

# Three-Phase Rotating Machines

FESTO

FESTO

Electricity and New Energy

LabVolt Series

Student Manual



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Student Manual

Three-Phase Rotating Machines

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**Electricity and New Energy**

# **Three-Phase Rotating Machines**

**Student Manual**

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By the staff of Festo Didactic

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# Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
	<b>DANGER</b> indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	<b>WARNING</b> indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	<b>CAUTION</b> indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	<b>CAUTION</b> used without the <i>Caution, risk of danger</i> sign  , indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

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# Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

# Table of Contents

Preface .....	IX
About This Manual .....	XI
<b>Unit 1</b>	<b>Fundamentals for Rotating Machines..... 1</b>
	DISCUSSION OF FUNDAMENTALS..... 1
	Basic motor operation ..... 1
	The rotating electromagnet principle ..... 3
	The generator principle ..... 7
	Work, torque, and power ..... 10
	Work..... 10
	Torque..... 10
	Power..... 11
<b>Ex. 1-1</b>	<b>Prime Mover and Brake Operation..... 13</b>
	DISCUSSION..... 13
	Introduction to the Four-Quadrant Dynamometer/Power Supply..... 13
	Two-quadrant, constant-torque brake ..... 13
	Clockwise constant-speed prime mover/brake..... 14
	Counterclockwise constant-speed prime mover/brake..... 15
	Speed, torque, and mechanical power measurements using the Four-Quadrant Dynamometer/Power Supply ..... 16
	Motor operation..... 16
	Generator operation..... 16
	PROCEDURE ..... 17
	Set up and connections..... 17
	Two-quadrant, constant-torque brake operation ..... 19
	Constant-speed prime mover operation ..... 21
	Constant-speed prime mover driving a generator..... 24
<b>Unit 2</b>	<b>Three-Phase Squirrel-Cage Induction Machines..... 31</b>
	DISCUSSION OF FUNDAMENTALS..... 31
	Introduction to ac motors..... 31
<b>Ex. 2-1</b>	<b>The Three-Phase Squirrel-Cage Induction Motor ..... 35</b>
	DISCUSSION..... 35
	Three-phase squirrel-cage induction motor operation ..... 35
	Relationship between speed and torque in three-phase squirrel-cage induction motors ..... 39
	Efficiency of three-phase squirrel-cage induction motors ..... 41
	Relationship between reactive power, power factor, and motor efficiency in three-phase squirrel-cage induction motors..... 42
	High-efficiency motors..... 43

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# Table of Contents

	PROCEDURE .....	44
	Set up and connections.....	45
	Three-phase induction motor no-load and full-load operation.....	47
	Three-phase induction motor operation characteristics .....	49
	Three-phase induction motor direction of rotation.....	53
<b>Ex. 2-2</b>	<b>Eddy-Current Brake and Asynchronous Generator .....</b>	<b>57</b>
	DISCUSSION.....	57
	Eddy-current brake operation .....	57
	Three-phase squirrel-cage induction machine operating as an asynchronous generator.....	59
	PROCEDURE .....	61
	Set up and connections.....	61
	Three-phase induction machine operating as an eddy- current brake .....	63
	Three-phase induction machine operating as a motor .....	66
	Three-phase induction machine operating as an asynchronous generator.....	68
<b>Unit 3</b>	<b>Synchronous Motors .....</b>	<b>75</b>
	DISCUSSION OF FUNDAMENTALS .....	75
	Introduction to synchronous motors .....	75
<b>Ex. 3-1</b>	<b>The Three-Phase Synchronous Motor .....</b>	<b>79</b>
	DISCUSSION.....	79
	Three-phase synchronous motor operation .....	79
	PROCEDURE .....	81
	Set up and connections.....	81
	Starting a three-phase synchronous motor .....	83
	Characteristics of a three-phase synchronous motor.....	86
<b>Ex. 3-2</b>	<b>Synchronous Motor Pull-Out Torque.....</b>	<b>91</b>
	DISCUSSION.....	91
	Synchronous motor pull-out torque definition and characteristics.....	91
	PROCEDURE .....	92
	Set up and connections.....	92
	Synchronous motor pull-out torque .....	95

# Table of Contents

<b>Unit 4</b>	<b>Synchronous Generators (Alternators).....</b>	<b>101</b>
	DISCUSSION OF FUNDAMENTALS.....	101
	Introduction to three-phase synchronous generators.....	101
<b>Ex. 4-1</b>	<b>Three-Phase Synchronous Generator No-Load Operation ...</b>	<b>105</b>
	DISCUSSION.....	105
	Characteristics of a three-phase synchronous generator operating without load .....	105
	PROCEDURE .....	107
	Set up and connections.....	107
	Three-phase synchronous generator no-load operation.....	109
	Three-phase synchronous generator characteristics.....	111
<b>Ex. 4-2</b>	<b>Voltage Regulation Characteristics .....</b>	<b>119</b>
	DISCUSSION.....	119
	Equivalent circuit of a three-phase synchronous generator..	119
	Voltage regulation characteristics of three-phase synchronous generators .....	120
	Voltage regulation calculations for a resistive load .....	121
	Voltage regulation calculations for an inductive load .....	122
	Voltage regulation calculations for a capacitive load.....	122
	PROCEDURE .....	124
	Set up and connections.....	124
	Three-phase synchronous generator voltage regulation characteristic for resistive, inductive, and capacitive loads...	127
	Voltage regulation characteristic when the three-phase synchronous generator supplies power to a resistive load.....	127
	Voltage regulation characteristic when the three-phase synchronous generator supplies power to an inductive load....	128
	Voltage regulation characteristic when the three-phase synchronous generator supplies power to a capacitive load....	130
<b>Ex. 4-3</b>	<b>Generator Synchronization.....</b>	<b>133</b>
	DISCUSSION.....	133
	Introduction to generator synchronization .....	133
	Manual synchronization of a synchronous generator.....	134
	Electrical transient and mechanical stress at generator synchronization.....	136
	Generator operation after synchronization to an ac power network .....	138
	Synchronous generator active power control after synchronization .....	139
	Synchronous generator reactive power control after synchronization .....	140

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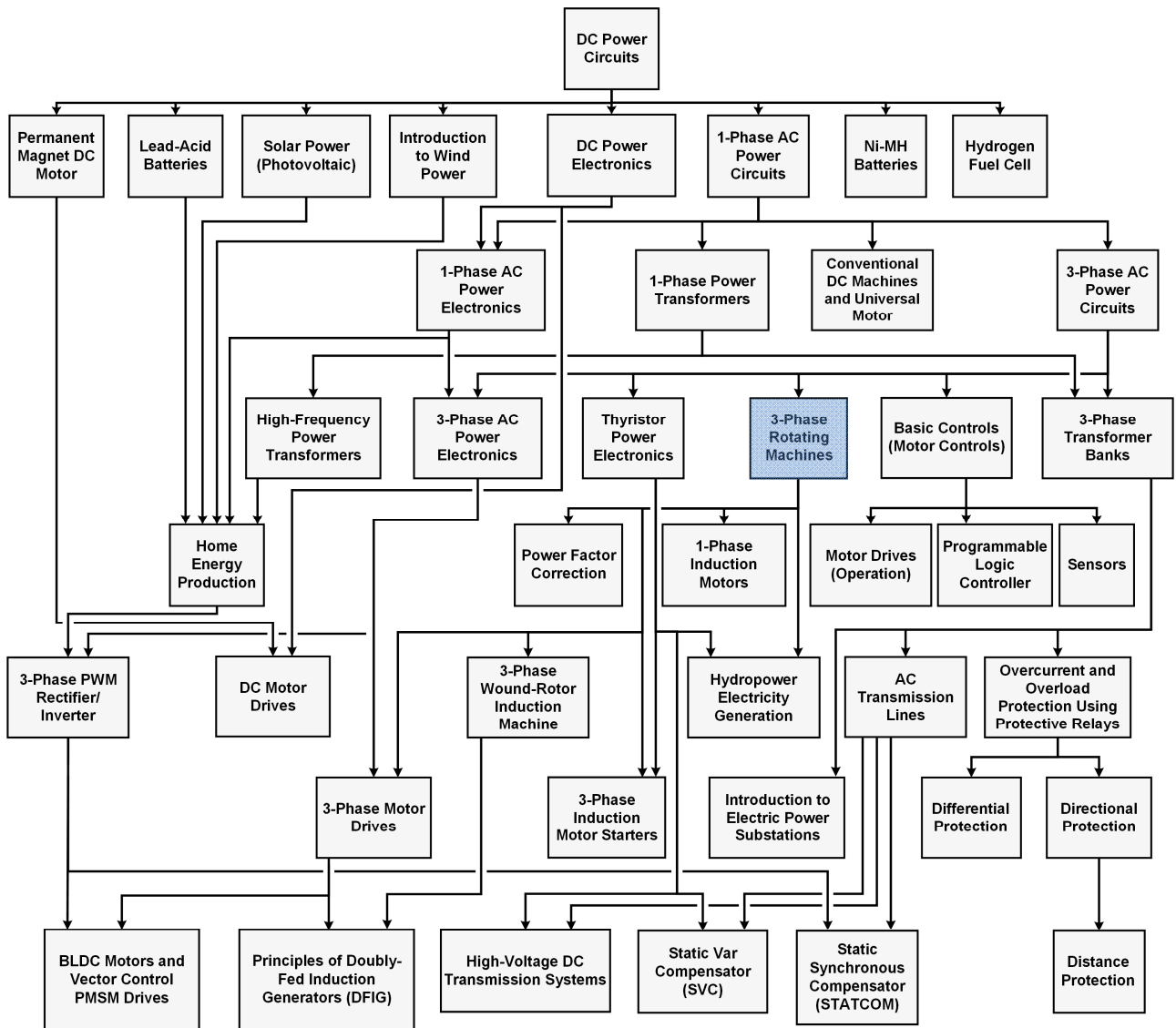
# Table of Contents

PROCEDURE .....	143
Set up and connections.....	144
Generator manual synchronization .....	147
Generator transients and mechanical stress at synchronization.....	153
Generator operation after synchronization to the ac power network .....	158
 <b>Appendix A Equipment Utilization Chart.....</b>	<b>165</b>
 <b>Appendix B Glossary of New Terms .....</b>	<b>167</b>
 <b>Appendix C Impedance Table for the Load Modules .....</b>	<b>171</b>
 <b>Appendix D Circuit Diagram Symbols .....</b>	<b>173</b>
 Index of New Terms .....	179
Bibliography .....	181

# Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



## The Electric Power Technology Training Program.

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# Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to [did@de.festo.com](mailto:did@de.festo.com).

The authors and Festo Didactic look forward to your comments.

# About This Manual

Rotating machines such as electrical motors and generators (or alternators) are found in almost every sector of industry. The basic principles of operation of rotating machines have been known for almost two centuries. Rotating machines operate due to the interaction between magnetic fields and current-carrying conductors, and are split into two basic categories: motors and generators.

Three-phase motors are machines that convert three-phase ac power into mechanical power. They are used in a wide array of applications, such as pumps, fans, blowers, compressors, and conveyor drives. Two types of three-phase motors are covered in this manual: the three-phase squirrel-cage induction motor and the three-phase synchronous motor.

Three-phase squirrel-cage induction motors are the most widely used motors in industry today. They are simple to use, do not require much maintenance, and can develop high torque. Three-phase synchronous motors, on the other hand, are mainly used due to their ability to rotate at a fixed speed (i.e., at the synchronous speed). However, they require external assistance to start properly.

Three-phase generators (or alternators) are machines that convert mechanical power into three-phase ac power. They are used worldwide in hydroelectric, diesel, coal-fired, and nuclear power plants, as well as in wind turbines. A type of three-phase generator used widely is the three-phase synchronous generator. Three-phase synchronous generators are basically three-phase synchronous machines operating at the synchronous speed and driven by a prime mover (e.g., a water turbine, a steam turbine, a wind turbine).



**Generators (or alternators) have been used to generate ac power for more than a century.**

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# About This Manual

This manual, *Three-Phase Rotating Machines*, familiarizes the student with the various three-phase machines used in commercial and industrial motor applications, as well as for large-scale production of electricity from wind power, hydropower, etc. The course begins with fundamentals of rotating machines such as the torque, rotation speed, direction of rotation, motor power, power losses in motor, motor efficiency, etc. The student then studies the operation (both as a motor and a generator) of the following three-phase machines: squirrel-cage induction machine and synchronous machine.

## **Safety considerations**

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

## **Prerequisite**

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, part number 86350, *Single-Phase AC Power Circuits*, part number 86358, and *Three-Phase AC Power Circuits*, part number 86360.

