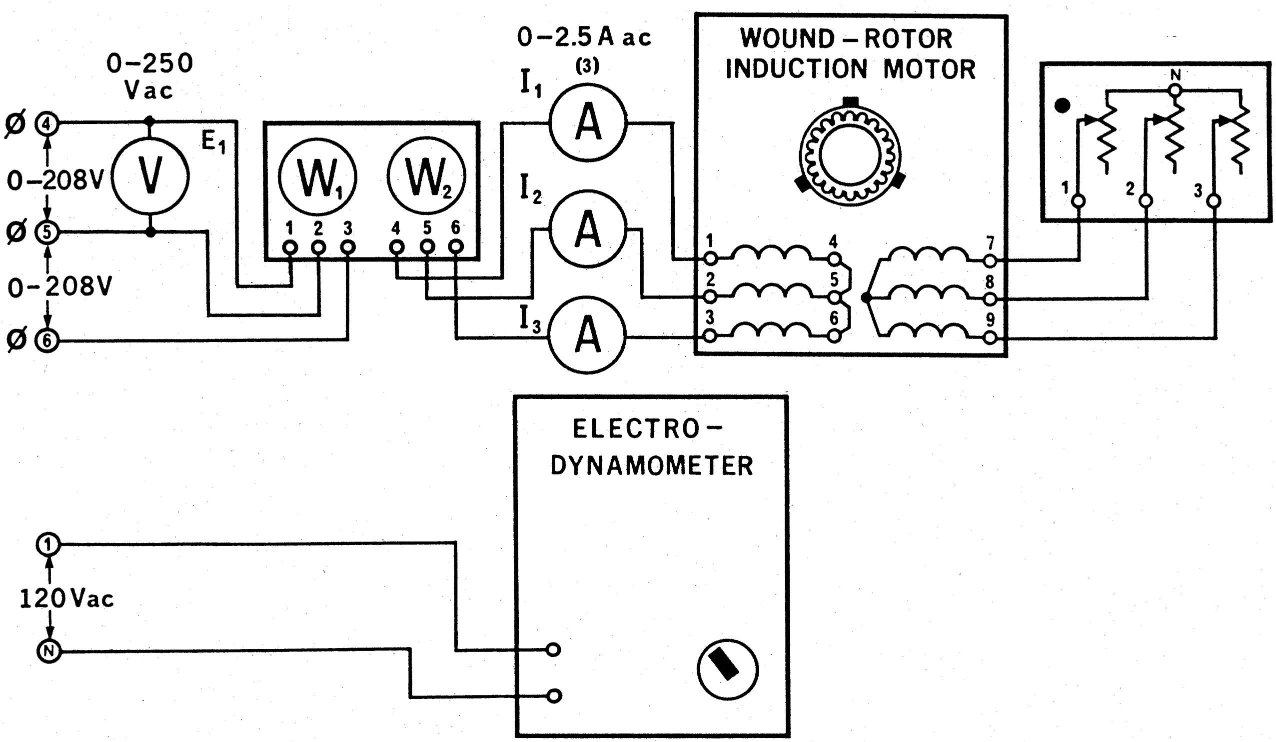


Figure 5-1.

☐ 4. a. Couple the motor to the electrodynamometer with the timing belt.

b. Set the dynamometer control knob at its full ccw position.

c. Repeat procedures 3 for each of the torques listed in Table 5-1, maintaining the input voltage at 208 V ac.

d. Return the voltage to zero and turn off the power supply.

TORQUE (N·m)	**I_1 (amps)**	**I_2 (amps)**	**I_3 (amps)**	**W_1 (watts)**	**W_2 (watts)**	**SPEED (r/min)**
0						
0.3						
0.6						
0.9						
1.2						

Table 5-1.

TORQUE (lbf·in)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
3						
6						
9						
12						

Table 5-1.

☐ 5. a. Set the speed control rheostat knob at its full cw position for maximum resistance.

b. Uncouple the motor from the electrodynamometer.

☐ 6. a. Turn on the power supply and adjust E_1 to 208 V ac. The motor should be running.

b. Measure and record in Table 5-2, the three line currents, the two wattmeter indications and the motor speed.

c. Return the voltage to zero and turn off the power supply.

TORQUE (N·m)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
0.3						
0.6						
0.9						
1.2						

Table 5-2.

TORQUE (lbf·in)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
3						
6						
9						
12						

Table 5-2.

☐ 7. a. Couple the motor to the electrodynamometer with the timing belt.

b. Set the dynamometer control knob at its full ccw position.

c. Repeat procedure 6 for each of the torques listed in Table 5-2, maintaining the input voltage at 208 V ac.

d. With a developed torque of 0.9 N·m [9 lbf·in], rotate the speed control rheostat knob from full cw to full ccw.

e. Does the motor speed change?

☐ Yes ☐ No

f. Does the developed torque change?

☐ Yes ☐ No

g. Return the voltage to zero and turn off the poser supply.

☐ 8. a. Connect the circuit shown in Figure 5-2. Note that the fixed 3φ output of the power supply, terminals 1, 2 and 3 are now being used.

b. Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor).

c. Set the speed control rheostat knob at its full cw position (to provide maximum resistance).

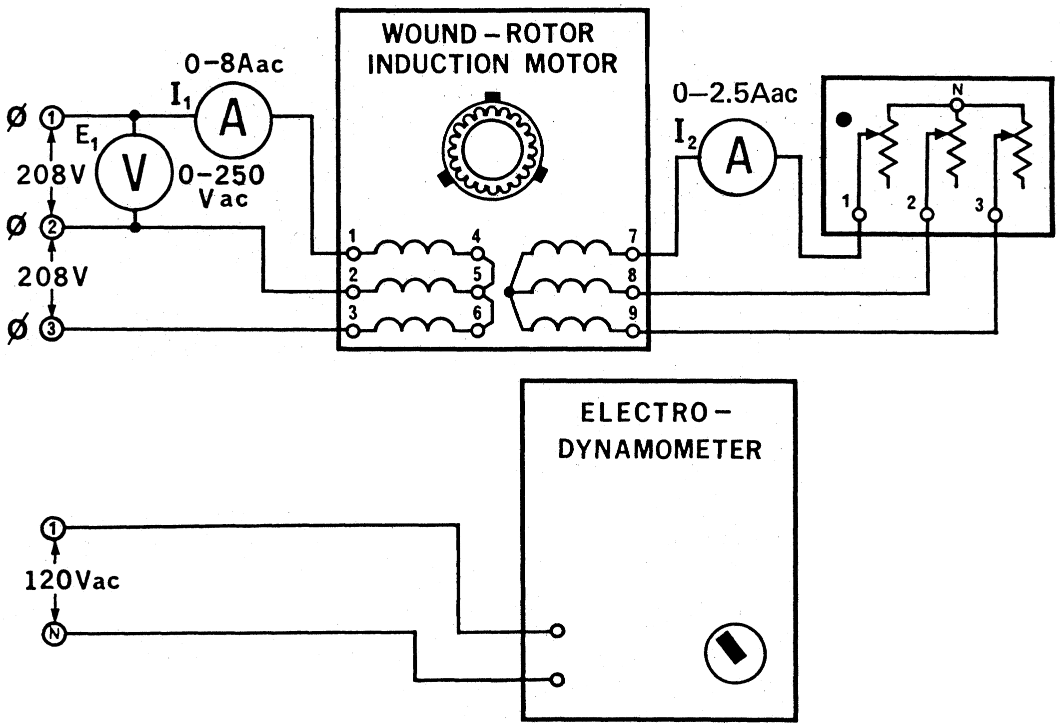


Figure 5-2.

☐ 9. a. Turn on the power supply and quickly measure E_1, I_1, I_2 and the developed starting torque. Turn off the power supply.

I_1 = ______ A ac, I_2 = ______ A ac

E_1 = ______ V ac, Torque = ______ N·m [lbf·in]

b. Calculate the apparent power to the motor at starting torque.

Apparent power = ______ VA

REVIEW QUESTIONS

1. Using the results of Table 5-1, calculate the no-load characteristics of the wound-rotor motor.

a) average current

____

______________________________ = ______________ A ac

b) apparent power

____

______________________________________ = ______________ VA

c) active power

____

______________________________________ = _______________ W

d) reactive power

____

______________________________________= ______________ var

e) power factor

____

______________________________________ = _________________

2. Using the results of Table 5-1, calculate the 0.9 N·m [9 lbf·in] characteristics of the wound-rotor motor (with 0 Ω external rotor resistance).

a) average current

____

______________________________________ = _____________ A ac

b) apparent power

____

______________________________________ = ______________ VA

c) active power

____

______________________________________ = _______________ W

d) reactive power

____

______________________________________ = ______________ var

e) power factor

____

____________________________ = ____________

f) mechanical output power

____

____________________________ = __________ W [hp]

g) efficiency

____

____________________________ = ___________ %

3. Using the results of Table 5-2, calculate the 0.9 N·m [9 lbf·in] characteristics of the wound-rotor motor (with 16 Ω external rotor resistance).

a) average current

____

____________________________ = __________ A ac

b) apparent power

____

____________________________ = ___________ VA

c) active power

____

____________________________ = ___________ W

d) reactive power

____

____________________________ = ___________ var

e) power factor

____

______________________________________ = _________________

f) mechanical output power

____

______________________________________ = ____________ W [hp]

g) efficiency

____

______________________________________ = _______________ %

4. Using the results of procedure 9 and Table 5-2, make the following ratio calculations (use the 0.9 N·m [9 lbf·in] characteristics for the full-load values).

a) starting current to full-load current

____

______________________________________ = _________________

b) starting torque to full-load torque

____

___________________________________ = ____________________

c) full load current to no-load current

____

______________________________________ = _________________

5. The efficiency of the motor is much lower when the external resistance is in the motor circuit. Explain.

____

____

____

6. The power factor improves with loading. Explain.

Experiment 6

The Squirrel-Cage Induction Motor

OBJECTIVE

- To examine the construction of the three-phase squirrel-cage motor.
- To determine its starting, no-load and full-load characteristics.

DISCUSSION

The simplest and most widely-used rotor for induction motors is the so-called squirrel-cage rotor, from which the squirrel-cage induction motor gets its name. The squirrel-cage rotor consists of a laminated iron core which is slotted lengthwise around its periphery. Solid bars of copper or aluminum are tightly pressed or embedded into the rotor slots. At both ends of the rotor, short-circuiting rings are welded or brazed to the bars to make a solid structure. The short-circuited bars, because their resistance is much less than the core, do not have to be specially insulated from the core. In some rotors the bars and end rings are cast as a single integral structure for placement on the core. The short-circuiting elements actually form shorted turns that have high currents induced in them by the stator field flux.

Compared to the intricately wound and arranged wound rotor or the armature of the DC motor, the squirrel-cage rotor is relatively simple. It is easy to manufacture and is essentially trouble-free in actual service.

In an assembled squirrel-cage induction motor, the periphery of the rotor is separated from the stator by a very small air gap. The width of this air gap, in fact, is as small as mechanical clearance needs will permit. This insures that the strongest possible electromagnetic induction action will take place.

When power is applied to the stator of a practical induction motor, a rotating magnetic field is created by any one of the means you learned about. As the field begins to revolve, its flux lines cut the shorted turns embedded around the surface of the squirrel-cage rotor and generate voltages in them by electromagnetic induction. Because these turns are short-circuits with very low resistance, the induced voltages cause high currents then produce their own strong magnetic fields. These local rotor flux fields produce their own magnetic poles, which are attracted to the rotating field. Thus, the rotor revolves with the main field.

The starting torque of the basic squirrel-cage induction motor is low, because at rest the rotor has a relatively large inductive reactance (X_L) with respect to its resistance (R). Under these conditions we would expect the rotor current to lag rotor voltage by 90°. We thus say that the power factor in the circuit is low. This means that the motor is inefficient as a load and cannot derive really useful energy for its operation from the power source.

Despite the inefficiency, torque is developed and the motor begins to turn. As it starts turning, the difference in speed between rotor and rotating field, or slip, goes from a maximum of 100% to some intermediate value, say 50%. As the slip decreases in this manner, the frequency of the voltage induced in the rotor decreases, because the rotating field cuts conductors at a decreased rate; this in turn, causes the overall inductive reactance in the circuit to decrease. As inductive reactance decreases, the power factor begins to increase. This improvement is reflected as an increase in torque and a subsequent increase in speed.

When the slip drops to some value between 2 and 10%, the motor speed stabilizes. This stabilization occurs because every tendency for the motor speed to increase to where slip will drop below 2% is naturally offset by the fact that, as the rotor approaches within 2" of the synchronous speed, the effects of reduced induction overcome the previous tendency to increase torque as the motor is speeded up from start-up. Thus, the motor exhibits an automatic speed control characteristics similar to that of the DC shunt motor.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Examine the construction of the Four-Pole Squirrel-Cage Induction Motor, paying particular attention to the motor, connection terminals and the wiring.

☐ 2. a. Identify the stator windings. Note that they consist of many turns of small diameter wire evenly spaced around the stator. (The stator windings are identical to that of the wound rotor induction motors).

b. Identify the cooling fan.

c. Identify the end rings of the squirrel-cage rotor.

d. Note the length of the air gap between the stator and the rotor.

e. Is there any electrical connection between the rotor and any other part of the motor?

☐ Yes ☐ No

☐ 3. Viewing the front face of the module:

a. The three separate stator windings are connected to terminals _____ and _____, _____ and _____, _____ and _____.

b. What is the rated current of the stator windings? _____

c. What is the rated voltages of the stator windings? _____

d. What is the rated speed and mechanical output power of the motor?

Speed = _____ r/min

Power = _____ W

☐ 4. Using your Four-Pole Squirrel-Cage Induction Motor, Electrodynamometer, Three-Phase Wattmeter, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 6-1. Do not couple the motor to the dynamometer at this time! Note that the stator windings are wye-connected through the wattmeter to the variable 3φ output of the power supply, terminals 4, 5 and 6.

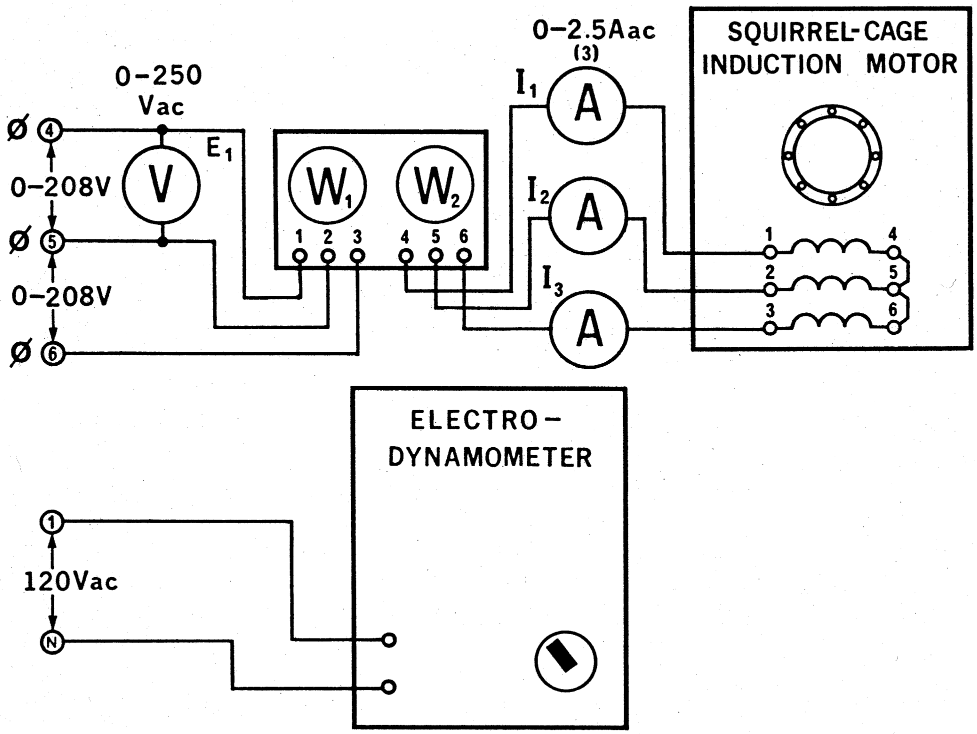


Figure 6-1.

☐ 5. a. Turn on the power supply and adjust E_1 to 208 V ac. The motor should be running.

b. Measure and record in Table 6-1, the three line currents, the two wattmeter indications, and the motor speed.

c. Return the voltage to zero and turn off the power supply.

TORQUE (N·m)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
0.3						
0.6						
0.9						
1.2						

Table 6-1.

TORQUE (lbf·in)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
3						
6						
9						
12						

Table 6-1.

☐ 6. a. Couple the motor to the electrodynamometer with the timing belt.

b. Set the dynamometer control knob at its full ccw position.

c. Repeat procedure 5 for each of the torques listed in Table 6-1, maintaining the input voltage at 208 V ac.

d. Return the voltage to zero and turn off the power supply.

☐ 7. a. Connect the circuit shown in Figure 6-2. Note that the fixed 3φ output of the power supply, terminals 1, 2 and 3 is now being used.

b. Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor.

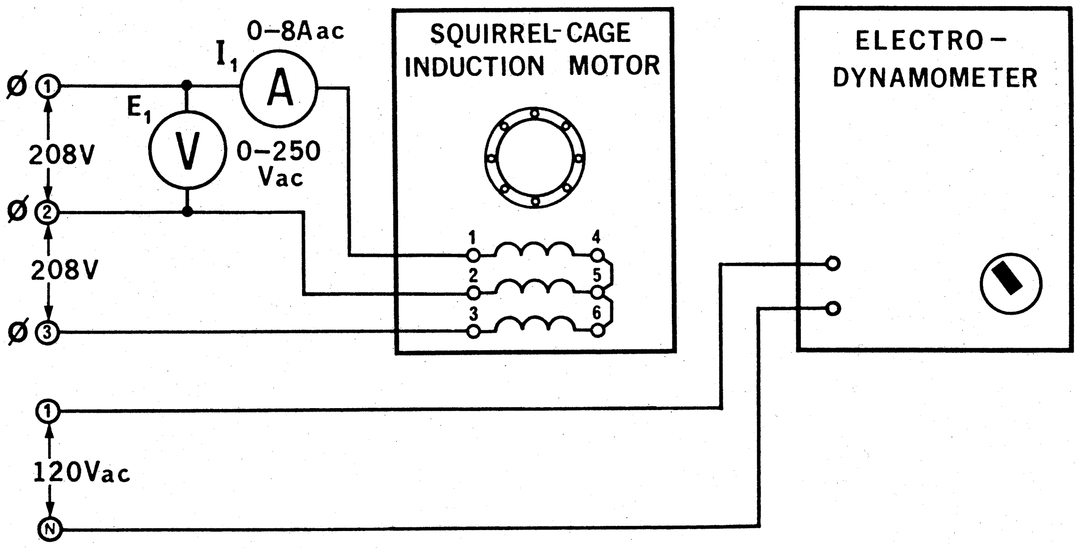


Figure 6-2.

☐ 8. a. Turn on the power supply and quickly measure E_1, I_1 and the developed starting torque.

E_1 = ______ V ac, I_1 = ______ A ac

Starting torque = ______ N·m [lbf·in]

b. Calculate the apparent power to the motor at starting torque.