## **Systems of units**

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

## Fundamentals for Rotating Machines

### UNIT OBJECTIVE

When you have completed this unit, you will be familiar with the basic operation of motors and generators. You will know how to calculate the work, torque, and power produced in a system. You will also be familiar with the basic functions of the Four-Quadrant Dynamometer/Power Supply used in this manual. You will be able to determine the polarity of the speed, torque, and mechanical power measured for a machine operating as either a motor or a generator.

### DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Basic motor operation
- The rotating electromagnet principle
- The generator principle
- Work, torque, and power

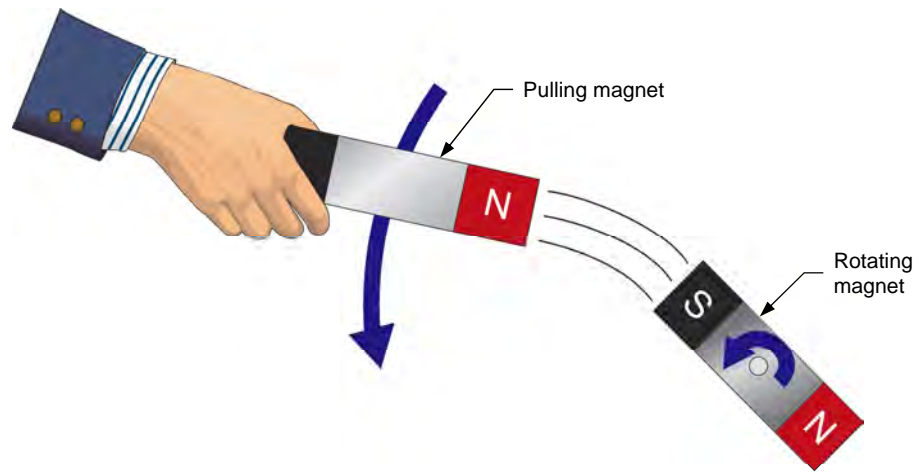
### DISCUSSION OF FUNDAMENTALS

#### Basic motor operation

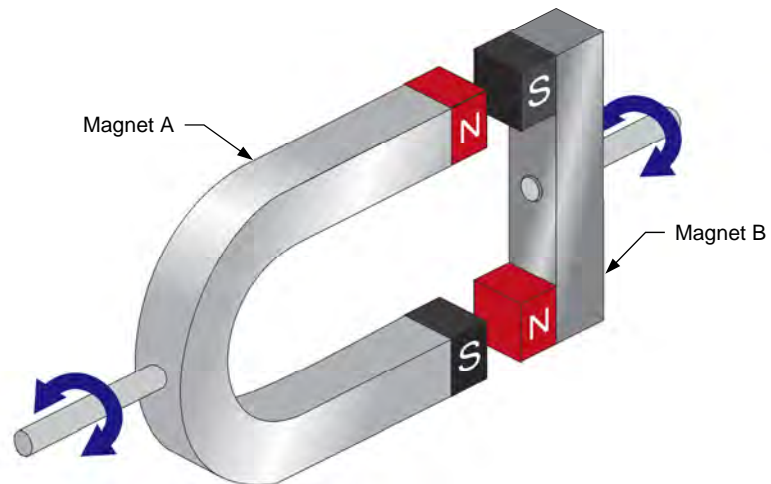
Everyone is familiar with some type of **electric motor** or another, whether it is the tiny **dc motor** in battery-operated toys, the dc starter motor in automobiles, or the **ac motor** in washing machines and clothes dryers. Electric motors are also used in fans, electric drills, pumps and many other familiar devices. But how and why do these motors work, and why do they turn? The answer is surprisingly simple: it is due to the interaction between two magnetic fields.

If you take two magnets and fix one of them on a shaft so that it can rotate, and then move the second magnet (pulling magnet) in a circle around the first, the rotating magnet will be pulled along by the **magnetic force** of attraction between the two, as shown in Figure 1-1a. As a result, the rotating magnet will rotate in synchronization with the pulling magnet.

The interaction between two magnets is shown more realistically in Figure 1-1b. In the figure, magnets A and B can both rotate freely on the same axis. When magnet A is turned, magnet B follows, and vice-versa, due to the magnetic attraction between the two.



(a) Rotating magnet pulled along as another magnet rotates around it



(b) Interaction between two rotating magnets

**Figure 1-1. Interacting magnetic forces cause motor rotation.**

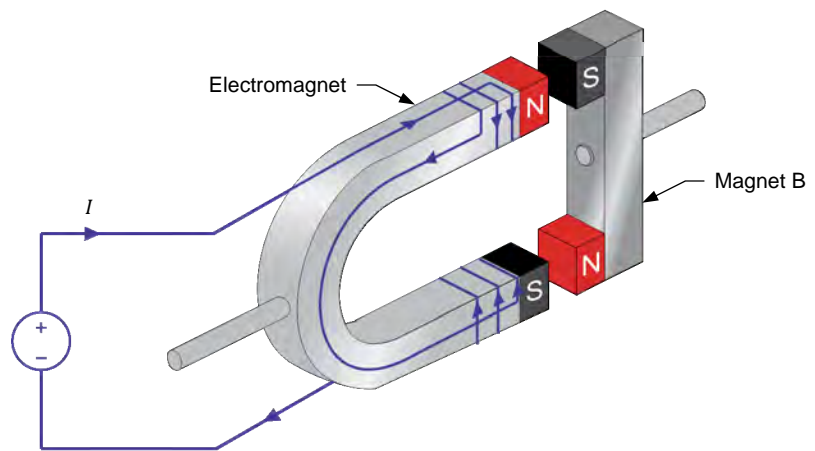
### The rotating electromagnet principle



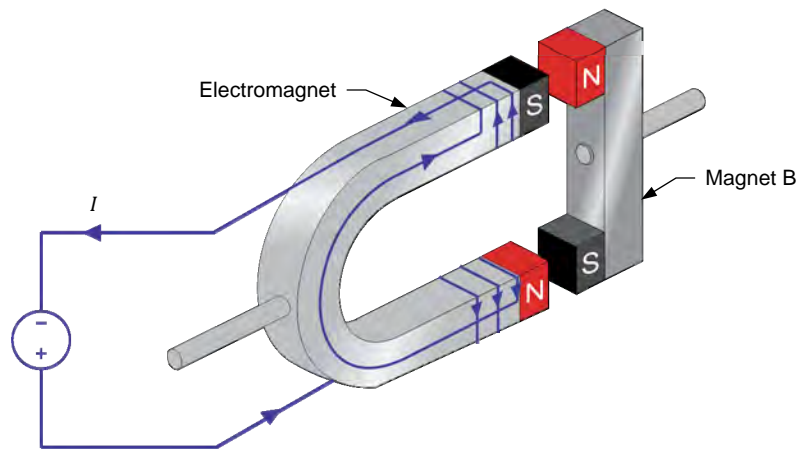
Figure 1-2. The English physicist Michael Faraday is generally credited with the discovery of electromagnetic induction.

Figure 1-3a shows how magnet A from Figure 1-1b can be used to make an **electromagnet**. First, a coil of wire is wrapped around the iron core of the magnet. The ends of the coil are then connected to a dc power source in order to make current flow in the coil, thus producing a north **magnetic pole** and a south magnetic pole. Due to these induced magnetic poles, magnet A has become an electromagnet.

When the electromagnet in Figure 1-3 is rotated manually, it causes magnet B to rotate, like the two magnets in Figure 1-1. At first glance, this setup offers no advantage because a first object (the electromagnet) must still be rotated in order to cause a second object (magnet B) to rotate. Furthermore, to prevent the leads interconnecting the dc power source and the electromagnet from twisting, the source would have to rotate with the electromagnet, which would not be convenient.



(a)



(b)

Figure 1-3. Electric current flow produces an electromagnet.



However, if the polarity of the dc power source is reversed as in Figure 1-3b, the positions of the north and south poles on the electromagnet are interchanged, causing magnet B to rotate one half turn. As you can see, inverting the direction of current flow in the electromagnet causes magnet B to rotate without having to rotate the electromagnet. By combining two electromagnets, two dc power sources, and continually inverting the voltage and polarity of the dc power sources, it is thus possible to make magnet B rotate in a given direction without having to move the electromagnet. Figure 1-4 shows how the electromagnet of Figure 1-3 can be modified to achieve this. When the currents  $I_1$  and  $I_2$  that flow in the two electromagnets alternate as shown in Figure 1-4, the magnetic poles created in the electromagnets change polarity in succession. The resulting sequence of attraction and repulsion between the magnets makes the rotating magnet rotate in the clockwise direction. Current switching has thus resulted in the electrical equivalent of a rotating magnet. This is the operating principle of all motors.

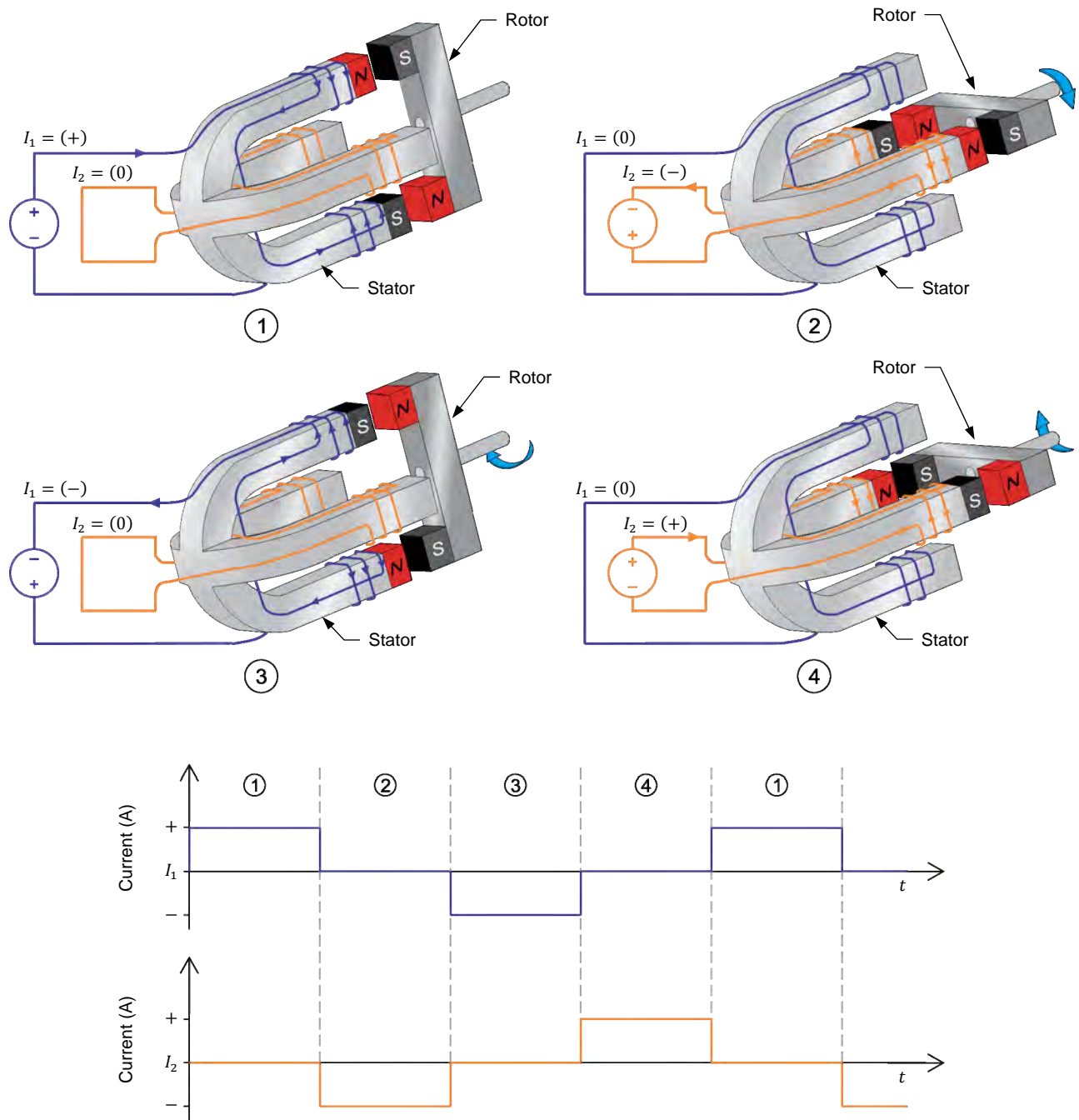
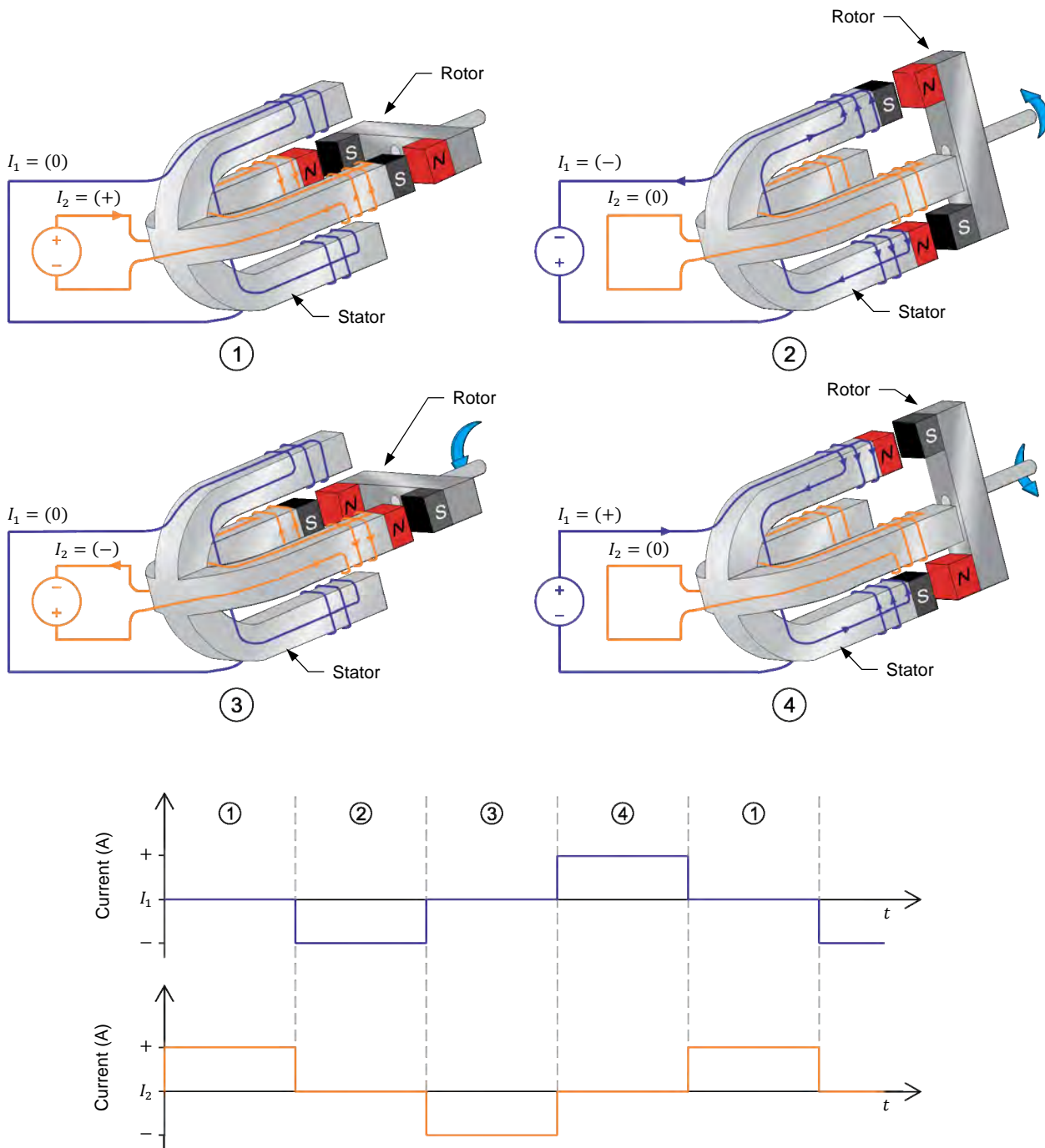