Apparent power = ______ VA

REVIEW QUESTIONS

1. Using the result of Table 6-1, calculate the no load characteristics of the squirrel-cage motor.

a) average current

____

______________________________ = ____________ A ac

b) apparent power

____

______________________________ = ____________ VA

c) active power

____

__________________________________ = ______________ W

d) reactive power

____

__________________________________ = ______________ var

e) power factor

____

__________________________________ = ________________

2. Using the results of Table 6-1, calculate the 1.2 N·m [9 lbf·in] characteristics of the squirrel-cage motor.

a) average current

____

__________________________________ = ______________ A ac

b) apparent power

____

__________________________________ = ______________ VA

c) active power

____

__________________________________ = ______________ W

d) reactive power

____

__________________________________ = ______________ var

e) power factor

____

____________________________ = ____________

f) mechanical output power

____

____________________________ = __________ W [hp]

g) efficiency

____

____________________________ = ____________ %

3. Using the results of procedure 8 and Table 6-1, make the following ratio calculations (use the 1.2 N·m [9 lbf·in] characteristics as the full-load values).

a) starting current to full-load current

____

____________________ / ____________________

b) starting torque to full-load torque

____

____________________ / ____________________

c) full-load current to no-load current

____

____________________ / ____________________

4. Compare the operating characteristics of the squirrel-cage motor to the wound rotor motor.

____

____

____

____

5. The squirrel-cage induction motor is one of the most reliable machines used in industry. Explain.

____

____

____

____

6. If the power line frequency were 50 Hz:

a) At what speed would the motor run?

____

______________________________ = ______________

b) Would the exciting current increase, decrease of remain the same?

____

Experiment 7

The Synchronous Motor – Part I

OBJECTIVE

- To examine the construction of the 3φ synchronous motor.
- To obtain the starting characteristics of the 3φ synchronous motor.

DISCUSSION

The synchronous motor gets its name from the term synchronous speed, which is the natural speed of the rotating magnetic field of the stator. As you have learned, this natural speed of rotation is controlled strictly by the number of pole pairs and the frequency of the applied power.

Like the induction motor, the synchronous motor makes use of the rotating magnetic field. Unlike the induction motor, however, the torque developed does not depend on the induction currents in the rotor. Briefly, the principle of operation of the synchronous motor is as follows. A multiphase source of AC is applied to the stator windings and a rotating magnetic field is produced. A direct current is applied to the rotor windings and a fixed magnetic field is produced. The motor is so constructed that these two magnetic fields react upon each other causing the rotor to rotate at the same speed as the rotating magnetic field. If a load is applied to the rotor shaft, the rotor will momentarily fall behind the rotating field but will continue to rotate at the same synchronous speed.

The falling behind is analogous to the rotor being tied to the rotating field with a rubber band. Heavier loads will cause stretching of the band so the rotor position lags the stator field but the rotor continues at the same speed. If the load is made too large, the rotor will pull out of synchronism with the rotating field and, as a result, will no longer rotate at the same speed. The motor is then said to be overloaded.

The synchronous motor is not a self-starting motor. The rotor is heavy and, from a dead stop, it is not possible to bring the rotor into magnetic lock with the rotating magnetic field. For this reason, all synchronous motors have some kind of starting device. A simple starter is another motor which brings the rotor up to approximately 90% of its synchronous speed. The starting motor is then disconnected and the rotor locks in step with the rotating field. The more commonly used starting method is to have the rotor include a squirrel cage induction winding. This induction winding brings the rotor almost to synchronous speed as an induction motor. The squirrel-cage is also useful even after the motor has attained synchronous speed, because it tends to dampen rotor oscillations caused by sudden changes in loading. Your Three-Phase Synchronous Motor/Generator contains a squirrel-cage-type rotor.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Examine the construction of the Three-Phase Synchronous Motor/Generator, paying particular attention to the motor, slip rings, rheostat, connection terminals and the wiring.

☐ 2. Viewing the motor from the rear of the module:

a. Identify the two slip rings and brushes.

b. Can the brushes be moved?

☐ Yes ☐ No

c. Note that the two rotor windings are brought out to the two slip rings via a slot in the rotor shaft.

d. Identify the DC damper windings on the rotor. (Although there are only two windings, they are connected so that their magnetomotive forces act in opposition, thus, creating four poles.

e. Identify the four salient poles just beneath the damper windings.

f. Identify the stator winding and note that it is identical to that of the three-phase squirrel cage and wound rotor motors.

☐ 3. Viewing the front face of the module:

a. The three separate stator windings are connected to terminals ______ and ______, ______ and ______, ______ and ______.

b. What is the rated voltage of the stator windings? ______

c. What is the rated current of the stator windings? ______

d. The rotor winding is connected through the 208 Ω rheostat (and a toggle switch S) to terminals ______ and ______.

e. What is the rated voltage of the rotor winding? ______

f. What is the rated speed and mechanical output power of the motor?

Speed = ______ r/min

Power = ______ W

Starting Characteristics

☐ 4. Using your Three-Phase Synchronous Motor/Generator, Power Supply and AC Ammeter, connect the circuit shown in Figure 7-1. Note that the three stator windings are wye-connected to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3.

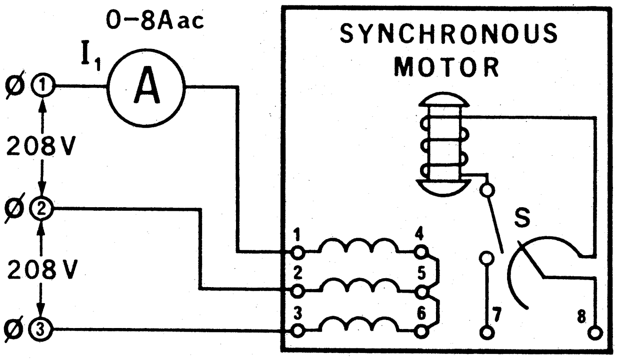


Figure 7-1.

☐ 5. a. Turn on the power supply. Note that the motor starts smoothly and continues to run as an ordinary induction motor.

b. Note the direction of rotation.

Rotation = ______, I_1 = ______ A ac

c. Turn off the power supply and interchange any two of the leads from the power supply.

d. Turn on the power supply and note the direction of rotation.

Rotation = ______, I_1 = ______ A ac

e. Turn off the power supply.

☐ 6. Using your Electrodynamometer and Synchronizing Module, connect the circuit shown in Figure 7-2. Couple the motor to the electrodynamometer with the timing belt.

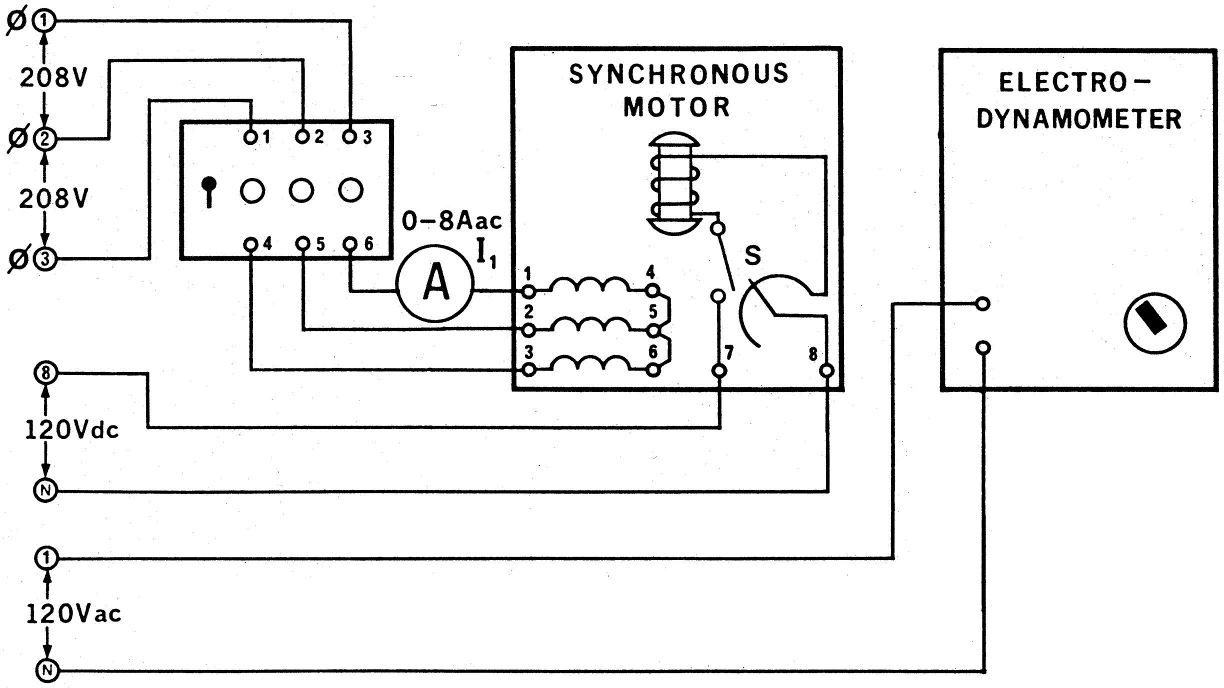


Figure 7-2.

☐ 7. a. The synchronizing module will be used as an on-off switch for the 3φ power to the stator windings. Set the switch in its off position.

b. The electrodynamometer is connected to the fixed 120 V ac output of the power supply, terminals 1 and N. Set the dynamometer control knob for approximately 40% excitation.

c. The rotor of the synchronous motor is connected to the fixed 120 V dc output of the power supply, terminals 8 and N. Set the field rheostat for zero resistance (control knob turned fully cw) and close the switch S.

☐ 8. a. Turn on the power supply. Then apply 3φ power by closing the synchronizing switch and observe what happens. *Do not leave the power on for longer than 10 seconds!*

b. Describe what happened.

____

____

____

c. What did the ammeter indicate?

d. Should a synchronous motor, under load, be started with DC excitation on its field?

☐ Yes ☐ No

☐ 9. a. Connect the rotor of the synchronous motor to the variable 0-120 V dc output of the power supply, terminals 7 and N. Do not disturb any of the other connections or change any control settings.

b. With the variable output voltage control at zero, turn on the power supply. Apply 3φ power by closing the synchronizing switch and observe what happens.

c. Describe what happened.

d. Is your motor operating as an induction motor?

☐ Yes ☐ No

e. Carefully adjust the power supply output to 120 V dc as indicated on the power supply meter.

f. Describe what happened.

g. Is your motor operating as a synchronous motor?

☐ Yes ☐ No

h. Return the voltage to zero and turn off the power supply.

☐ 10. a. Connect the circuit shown in Figure 7-3. Note that the synchronous motor is wired in its normal starting configuration (as a three-phase squirrel-cage induction motor).

b. Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the synchronous motor).

c. Close the switch S.

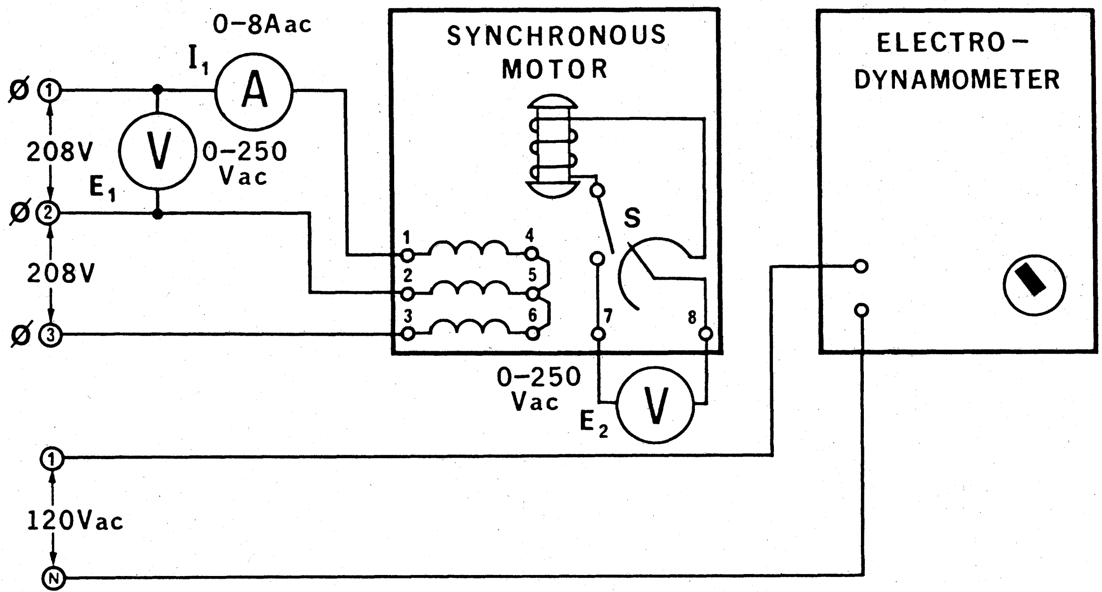


Figure 7-3.

☐ 11. a. Turn on the power supply and quickly measure E_1, E_2, I_1 and the developed starting torque. Turn off the power supply.

E_1 = ______ V ac, E_2 = ______ V ac, I_1 = ______ A ac,

Starting torque = ______ N·m [lbf·in]

b. Calculate the apparent power to the motor at starting torque.

Apparent power = ______ VA

c. Calculate the full-load torque corresponding to 175 W at 1800 r/min.

Full-load torque = ______ N·m [lbf·in]

d. Calculate the ratio of starting torque to full-load torque.

Ratio = ______

e. Explain why a large AC voltage E_2 was induced in the rotor windings.

____

____

☐ 12. With your circuit unchanged, turn on the power supply and slowly turn the dynamometer control knob ccw to reduce the loading. The motor will come up to full speed and run as a squirrel-cage induction motor. Note the effect upon the induced voltage E_2.

Why does E_2 decrease as the motor speed increases?

____

REVIEW QUESTIONS

1. What precautions should be taken during the start-up period of a synchronous motor?

____

____

2. If the squirrel-cage winding were removed from a synchronous motor, could it start by itself?

☐ Yes ☐ No

3. State two reasons why the rotor winding of a synchronous motor is usually connected to an external resistance during start-up.

a) ____

____

b) ____

____

4. Compare the starting characteristics of the synchronous motor with those of the three-phase squirrel-cage induction motor (Experiment 6).

____

____

Experiment 8

The Synchronous Motor – Part II

OBJECTIVE

- To observe how a synchronous motor can act as a variable inductance or capacitance.
- To obtain the DC current vs AC current characteristics curve for the synchronous motor.

DISCUSSION

You have learned that positive reactive power is needed to create the magnetic field in an alternating current motor. This reactive power has the disadvantage of producing a low power factor. Low power factors are undesirable for several reasons. Generators, transformers, and supply circuits are limited in ratings by their current carrying capacities. This means that the kilowatt load that they can deliver is directly proportional to the power factor of the loads that they supply. For example, a system can deliver only 70% of the kilowatt load at 0.7 power factor that it can deliver at unity power factor.

The synchronous motor requires considerable reactive power when it operates at no-load without any DC excitation to the rotor. It acts like a three-phase inductance load on the power line. When the rotor is excited, it will produce some of the magnetism in the motor with the result that the stator has to supply less, and the reactive power drawn from the power line decreases. If the rotor is excited until it produces all the magnetism, the power line will only have to supply active power to the stator, and the power factor will be unity. As far as the power line is concerned, the synchronous motor now looks like a three-phase resistance load.

If the rotor is excited still further, tending to create more magnetism than the motor needs, then the power line starts supplying negative reactive power to the stator in its attempt to keep the total flux constant. But negative reactive power corresponds to a capacitor, and the synchronous motor now looks like a three-phase capacitance load to the power line.

At no-load, the synchronous motor has the property of acting like a variable inductor/variable capacitor, the value of reactance (X_L or X_C) being determined by the amount of DC current flowing in the rotor.

A synchronous motor when used on the same power system with induction motors improves the overall system power factor.

The Synchronous Motor – Part II

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. a. Using your Three-Phase Synchronous Motor/Generator, Single-Phase Wattmeter, Power Supply, AC Ammeter, AC Voltmeter and DC Voltmeter/Ammeter, connect the circuit shown in Figure 8-1. Note that the stator windings are connected, through the wattmeter, to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3. The rotor winding is connected, through the ammeter, to the variable 0-120 V dc output of the power supply, terminals 7 and N. The voltage adjust control knob should be at zero.

b. Open the switch S and set the field rheostat for zero resistance (knob turned fully cw).

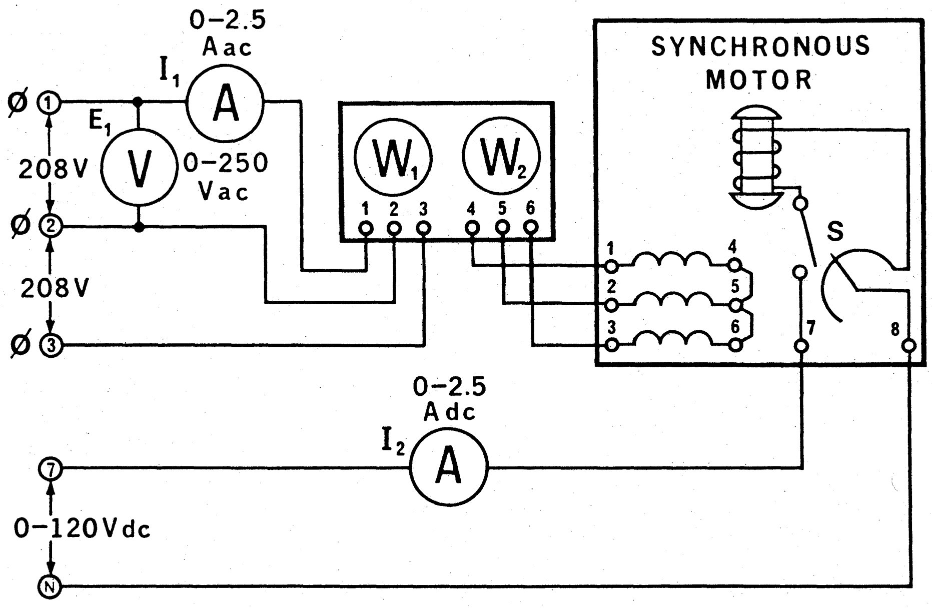


Figure 8-1.

☐ 2. a. Turn on the power supply; the motor should be running. Note the value of AC current I_1. The motor is drawing positive reactive power from the power supply at zero DC excitation and looks like an inductor.

b. Close the switch S and gradually increase the DC excitation until the AC current I_1 is at its minimum value. Both wattmeters should have equal positive indications, and, as far as the power supply is concerned, the motor looks like a resistor.

c. Note I_1, I_2, W_1 and W_2.

I_1 min = ______ A ac I_2 = ______ A dc

W_1 = ______ W W_2 = ______ W

d. Increase the DC excitation and note that the AC current I_1 begins to increase again. The motor is drawing negative reactive power from the power supply and looks like a capacitor.

☐ 3. a. With the DC excitation at zero, measure and record E_1, I_1, W_1 and W_2 in Table 8-1.

b. Repeat for each of the DC current values listed in Table 8-1. Take your measurements as quickly as possible when the excitation exceeds 0.6 A dc. Turn off the power supply and change ammeter ranges when the currents drop below 0.5 A dc. Remember to note the polarity of the wattmeter indications.

c. Return the voltage to zero and turn off the power supply.

☐ 4. Complete Table 8-1 by calculating apparent power (remember to multiply by 1.73) active power and power factor for each of the DC currents listed.

☐ 5. a. From the results of Table 8-1, calculate the reactive power at zero DC rotor current.

____ Q = ______ var

b. Is the power factor leading or lagging?

____

I_2 (amps)	E_1 (volts)	I_1 (amps)	POWER (VA)	W_1	W_2	POWER (watts)	PF
0							
0.1							
0.2							
0.3							
0.4							
0.5							
0.6							
0.7							
0.8							
0.9							

Table 8-1.

☐ 6. a. From the results of Table 8-1, calculate the reactive power at maximum DC rotor current.

____ Q = ______ var

b. Is the power factor leading or lagging?

____

☐ 7. From the results of Table 8-1, calculate the reactive power at minimal stator current.

____ Q = ______ var

REVIEW QUESTIONS

1. a) Plot the recorded AC current values vs DC current values from Table 8-1 on the graph of Figure 8-2.

   b) Draw a smooth curve through your plotted points.

   c) Plot the recorded power factors vs DC current values from Table 8-1 on the graph of Figure 8-2.

   d) Draw a smooth curve through your plotted points.

e) Comment on the appearance of both curves.

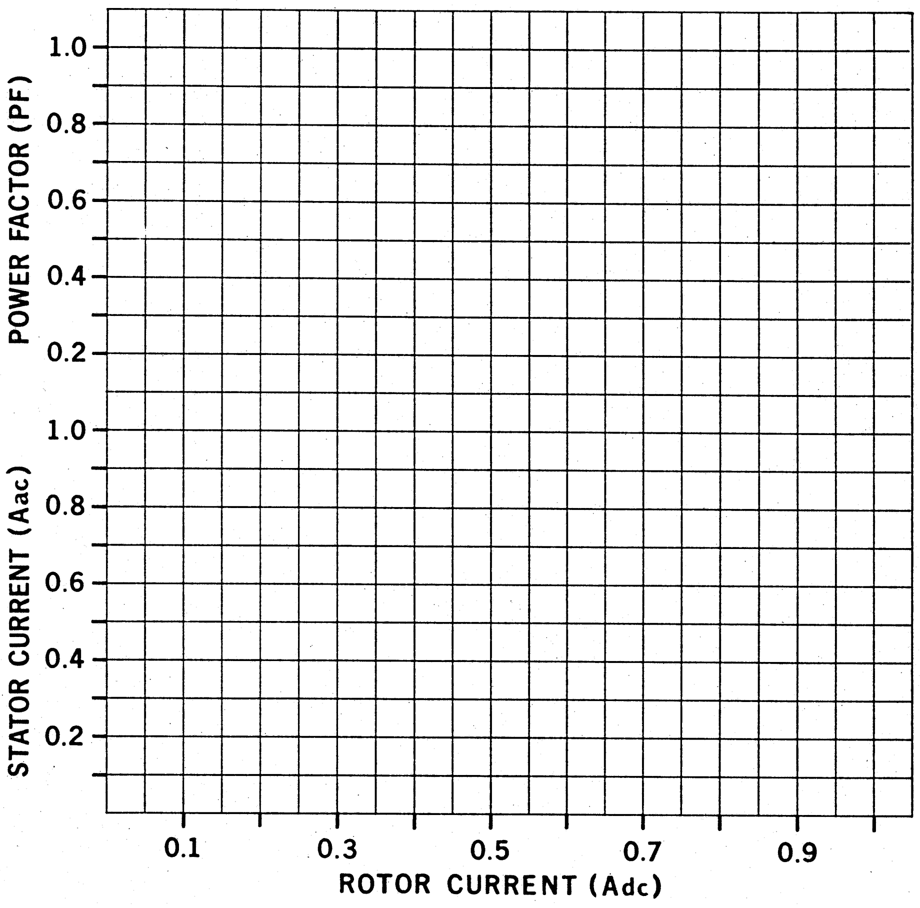


Figure 8-2.

2. A synchronous motor is sometimes called synchronous capacitor. Explain.

3. Might a synchronous motor equally well be called a synchronous inductor?

☐ Yes ☐ No

4. Comment on the active power consumed by the motor during procedure 3.

Experiment 9

The Synchronous Motor – Part III

OBJECTIVE

- To determine the full-load characteristics of the synchronous motor.
- To determine the pull-out torque of the synchronous motor.

DISCUSSION

Just as it was possible to vary the power factor of the synchronous motor at no-load, it is possible to vary it under full-load condition. Although the power factor is normally held close to 100%, the synchronous motor may be over-excited with direct current so as to improve the overall power factor of a large electrical system.

When operated on the same electrical power system with induction motors or other devices that operate at lagging power factors, the leading reactive kilovars, supplied by the synchronous motors compensate for the lagging kilovars, of the induction motors or other devices, resulting in an improvement in the overall electrical system's power factor.

Synchronous motors, like induction motors, may be temporarily overloaded. However, unlike the induction motor, the synchronous motor will maintain constant speed under overload conditions up to a certain point. This maximum overload point depends on the DC rotor excitation. Beyond this overload point the rotor poles will "unlock" from the revolving stator field and the rotor will fall out of synchronism. This overload point is called the pull-out torque of the motor. If it were not for the squirrel-cage windings, it would cease to develop any torque at all, and consequently, come to a quick stop. A synchronous motor which has been pulled out of synchronism should be disconnected from the power line as quickly as possible.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Synchronous Motor/Generator, Single-Phase Wattmeter, Electrodynamometer, Power Supply, AC Ammeter, AC Voltmeter and DC Voltmeter/Ammeter, connect the circuit shown in Figure 9-1. Note that the stator windings are connected to the variable three-phase output of the power supply, terminals 4, 5 and 6 and that the rotor winding is connected to the fixed DC output of the power supply, terminals 8 and N.

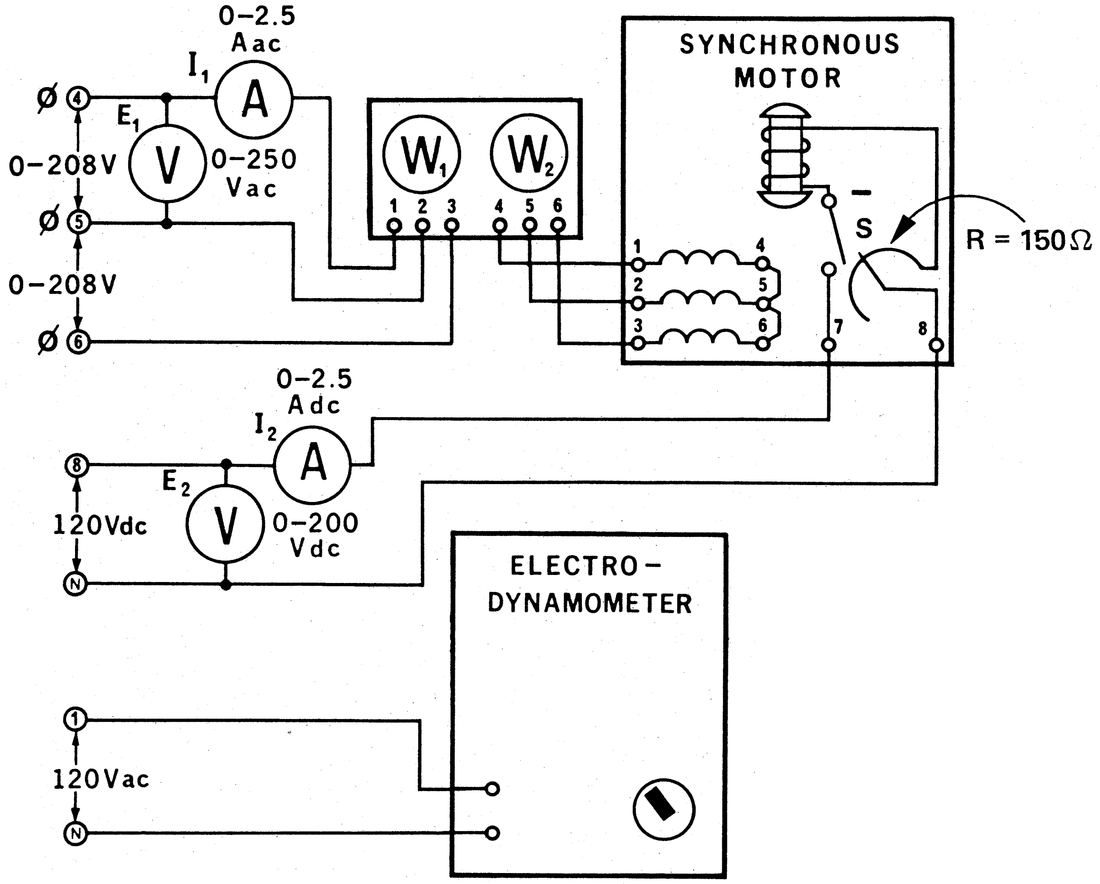


Figure 9-1.

☐ 2. a. Couple the motor to the electrodynamometer with the timing belt.

b. Set the dynamometer control knob at its full ccw position.

c. Set the synchronous motor rheostat at its full ccw position for maximum resistance, keep the switch S open.

d. Turn on the power supply and quickly adjust E_1 to 208 V ac as indicated by the voltmeter. The motor should be running.

☐ 3. a. Close the switch S.

b. Gradually increase the torque to 1.1 N·m [9 lbf·in] while varying the DC excitation until the indications on both wattmeters are equal. This corresponds to unity power factor. (I_1 should also be at its minimum value).

c. Measure and record I_1, I_2, E_1, E_2, W_1 and W_2.

I_1 = ______ A ac, I_2 = ______ A dc, E_1 = ______ V ac

E_1 = ______ V ac W_1 = ______ W, W_2 = ______ W

☐ 4. Without changing the DC excitation of procedure 3, gradually increase the loading until the motor falls out of synchronization. Record the torque required and turn off the power supply.

Pull-out torque = ______ N·m [lbf·in]

☐ 5. a. Repeat procedures 2 and 3 but this time, increase the DC excitation to 0.8 A dc while maintaining a torque of 1.1 N·m [9 lbf·in].

b. Measure and record I_1, I_2, E_1, E_2, W_1 and W_2.

I_1 = ______ A ac, I_2 = ______ A dc, E_1 = ______ V ac

E_1 = ______ V ac W_1 = ______ W, W_2 = ______ W

c. Explain why I_1 increased in value.

____

____

d. Is the power factor leading or lagging?

____

☐ 6. Determine the pull-out torque with 0.8 A dc excitation. Turn off the power supply.

Pull-out torque = ______ N·m [lbf·in]

REVIEW QUESTIONS

1. Using the results from procedure 3, calculate the 1.1 N·m [9 lbf·in] characteristics of the synchronous motor.

   a) apparent power

   ____

   ______________________________ = ___________ VA

   b) active power

   ____

   ______________________________ = ___________ W

   c) reactive power

   ____

   ______________________________ = ___________ var

   d) power factor

   ____

   ______________________________ = ___________

   e) DC power

   ____

   ______________________________ = ___________

   f) mechanical output power

   ____

   ______________________________ = _________ W [hp]

   g) efficiency

   ____

   ______________________________ = ___________ %

2. Calculate the ratio of pull-out torque (procedure 3) to full-load torque.

   ____

   ______________________ / ______________________

3. Using the results from procedure 5, calculate the 1.1 N·m [9 lbf·in] characteristics (with over excited rotor) of the synchronous motor.

   a) apparent power

   ____

   ______________________________ = ____________ VA

   b) active power

   ____

   ______________________________ = ____________ W

   c) reactive power

   ____

   ______________________________ = ____________ var

   d) power factor

   ____

   ______________________________ = ______________

   e) DC power

   ____

   ______________________________ = ____________ W

   f) mechanical output power

   ____

   ______________________________ = __________ W [hp]

4. Is the reactive power in Question 3 positive or negative?

   ____

5. The pull-out torque is affected by the degree of DC excitation. Explain.

Experiment 10

The Three-Phase Alternator

OBJECTIVE

- To obtain the no-load saturation curve of the alternator.
- To obtain the short-circuit characteristics of the alternator.

DISCUSSION

The terms alternating current generator, synchronous generator, synchronous alternator, and alternator are commonly used interchangeably in engineering literature. Because synchronous generators are so much more commonly used than induction generators, the term alternator, as often used, and as used here, applies only to synchronous generators.

Alternators are, by far, the most important source of electric energy. Alternators generate an AC voltage whose frequency depends entirely upon the speed of rotation. The generated voltage value depends upon the speed, the DC field excitation and the power factor of the load.

As the DC field excitation of an alternator is increased, its speed being held constant, the magnetic flux, and hence, the output voltage, will also increase in direct proportion to the current. However, with progressive increases in DC field current, the flux will eventually reach a high enough value to saturate the iron in the alternator.

Saturation in the iron means that there will be a smaller increase in flux for a given increase in DC field current. Because the generated voltage is directly related to the magnetic flux intensity, it can be used as a measure of the degree of saturation.

The three phases of the alternator are mechanically spaced at equal intervals from each other, and therefore, the respective generated voltages are not in phase, but are displaced from each other by 120 electrical degrees.

When an alternator delivering full rated output voltage is suddenly subjected to a short-circuit, very large currents will initially flow. However, these large short-circuit currents drop off rapidly to save values if the short-circuit is maintained.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Synchronous Motor/Generator, Four-Pole Squirrel-Cage Induction Motor, Power Supply, AC Voltmeter and DCVoltmeter/Ammeter, connect the circuit shown in Figure 10-1. The squirrel-cage motor will be used to drive the synchronous motor/generator as an alternator. Its speed will be assumed constant during this Experiment. Note that the squirrel-cage motor is connected to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3. The rotor of the alternator is connected to the variable 0-120 output of the power supply, terminals 7 and N.

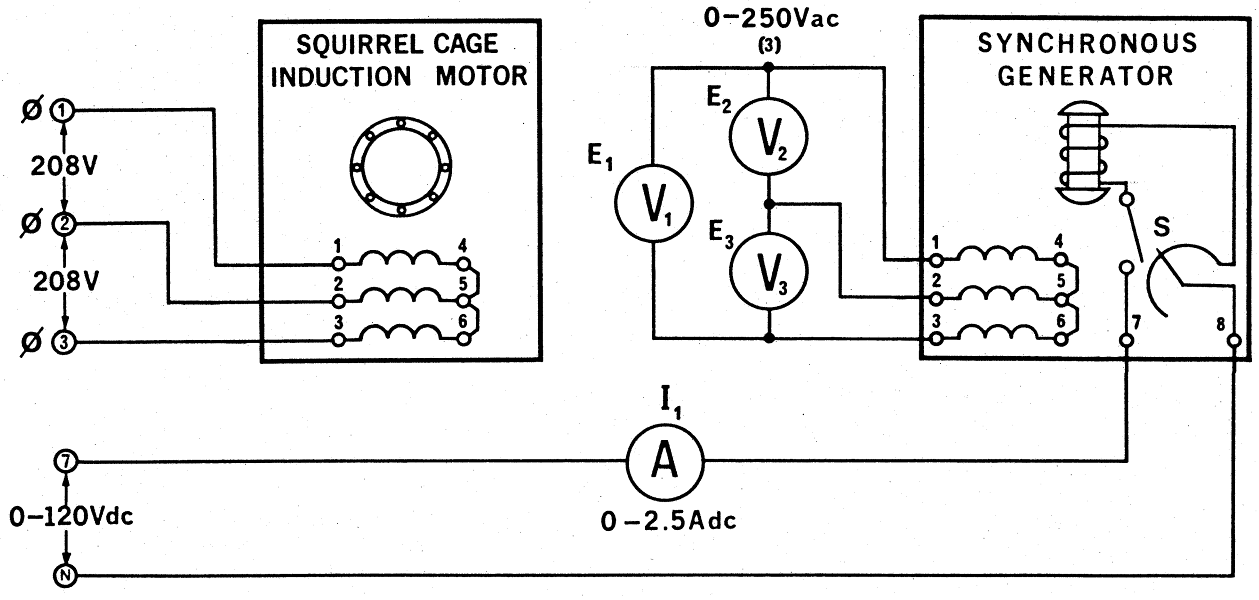


Figure 10-1.

☐ 2. a. Couple the squirrel-cage motor to the alternator with the timing belt.

b. Set the alternator field rheostat at its full cw position (for zero resistance). Open switch S.

c. Set the power supply voltage control at its full ccw position (for zero DC voltage).

☐ 3. a. Turn on the power supply. The motor should be running.

b. With zero DC excitation measure and record E_1, E_2, and E_3 (use the lowest ranges of the voltmeters).

E_1 = ______ V ac, E_2 = ______ V ac, E_3 = ______ V ac

c. Explain why there is an AC voltage generated in the absence of DC excitation.

____

____

☐ 4. a. Close the switch S.

b. Gradually increase the DC excitation from zero to 0.1 A dc.

c. Measure and record in Table 10-1 the three generated voltages E_1, E_2 and E_3.

d. Repeat (b) for each of the DC current listed in Table 10-1.

e. Return the voltage to zero and turn off the power supply.

I_1 (amps)	E_1 (volts)	E_2 (volts)	E_3 (volts)	E_{ac} (avg.)
0				
0.1				
0.2				
0.3				
0.4				
0.5				
0.6				
0.7				
0.8				
0.9				

Table 10-1.

☐ 5. Calculate and record in Table 10-1 the average output voltage of the alternator for each of the listed DC currents.

☐ 6. a. Turn on the power supply and adjust the DC excitation until E_1 = 208 V ac. Measure and record E_2 and E_3.

E_1 = 208 V ac, E_2 = ______ V ac, E_3 = ______ V ac

b. Turn off the power supply without touching the voltage adjust control.

c. Reconnect the three AC voltmeters so they will measure the voltages across each of the three stator windings.

d. Turn on the power supply. Measure and record the generated voltages across each of the wye connected stator windings.

$E_{1\text{ to }4}$ = ______ V ac, $E_{2\text{ to }5}$ = ______ V ac

$E_{3\text{ to }6}$ = ______ V ac

e. Return the voltage to zero and turn off the power supply.

f. Compare the results of (a) and (d). Do the results correspond to what you would expect to find coming from a normal three-phase power supply?

☐ Yes ☐ No

☐ 7. Using your Synchronizing Module, connect the circuit shown in Figure 10-2. Note that the switch is wired to present a dead short across the alternator windings when it is closed.