Figure 1-4. Electromagnet causing a magnet to rotate in the clockwise direction and graphs of the currents flowing in the electromagnet at each instant.

The direction of rotation of the rotating magnet can be reversed by interchanging currents  $I_1$  and  $I_2$ , as Figure 1-5 shows.



**Figure 1-5. Electromagnet causing a magnet to rotate in the counterclockwise direction and graphs of the currents flowing in the electromagnet at each instant.**

The machine shown in Figure 1-4 and Figure 1-5 converts electrical energy (i.e., the energy produced by the dc power source) into mechanical energy (i.e., the energy of the rotating magnet) and is called a motor.

A motor basically consists of two main components: a **stator** (the electromagnet) and a **rotor** (the rotating magnet). The stator is the motor component producing the electromagnetic field. As its name implies, a stator does not move in relation to the other motor components. The rotor, on the other hand, is the motor component that rotates along or inside the stator, thus producing mechanical work.

### The generator principle

The operation of **electric generators** (or alternators) is based on Faraday's law of **electromagnetic induction**, which states the following:

1. A voltage is induced between the terminals of a wire loop if the magnetic flux passing through the loop varies as a function of time.
2. The value of the induced voltage is proportional to the rate of change of the magnetic flux.



**Figure 1-6.** Most of the electricity worldwide is produced by three-phase synchronous generators. The above picture shows the Three-Gorges Dam hydropower plant, on the Yangtze River, in China. It contains thirty 700 MW three-phase synchronous generators, each weighing about 6 000 000 kg (about 6000 tons).

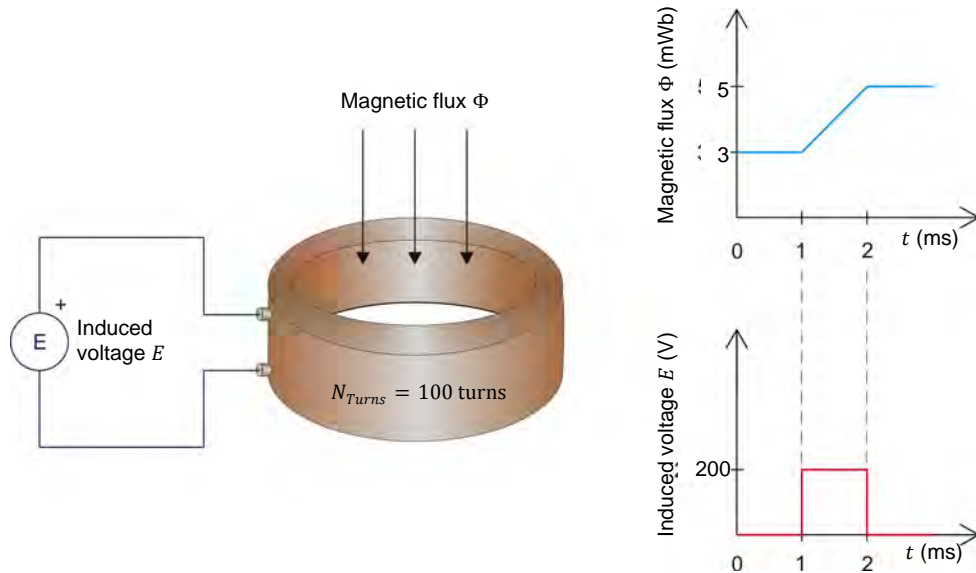
The voltage induced between the terminals of a wire loop when the magnetic flux passing through the loop varies can be calculated using the following equation:

$$E = N_{Turns} \frac{\Delta\Phi}{\Delta t} \quad (1-1)$$

In Equation 1-1, the polarity of the induced voltage is not taken into account as it is not important for the purpose of this discussion.

where  $E$  is the magnitude of the voltage induced between the terminals of a wire loop, expressed in volts (V).  
 $N_{Turns}$  is the number of turns of wire in the loop.  
 $\Delta\Phi$  is the variation in intensity of the magnetic flux passing through the wire loop, expressed in webers (Wb).  
 $\Delta t$  is the time interval during which the magnetic flux variation occurs, expressed in seconds (s).

Figure 1-7 gives an example of the voltage induced in a wire loop that is exposed to a magnetic flux varying in intensity.



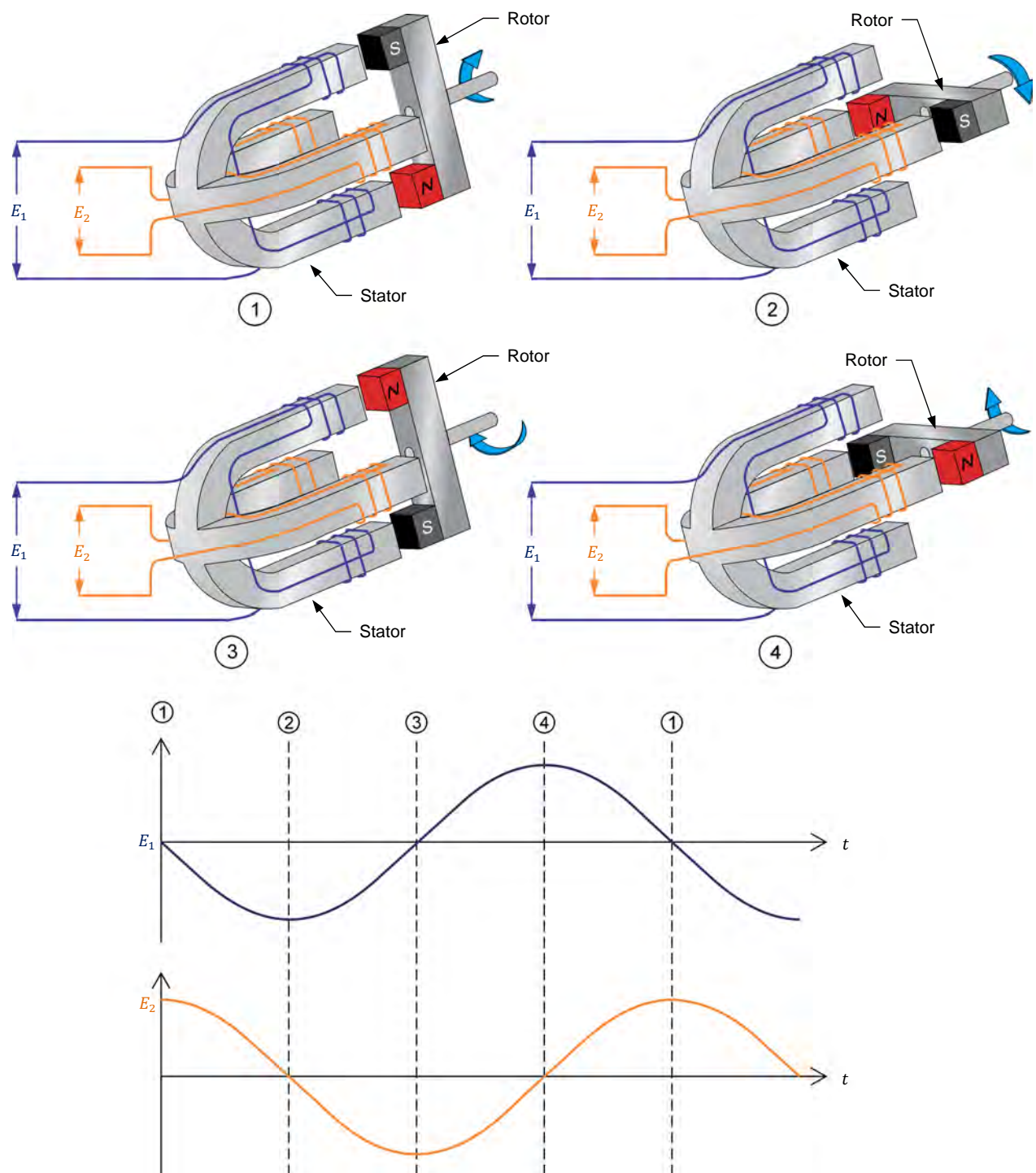
**Figure 1-7.** Voltage induced in a wire loop that is exposed to a magnetic flux varying in intensity.

Using the values given in Figure 1-7, the voltage  $E$  induced in the coil is equal to:

$$E = N_{Turns} \frac{\Delta\Phi}{\Delta t} = 100 \text{ turns} \frac{0.005 \text{ Wb} - 0.003 \text{ Wb}}{0.001 \text{ s}} = 200 \text{ V}$$

The principle of operation of a generator can be illustrated using the electromagnet and the rotating magnet of Figure 1-4 and Figure 1-5. If the rotating magnet (i.e., the rotor) is turned manually, a magnetic field variation is created in the electromagnet (i.e., the stator). Following Faraday's law of electromagnetic induction, this magnetic field variation will induce a variable voltage in the conductors wound around the stator, as shown in Figure 1-8.





**Figure 1-8. Generator operation and resulting voltage waveforms induced across the stator windings at each instant.**

The machine shown in Figure 1-8 converts mechanical energy (i.e., the energy of the rotating magnet) into electrical energy (i.e., the energy of the voltage induced across the stator conductors) and is called a generator (or alternator).