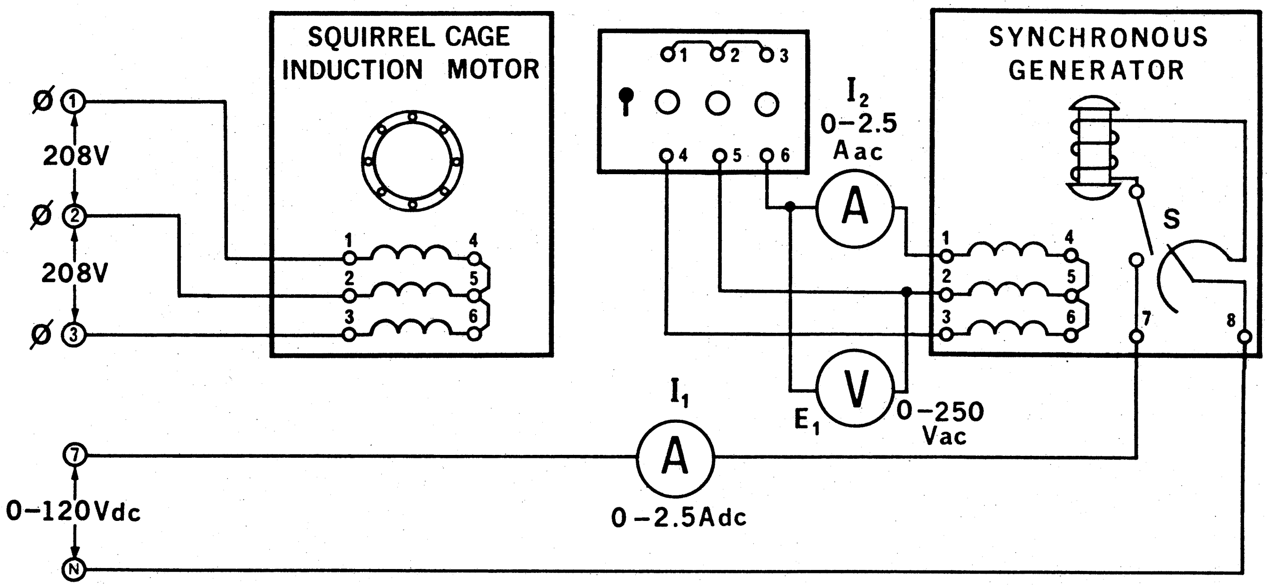


Figure 10-2.

☐ 8. a. Set the synchronizing switch to its open position.

b. Turn on the power supply and adjust the DC excitation until E_1 = 208 V ac. The motor should be running and the three lamps on the synchronizing module should be illuminated.

c. Measure and record the DC exciting current I_1.

I_1 = ______ A dc

d. Apply a short-circuit to your alternator by closing the synchronizing switch and note the behavior of the AC current I_2.

e. To what approximate peak value did I_2 increase?

I_2 = ______ A ac

f. What is the final steady-state value of I_2 and I_1?

I_1 = ______ A dc, I_2 = ______ A ac

g. Return the voltage to zero and turn off the power supply.

REVIEW QUESTIONS

1. a) Plot your recorded average voltage values vs DC current values from Table 10-1 on the graph of Figure 10-3.

b) Draw a smooth curve through your plotted points.

c) Up to what voltage is the curve a reasonably straight line?

E = ______ V ac

d) Where would you say is the knee of the saturation curve?

E = ______ V ac

e) Explain why the voltage increases less rapidly as the DC current increases.

____

____

____

____

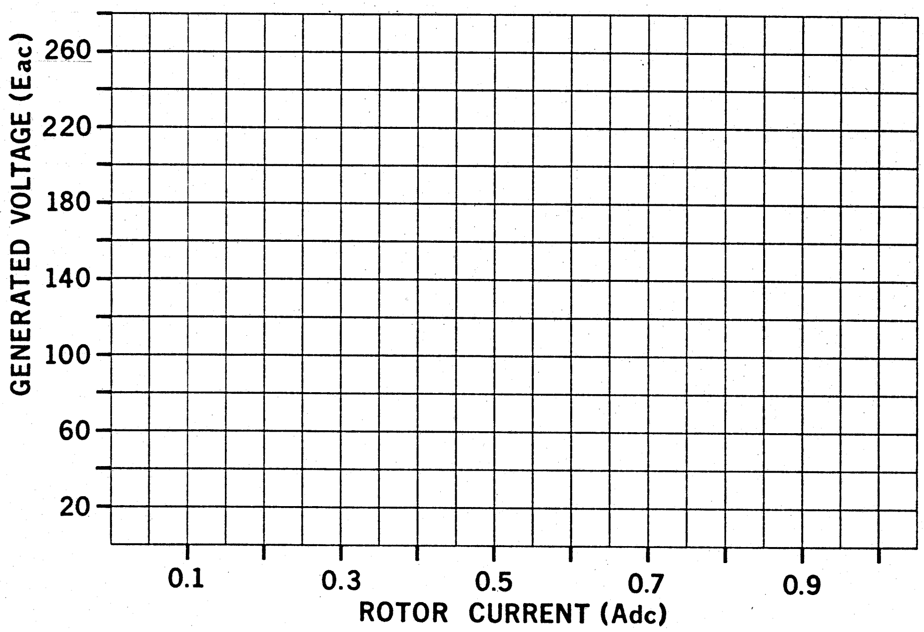


Figure 10-3.

2. Comment on the reasons for not operating an alternator near the knee of its saturation curve.

3. An alternator is much less likely to burn out on a sustained short-circuit than a separately-excited DC shunt generator. Explain.

Experiment 11

The Alternator Under Load

OBJECTIVE

- To determine the voltage regulation characteristics of the alternator with resistive, capacitive and inductive loading.
- To observe the effect of unbalanced loads on the output voltage.

DISCUSSION

The output voltage of an alternator depends essentially upon the total flux in the air-gap. At no-load, this flux is established and determined exclusively by the DC field excitation.

Under load, however, the air-gap flux is determined by the ampere-turns of the rotor and the ampere-turns of the stator. The latter may aid or oppose the MMF (magnetomotive force) of the rotor depending upon the power factor of the load. Leading power factors assist the rotor, and lagging power factors oppose it.

Because the stator MMF has such an important effect upon the magnetic flux, the voltage regulation of alternators is quite poor, and the DC field current must continuously be adjusted to keep the voltage constant under variable load conditions.

If one phase of a three-phase alternator is heavily loaded, its voltage will decrease due to the IR and IX_L drops in the stator winding. This voltage drop cannot be compensated by modifying the DC field current because the voltages of the other two phases will also be changed. Therefore, it is essential that three-phase alternators do not have loads that are badly unbalanced.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Synchronous Motor/Generator, DC Motor/Generator, Resistive Load, Power Supply, AC Ammeter, AC Voltmeter and DC Voltmeter/Ammeter, connect the circuit shown in

Figure 11-1. Note that the balanced resistive load is wye-connected to the three-phase output of the alternator. The alternator rotor is connected to the variable 0-120 V dc output of the power supply, terminals 7 and N. The DC shunt motor winding is connected to the fixed 120 V dc output of the power supply, terminals 8 and N.

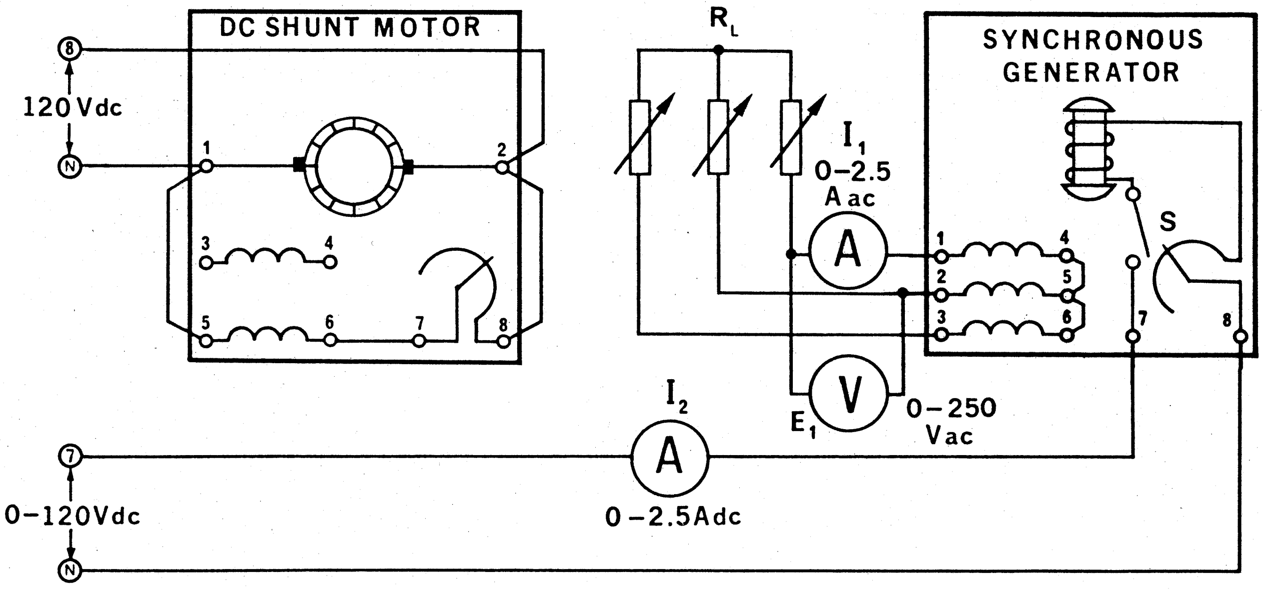


Figure 11-1.

☐ 2. a. Couple the DC motor to the alternator with the timing belt.

b. Set the DC motor field rheostat at its full cw position (for minimum resistance).

c. Set the alternator field rheostat at its full ccw position (for maximum resistance).

d. Adjust each resistance section for a resistance of 300 Ω.

☐ 3. a. Turn on the power supply and, using your hand tachometer, adjust the DC motor rheostat for a motor speed of 1800 r/min.

Note: *This speed must be kept constant for the remainder of this Experiment!*

b. Close the switch S.

c. Adjust the DC excitation of the alternator until the output voltage E_1 = 208 V ac. Measure and record the full load I_1 and I_2.

I_1 = ______ A ac, I_2 = ______ A dc

d. Open the three resistance load switches for no load on the alternator and measure and record the no load E_1 and I_2. Remember to check the motor speed and readjust to 1800 r/min if required.

E_1 = ______ V ac, I_2 = ______ A dc

e. Return the voltage to zero and turn off the power supply.

f. Calculate the alternator regulation with resistive loading.

$$\text{Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

____

______________________________ = ______________ %

☐ 4. a. Using your Inductance Module, replace the resistive load with an inductive load.

b. Adjust each inductance section for a reactance X_L of 300 Ω.

c. Repeat procedure 3 and record the full load values of I_1 and I_2.

I_1 = ______ A ac, I_2 = ______ A dc

d. Measure and record the no load values of E_1 and I_2.

E_1 = ______ V ac, I_2 = ______ A dc

e. Return the voltage to zero and turn off the power supply.

f. Calculate the alternator regulation with inductive loading.

____

______________________________ = ______________ %

g. With an inductive load, does the stator MMF aid or oppose the rotor MMF?

____

☐ 5. a. Using your Capacitance Module, replace the inductive load with a capacitive load.

b. Adjust each capacitance section for a reactance X_C of 300 Ω.

c. Repeat procedure 3 and record the full-load value of I_1 and I_2.

I_1 = ______ A ac, I_2 = ______ A dc

d. Measure and record the no load values of E_1 and I_2.

E_1 = ______ V ac, I_2 = ______ A dc

e. Return the voltage to zero and turn off the power supply.

f. Calculate the alternator regulation with inductive loading.

____

______________________________ = _______________ %

g. With an inductive load, does the stator MMF aid or oppose the rotor MMF?

____

☐ 6. a. With a capacitive reactance load of 1200 Ω per phase, turn on the power supply and adjust for a motor speed of 1800 r/min.

b. Adjust the DC excitation of the alternator until the output voltage E_1 = 208 V ac.

c. Increase the capacitive loading by placing an additional reactance of 600 Ω in parallel with each of the 1200 Ω sections and observe what happens.

____

____

d. Increase the capacitive loading further by placing an additional reactance of 300 Ω across each section and observe what happens.

____

____

e. Return the voltage to zero and turn off the power supply.

f. Explain, if you can, the phenomenon you have just observed.

____

____

____

☐ 7. a. Connect the circuit shown in Figure 11-2. Note that only one of the alternator phases has a load.

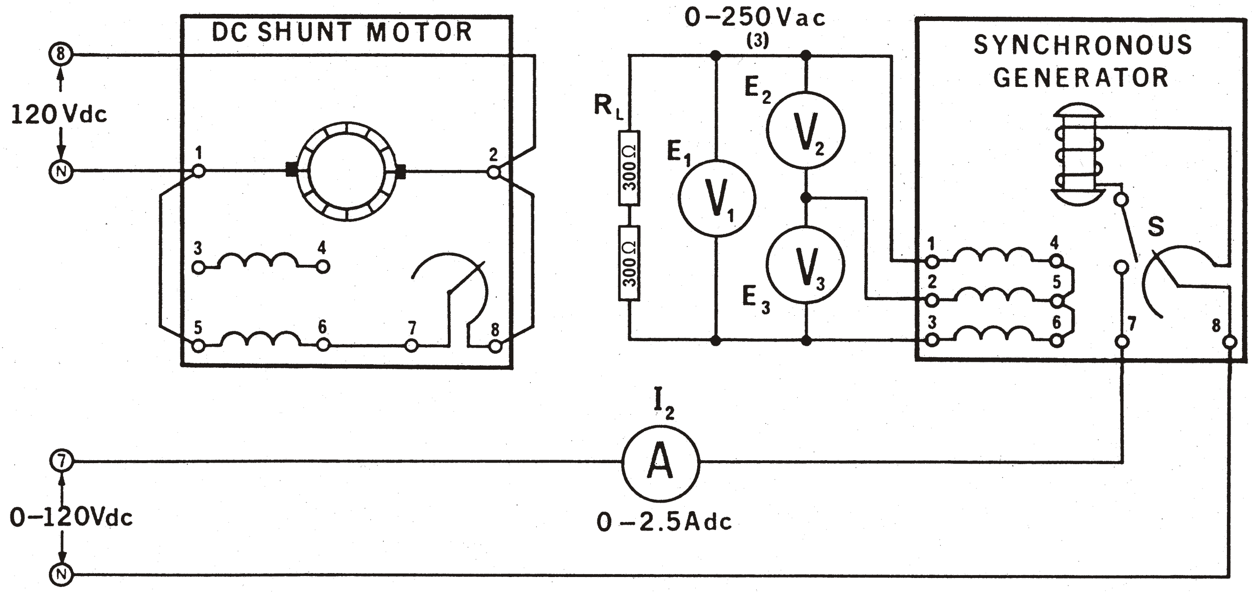


Figure 11-2.

b. Turn on the power supply and adjust the DC motor rheostat for a motor speed of 1800 r/min.

c. Adjust the DC excitation of the alternator until the voltage across the 600 Ω load E_1 = 208 V ac. Measure and record the two other phase voltages E_2 and E_3.

E_2 = ______ V ac, E_3 = ______ V ac

d. Turn off the power supply without touching any of the variable controls.

e. Reconnect the three AC voltmeters so they will measure the voltages across each of the three stator windings.

f. Turn on the power supply. Measure and record the voltages across each of the alternator windings.

$E_{1\text{ to }4}$ = ______ V ac

$E_{2\text{ to }5}$ = ______ V ac

$E_{3\text{ to }6}$ = ______ V ac

g. Return the voltage to zero and turn off the power supply.

h. Did the single-phase load produce a large unbalance?

☐ Yes ☐ No

REVIEW QUESTIONS

1. Explain why the alternator output voltage increases with capacitance loading.

2. Could it be dangerous to connect an alternator to a long transmission line, if the line looks like a capacitor? Explain.

   ☐ Yes ☐ No

3. The rotor of an alternator, at rated power, dissipates more heat at a low power factor (lagging) load than a high power factor load. Explain.

4. If an industrial customer of an electrical power company connects a large single-phase load to a three-phase power line, then every other user on that power line will have unbalanced three-phase power, even if their loads are balanced. Explain why.

Experiment 12

Alternator Synchronization

OBJECTIVE

- To learn how to synchronize an alternator to the electric power utility system.
- To observe the effects of improper phase conditions upon the synchronizing process.

DISCUSSION

The frequency of a large electric power utility system is established by the speed of rotation of many powerful alternators all connected by various tie-lines into the total network. The collective inertia and power of these generators is so great that there is no single load or disturbance which would be large enough to change their speed of rotation. The frequency of an electric system is, therefore, remarkably stable.

An alternator can only deliver power to an existing electric power system if it operates at the same frequency as the system. A system whose frequency is 60 Hz cannot receive power from an alternator operating at 60.001 Hz. They must both operate at exactly the same frequency. This is not as difficult to realize as may first appear, because automatic forces come into play when an alternator is connected into an existing system to keep its frequency constant.

Synchronization of an alternator with a large utility system, or “infinite buss” as it is called is analogous to meshing a small gear to another of enormous size and power. If the teeth of both gears are properly synchronized at the moment of contact, then the meshing will be smooth. But should tooth meet tooth at the critical instant, shock will result with possible damage to the smaller gear.

Smooth synchronization of an alternator means first that its frequency must be equal to that of the supply. In addition, the phase sequence (or rotation) must be the same. Returning to our example of the gears, we would not think of trying to mesh two gears going in opposite directions, even if their speeds were identical.

The next thing to watch for when we push gears together is to see that the tooth of one meets the slot of the other. In electrical terms the voltage of the alternator must be in phase with the voltage of the supply.

Finally, when meshing gears we always choose a tooth depth which is compatible with the master gear. Electrically, the voltage amplitude of the alternator should be equal to the supply voltage amplitude. With these conditions met, the alternator is perfectly synchronized with the network and the switch between the two can be closed.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Synchronous Motor/Generator, DC Motor/Generator, Synchronizing Module, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 12-1. Note that the output of the alternator is connected through the synchronizing switch to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3. The rotor of the alternator is connected to the variable 0-120 V dc output of the power supply, terminals 7 and N. The DC shunt motor is connected to the fixed 120 V dc output of the power supply, terminals 8 and N.

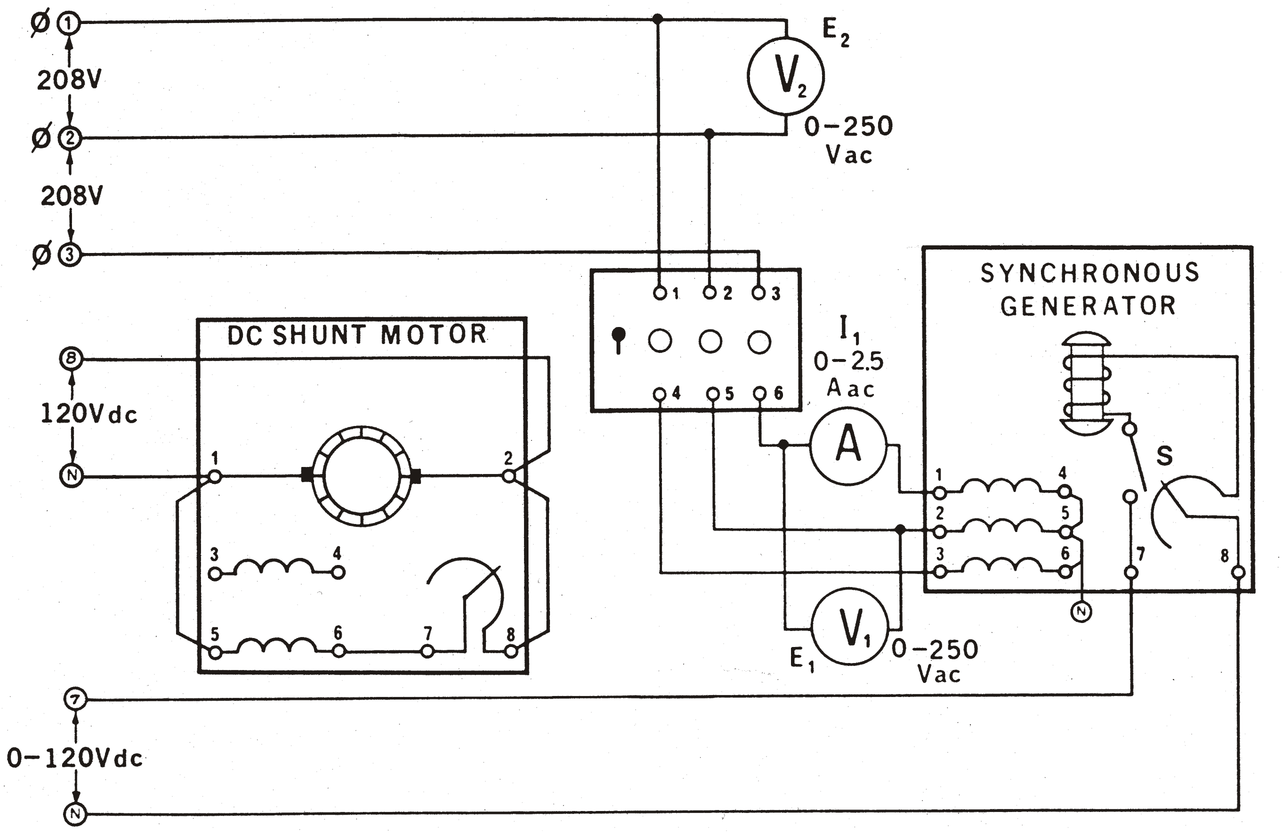


Figure 12-1.