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## Work, torque, and power

### Work

The mechanical work  $W$  that is done when a force  $F$  moves an object over a distance  $d$  can be calculated using the following equation:

$$W = Fd \quad (1-2)$$

where  $W$  is the mechanical work done by the force, expressed in joules (J) or in pound-force inches (lbf·in).

$F$  is the magnitude of the force moving the object, expressed in newtons (N) or in pound-forces (lbf).

$d$  is the distance over which the force moves the object, expressed in meters (m) or in inches (in).

Figure 1-9 shows the example of a block that is moved over a distance  $d$  of 1 m (39.4 in) by a force  $F$  of 1 N (0.22 lbf). Using Equation (1-2), it can be calculated that a mechanical work  $W$  of 1 J (8.85 lbf·in) has been done.

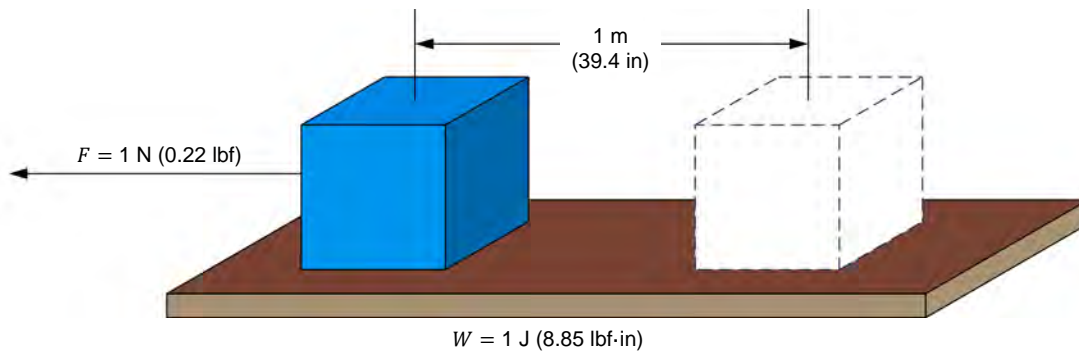


Figure 1-9. Work required to move a block.

### Torque

Consider now that the block in Figure 1-9 is moved over the same distance using a pulley that has a radius  $r$ , as shown in Figure 1-10.

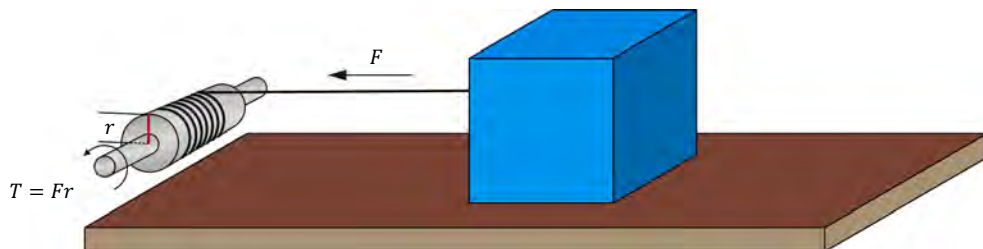


Figure 1-10. Moving a block using a pulley.

A twisting force must be applied on the pulley shaft to make it rotate so that the rope wound around the pulley shaft pulls the block with a force  $F$ . This twisting force is known as the **torque**  $T$  and is defined by the following equation:

$$T = Fr \quad (1-3)$$

where  $T$  is the torque exerted on the pulley shaft, expressed in newton-meters (N·m) or in pound-force inches (lbf·in).

$F$  is the magnitude of the force acting on the pulley shaft, expressed in newtons (N), or in pound forces (lbf).

$r$  is the radius of the pulley, expressed in meters (m) or in inches (in).

At the end of each complete rotation of the pulley, the block has been pulled a distance of  $(2\pi \times r)$  m or in, meaning that  $(2\pi \times r \times F)$  J or lbf·in of work has been done. Since  $T = F \times r$ , the amount of work  $W$  done in one revolution can be expressed as  $(2\pi \times T)$  J or lbf·in.

### **Power**

Power  $P$  is defined as the rate of doing work, and it is calculated using the following equation when the work  $W$  is expressed in joules.

$$P = \frac{W}{t} \quad (1-4)$$

where  $P$  is the power of the device doing the work, expressed in watts (W).

$W$  is the amount of work done, expressed in joules (J).

$t$  is the time taken to do the work, expressed in seconds (s).

In Equation (1-5) and Equation (1-7), the term  $1/8.85$  is used to convert the work  $W$ , expressed in pound-force inches (lbf·in), into a work  $W$ , expressed in joules (J).

When work  $W$  is expressed in pound-force inches (lbf·in), the following equation must be used to calculate the power  $P$ :

$$P = \frac{W}{t} \frac{1}{8.85} = \frac{W}{8.85t} \quad (1-5)$$

where  $W$  is the amount of work done, expressed in pound-force inches (lbf·in).

Since power is work done per unit of time, the power  $P$  of a motor turning at a **speed**  $n$ , can be found using the following equation when the torque  $T$  is expressed in newton-meters (N·m).



In Equation (1-6) and Equation (1-7), the term  $1/60 \text{ s}$  is used to convert the speed  $n$ , expressed in revolutions per minute (r/min), into a speed  $n$  expressed in revolutions per second (r/s).

$$P = n \frac{1 \text{ min}}{60 \text{ s}} 2\pi T = n \frac{1 \text{ min}}{9.55 \text{ s}} T = \frac{nT}{9.55} \quad (1-6)$$

where  $n$  is the motor speed of rotation, expressed in revolutions per minute (r/min).

When torque  $T$  is expressed in pound-force inches (lbf·in), the power  $P$  of the motor can be found using the following equation:

$$P = n \frac{1 \text{ min}}{60 \text{ s}} 2\pi T \frac{1}{8.85} = nT \frac{1 \text{ min}}{84.5 \text{ s}} = \frac{nT}{84.5} \quad (1-7)$$

It is possible to obtain the power  $P$ , expressed in horsepower (hp), for any given power  $P$ , expressed in watts (W), by dividing the power value in watts by 746.

## Prime Mover and Brake Operation

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the basic functions of the Four-Quadrant Dynamometer/Power Supply used in this manual. You will also be familiar with the polarity of the speed, torque, and mechanical power for a machine operating as either a motor or a generator.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to the Four-Quadrant Dynamometer/Power Supply
- Speed, torque, and mechanical power measurements using the Four-Quadrant Dynamometer/Power Supply

### DISCUSSION

#### Introduction to the Four-Quadrant Dynamometer/Power Supply

The Four-Quadrant Dynamometer/Power Supply module used in this manual consists of complex power electronics circuits, a microcontroller, and a permanent-magnet dc motor. The module can be used to implement a multitude of functions. All mechanical functions (i.e., all functions using the dc motor) enable the Four-Quadrant Dynamometer/Power Supply module to act as a **dynamometer**, i.e., to measure the torque created by the machine connected to it. The following three basic functions will be used to perform most of the exercises in this manual:

1. Two-quadrant, constant-torque brake
2. Clockwise constant-speed **prime mover**/brake
3. Counterclockwise constant-speed prime mover/brake

These three functions are explained in more detail below.

#### *Two-quadrant, constant-torque brake*

This function is used to study three-phase rotating machines operating as motors (i.e., converting electrical energy into mechanical energy). The two-quadrant constant-torque brake can be used to mechanically load a motor (i.e., to create an opposition torque acting against the torque produced by the motor to rotate), as shown in Figure 1-11. It is thus possible to study the speed, torque, and mechanical power of the motor under test as load torque is applied to it.

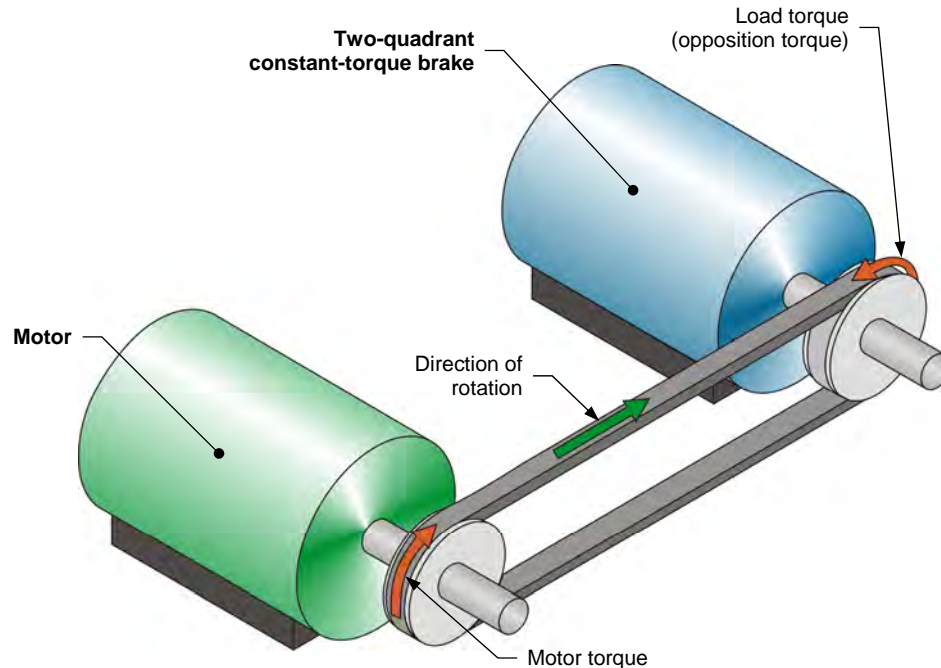


Figure 1-11. Motor coupled to a two-quadrant constant-torque brake.

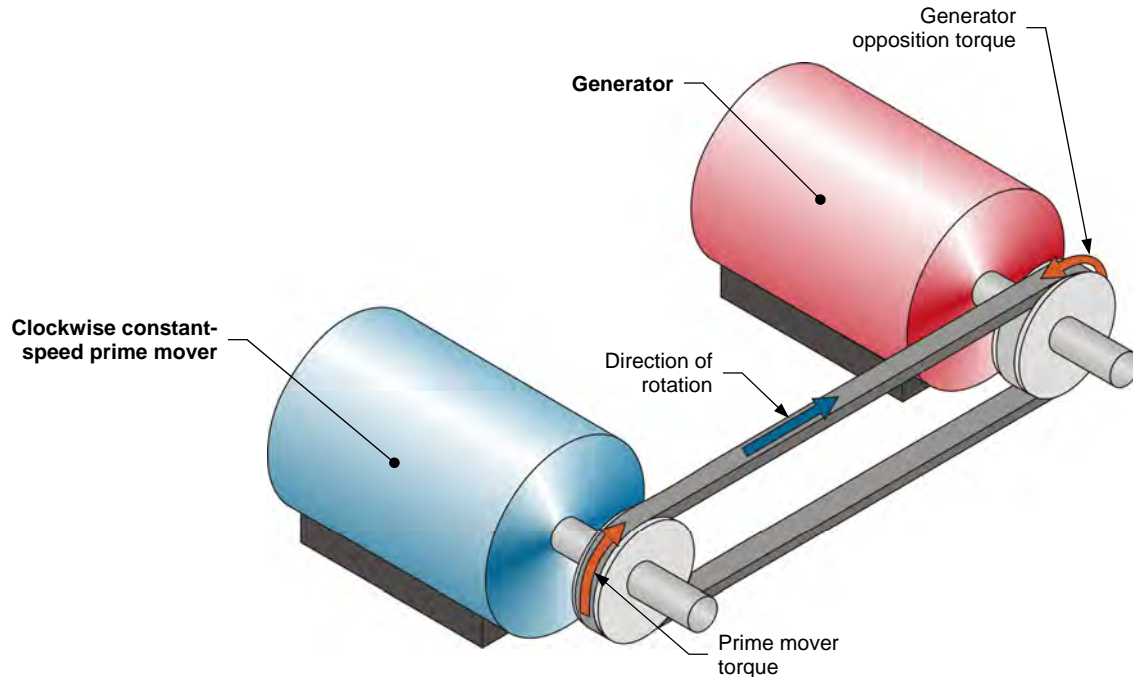
When the Four-Quadrant Dynamometer/Power Supply is operating as a two-quadrant, constant-torque brake, it is possible to set the magnitude of the load torque produced by the brake. In the Four-Quadrant Dynamometer/ Power Supply window, speed, torque, power, and energy meters indicate the different parameters measured for the machine under test. For example, the torque indicated by the torque meter corresponds to the torque produced by the motor under test, and not to the load torque produced by the two-quadrant, constant-torque brake.