☐ 2. a. Couple the DC motor to the alternator with the timing belt.

b. Set the DC motor field rheostat at its full cw position (for minimum resistance).

c. Place the synchronizing switch in its open position.

☐ 3. a. Turn on the power supply and, using your hand tachometer, adjust the power supply output for a motor speed of approximately 1800 r/min.

b. Measure the power company supply voltage E_2.

E_2 = ______ V ac

c. Close the switch S.

d. Adjust the DC excitation of the alternator until the alternator output voltage E_1 is equal to the power company voltage E_2.

Note: *These two voltages must be kept equal for the remainder of this Experiment.*

e. The three synchronizing lights should be flickering on and off.

☐ 4. a. Carefully adjust the DC motor speed until the beat frequency becomes quite low.

b. Do all three lights become bright and then dark, at the same time?

☐ Yes ☐ No

c. If they do not all become dark and then bright simultaneously, the phase sequence is wrong. Turn off the power supply and interchange any two of the leads coming from the stator.

d. Carefully adjust the motor speed until all three lights slowly darken and then slowly brighten. Your alternator frequency is very nearly equal to that of the power company.

e. When all of the lights are completely dark, the alternator and supply voltages are in phase.

f. When all of the lights are fully bright, the alternator and supply voltages are 180° out of phase. (This is the “tooth-to-tooth” condition, and the synchronizing switch should never be closed under these conditions).

g. Check to see that the two voltages E_1 and E_2 are equal. If not, readjust the DC excitation to the alternator.

☐ 5. a. Close the synchronizing switch when all three lights are dark and note the behavior of I_1 at the moment of closure.

b. Close the synchronizing switch when all three lights are dim and note the behavior of I_1 at the moment of closure.

c. Close the synchronizing switch when all three lights are partially bright and note the behavior of I_1 at the moment of closure.

☐ 6. a. With the synchronizing switch open, adjust the DC excitation to the alternator until the output voltage E_1 = 250 V ac.

b. Adjust the motor speed until all three lamps are synchronized.

c. Close the synchronizing switch when all three lights are dimmest and note the effect upon I_1 at the moment of closure and after closure.

I_1 at closure = ______________________

I_1 after closure = ______________________

d. Open the synchronizing switch.

e. Return the voltage to zero and turn off the power supply.

☐ 7. a. Reverse the rotation of the DC motor by interchanging the shunt field.

b. Attempt to synchronize the alternator as before.

c. How do the lights react?

d. What does this indicate?

e. Return the voltage to zero and turn off the power supply.

f. How can you remedy this situation without again reversing the DC motor?

REVIEW QUESTIONS

1. What conditions must be met to synchronize an alternator to an existing three-phase power line?

2. An alternator could be severely damaged mechanically in attempting to synchronize it with the power line. Under what two conditions could this happen?

3. An alternator generating a different value of voltage also may not be exactly in phase with the power line, but one condition must be met in order for it to deliver power. What is that condition?

Experiment 13

Alternator Power

OBJECTIVE

- To observe the effect of DC excitation upon the power delivered by an alternator.
- To observe the effect of power delivered by an alternator upon the torque of the prime mover.

DISCUSSION

Apart from portable or mobile engine driven AC alternators operating in remote areas or for emergency use, most AC generators feed into large electrical distribution networks where the frequency and voltage have been established by other generators operating in the system. Alternators are then said to feed into an “infinite buss”, meaning literally, a large electrical distribution system of tremendous power. The existing frequency and voltage of this infinite buss cannot be altered by the addition of any incoming alternator.

The incoming alternator will have a constant flux in its air-gap because of the fixed-frequency and voltage of the “infinite buss” it is connected to. The flux is normally produced by the DC rotor current and/or the AC currents in the stator. Should the DC current be less than that needed to produce the required flux, then the stator must supply the difference by drawing lagging reactive power from the infinite buss.

Conversely, if the DC rotor current is larger than required, the stator will draw leading reactive power from the infinite buss, and the alternator looks like a capacitor.

Changing the DC excitation of an alternator that is “tied” into an infinite buss can only cause it to exchange more or less reactive power with the infinite buss.

An alternator can only deliver active power (watts) to an infinite buss by forcing its rotor to move ahead of its normal no-load position. Mechanical torque must be exercised to attain and keep this advanced rotor position. The torque multiplied by the speed is a measure of the mechanical power which the alternator receives and, therefore, the electric power it delivers. It is clear then, that the prime mover must apply torque to the rotor. The more torque applied the greater will be the active power delivered by the alternator until it reaches the limit of its capacity.

An alternator can smoothly glide into synchronous motor operation when the prime mover ceases to deliver driving torque to it. In fact, an alternator (operating as a synchronous motor off the infinite buss) may deliver mechanical power to its prime mover. An alternator, driven by a water turbine, can, in stepless fashion, become a synchronous motor, driving the water turbine as a water pump.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Synchronous Motor/Generator, DC Motor/Generator, Synchronizing Module, Power Supply, AC Ammeter, AC Voltmeter and DC Voltmeter/Ammeter, connect the circuit shown in Figure 13-1. Note that the alternator output is connected through the wattmeter and synchronizing switch to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3. The alternator rotor is connected to the variable 0-120 V dc output of the power supply, terminals 7 and N. The DC shunt motor is connected to the fixed 120 V dc.

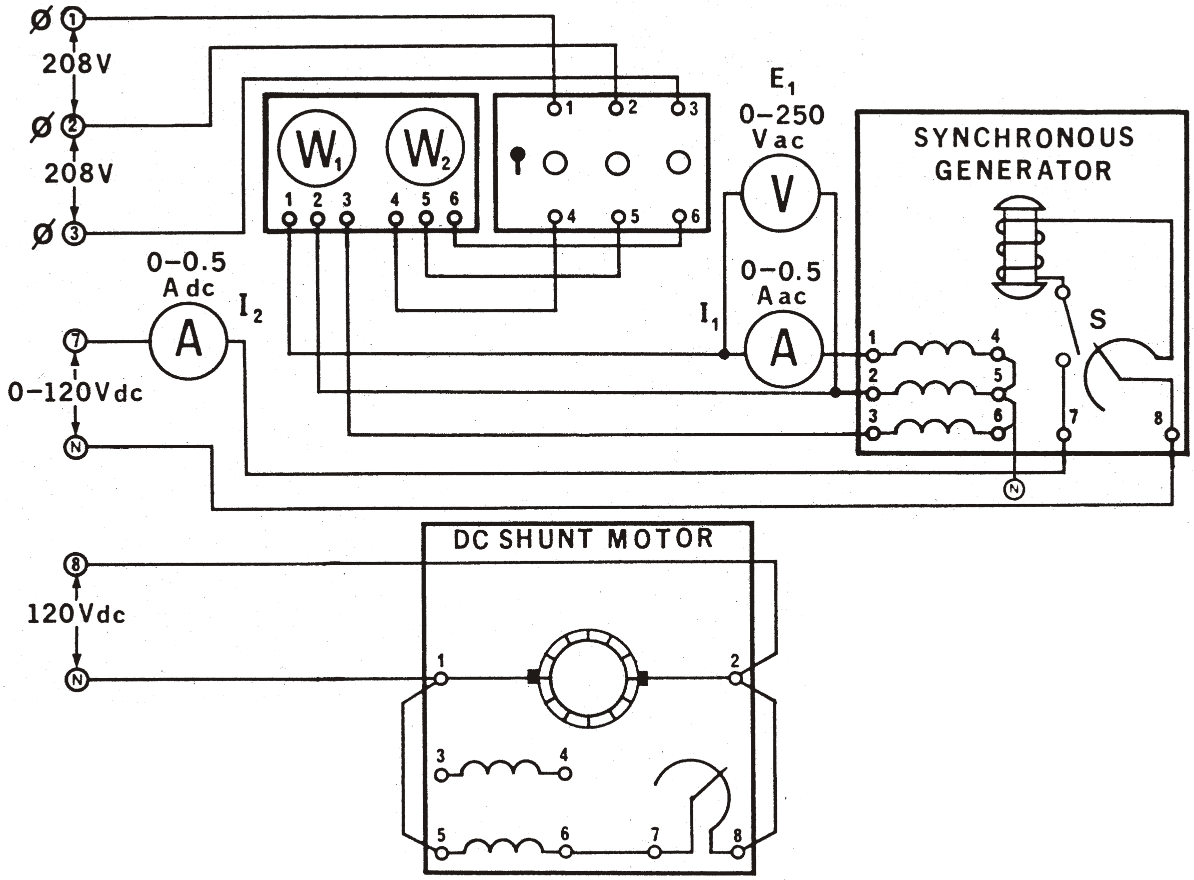


Figure 13-1.

☐ 2. a. Couple the DC motor to the alternator with the timing belt.

b. Set the DC motor field rheostat at its full cw position (for minimum resistance).

c. Place the synchronizing switch in its open position.

☐ 3. a. Turn on the power supply and, using your hand tachometer, adjust the DC motor rheostat for a motor speed of 1800 r/min.

b. Close the switch S and adjust the DC excitation of the alternator until the output voltage E_1 = 208 V ac.

c. Synchronize the alternator with the power line and close the synchronizing switch.

e. Carefully adjust the DC excitation of the alternator as well as the speed of the motor until both wattmeters indicate zero watts. Measure E_1, I_1 and I_2.

E_1 = ______ V ac, I_1 = ______ A ac, I_2 = ______ A dc

The alternator is now “floating” on the power line. It is neither receiving power from the line nor delivering power to the line.

☐ 4. a. Slowly increase only the DC excitation of the alternator until I_1 = 0.33 A ac (rated current). Measure W_1, W_2, E_1 and I_2.

W_1 = ______ W, W_2 = ______ W

E_1 = ______ V ac, I_2 = ______ A dc

b. Return the voltage to zero and turn off the power supply.

c. Calculate the apparent and active power delivered by the alternator.

Apparent power (S) ____

____

____ = ___________ VA

Active power (P)____

____

____ = ___________ W

d. Did an increase in DC excitation affect mainly the active or the reactive power delivered by the alternator?

____

☐ 5. Repeat procedure 3 until both wattmeters indicate 0 W.

☐ 6. a. Slowly decrease only the DC excitation of the alternator until I_1 = 0.33 A ac. Measure W_1 W_2 E_1 and I_2.

W_1 = ______ W, W_2 = ______ W

E_1 = ______ V ac, I_2 = ______ A dc

b. Return the voltage to zero and turn off the power supply.

c. Calculate the apparent and active power delivered by the alternator.

Apparent power (S) ____

____

____ = ___________ VA

Active power (P)____

____

____ = ____________ W

d. Did a decrease in DC excitation affect mainly the active or the reactive power delivered by the alternator?

____

e. Was the nature (positive, negative) of the reactive power the same in procedures 4 and 6? Explain.

☐ Yes ☐ No

____

____

____

☐ 7. Repeat procedure 3 until both wattmeters indicate 0 W.

☐ 8. a. Slowly decrease only the field excitation of the DC motor causing it to increase its torque until I_1 = 0.33 A ac.

(The motor speed, being locked-in with the alternator speed, which, in turn, is locked-in with the power line frequency, cannot increase).

Measure W_1 W_2 E_1 and I_2.

W_1 = ______ W, W_2 = ______ W

E_1 = ______ V ac, I_2 = ______ A dc

b. Return the voltage to zero and turn off the power supply.

c. Calculate the apparent and active power delivered by the alternator.

Apparent power ____

____

____ = ___________ VA

Active power ____

____

____ = ___________ W

d. Did an increase in torque affect mainly the active or the reactive power delivered by the alternator?

____

☐ 9. Repeat procedure 3 until both wattmeters indicate 0 W.

☐ 10. Adjust the DC excitation of the alternator and the torque of the DC motor so that the alternator delivers 60 W of active power at a power factor of 50%. Make measurements using each method.

a. Alternator over-excited

W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A dc

E_1 = ______ V ac

b. Alternator under-excited

W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A dc

E_1 = ______ V ac

☐ 11. Adjust the DC excitation of the alternator and the torque of the DC motor so that the alternator behaves as a perfect three-phase capacitance with a capacity of 120 var. Measure W_1, W_2, E_1, I_1 and I_2.

W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A dc

E_1 = ______ V ac

☐ 12. Adjust the DC excitation of the alternator and the torque of the DC motor so that the alternator behaves as a perfect three-phase inductance with a capacity of 120 var. Measure W_1, W_2, E_1, I_1 and I_2.

W_1 = ______ W, W_2 = ______ W

I_1 = ______ A ac, I_2 = ______ A dc

E_1 = ______ V ac

REVIEW QUESTIONS

1. An AC generator, driven by a water turbine, delivers 10 000 kVA at a leading power factor of 95%.

   a) If the DC excitation is reduced, will the apparent power increase or decrease?

   ____

   b) If the DC excitation is increased, will the apparent power increase of decrease?

   ____

2. A DC motor driving an alternator develops a mechanical output power of 100 kW [100 hp]. If the efficiency of the alternator is 94%, calculate the active power it can deliver to an infinite bus.

   ____

   ____

   ______________________________ = ______________ W

3. The power factor of an alternator which is connected to an infinite bus does not depend upon the electro-mechanical devices also connected to that bus. Explain.

____

____

____

____

4. The output frequency of an alternator tied to an infinite bus is dependent upon the frequency of the infinite bus. Explain.

____

____

____

Experiment 14

Three-Phase Motor Starter

OBJECTIVE

- To examine the construction of a three-phase magnetic starter and to study its operation.
- To examine the construction of an automatic synchronous motor starter and evaluate its performance.

DISCUSSION

Magnetic Starter

You have studied in previous Experiments the characteristics of different type of three phase motors: squirrel-cage, wound rotor, and synchronous. For these experiments, you have been using a laboratory-type power supply with variable output.

For economic reasons and for simplicity of operation, the industry does not use this kind of power supply for each motor. Whenever possible, motors are connected directly across the line by means of a device which includes an overload protection for the motor.

The simplest means of starting a motor, which is called a manual starter, is an on-off switch which includes an overload device that automatically returns the switch to its off position when the current drawn by the motor exceeds a certain value.

The overload is normally an inverse-time device which will let high currents, like starting currents, go through for short periods of time but will trip on sustained currents above a certain value.

The magnetic starter is another starting device which is very extensively used to start three-phase induction motors. Figure 14-1 shows a typical magnetic starter circuit with pilot light. When the START button is depressed momentarily, current goes from one phase of the line side through the stop and start buttons, the coil and the overload contact, to a different phase of the line. The energized coil closes contacts M to make the circuit to the load side and close an auxiliary contact across the start button. The button can now be released and the coil remains energized. This is called a self-holding or electrically-held circuit. If the motor is overloaded and draws a higher than normal current, the heating elements of the overload device open the overload contact O/L, which breaks the coil circuit and disconnects the motor from the line through contacts M. The same action occurs when the normally closed STOP button is depressed.

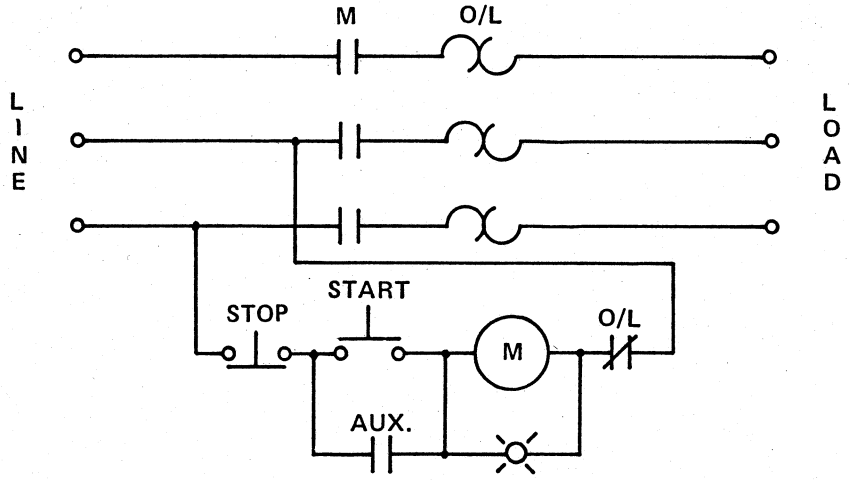


Figure 14-1.

Synchronous Motor Starter

As you have probably guessed, a synchronous motor cannot be started automatically in the same manner as a squirrel-cage motor. You have learned in previous Experiments that the rotor winding must generally be connected to an external resistor during start-up, to prevent excessive voltage build-up. When the rotor approaches synchronous speed, the resistor must be disconnected and DC current must be injected into the rotor windings to bring the rotor to synchronous speed and lock it into synchronism with the rotating magnetic field.

Various methods are used to detect the exact moment when the DC current should be injected. One method, which is fully described and experimented in the Lab-Volt Control of Industrial Motors Program, uses a slip-frequency control relay. This relay indirectly measures the speed of the motor by detecting the slip frequency, and applies the DC voltage at the very precise moment when a stator pole is slightly leading a rotor pole of opposite polarity. A simpler method is the definite-time starter: in this case, the motor is started like a squirrel-cage motor and, when sufficient time has been allowed for the motor to reach close to synchronous speed, a time-delay relay applies the DC voltage to the rotor excitation winding.

Another simple synchronous motor starter is described in this Experiment. It makes use of a current measuring device to initiate the closure of a relay when the line current has decreased to a predetermined level, and provide DC excitation to the rotor winding. The Synchronous Motor Starter consists of a full-voltage three-phase starter, a current sensing device and excitation relay and a built-in 120 V dc power supply. This power supply is made of an isolation transformer and a full-wave rectifier. When the motor reaches approximately 90% of synchronous speed, the line current falls below a certain value, and the current sensing device closes a relay to supply DC excitation current to the motor field, thus locking the motor into synchronism.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

Three-Phase Line Starter

☐ 1. Examine the front face of the Three-Phase Full-Voltage Starter. Six connections terminals are provided for connecting the starter to the power source (1, 2, 3) and the motor load (4, 5, 6). A combined start-stop (I-O) push-button is the controlling device, and a pilot lamp is used to indicate that the load is energized. What is the rated current of the starter?