When determining the torque produced by the motor to which it is coupled, the Four-Quadrant Dynamometer/Power Supply automatically compensates for its own friction torque and for the belt friction torque. Thus, the torque indicated by the torque meter in the Four-Quadrant Dynamometer/Power Supply window of the LVDAC-EMS software represents the actual torque produced at the shaft of the motor under test. Similarly, the mechanical power indicated by the power meter in the Four-Quadrant Dynamometer/Power Supply window represents the corrected mechanical power at the shaft of the motor under test.

#### ***Clockwise constant-speed prime mover/brake***

This control function is used mainly to study three-phase rotating machines operating as generators (i.e., converting mechanical energy into electrical energy). The clockwise constant-speed prime mover/brake can be used to drive a rotating machine (i.e., to make the machine rotate with the prime mover/brake), as shown in Figure 1-12. In this case, the Four-Quadrant Dynamometer/Power Supply operates as a prime mover. Since the clockwise constant-speed prime mover/brake can operate in two quadrants, it can also be used to reduce the speed of a machine operating as a motor (i.e., to create an opposition torque acting against the torque produced by the motor to rotate). In this case, the Four-Quadrant Dynamometer/Power Supply operates as a brake.

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**Figure 1-12. Clockwise constant-speed prime mover coupled to a generator.**

When the Four-Quadrant Dynamometer/Power Supply is operating as a clockwise constant-speed prime mover/brake, it is possible to set the rotation speed. In the Four-Quadrant Dynamometer/Power Supply window, speed, torque, power, and energy meters indicate the different parameters measured for the machine under test.

The Four-Quadrant Dynamometer/Power Supply operating as a clockwise constant-speed prime mover/brake maintains constant the speed of the machine to which it is connected. When the machine speed differs from the specified value, the Four-Quadrant Dynamometer/Power Supply automatically adjusts the torque it produces in order to maintain the machine speed to the specified value.

#### ***Counterclockwise constant-speed prime mover/brake***

This function is identical to the clockwise constant-speed prime mover/brake, except that it makes the Four-Quadrant Dynamometer/Power Supply rotate in the counterclockwise direction. The polarity of the parameters measured for the machine under test is modified accordingly.

### **Speed, torque, and mechanical power measurements using the Four-Quadrant Dynamometer/Power Supply**

In this manual, the speed of a machine rotating in the clockwise direction is of a positive polarity, while the speed of a machine rotating in the counterclockwise direction is of a negative polarity.

The polarity of the torque and mechanical power measured for the machine connected to the Four-Quadrant Dynamometer/Power Supply depends on the machine's current mode of operation. There are two modes of operation: motor and generator.

#### ***Motor operation***

As Figure 1-11 shows, when a machine operates as a motor, the motor torque is in the same direction as the motor's direction of rotation, i.e., the speed at which the motor rotates is of the same polarity as the torque produced by the motor. Consequently, the mechanical power produced by the motor, which is proportional to the product of the motor speed and torque, is always positive, regardless of the motor's direction of rotation (i.e., regardless of whether the motor speed and torque are positive or negative). This is consistent with the definition of a motor, which states that a motor uses electrical energy to produce mechanical energy, thus resulting in a positive mechanical power value.

Any load torque applied to the motor (such as the load torque created by the brake in Figure 1-11) acts against the torque produced by the motor and thus, has a polarity that is opposite to the polarity of the motor torque and speed.

#### ***Generator operation***

As Figure 1-12 shows, when a machine operates as a generator, the generator torque is in the direction opposite to the direction of rotation, i.e., the speed at which the generator rotates is of a polarity that is opposite to the polarity of the torque produced by the generator. Consequently, the mechanical power at the shaft of the generator, which is proportional to the product of the motor speed and torque, is always negative, regardless of the generator's direction of rotation (i.e., regardless of whether the generator speed is positive or negative). This is consistent with the definition of a generator, which states that a generator uses mechanical energy to produce electrical energy, thus resulting in a negative mechanical power value.

The torque produced by the machine driving the generator (such as the prime mover torque in Figure 1-12) acts against the generator torque and thus, is of the same polarity as the generator speed.

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Two-quadrant, constant-torque brake operation
- Constant-speed prime mover operation
- Constant-speed prime mover driving a generator

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections



*In this exercise, you will use a three-phase synchronous machine to study the general principles of operation of motors and generators. Three-phase synchronous machines will be studied in more detail in Units 3 and 4.*

*In this section, you will mechanically couple the Synchronous Motor/Generator to the Four-Quadrant Dynamometer/Power Supply. You will then set the equipment to study the two-quadrant, constant-torque brake operation.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Synchronous Motor/Generator](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

3. Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

4. Turn the **Four-Quadrant Dynamometer/Power Supply** on, then set the **Operating Mode** switch to **Dynamometer**. This setting allows the **Four-Quadrant Dynamometer/Power Supply** to operate as a prime mover, a brake, or both, depending on the selected function.
5. Turn the host computer on, then start the **LVDAC-EMS** software.

In the **LVDAC-EMS Start-Up** window, make sure that the **Four-Quadrant Dynamometer/Power Supply** is detected. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.

6. Connect the equipment as shown in Figure 1-13.

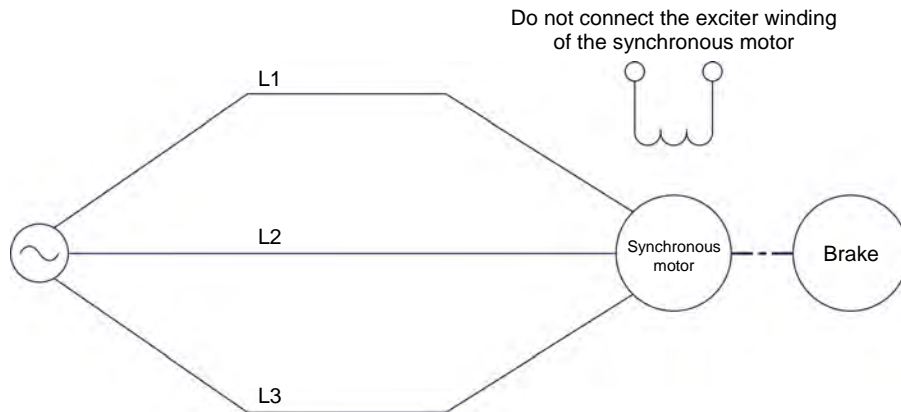


Figure 1-13. Synchronous motor coupled to a brake.



Appendix D shows in more detail the equipment and the connections that are required for each circuit diagram symbol used in this manual.

7. In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
  - Set the **Function** parameter to **Two-Quadrant, Constant-Torque Brake**. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a two-quadrant brake with a torque setting corresponding to the **Torque** parameter.
  - Make sure that the **Torque Control** parameter is set to **Knob**. This allows the torque of the two-quadrant brake to be controlled manually in the **Four-Quadrant Dynamometer/Power Supply** window.
  - Set the **Torque** parameter to the minimum (0.0 N·m or 0.0 lbf·in). This sets the torque command of the **Two-quadrant, constant-torque brake** (i.e., the load torque) to 0.0 N·m (0.0 lbf·in).



The torque command can also be set by using the **Torque** control knob in the **Four-Quadrant Dynamometer/Power Supply** window.



- Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the *Four-Quadrant Dynamometer/Power Supply* and the number of teeth on the pulley of the machine under test, respectively. It is important to ensure that the *Pulley Ratio* parameter corresponds to the actual pulley ratio between the *Four-Quadrant Dynamometer/Power Supply* and the machine under test.



The pulley ratio between the *Four-Quadrant Dynamometer/Power Supply* and all machines under test in this manual is 24:24.

## Two-quadrant, constant-torque brake operation

*In this section, you will make the three-phase synchronous motor rotate in a clockwise direction and observe what happens to the torque produced by the motor as the load torque applied to it increases. You will observe the polarity of the torque and the mechanical power produced by the three-phase synchronous motor, and confirm that the machine is operating as a motor. You will then make the three-phase synchronous motor rotate in a counterclockwise direction and observe what happens to the torque produced by the motor as the load torque applied to it increases. You will observe the polarity of the three-phase synchronous motor torque and mechanical power, and confirm that the machine can operate as a motor, regardless of the direction of rotation.*

8. In the *Four-Quadrant Dynamometer/Power Supply* window, start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

On the *Power Supply*, turn the three-phase ac power source on.

Observe the three-phase synchronous motor speed indicated by the *Speed* meter in the *Four-Quadrant Dynamometer/Power Supply* window. Is the motor speed  $n$  positive, indicating that the motor is rotating in the clockwise direction?

☐ Yes      ☐ No

9. In the *Four-Quadrant Dynamometer/Power Supply* window, slowly increase the value of the *Torque* parameter to 2.00 N·m (17.7 lbf·in). While you do so, observe the torque  $T$  produced by the three-phase synchronous motor (indicated by the *Torque* meter in the *Four-Quadrant Dynamometer/Power Supply* window).

What happens to the torque  $T$  produced by the three-phase synchronous motor as the load torque applied to the motor by the *Two-Quadrant, Constant-Torque Brake* increases?

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10. Is the torque  $T$  produced by the three-phase synchronous motor of the same polarity as the motor speed  $n$ ?

☐ Yes      ☐ No

11. Is the polarity of the motor mechanical power  $P_M$  positive (indicated by the *Power* meter in the *Four-Quadrant Dynamometer/Power Supply* window).

☐ Yes      ☐ No

Does this confirm that the synchronous machine currently operates as a motor?

☐ Yes      ☐ No

12. On the *Power Supply*, turn the three-phase ac power source off.

In the *Four-Quadrant Dynamometer/Power Supply* window, set the *Torque* parameter to 0.0 N·m (0.0 lbf·in).

13. On the *Power Supply*, interchange the connections at terminals *L2* and *L3*, then turn the three-phase ac power source on.



*Interchanging the connections at two terminals of a motor reverses the direction of rotation of the motor.*

Is the three-phase synchronous motor speed  $n$  negative, indicating that the direction of rotation of the motor has been reversed and that the motor is rotating in the counterclockwise direction?

☐ Yes      ☐ No

14. In the *Four-Quadrant Dynamometer/Power Supply* window, slowly increase the value of the *Torque* parameter to 2.00 N·m (17.7 lbf·in). While you do so, observe the torque  $T$  produced by the three-phase synchronous motor.

What happens to the torque  $T$  produced by the three-phase synchronous motor as the braking torque applied to the motor by the *Two-Quadrant, Constant-Torque Brake* increases?

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15. Is the torque  $T$  produced by the three-phase synchronous motor of the same polarity as the motor speed  $n$ ?

☐ Yes      ☐ No

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16. Is the polarity of the motor mechanical power  $P_M$  positive?

☐ Yes      ☐ No

Does this confirm that the synchronous machine currently operates as a motor?

☐ Yes      ☐ No

17. What is the effect of the three-phase synchronous motor's direction of rotation on the motor speed  $n$  and torque  $T$ ? Does changing the direction of rotation of the synchronous machine have any effect on the operating mode (motor or generator)?

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18. On the [Power Supply](#), turn the three-phase ac power source off.

In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the [Two-Quadrant, Constant-Torque Brake](#) by setting the [Status](#) parameter to [Stopped](#) or by clicking the [Start/Stop](#) button.

### Constant-speed prime mover operation

*In this section, you will set up a circuit containing a prime mover (implemented using the Four-Quadrant Dynamometer/Power Supply) mechanically coupled to a three-phase synchronous machine that operates neither as a motor or a generator. You will make the prime mover rotate in the clockwise direction and confirm that the three-phase synchronous machine rotates at the specified speed of the prime mover. You will also confirm that the torque produced by the machine is virtually zero. You will make the prime mover rotate in the counterclockwise direction and confirm that the three-phase synchronous machine speed is negative when it rotates in the counterclockwise direction. You will also confirm that the torque produced by the machine is virtually zero.*

19. Connect the equipment as shown in Figure 1-14.

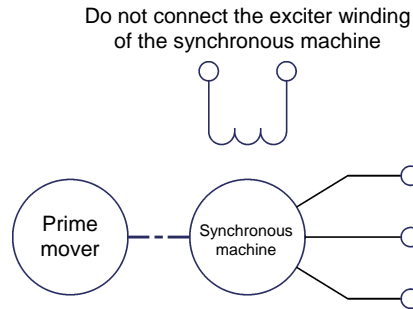


Figure 1-14. Prime mover coupled to a synchronous machine.

20. In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

- Set the **Function** parameter to **CW Constant-Speed Prime Mover/Brake**. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a clockwise prime mover/brake with a speed setting corresponding to the **Speed** parameter.
- Make sure that the **Speed Control** parameter is set to **Knob**. This allows the speed of the clockwise prime mover/brake to be controlled manually in the **Four-Quadrant Dynamometer/Power Supply** window.
- Set the **Speed** parameter (i.e., the speed command) to 800 r/min. This sets the speed of the **CW Constant-Speed Prime Mover/Brake** to 800 r/min. Note that the speed command is the targeted speed at the shaft of the machine coupled to the prime mover, i.e., the speed of the **Synchronous Motor/Generator** in the present case.



The speed command can also be set by using the **Speed** control knob in the **Four-Quadrant Dynamometer/Power Supply** window.

21. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **CW Constant-Speed Prime Mover/Brake**.

22. In the **Four-Quadrant Dynamometer/Power Supply** window, observe the three-phase synchronous machine speed  $n$  and torque  $T$ .

Is the motor speed  $n$  approximately equal to the **Speed** parameter of the **CW Constant-Speed Prime Mover/Brake**?

☐ Yes ☐ No

Is the motor speed  $n$  positive, indicating that the three-phase synchronous motor is rotating in the clockwise direction?

☐ Yes ☐ No

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Is the motor torque  $T$  virtually zero, indicating that no torque is produced by the three-phase synchronous motor?

☐ Yes      ☐ No

23. In the **Four-Quadrant Dynamometer/Power Supply** window, increase the **Speed** parameter to 1400 r/min.

Does the three-phase synchronous motor speed  $n$  increase with the **Speed** parameter of the **CW Constant-Speed Prime Mover/Brake**?

☐ Yes      ☐ No

24. In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **CW Constant-Speed Prime Mover/Brake**, then make the following settings:

- Set the **Function** parameter to **CCW Constant-Speed Prime Mover/Brake**. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a counterclockwise prime mover/brake with a speed setting corresponding to the **Speed** parameter.
- Make sure that the **Speed Control** parameter is set to **Knob**. This allows the speed of the counterclockwise prime mover/brake to be controlled manually in the **Four-Quadrant Dynamometer/Power Supply** window.
- Set the **Speed** parameter to -800 r/min. This sets the speed of the **CCW Constant-Speed Prime Mover/Brake** to 800 r/min in the counterclockwise direction.

25. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **CCW Constant-Speed Prime Mover/Brake**.

26. Wait a few seconds, then observe the three-phase synchronous motor speed and torque.

Is the motor speed  $n$  negative, indicating that the three-phase synchronous motor is rotating in the counterclockwise direction?

☐ Yes      ☐ No

Is the motor torque  $T$  virtually zero, indicating that no torque is produced by the three-phase synchronous motor?

☐ Yes      ☐ No

27. In the **Four-Quadrant Dynamometer/Power Supply** window, increase the speed of the **CCW Constant-Speed Prime Mover/Brake** to 1400 r/min (i.e., set the **Speed** parameter of the **CCW Constant-Speed Prime Mover/Brake** to -1400 r/min).

Does the three-phase synchronous motor speed  $n$  increase (with a negative polarity) as the **Speed** parameter of the **CCW Constant-Speed Prime Mover/Brake** increases?

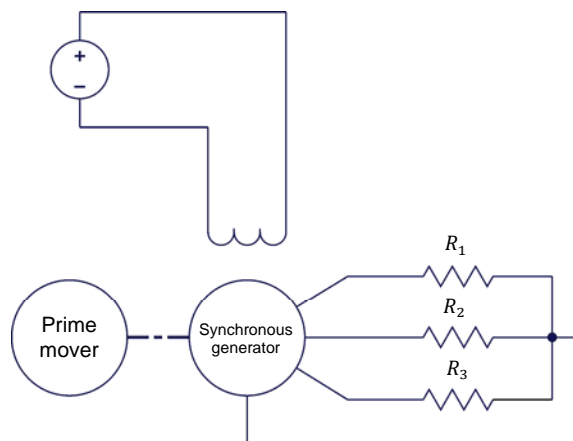
☐ Yes      ☐ No

28. In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **CCW Constant-Speed Prime Mover/Brake**.

### Constant-speed prime mover driving a generator

*In this section, you will set up a circuit containing a prime mover mechanically coupled to a three-phase synchronous generator. On the generator, you will set the exciter knob to a minimum. You will make the three-phase synchronous generator rotate at the synchronous speed. You will set the exciter knob to a maximum while observing the generator torque. You will confirm that the generator speed and torque are of opposite polarity, and that the generator mechanical power is negative, thus indicating that the machine is operating as a generator. You will then set the exciter knob on the three-phase synchronous generator to a minimum and make the generator rotate in the counterclockwise direction at the synchronous speed. You will set the exciter knob to a maximum while observing the generator torque. You will verify that the generator speed and torque are of opposite polarity, and that the generator mechanical power is negative. Finally, you will confirm that the machine can operate as a generator, regardless of the direction of rotation.*

29. Connect the equipment as shown in Figure 1-15. The resistance value for the resistors ( $R_1$ ,  $R_2$ ,  $R_3$ ) depends on your local ac power network voltage (see table in the diagram).



Local ac power network		$R_1, R_2, R_3$ ( $\Omega$ )
Voltage (V)	Frequency (Hz)	
120	60	600
220	50	2200
240	50	2400
220	60	2200

Figure 1-15. Prime mover coupled to a synchronous generator.

30. In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:
- Set the **Function** parameter to **CW Constant-Speed Prime Mover/Brake**.
  - Set the **Speed** parameter to the synchronous speed of the **Synchronous Motor/Generator**.



The synchronous speed of the **Synchronous Motor/Generator** is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz. The importance of the synchronous speed of a three-phase rotating machine will be discussed in Unit 2.

31. On the **Synchronous Motor/Generator**, set the **Exciter** switch to the closed position (I), then turn the **Exciter** knob fully counterclockwise (i.e., set it to the **MIN.** position).

In the **Four-Quadrant Dynamometer/Power Supply** window, start the **CW Constant-Speed Prime Mover/Brake**.

On the **Power Supply**, turn the dc power source on.

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- 32.** On the *Synchronous Motor/Generator*, slowly turn the *Exciter* knob clockwise until the knob is set to the *MAX.* position. While doing so, observe the three-phase synchronous generator speed  $n$  and torque  $T$ .

Describe what happens to the generator torque  $T$  as you turn the *Exciter* knob toward the *MAX.* position.

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Are the generator speed  $n$  and torque  $T$  of opposite polarity?

☐ Yes      ☐ No

- 33.** Is the polarity of the motor mechanical power  $P_M$  negative.

☐ Yes      ☐ No

Does this confirm that the synchronous machine currently operates as a generator?

☐ Yes      ☐ No

- 34.** On the Power Supply, turn the dc power source off.

In the *Four-Quadrant Dynamometer/Power Supply* window, stop the *CW Constant-Speed Prime Mover/Brake*.

On the *Synchronous Motor/Generator*, turn the *Exciter* knob fully counterclockwise (i.e., set it to the *MIN.* position).

- 35.** In the *Four-Quadrant Dynamometer/Power Supply* window, make the following settings:

- Set the *Function* parameter to *CCW Constant-Speed Prime Mover/Brake*.
- Set the *Speed* parameter to the synchronous speed of the *Synchronous Motor/Generator* (with a negative polarity).

- 36.** In the *Four-Quadrant Dynamometer/Power Supply* window, start the *CCW Constant-Speed Prime Mover/Brake*.

On the *Power Supply*, turn the dc power source on.

- 37.** On the *Synchronous Motor/Generator*, slowly turn the *Exciter* knob clockwise until the knob is set to the *MAX.* position. While doing so, observe the three-phase synchronous generator speed  $n$  and torque  $T$ .

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Describe what happens to the generator torque  $T$  as you turn the *Exciter* knob toward the *MAX.* position.

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Are the generator speed  $n$  and torque  $T$  of opposite polarity?

☐ Yes      ☐ No

**38.** Is the polarity of the motor mechanical power  $P_M$  negative.

☐ Yes      ☐ No

Does this confirm that the synchronous machine currently operates as a generator?

☐ Yes      ☐ No

**39.** What is the effect of the three-phase synchronous generator's direction of rotation on the generator speed  $n$  and torque  $T$ ? Does changing the direction of rotation of the synchronous machine have any effect on its operating mode (i.e., motor or generator)?

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**40.** On the *Power Supply*, turn the dc power source off.

In the *Four-Quadrant Dynamometer/Power Supply* window, stop the *CCW Constant-Speed Prime Mover/Brake*.

**41.** Close *LVDAC-EMS*, then turn off all the equipment. Disconnect all leads and return them to their storage location.

## CONCLUSION

In this exercise, you familiarized yourself with the basic functions of the Four-Quadrant Dynamometer/Power Supply used in this manual. You observed the polarity of the speed, torque, and mechanical power for a machine operating as either a motor or a generator.



**REVIEW QUESTIONS**

1. Calculate the power  $P$  of a motor rotating at a speed  $n$  of 1740 r/min and producing a torque  $T$  of 1.4 N·m (12.4 lbf·in).

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2. Briefly describe what a brake is and what a prime mover is.

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3. Briefly describe the energy conversion occurring in a motor, as well as the energy conversion occurring in a generator.

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4. Consider a motor rotating in the clockwise direction that is coupled to a brake applying a load torque to the motor. Determine the polarity of the motor speed and torque, as well as the polarity of the braking torque. Also determine the polarity of the motor mechanical power.

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5. Consider a prime mover making a generator rotate in the counterclockwise direction. Determine the polarity of the prime mover torque, as well as the polarity of the generator speed and torque. Also determine the polarity of the generator mechanical power.

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## Unit Test

1. A force  $F$  of 12.0 N (2.70 lbf·in) is applied on a pulley having a diameter of 5 cm (1.97 in). Determine the work  $W$  that is done when the pulley rotates ten complete turns.
  - a. 1.88 J (16.6 lbf·in)
  - b. 3.77 J (33.4 lbf·in)
  - c. 18.8 J (167 lbf·in)
  - d. 37.7 J (334 lbf·in)
  
2. A moving loop of wire passes through a magnetic field. Knowing that the magnetic flux  $\Phi$  linking the loop rises from 0 mWb to 280 mWb in 0.05 s as the loop passes through the magnetic field, determine the voltage  $E$  induced across the loop of wire.
  - a.  $E = 14.0 \text{ V}$
  - b.  $E = 5.60 \text{ V}$
  - c.  $E = 28.0 \text{ V}$
  - d.  $E = 11.2 \text{ V}$
  
3. The motor of a water pump produces a torque  $T$  of 10 N·m (88.5 lbf·in). How much work is done by the pump motor if it rotates at a speed of 3000 r/min during 10 minutes?
  - a. 188 kJ ( $1.67 \cdot 10^6$  lbf·in)
  - b. 1.88 MJ ( $16.7 \cdot 10^6$  lbf·in)
  - c. 314 kJ ( $3.34 \cdot 10^6$  lbf·in)
  - d. 3.14 kJ ( $33.4 \cdot 10^6$  lbf·in)
  
4. Knowing that a motor has a power  $P$  of 300 W, calculate the torque  $T$  that the motor must produce in order to rotate at a speed  $n$  of 1600 r/min.
  - a.  $T = 1.79 \text{ N·m}$  (15.8 lbf·in)
  - b.  $T = 2.50 \text{ N·m}$  (22.1 lbf·in)
  - c.  $T = 5.33 \text{ N·m}$  (47.2 lbf·in)
  - d.  $T = 4.14 \text{ N·m}$  (36.6 lbf·in)
  
5. A two-quadrant, constant-torque brake is mainly used to
  - a. study the operation of a generator.
  - b. supply electrical power to a rotating machine.
  - c. drive a rotating machine at a specified speed.
  - d. apply load torque to a rotating machine.
  
6. A constant-speed prime mover is mainly used to
  - a. study the operation of a motor.
  - b. supply electrical power to a rotating machine.
  - c. drive a rotating machine at a specified speed.
  - d. apply load torque to a rotating machine.

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7. The mechanical power produced by a motor is
  - a. always positive.
  - b. positive only when the motor rotates in the clockwise direction.
  - c. always negative.
  - d. positive only when the motor rotates in the counterclockwise direction.
  
8. The mechanical power produced by a generator is
  - a. always positive.
  - b. positive only when the generator rotates in the clockwise direction.
  - c. always negative.
  - d. positive only when the generator rotates in the counterclockwise direction.
  
9. When a motor rotates in the counterclockwise direction,
  - a. the motor speed is of negative polarity, while the motor torque is of positive polarity.
  - b. the motor speed and torque are of negative polarity.
  - c. the motor speed is of positive polarity, while the motor torque is of negative polarity.
  - d. the motor speed and torque are of positive polarity.
  
10. When a generator rotates in the clockwise direction,
  - a. the generator speed is of negative polarity, while the generator torque is of positive polarity.
  - b. the generator speed and torque are of negative polarity.
  - c. the generator speed is of positive polarity, while the generator torque is of negative polarity.
  - d. the generator speed and torque are of positive polarity.