I = ______ A ac

☐ 2. Viewing the inside of the module:

   a. Identify the four-pole magnetic contactor, three poles correspond to contacts M shown in Figure 14-1 while the other one is the auxiliary contact (AUX.).

   b. Identify the three-phase overload relay.

   c. Note the calibrated adjustable dial. Its setting determines the tripping point in amperes. The overload should be set at 1.2 A when used in conjunction with the Four-Pole Squirrel-Cage Induction Motor.

   d. Note the reset button on the overload relay. Press it.

☐ 3. Using your Three-Phase Full-Voltage Starter, Four-Pole Squirrel-Cage Induction Motor, Electrodynamometer, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 14-2. Couple the motor to the electrodynamometer with the timing belt.

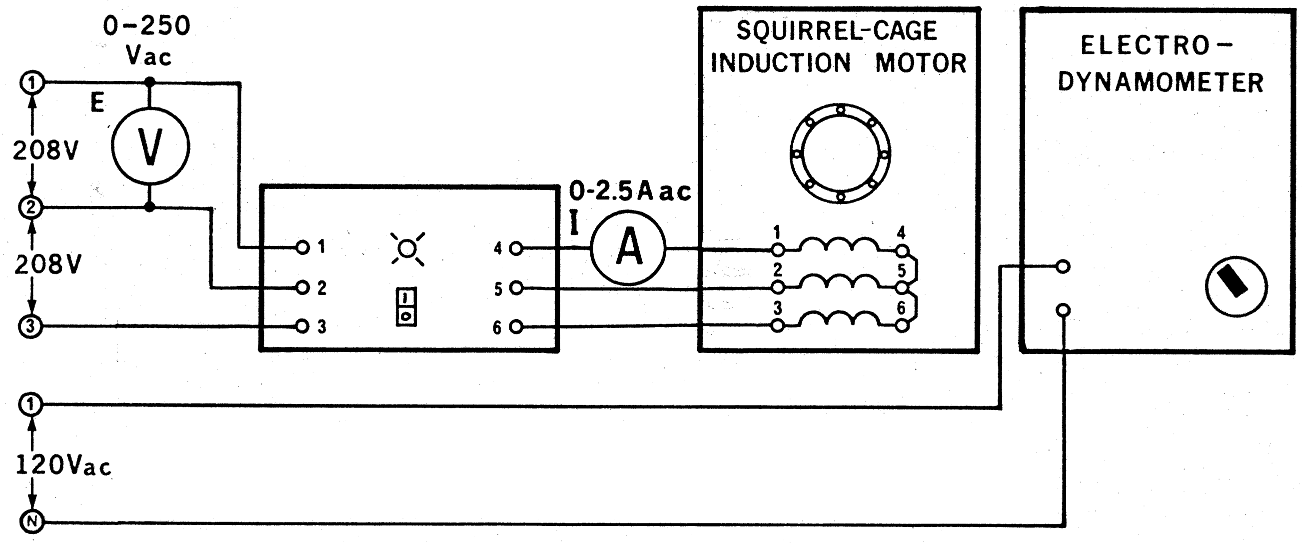


Figure 14-2.

☐ 4. a. Note that the LINE side of the starter is connected to the fixed 208 V, 3φ output of the power supply, terminals 1, 2 and 3.

b. Note that the LOAD side of the starter is connected through the AC ammeter to the wye-connected motor windings.

☐ 5. a. Turn on the power supply. Measure and note the voltage E.

E = ______ V ac

b. Is the motor turning?

☐ Yes ☐ No

c. Is the pilot lamp on?

☐ Yes ☐ No

d. Set the electrodynamometer control knob at its full ccw position (to provide a minimum starting load for the motor).

e. Push the start button (I) and release it immediately. Is the motor running?

☐ Yes ☐ No

Is the pilot lamp on?

☐ Yes ☐ No

f. Measure and note the motor line current.

I = ______ A ac

g. Press momentarily the stop button (O). Describe what happens.

____

____

h. Press the start button. Set the electrodynamometer control knob to obtain a motor line current of 1.8 A ac (50% overload current on the motor). Measure and note the time required for the overload relay to operate.

t = ______ s

i. Turn off the power supply.

j. Allow approximately 5 minutes for the overload relay to cool. Retrieve the Three-Phase Full-Voltage Starter from the console and press the overload relay reset button. Replace the module in the console.

k. Set the ammeter on the 0-8 A ac scale.

l. Turn on the power supply.

m. Set the electrodynamometer control knob at its full cw position (to provide a maximum starting load for the motor).

n. Push the start button (I) and measure the motor current and the time required for the overload relay to operate.

I = ______ A ac   t = ______ s

p. Turn off the power supply and reset the overload relay. You may have to let it cool first.

Synchronous Motor Starter

☐ 6. a. Examine the front face of the Synchronous Motor Starter. Connection terminals 1, 2 and 3 (LINE) are provided for connecting to the power source. The motor stator winding should be connected to terminals 4, 5 and 6 (LOAD). A 120 V dc power source is also available at terminals 7 and 8 to supply the synchronous motor excitation winding. A combined start-stop (I-O) push-button is the controlling device. Two pilot lamps are used to indicate that the starter is energized and that the motor is synchronized. The 120 V dc source is protected by a circuit breaker mounted to the left of the push-button.

b. Note the current rating of the starter.

I = ______ A ac

c. Note the rated voltage and current of the DC power source.

E = ______ V dc   I = ______ A dc

☐ 7. Viewing the inside of the module:

a. Identify the four-pole magnetic contactor and the overload relay. Are they similar to those of the three-phase line starter?

☐ Yes   ☐ No

b. Identify the transformer which forms part of the field power source.

c. Note the circuit board at the back. It contains the rectifier circuit for the DC source, and the current measuring device made of resistors, condensers and a control relay.

d. Set the variable overload relay at 0.8 A when used in conjunction with the Three-Phase Synchronous Motor/Generator. Press the reset button.

☐ 8. a. Using your Synchronous Motor Starter, Three-Phase Synchronous Motor/Generator, Electrodynamometer, Power Supply, AC Ammeter, AC Voltmeter and DC Voltmeter/Ammeter, connect the circuit shown in Figure 14-3. Couple the motor to the electrodynamometer with the timing belt.

b. Note that the LINE side of the starter is connected to the fixed 208 V, 3φ output of the power supply, terminals 1, 2 and 3.

c. Note that the LOAD side of the starter is connected through the ammeter to the wye-connected motor stator windings.

d. Note the excitation winding is connected to the synchronous motor starter built-in DC source, terminals 7 and 8.

e. Close switch S.

f. Set the field rheostat for zero resistance (control knob fully cw).

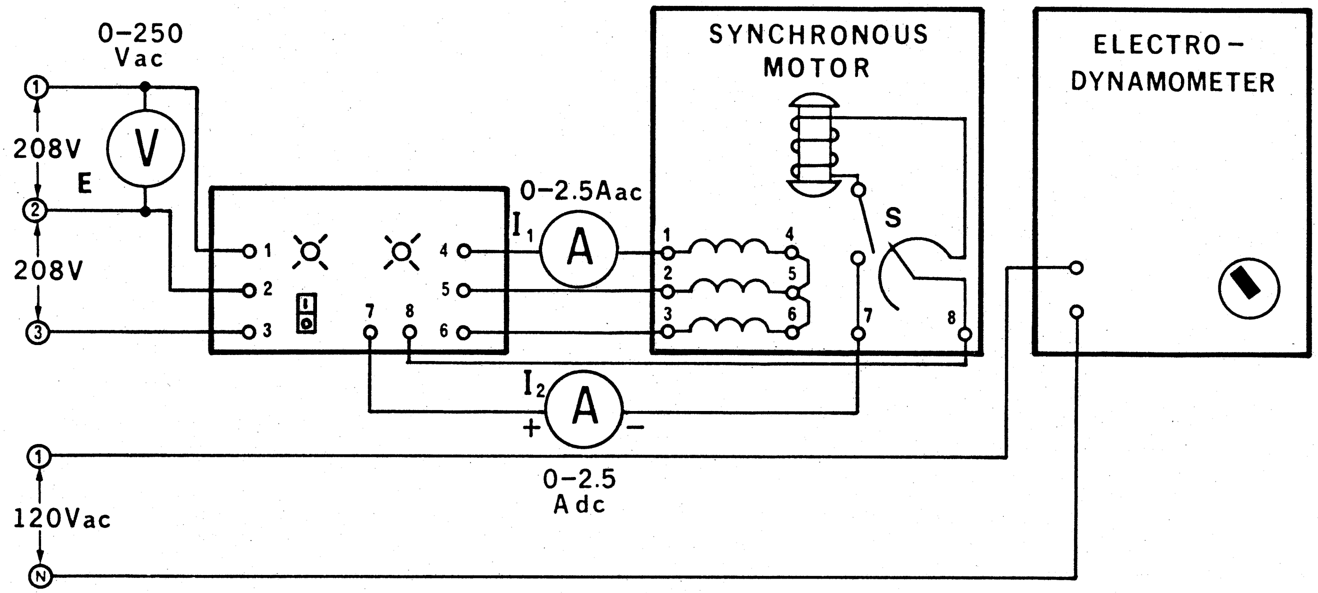


Figure 14-3.

☐ 9. a. Turn on the power supply. Measure and note the voltage E.

E = ______ V ac

b. Is the motor running?

☐ Yes ☐ No

c. Is any pilot lamp on?

☐ Yes ☐ No

d. Set the electrodynamometer control knob at its full ccw position (to provide a minimum starting load for the motor).

e. Push the start button (I) and release it immediately. Describe what happens.

____

____

f. Push the start button (I) until the “Motor Synchronized” lamp comes on. Release the button. Describe what happens.

____

____

g. Measure and note the motor line current.

I = ______ A ac

h. Press momentarily the stop button (O). Describe what happens.

____

____

i. Start the motor. Set the motor field rheostat for a minimum line current.

j. Set the electrodynamometer control knob to obtain a motor line current of 1.2 A ac (50% overload current on the motor). Measure and note the time required for the overload relay to operate.

t = ______ s

k. Turn off the power supply.

☐ 10. a. Allow approximately 5 minutes for the overload relay to cool, and reset the overload relay.

b. Set the ammeter I_1 on the 0-8 A ac scale.

c. Turn on the power supply.

d. Set the electrodynamometer control knob at its full cw position (to provide a maximum starting load for the motor).

e. Press and hold the start button (I), and measure the motor line current and the time required for the overload relay to operate.

I = ______ A ac

t = ______ s

f. Turn off the power supply. Allow 2 minutes for the overload relay to cool and reset it.

☐ 11. a. Turn on the power supply.

b. Set the electrodynamometer control knob at its full ccw position.

c. Start the motor.

d. Gradually increase the loading on the synchronous motor until it falls out of synchronism. Record the torque required.

Torque = ______ N·m [lbf·in]

Describe what happens.

____

____

____

REVIEW QUESTION

1. Why does industry use a motor starter to control a squirrel-cage induction motor.

   ____

   ____

   ____

2. Explain why the "Motor Synchronized" lamp did not come on in procedure 9 (e) and why you had to hold the Start button (**I**) depressed.

   ____

   ____

3. Explain why the overload tripping time is shorter in procedure 5 (n) than in procedure 5 (h)?

   ____

   ____

4. What would have happened in procedure 5 (h) if the variable overload relay had been set at 0.8 A?

   ____

   ____

   ____

Experiment 15

Frequency Conversion

OBJECTIVE

- To observe the no-load and full-load characteristics of a rotary frequency converter.
- To operate a three-phase squirrel-cage motor from a 120 Hz power source.

DISCUSSION

You learned in Experiment 3 that if the stator of a wound rotor induction motor is connected to a three-phase supply and the rotor is turned mechanically, the frequency of the rotor output voltage will vary according to the speed and direction of rotation.

In this Experiment the stator of the wound rotor induction motor will be connected to the 60 Hz power supply and the rotor will be driven at 1800 r/min by the synchronous motor. The direction of rotation will be opposite to that of the revolving magnetic field created by the stator windings; consequently, the frequency of the rotor output voltage will be 120 Hz.

The electrical power delivered by a rotary frequency converter comes from two sources:

a) The electrical power supply to which the stator windings are connected.

b) The mechanical power delivered to the rotating rotor shaft.

In the specific case where the output frequency is doubled, the mechanical power and the electrical power to the stator are equal. Therefore, the rotary frequency converter delivers twice as much electric power to its load as its stator receives. The difference comes from the source of mechanical power driving the rotor.

Rotary frequency converters of this type are employed in industries to generate the higher frequencies necessary to drive small, high-speed induction motors.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Synchronous Motor/Generator, Three-Phase Wound-Rotor Induction Motor, Three-Phase Wattmeter, Resistive Load, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 15-1. Note that the stator of the synchronous motor is connected to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3. The rotor of the synchronous motor is connected to the fixed 120 V dc output of the power supply, terminals 8 and N. The stator of the wound rotor motor is connected, through the wattmeter, to the variable 0-208 V 3φ output of the power supply, terminals 4, 5 and 6. The rotor windings are terminated at the star connected resistance load R_L (two Resistive Load in parallel).

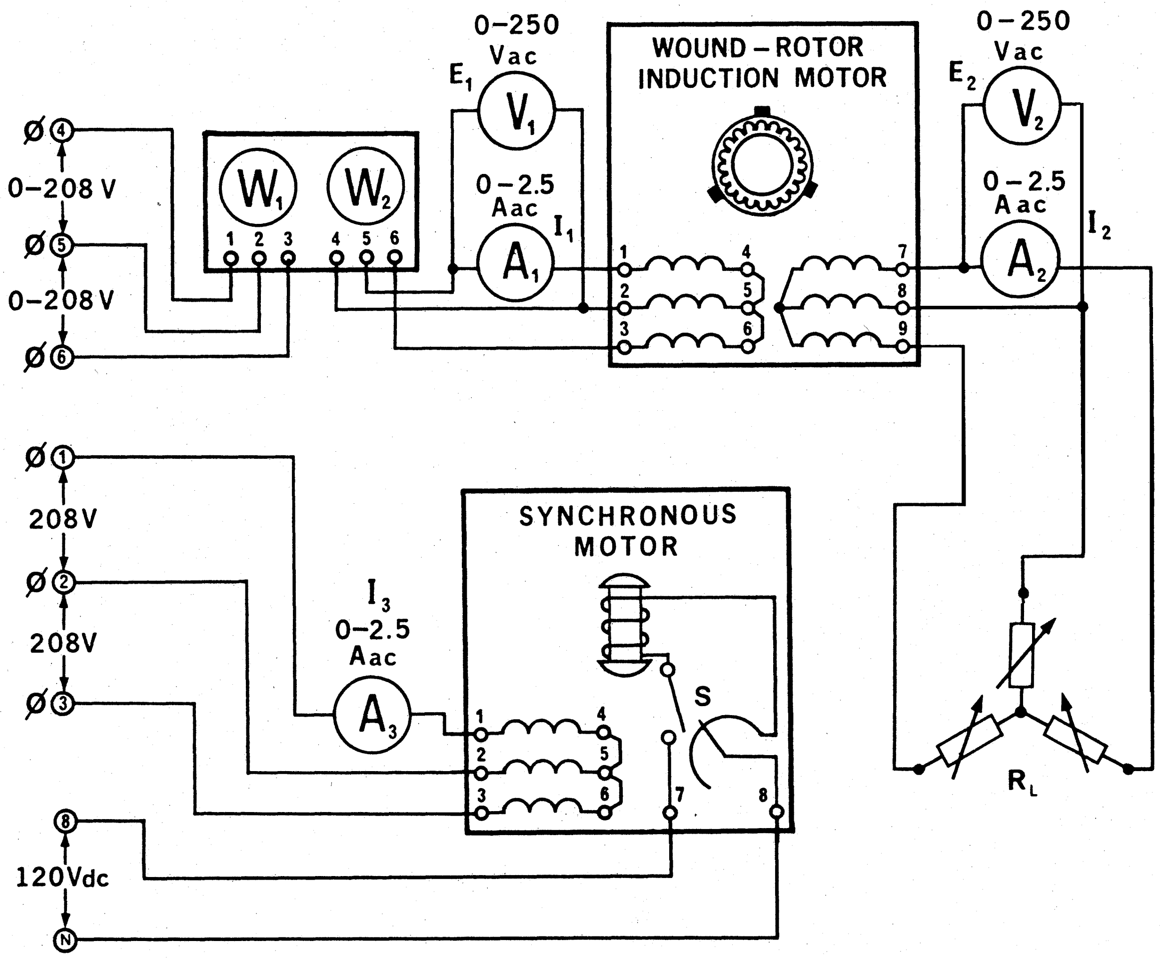


Figure 15-1.

☐ 2. a. Couple the synchronous motor to the wound rotor frequency converter with the timing belt.

b. Adjust all of the load resistance switches to their open positions.

c. Set the field control rheostat at its full ccw position (for maximum resistance) and keep the switch S open.

☐ 3. a. Turn on the power supply. The synchronous motor should be running.

b. Close the switch S.

c. Adjust the power supply voltage until E_1 = 208 V ac.

Note: *If the* E_2 *is zero, the rotor is revolving in the same direction as the magnetic field of the stator. Turn off the power supply and interchange any two of the leads to the stator.*

d. Adjust the DC excitation of the synchronous motor so that I_3 is at its minimum value. Remember to do this for all succeeding procedures.

e. Measure and record E_2, I_2 I_1, W_1 and W_2.

E_2 = ______ V ac, I_2 = ______ A ac, I_1 = ______ A ac

W_1 = ______ W, W_2 = ______ W

☐ 4. a. Gradually increase the three-phase resistance loading by adjusting each resistance section to 171 Ω to obtain an equivalent resistance of 86 Ω per phase.

b. Measure and record E_2, I_2 I_1, W_1 and W_2.

E_2 = ______ V ac, I_2 = ______ A ac, I_1 = ______ A ac

W_1 = ______ W, W_2 = ______ W

c. Remove the load by opening the resistance switches.

d. Return the voltage to zero and turn off the power supply.

☐ 5. In procedure 4 calculate the active power delivered to the stator and the active power delivered to the delta connected load.

a. Power to stator ______________________________

____

______________________________ = ______________ W

b. Power to load ______________________________

____

______________________________ = ______________ W

c. Explain how it is possible for the power to the load to exceed the power to the stator.

____

____

____

____

☐ 6. Using your Four-Pole Squirrel-Cage Induction Motor, replace the delta connected resistance load with the wye-connected motor load as shown in Figure 15-2. Do not disturb any of your circuit wiring.