## Three-Phase Squirrel-Cage Induction Machines

### UNIT OBJECTIVE

When you have completed this unit, you will know how three-phase squirrel-cage induction machines operate as motors, eddy-current brakes, or asynchronous generators. You will be familiar with the characteristics of three-phase squirrel-cage induction machines related to each of these operating modes.

### DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Introduction to ac motors

### DISCUSSION OF FUNDAMENTALS

#### Introduction to ac motors

As already seen in Unit 1, a voltage is induced between the ends of a wire loop when the magnetic flux passing through the loop varies as a function of time. If the ends of the wire loop are short-circuited together, a current flows in the loop. Figure 2-2 shows a magnet that is displaced rapidly toward the right above a group of conductors. The conductors are short-circuited at their extremities by bars A and B and form a structure similar to a ladder.

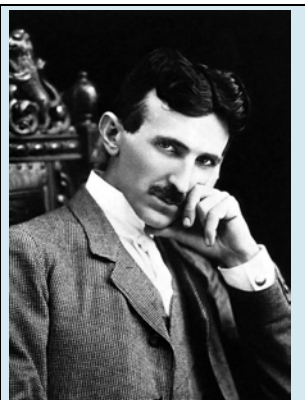


Figure 2-1. The principles behind the operation of alternating current motors are usually credited to scientist Nikola Tesla.

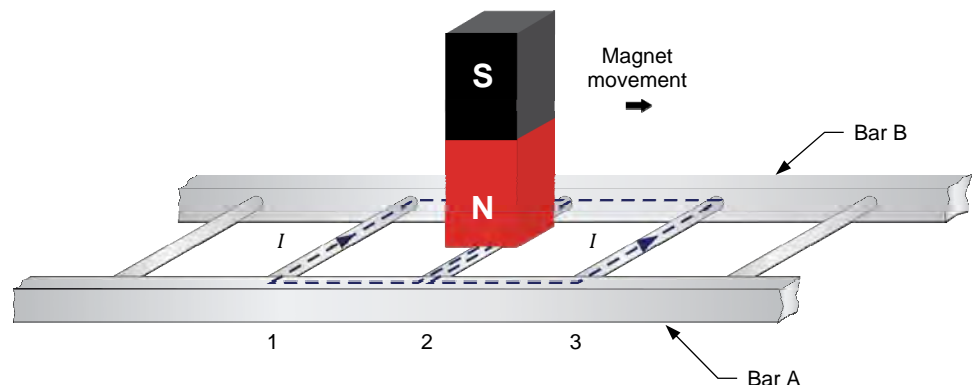
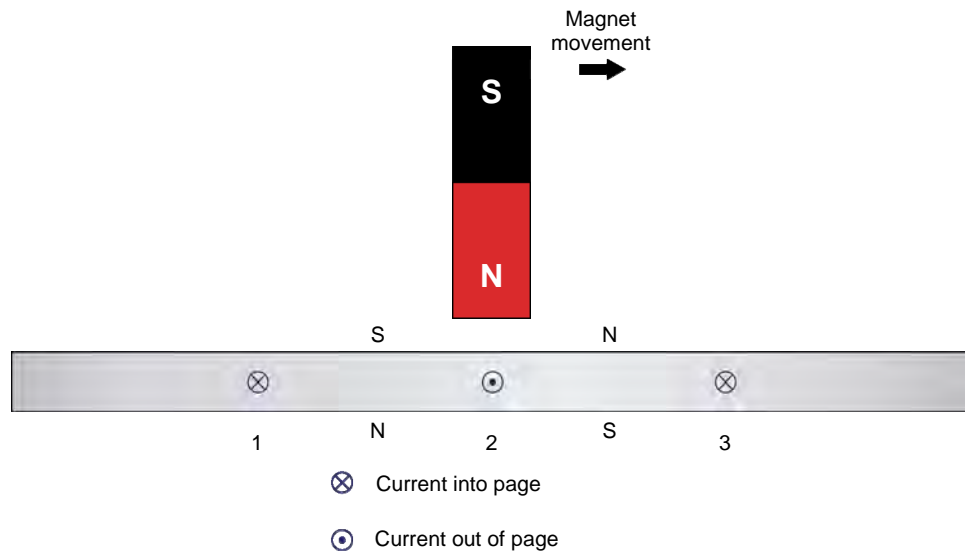


Figure 2-2. Magnet moving above a conducting ladder.

Current flows in the loop formed by conductors 1 and 2, as well as in the loop formed by conductors 2 and 3. These currents create magnetic fields having north and south poles as shown in Figure 2-3.

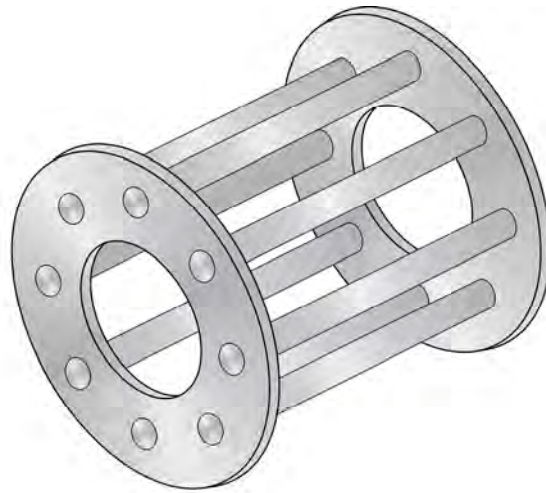


**Figure 2-3. Current in the conductors creates magnetic fields.**

The interaction between the magnetic field of the magnet and the magnetic fields produced by the currents induced in the ladder creates a force between the moving magnet and the ladder. This force causes the ladder to be pulled along in the direction of the moving magnet. However, if the ladder moves at the same speed as the magnet, there is no longer any variation in the magnetic flux passing through the ladder. Consequently, there is no longer any induced voltage causing current to flow in the wire loops and thus, no longer any magnetic force acting on the ladder. Therefore, to create a magnetic force pulling the ladder in the direction of the moving magnet, the ladder must move at a speed lower than the speed of the moving magnet. The greater the speed difference between the ladder and the moving magnet, the greater the variation in the magnetic flux passing through the ladder, and therefore, the greater the magnetic force acting on the ladder.

A three-phase squirrel-cage induction machine is often referred to simply as a three-phase induction machine for brevity purposes. When not specified otherwise, a three-phase induction machine is by default of squirrel-cage type.

The rotor of a three-phase **squirrel-cage induction machine** is made by closing a ladder similar to the one shown in Figure 2-2 upon itself to form the structure shown in Figure 2-4. The name squirrel-cage is derived from the appearance of the resulting rotor, which resembles a squirrel cage.



**Figure 2-4. Closing a ladder upon itself forms a squirrel cage.**

To make it easier for the magnetic flux to circulate, the rotor of a three-phase squirrel-cage induction machine is placed inside a laminated iron cylinder. The stator of the three-phase squirrel-cage induction machine acts as a rotating electromagnet. The rotating electromagnet produces a torque which pulls the rotor along in much the same manner as the moving magnet in Figure 2-2 pulls the ladder.



## The Three-Phase Squirrel-Cage Induction Motor

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operation and the main characteristics of three-phase squirrel-cage induction motors. You will know what motor efficiency and high-efficiency motors are. You will also know the relationships between the different parameters related to the operation of three-phase squirrel-cage induction motors, such as the motor speed, torque, mechanical power, active power, reactive power, power factor, and efficiency.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Three-phase squirrel-cage induction motor operation
- Relationship between speed and torque in three-phase squirrel-cage induction motors
- Efficiency of three-phase squirrel-cage induction motors
- Relationship between reactive power, power factor, and motor efficiency in three-phase squirrel-cage induction motors
- High-efficiency motors

### DISCUSSION

#### Three-phase squirrel-cage induction motor operation

One way of creating a rotating electromagnet is to connect a three-phase ac power source to a stator made of three electromagnets A, B, and C that are physically located at an angle of  $120^\circ$  one to another, as shown in Figure 2-5.



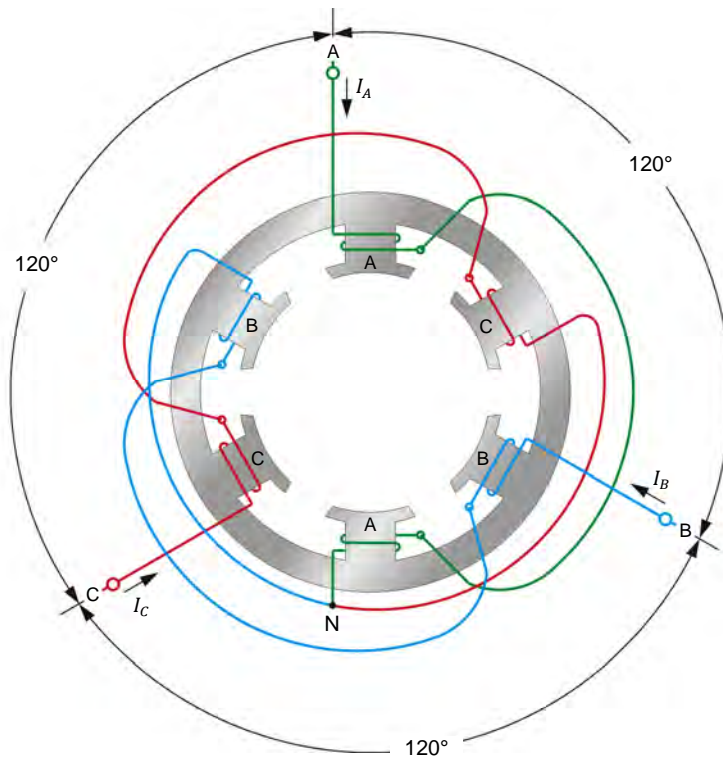


Figure 2-5. Three-phase stator windings (two poles per phase).

When sine-wave currents that are similarly phase shifted at an angle of  $120^\circ$  one to another flow in stator electromagnets A, B, and C, a magnetic field that rotates very regularly is obtained. Figure 2-6 shows how the three sine wave currents vary through time, from instant 1 to instant 6, after which the cycle starts again at instant 1.

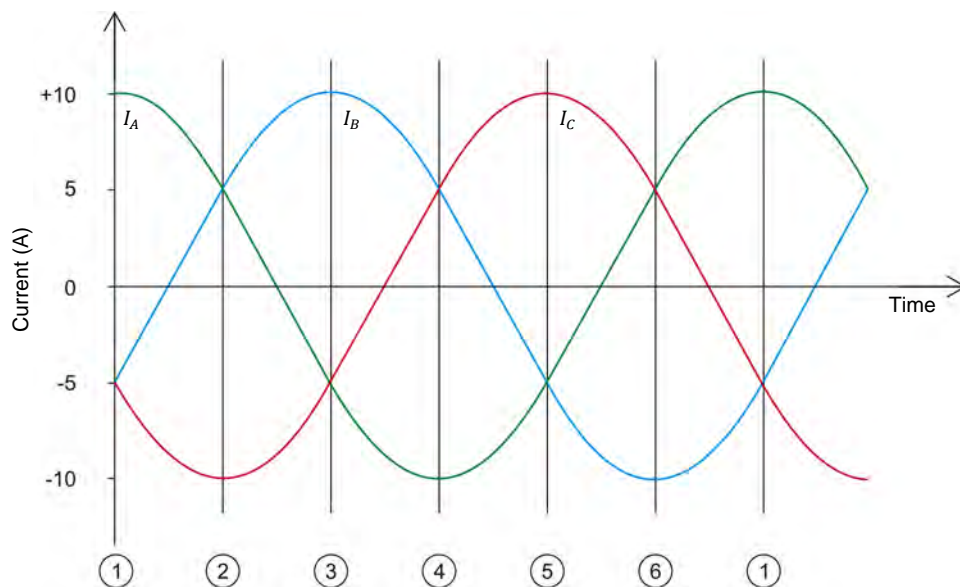


Figure 2-6. Three-phase sine wave currents flowing in the stator windings.

Figure 2-7 shows the position of the rotating magnetic field created by stator electromagnets A, B, and C as the sine wave currents illustrated in Figure 2-6 flow in the stator electromagnets. Instants 1 to 6 in Figure 2-6 correspond to instants 1 to 6 in Figure 2-7. Notice that the magnetic lines of force exit at the north pole of each stator electromagnet and enter at the south pole. As can be seen, the resulting magnetic field rotates clockwise.