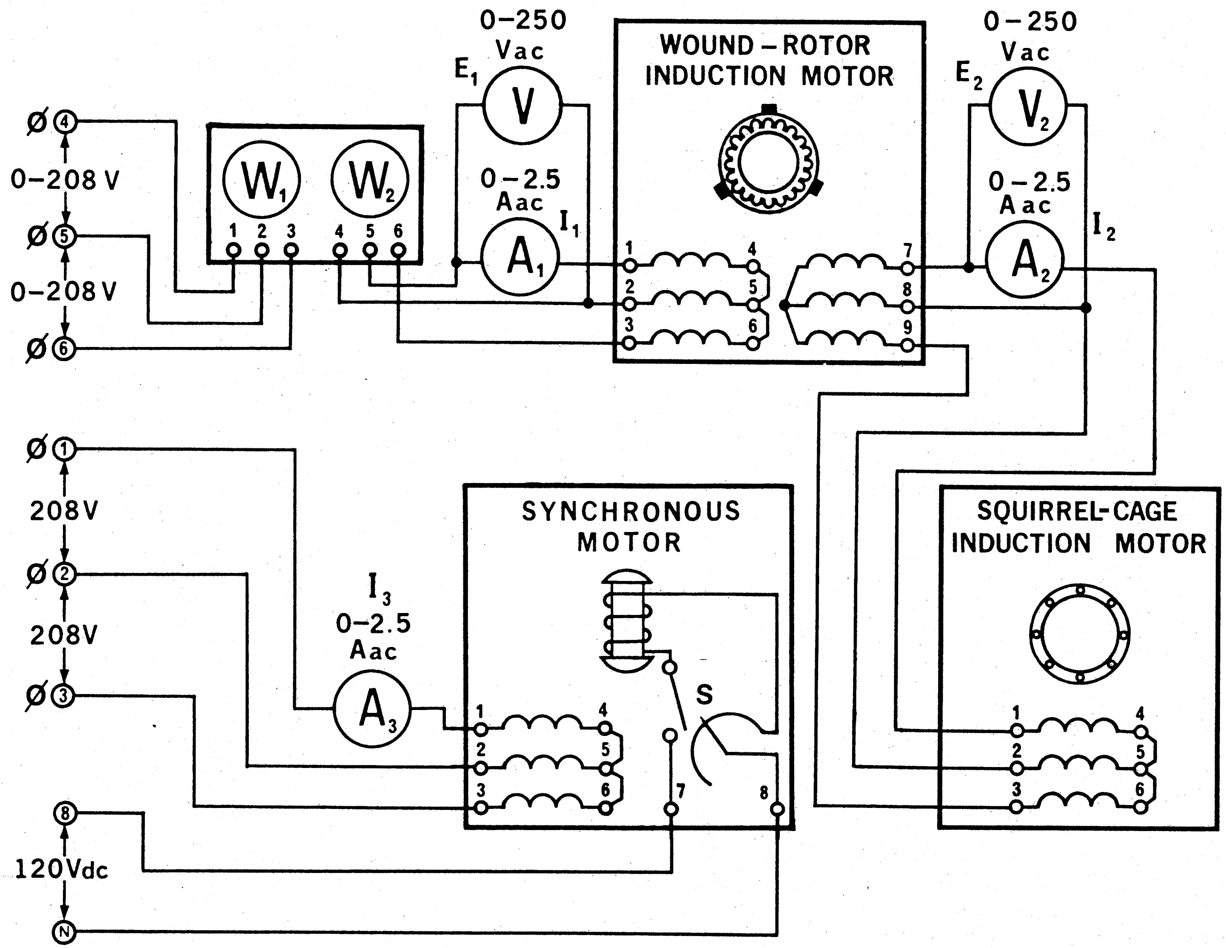


Figure 15-2.

☐ 7. a. Turn on the power supply and adjust until E_1 = 208 V ac.

b. Measure and record the squirrel-cage motor speed, I_1, I_2, E_2, W_1 and W_2.

E_2 = ______ V ac, I_2 = ______ A ac, I_1 = ______ A ac

W_1 = ______ W, W_2 = ______ W, Speed = ______ r/min

c. Return the voltage to zero and turn off the power supply.

REVIEW QUESTIONS

1. Explain why the squirrel-cage motor revolves so fast in procedure 7.

2. What frequency would be generated by the wound rotor machine if the rotor were turning at 900 r/min? (Two answers are possible).

3. A six-pole wound rotor induction motor having a nominal speed of 1200 r/min is driven by a 3600 r/min squirrel-cage induction motor.

   a) What is the highest frequency that can be obtained with this combination?

   b) What is the lowest frequency that can be obtained?

Experiment 16

Reactance and Frequency

OBJECTIVE

- To show that inductive reactance is doubled when the frequency is doubled.
- To show that capacitive reactance is halved when the frequency is doubled.

DISCUSSION

Capacitive and inductive reactance and the formulas relating to them were introduced in previous Experiments. We will now have a brief review of the term “reactance” and its frequency-dependent properties.

Inductive Reactance

In an inductive DC circuit, the inductance affects the current flow only when the current is changing in value. When a DC circuit is energized, the inductance opposes the increase in current; when the circuit is de-energized, it opposes the decrease in current. However, the flow of a steady direct current is opposed only by the resistance of the circuit.

In an inductive AC circuit, the current is changing continuously and, therefore, is continuously inducing an EMF by self-induction. Because in current flow, its effect is measured in ohms. Opposition of inductance to the flow of alternating current is called inductive reactance and is represented by the symbol X_L. The current flowing in a circuit that contains only inductive reactance is:

$$I = \frac{E}{X_L} \tag{1}$$

where: I = effective current in amperes (A)
E = effective voltage across the reactance in volts (V)
X_L = inductive reactance in ohms (Ω)

The value of inductive reactance in any circuit depends on the circuit inductance and on the rate at which the current is changing. The rate of change of current depends on the frequency of the applied voltage. Inductive reactance in ohms may be calculated from the formula:

$$X_L = 2\pi f L \tag{2}$$

where: π = 3.14
f = frequency in hertz (Hz)
L = inductance in henrys (H)

Capacitive Reactance

Capacitive reactance is the opposition offered by a capacitor or by any capacitive circuit to the flow of current. The current flowing in a capacitive circuit is directly proportional to the capacitance and to the rate at which the applied voltage is changing. The rate at which the voltage changes is determined by the frequency of the supply. Therefore, if either the frequency or the capacitance of a given circuit increases, the current flow increases. This is equivalent to saying that if either the frequency or capacitance is increased, the opposition to the current flow is decreased. Therefore, capacitive reactance, which is the opposition to current flow, is inversely proportional to frequency and capacitance. Capacitive reactance, X_C, is measured in ohms, as is resistance and inductive reactance, and may be calculated by the formula:

$$X_C = \frac{1}{2\pi f C} \tag{3}$$

where: π = 3.14
f = frequency in hertz (Hz)
C = capacitance in farads (F)

The current flowing in a circuit containing only capacitive reactance is:

$$I = \frac{E}{X_C} \tag{4}$$

where: I = effective current in amperes (A)
E = effective voltage across the capacitive reactance in volts (V)
X_C = capacitance reactance in ohms (Ω)

In this Experiment you will test the validity of these statements, using a 60 Hz and a 120 Hz power source. The wound-rotor induction motor, connected as a rotary frequency converter, will be used to furnish 120 Hz power. You will also observe the resonance effects of a parallel LC circuit operating at each of these frequencies.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Capacitive Load, Resistive Load, Inductive Load, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 16-1.

Note that the paralleled resistance, capacitance and inductance are connected to the variable 0-120 V ac output of the (60 Hz) power supply, terminals 4 and N.

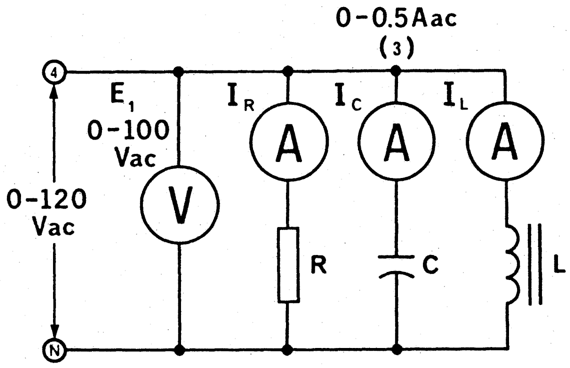


Figure 16-1.

☐ 2. a. Adjust the resistance load for a resistance of 300 Ω.

b. Adjust the capacitance load for a reactance of 300 Ω.

c. Adjust the inductance load for a reactance of 300 Ω.

d. Turn on the power supply and adjust E_1 to 75 V ac.

e. Measure and record the three load currents.

I_R = ______ A ac, I_C = ______ A ac, I_L = ______ A ac

f. Return the voltage to zero and turn off the power supply.

☐ 3. a. Using the results of procedure 2, calculate each of the 60 Hz load values.

$R = E_1 / I_R$ = ______ Ω

$X_C = E_1 / I_C$ = ______ Ω

$X_L = E_1 / I_L$ = ______ Ω

b. Do your calculated load values compare with the listed load values?

☐ Yes ☐ No

☐ 4. a. Connect the circuit shown in Figure 16-2.

b. Adjust the capacitance load for a reactance of 1200 Ω.

c. Adjust the inductance load for a reactance of 300 Ω.

d. Turn on the power supply and adjust E_1 to 75 V ac.

e. Measure and record the total current, and each load current.

I_T = ______ A ac, I_C = ______ A ac, I_L = ______ A ac

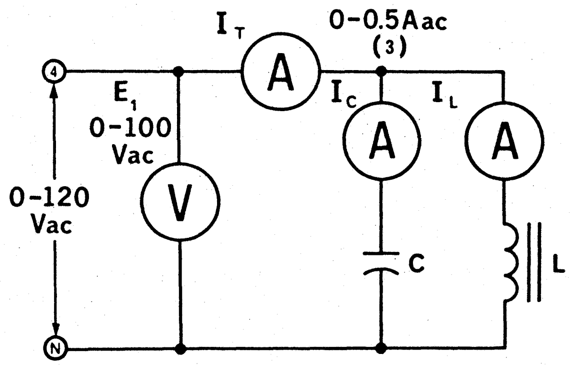


Figure 16-2.

☐ 5. Repeat procedures 2 and 4 using a 75 V-120 Hz power source.

a. Using your Three-Phase Wound-Rotor Induction Motor and Three-Phase Synchronous Motor/Generator, connect the circuit shown in Figure 16-3. Note that the stator of the synchronous motor is connected to the fixed 208 V 3φ output of the power supply, terminals 1, 2 and 3. The rotor of the synchronous motor is connected to the variable 0-208 V 3φ output of the power supply, terminals 4, 5 and 6. The loads are connected to rotor terminals 7 and 9.

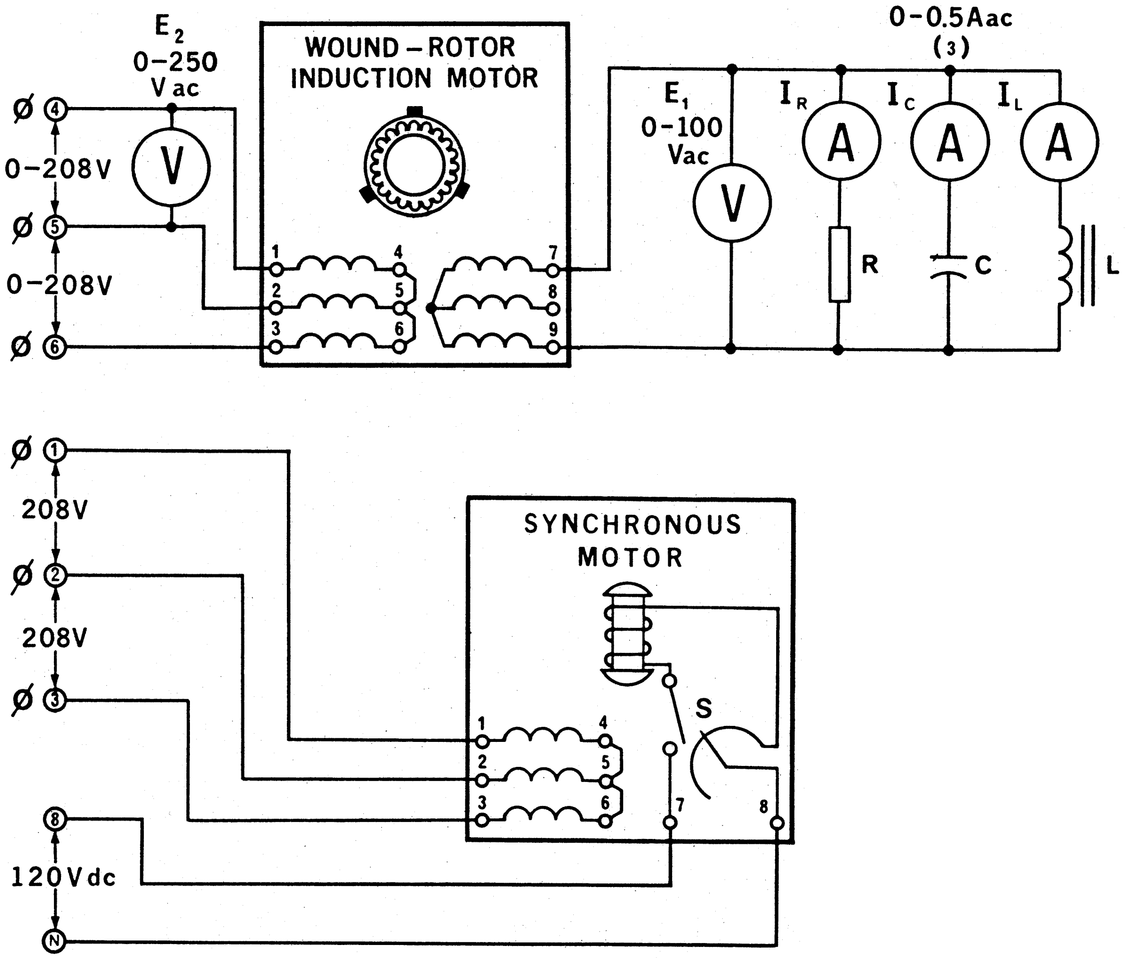


Figure 16-3.

☐ 6. a. Couple the synchronous motor to the wound rotor frequency converter with the timing belt.

b. Set the synchronous motor switch S to the open position.

c. Set the load module switches to the open positions.

☐ 7. a. Turn on the power supply. The synchronous motor should be running.

b. Close the witch S.

c. Adjust the power supply control knob until the load voltage E_1 = 75 V ac.

Note: *If E_1 is zero, the rotor is revolving in the same direction as the magnetic field of the stator. Turn off the power supply and interchange any two leads to the stator.*

☐ 8. Repeat procedure 2 by:

a. Adjusting the resistance load to 300 Ω.

b. Adjusting the capacitance load for a 60 Hz reactance of 300 Ω. What is the 120 Hz reactance?

____

c. Adjusting the inductance load for a 60 Hz reactance of 300 Ω. What is the 120 Hz reactance?

____

d. Adjust the power supply, if necessary, to maintain E_1 at 75 V ac.

e. Measure and record the three 120 Hz load currents.

I_R = ______ A ac, I_C = ______ A ac, I_L = ______ A ac

f. Open all of the load switches.

g. Return the voltage to zero and turn off the power supply.

☐ 9. a. Using the results of procedure 8 calculate each of the 120 Hz load values.

$R = E_1 / I_R$ = ______ Ω

$X_C = E_1 / I_C$ = ______ Ω

$X_L = E_1 / I_L$ = ______ Ω

b. Compare your calculated 120 Hz load values with your calculated 60 Hz load values from procedure 3 and explain the difference.

____

____

____

____

____

☐ 10. Connect the load circuit of Figure 16-2 to the 75 V ac output of the rotary converter, terminals 7 and 9 as shown in Figure 16-4.

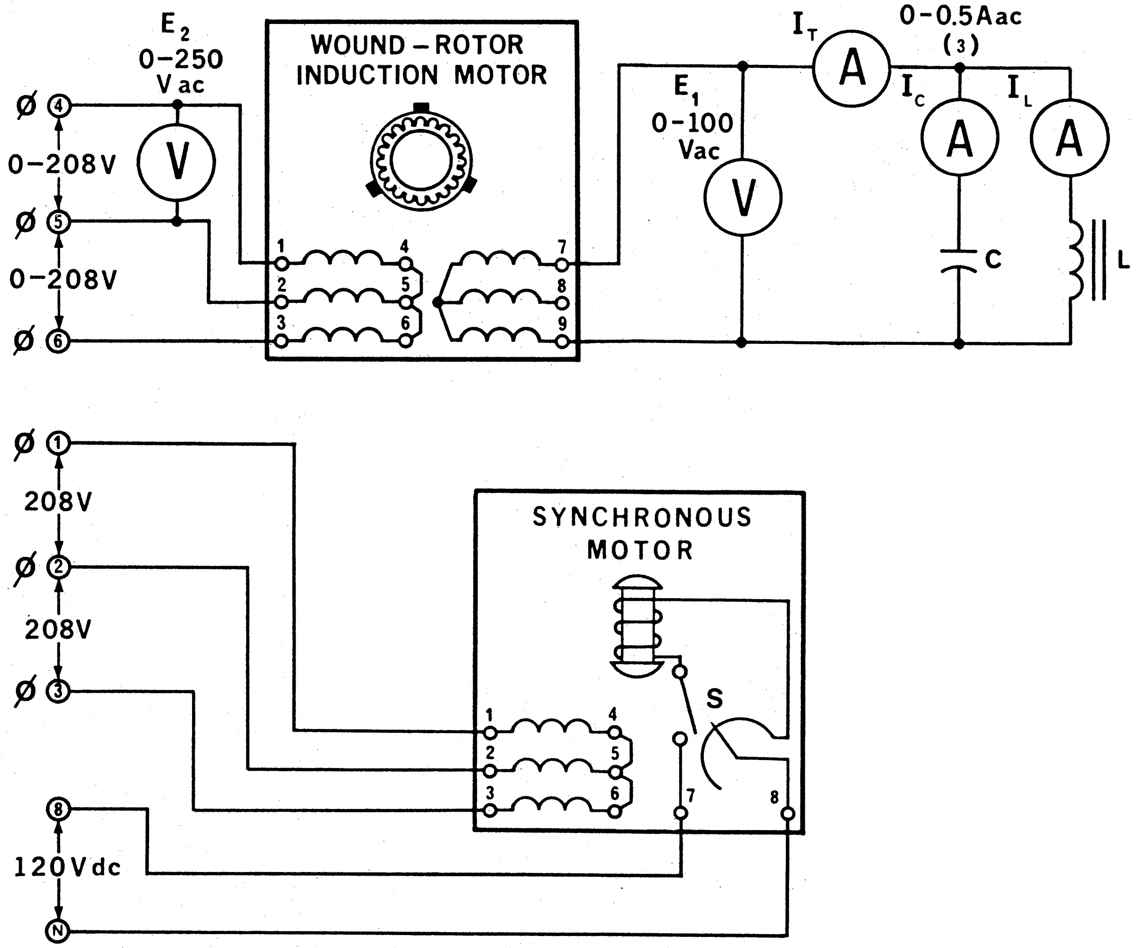


Figure 16-4.

a. Open both load switches.

b. Turn on the power supply and adjust the power supply control knob until the load voltage E_1 = 75 V ac.

c. Adjust the capacitance load for a 60 Hz reactance of 1200 Ω. What is the 120 Hz reactance?

d. Adjust the inductance load for a 60 Hz reactance of 300 Ω. What is the 120 Hz reactance?

e. Adjust the power supply, if necessary, to maintain E_1 at 75 V ac.

f. Measure and record the total current, and each load current.

I_T = ______ A ac, I_C = ______ A ac, I_L = ______ A ac

g. Is there now a condition of parallel resonance?

☐ Yes ☐ No

h. Open the two load switches.

i. Return the voltage to zero and turn off the power supply.

REVIEW QUESTIONS

1. In this Experiment, did the change in frequency affect the value of the load:

   a) Resistance? ______

   b) Capacitance? ______

   c) Inductance? ______

   d) Capacitive reactance? ______

   e) Inductive reactance? ______

2. Does inductive reactance vary in direct proportion to frequency?

   ☐ Yes ☐ No

3. Does capacitive reactance vary in direct proportion to frequency?

   ☐ Yes ☐ No

4. In procedure 4, calculate the value of I_L, I_C and I_T for an applied voltage of 120 V ac at 240 Hz.

   I_L = ____

   ____

   ______________________________ = __________ A ac

I_C = ____

____

______________________________ = __________ A ac

I_T = ____

____

______________________________ = __________ A ac

Experiment 17

Selsyn Control

OBJECTIVE

- To show the principle of remote control using a Selsyn (self-synchronous) system.

DISCUSSION

A mechanical effort can be transmitted over a certain distance by the use of shafts and other mechanical linkages. Practical considerations militate against the transmission of mechanical power over great distances, and in such cases, remote control using Selsyn in particularly useful.

As an example, a Selsyn system permits the transmission and exact duplication of mechanical motion between widely separated locations using wires instead of a shaft. The basic system consists of a transmitter and a receiver connected together by wires and excited from an AC source.

The transmitter converts mechanical motion into an electrical signal, while the receiver converts the electrical signal into mechanical motion. The receiver and transmitter are actually wound rotor induction machines, having three-phase stators and single-phase AC power source, and the stator windings are simply connected to each other. The rotors will automatically line up together in the same position when they are excited. The respective voltages in all three phases are then identical, and no currents circulate in the stators.

However, if the rotor of the transmitter is turned through a small angle, the voltages induced in the stator windings of the transmitter are no longer identical to those in the receiver. This imbalance causes currents to circulate in the stator windings, which set up a magnetic field forcing the rotor of the receiver to take up the same position as the rotor of the transmitter.

Depending upon the size of the transmitter and receiver, forces of considerable magnitude can be transmitted over electric wires. In most cases, the Selsyn transmitter and receiver are small because only position information (radar antenna direction, wind direction, etc.) is transmitted.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

> **Note:** *You will need to borrow a Three-Phase Wound-Rotor Induction Motor from your neighbor to perform procedures 5 and 6.*

PROCEDURE

CAUTION!

High voltages are present in this Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement!

☐ 1. Using your Three-Phase Wound-Rotor Induction Motor and AC Voltmeter, connect the circuit shown in Figure 17-1. Note that rotor terminals 7 and 8 are connected to the variable 0-120 V ac output of the power supply, terminals 4 and N.

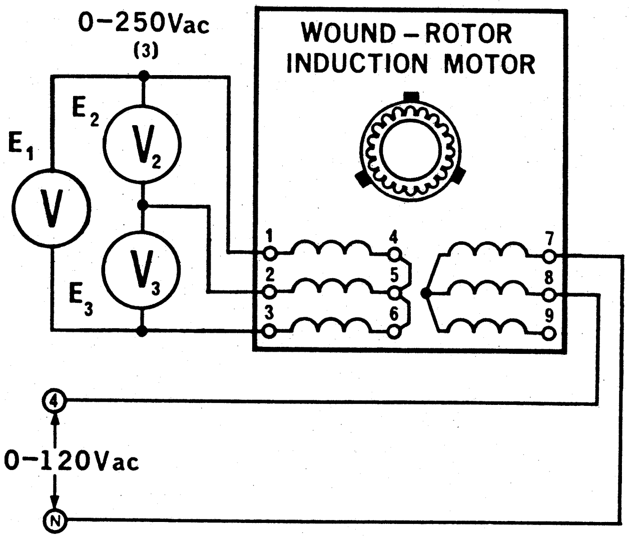


Figure 17-1.

☐ 2. a. Lower the front face of the motor module to enable you to turn the rotor shaft by hand.

b. Turn on the power supply and adjust to 50 V ac as indicated by the power supply voltmeter.

c. Note the three stator voltages E_1, E_2 and E_3.

d. Carefully reach in and slowly turn the rotor shaft by hand. Note how the three stator voltages change in value as the rotor is turned.

e. Turn the rotor shaft until E_1 is as its maximum value. Measure all three induced stator voltages.

E_1 = ______ V ac, E_2 = ______ V ac, E_3 = ______ V ac

f. Turn the rotor shaft until E_2 is at its maximum value. Measure all three induced stator voltages.

E_1 = ______ V ac, E_2 = ______ V ac, E_3 = ______ V ac

g. Return the rotor until E_3 is at is maximum value. Measure all three induced stator voltages.

E_1 = ______ V ac, E_2 = ______ V ac, E_3 = ______ V ac

h. Return the voltage to zero land turn off the power supply.

☐ 3. Connect the circuit shown in Figure 17-2. Note that there is a current meter in series with each of the stator windings.

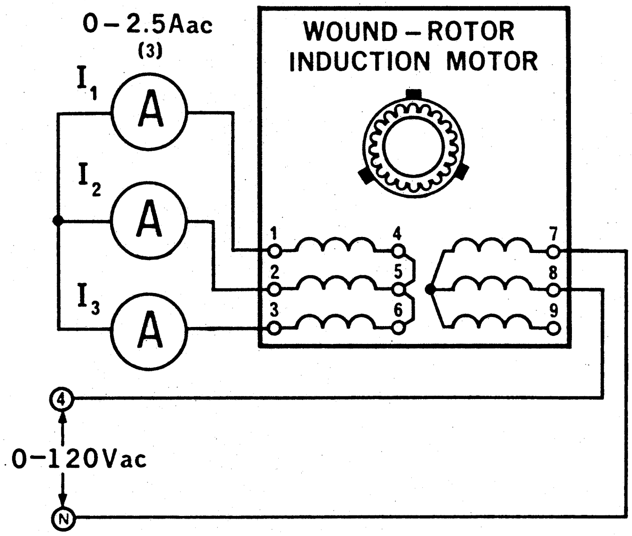


Figure 17-2.

☐ 4. a. Lower the front face of the motor module.

b. Turn on the power supply and adjust to 50 V ac as indicate by the power supply voltmeter.

c. Carefully reach in and turn the rotor shaft by hand. Note how the three stator currents change in value as the rotor is turned.

d. Turn the rotor shaft until I_1 is as its maximum value. Measure all three induced stator currents.

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

e. Turn the rotor shaft until I_2 is as its maximum value. Measure all three induced stator currents.

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

f. Turn the rotor shaft until I_3 is as its maximum value. Measure all three induced stator currents.

I_1 = ______ A ac, I_2 = ______ A ac, I_3 = ______ A ac

g. Return the voltage to zero and turn off the power supply.

☐ 5. Using two Three-Phase Wound-Rotor Induction Motor, connect the circuit shown in Figure 17-3. Note that the stator windings of each motor are connected to each other. The rotor windings are paralleled and connected to the variable 0-120 V ac output of the power supply terminals 4 and N.

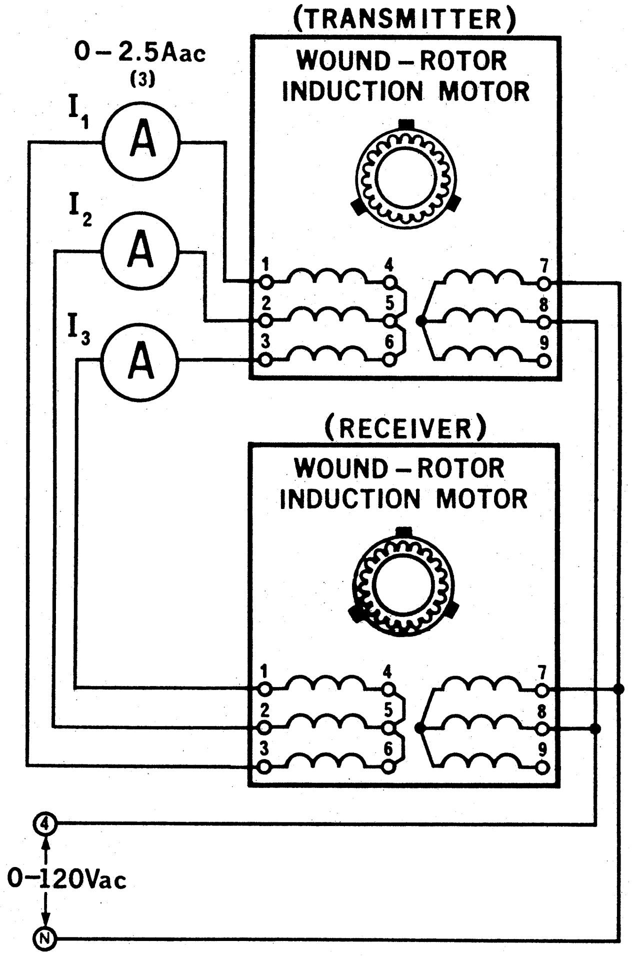


Figure 17-3.

☐ 6. a. Lower the front face of one of the motors (this motor will be the transmitter and the other motor will be the receiver).

b. Turn on the power supply and adjust to 100 V ac as indicated by the power supply voltmeter.

c. Carefully reach in and turn the rotor shaft of the transmitter and note that the rotor of the receiver follows in step.

d. Make one complete turn of the transmitter. Does the receiver also make one complete turn?

☐ Yes ☐ No

e. Lower the front face of the receiver module.

f. Carefully reach in and hold the rotor shaft of the receiver with your hand while turning the rotor shaft of the transmitter.

g. Is there appreciable torque developed?

☐ Yes ☐ No

h. Make a complete turn of the transmitter and note the behavior of the three stator currents while braking the rotor of the receiver with your hand.

____

____

____

i. Note that all three stator currents are zero when the rotors are lined up.

REVIEW QUESTIONS

1. Do you think that your experimental transmitter and receiver would operate well at a separating distance of 10 meters? 100 meters? 1000 meters? Explain.

☐ Yes ☐ No

____

____

____

2. In the space provided, draw a sketch showing a means of transmitting the instantaneous angular position of a revolving radar antenna to an indicator in a remotely located control room. Label all parts and wiring.

3. Name at least four applications where Selsyns can be used.

Appendix A

Equipment Utilization Chart

MODEL	EQUIPMENT[1]	ELECTRICAL POWER TECHNOLOGY EXPERIMENT																	
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
8110	Mobile Workstation	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8211	DC Motor/Generator			1	1								1	1	1				
8221	Four-Pole Squirrel-Cage Induction Motor							1				1				1	1		
8231	Three-Phase Wound-Rotor Induction Motor				1	1	1										1	1	2[3]
8241	Three-Phase Synchronous Motor/Generator								1	1	1	1	1	1	1	1	1	1	
8311	Resistive Load												1				2[3]	1	
8321	Inductive Load												1					1	
8331	Capacitive Load												1					1	
8341	Single-Phase Transformer		3																
8412	DC Voltmeter/Ammeter			1						1	1	1	1		1	1			
8425	AC Ammeter				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8426	AC Voltmeter	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8441	Three-Phase Wattmeter				1		1	1		1	1				1		1		
8621	Synchronizing Module								1			1		1	1				
8641	Synchronous Motor Starter															1			
8651	Three-Phase Full-Voltage Starter															1			
8731	Three-Phase Rheostat						1												
8821	Power Supply	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8911[2]	Electrodynamometer			1		1	1	1	1		1					1			
8920	Digital Tachometer			1	1		1	1	1				1	1	1		1		
8942	Timing Belt			1	1	1	1	1	1		1	1	1	1	1	1	1	1	
8951	Connection Leads	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

[1] The module storage facilities Storage Cabinet have not been included in this chart.

[2] The electrodynamometer Module EMS 8911 may be replaced by a Prony Brake Module EMS 8913.

[3] These experiments must be performed by two groups in collaboration.

Appendix B

Impedance Table for the Load Modules

The following table gives impedance values which can be obtained using either the Resistive Load, Model 8311, the Inductive Load, Model 8321, or the Capacitive Load, Model 8331. Figure B-1 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

IMPEDANCE (Ω)			SWITCH POSITIONS FOR LOAD ELEMENTS								
120 V 60 Hz	**220 V 50 Hz**	**240 V 50 Hz**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1200	4400	4800	I								
600	2200	2400		I							
300	1100	1200			I						
400	1467	1600	I	I							
240	880	960	I		I						
200	733	800		I	I						
171	629	686	I	I	I						
150	550	600	I			I	I	I			
133	489	533		I		I	I	I			
120	440	480			I		I	I			
109	400	436			I	I	I	I			
100	367	400	I		I	I	I	I			
92	338	369		I	I	I	I	I			
86	314	343	I	I	I	I	I	I			
80	293	320	I			I	I	I	I	I	I
75	275	300		I		I	I	I	I	I	I
71	259	282			I		I	I	I	I	I
67	244	267			I	I	I	I	I	I	I
63	232	253	I		I	I	I	I	I	I	I
60	220	240		I	I	I	I	I	I	I	I
57	210	229	I	I	I	I	I	I	I	I	I

Table B-1. Impedance table for the load modules.

Impedance Table for the Load Modules (cont'd)

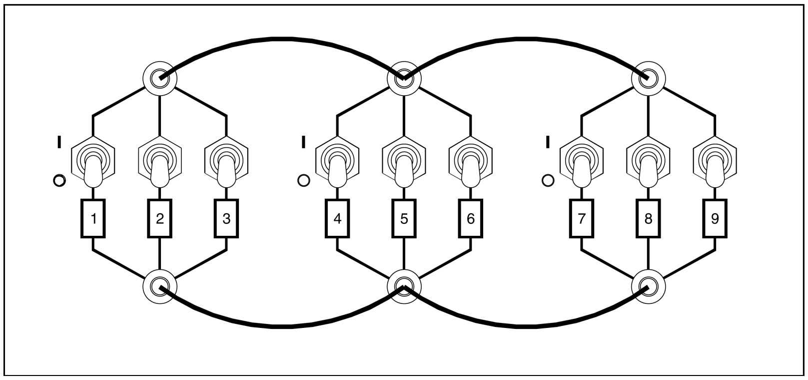


Figure B-1. Location of the load elements.

Appendix C

Performing the Electrical Power Technology Courseware Using the Lab-Volt Data Acquisition and Management System

The exercises in the *Electric Power / Controls* courseware have been designed to be performed using conventional instruments (AC/DC voltmeters and ammeters, power meters, etc). All these exercises can also be carried out using the Lab-Volt Data Acquisition and Management (LVDAM) System.

The LVDAM System consists of the Data Acquisition Interface (DAI) module, model 9062, and the corresponding LVDAM software. The system includes a user manual (p.n. 30328-EX) designed to familiarize users with the operation of the LVDAM System.

The Electrodynamometer (model 8911) and Precision Hand Tachometer (model 8920) are replaced in the LVDAM System by the Prime Mover / Dynamometer module (model 8960). In some exercises, the Prime Mover / Dynamometer module can also replace the Synchronous Motor/Generator (model 8241) to drive rotating machines mechanically. Refer to the manual titled *AC/DC Motors and Generators* (p.n. 30329) to familiarize yourself with the operation of the Prime Mover / Dynamometer module.

When performing the *Electric Power / Controls* courseware with the LVDAM System, the following guidelines should be taken into account:

- The "AC and DC voltmeters" are implemented using the high-voltage inputs E1, E2, and E3 of the DAI module. The voltage values are displayed on meters E1, E2, and E3 in the Metering application of the LVDAM System.

- The "AC and DC ammeters" are implemented using the high-current inputs I1, I2, and I3 of the DAI module. The current values are displayed on meters I1, I2, and I3 in the Metering application of the LVDAM System.

- The "Single-Phase Wattmeter" (model 8431) is implemented using one high-voltage input combined with one high-current input. This can be done using the inputs E1 with I1, E2 with I2, and E3 with I3 of the DAI module. The power values are displayed on meters PQS1, PQS2, and PQS3 in the Metering application of the LVDAM System.

  Note that the voltage and current values used in the power measurements can be displayed on the voltage and current meters in the Metering application of the LVDAM System. This is a useful feature which, in certain cases, can reduce the number of inputs required to measure the various parameters in a circuit. As an example, in a circuit where the line-to-line voltage is measured using input E1, it would be a wise choice to use inputs E1 and I1 to measure single-phase power in this circuit. This would prevent the line-to-line voltage from being measured twice and using two voltage inputs.

- The "Three-Phase Wattmeter" (model 8441) is implemented using two "wattmeters" (each of them being implemented using one high-voltage input combined with one high-current input). This can be done using inputs E1 with I1 to produce P1, E2 with I2 to produce P2, and E3 with I3 to produce P3. The power values are displayed on meters PQS1, PQS2, or PQS3 in the Metering application of the LVDAM System. As an example, using inputs E1 with I1 and E3 with I3, and selecting functions PQS1 and PQS3, allow one to measure W1 and W2 present on the Three-Phase Wattmeter.

EXERCISES WHERE THE NUMBER OF AVAILABLE INPUTS IS EXCEEDED

In some exercises of the *Electric Power / Controls* courseware, four or five high-current inputs are required to perform all current measurements. Unfortunately, only three high-current inputs are available in the LVDAM system.

In the exercises where it is asked to measure the currents I_F, I_A, and the line currents I_1, I_2, and I_3, the number of available inputs is exceeded. Since the line currents are usually measured only to make sure that the motor operation is normal, you may consider measuring only one line current (or all but one at the same time).

In some exercises, the implementation of the Single-Phase Wattmeter, or Three-Phase Wattmeter, using high-voltage and high-current inputs also causes the number of available inputs to be exceeded.

The exercises where the number of available inputs is exceeded are listed below. A solution is also suggested for each case.

- **The DC Separately-Excited Shunt Generator**

  In the circuits of Figures 1, 2 and 3, use input I1 to measure current I_F, input I2 to measure current I_A, and input I3 to measure line current I_3.

- **The DC Self-Excited Shunt Generator**

  In the circuits of Figures 1 and 2, use input I1 to measure current I_A, and inputs I2 and I3 to measure line currents I_2 and I_3.

- **The DC Compound Generator**

  In the circuits of Figures 1 and 2, use input I1 to measure current I_A, and inputs I2 and I3 to measure line currents I_2 and I_3.

- **The DC Series Generator**

  In the circuits of Figures 4 and 5, use input I1 to measure current I_A, and inputs I2 and I3 to measure line currents I_2 and I_3.

- **Transformers in Parallel**

  In the circuit of Figure 1, the implementation of the Single-Phase Wattmeter using one high-voltage input and one high-current input from the LVDAM System increases the number of required high-current inputs to four.

  Use a programmable meter programmed to calculate I1 + I2 to measure the load current I_L ($I_1 + I_2 = I_L$ in this circuit).

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- **Frequency Conversion**

  In the circuits of Figures 1 and 2, the implementation of the Three-Phase Wattmeter using two high-voltage inputs and two high-current inputs from the LVDAM system increases the number of required high-current inputs to four.

  Use inputs E1-I1 and E3-I3 to implement the Three-Phase Wattmeter. In step 3d, use temporarily input I3 (currently used in the power measurement circuit) to adjust the DC excitation of the synchronous motor. Once the adjustment is completed, return input I3 in the power measurement circuit.