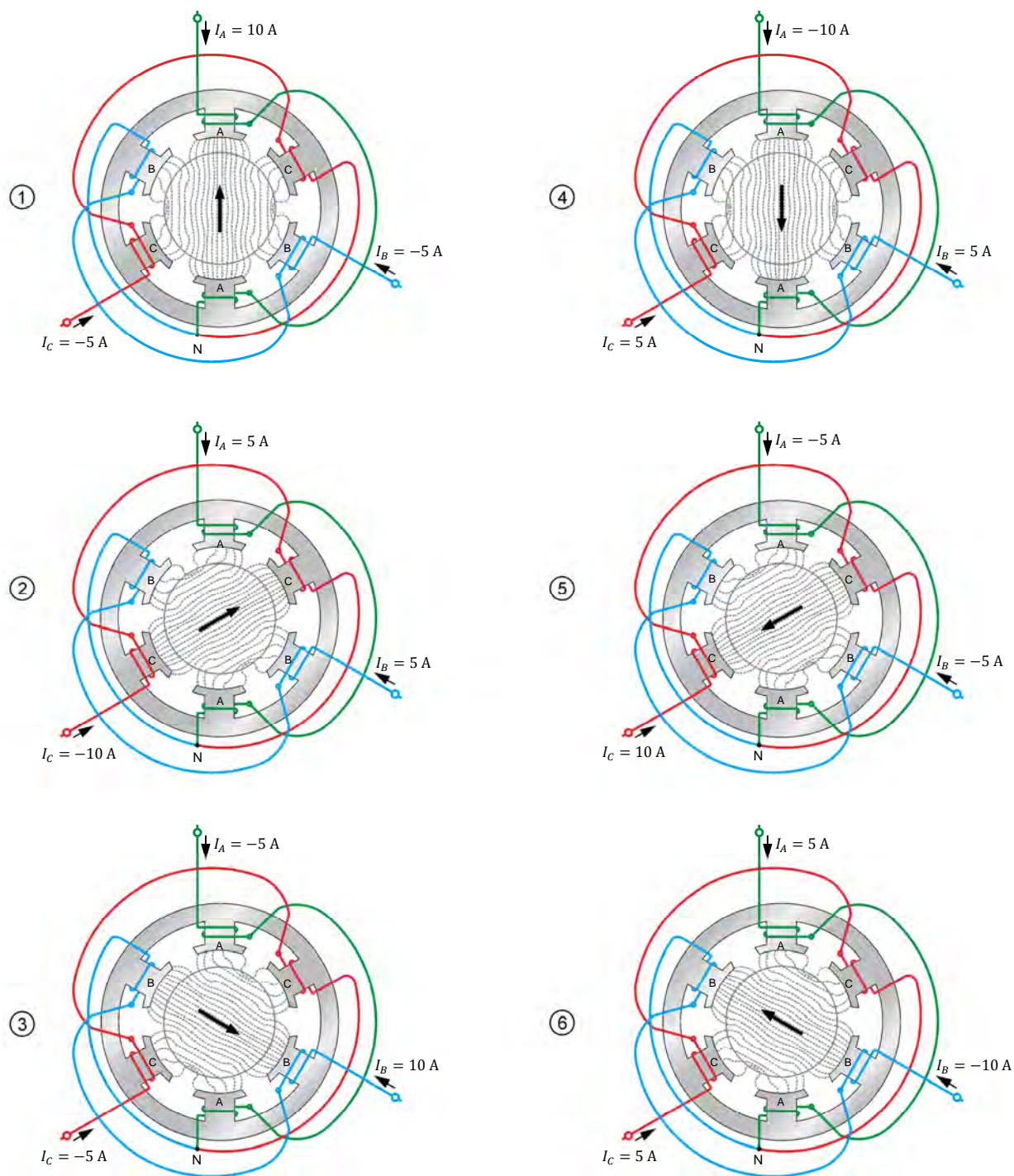


Figure 2-7. Position of the rotating magnetic field at various instants.

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The sine-wave currents flowing through the stator produce a magnetic field that rotates regularly and whose strength does not vary over time. The speed of the rotating magnetic field is known as the motor **synchronous speed**  $n_s$  and is proportional to the frequency of the three-phase ac power source, and inversely proportional to the number of magnetic poles in the motor per phase. The synchronous speed  $n_s$  of a motor operating at a given frequency  $f$  can be calculated using the following equation:

$$n_s = \frac{120f}{N_{Poles}} \quad (2-1)$$

where  $n_s$  is the motor synchronous speed, expressed in revolutions per minute (r/min).

$f$  is the frequency of the ac power source, expressed in hertz (Hz).

$N_{Poles}$  is the number of magnetic poles in the motor per phase.

The supplied Four-Pole Squirrel Cage Induction Motor has four magnetic poles for each phase. This means that, when operating at a frequency of 50 Hz, the motor synchronous speed  $n_s$  is equal to:

$$n_s = \frac{120f}{N_{Poles}} = \frac{120 \cdot 50 \text{ Hz}}{4 \text{ poles}} = 1500 \text{ r/min}$$

When operating at a frequency of 60 Hz, the motor synchronous speed  $n_s$  is equal to:

$$n_s = \frac{120f}{N_{Poles}} = \frac{120 \cdot 60 \text{ Hz}}{4 \text{ poles}} = 1800 \text{ r/min}$$

When a squirrel-cage rotor is placed inside the rotating magnetic field produced in the stator, the rotor is pulled along in the same direction as the stator rotating magnetic field. Interchanging the power connections to any two of the stator windings (interchanging A with B for example) interchanges two of the three stator currents and thus reverses the phase sequence. This causes the rotating magnetic field to reverse direction. As a result, the direction of rotation of the motor is also reversed.



**Figure 2-8.** Three-phase induction motors are the most commonly used alternating current motors in industrial applications worldwide. This is primarily due to the fact that induction motors are simple, robust, and relatively cheap compared to other types of alternating current motors (© Siemens AG 2012, all rights reserved).

### Relationship between speed and torque in three-phase squirrel-cage induction motors

As seen earlier in this unit, the torque produced by a three-phase squirrel-cage induction motor results from the difference between the speed of the rotating magnetic field and the speed of the rotor. It is thus easy to deduce that the torque produced by a three-phase squirrel-cage induction motor increases as the difference in speed between the rotating magnetic field (the speed of the rotating magnetic field corresponds to the motor synchronous speed  $n_s$ ) and the rotor increases. The difference in speed between the rotating magnetic field and the rotor is called **slip** and is calculated using the following equation:

$$\text{Motor slip} = N_s - N_r \quad (2-2)$$

where  $N_s$  is the motor synchronous speed, expressed in revolutions per minute (r/min).

$N_r$  is the rotation speed of the motor rotor, expressed in revolutions per minute (r/min).



The slip of a motor can also be expressed as a percentage (%), i.e., as a ratio between the speed of the rotor and the speed of the rotating magnetic field (the synchronous speed  $n_s$ ). In that case, motor slip is calculated using the following equation:

$$\text{Motor slip} = \frac{100 (N_s - N_r)}{N_s} \quad (2-3)$$

Figure 2-9 shows the torque versus speed curve of a typical three-phase squirrel-cage induction motor. As you can see, when the motor speed  $n$  is equal to the motor synchronous speed  $n_s$ , the torque  $T$  produced by the motor is zero. This is because slip (i.e., a difference between the rotor speed and the rotating magnetic field speed) is necessary in order for the motor to develop torque. As the torque  $T$  produced by the motor increases, the slip increases, and the motor speed  $n$  slowly decreases. When the torque  $T$  produced by the squirrel-cage induction motor reaches its nominal value, the speed  $n$  at which the motor is rotating corresponds to the squirrel-cage induction motor nominal speed. When the torque  $T$  produced by the motor increases further (i.e., as the slip continues to increase and the motor speed continues to decrease), a point of instability called the breakdown torque is eventually reached. At this point, the motor speed  $n$  continues to decrease, but the torque, which is at a maximum, begins to decrease. The motor torque  $T$  at a motor speed  $n$  of 0 r/min (i.e., when the motor is stopped), called locked-rotor torque, is usually lower than the breakdown torque.

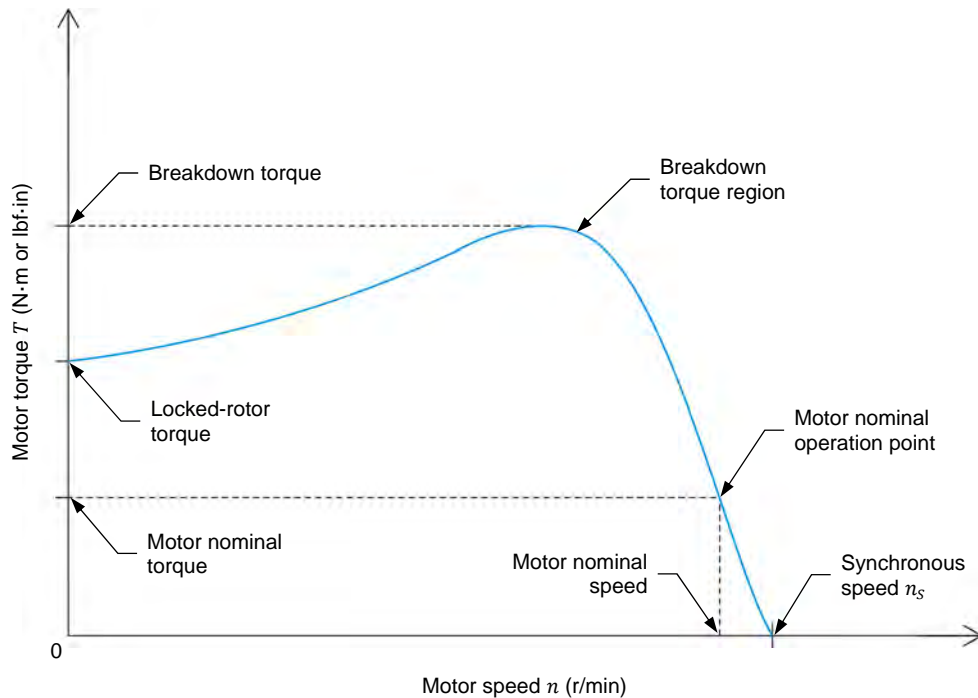


Figure 2-9. Typical three-phase squirrel-cage induction motor torque  $T$  versus speed  $n$  curve.

### Efficiency of three-phase squirrel-cage induction motors

**Motor efficiency**  $\eta$  is defined as the measure of how well a motor converts electrical energy into useful work (i.e., into mechanical energy), and can be calculated using the following equation.

$$\eta = \frac{P_M}{P} 100 \quad (2-4)$$

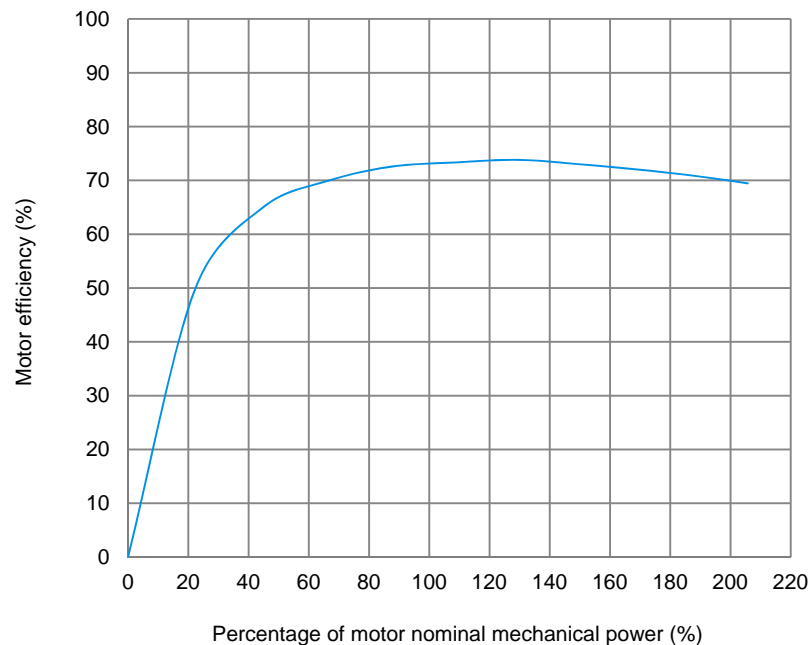
where  $\eta$  is the motor efficiency, expressed in percentage (%).

$P_M$  is the mechanical power produced by the motor, expressed in watts (W).

$P$  is the active power supplied to the motor, expressed in watts (W).

As you can see from Equation (2-4), the higher the mechanical power produced by the motor for a given amount of electrical power, the more efficient the motor.

Figure 2-10 shows a graph of the efficiency of a typical three-phase squirrel-cage induction motor as a function of the motor mechanical power. As the figure shows, the efficiency of a three-phase squirrel-cage induction motor does not vary much when the motor is operating at around 100% of its nominal mechanical power. Motor efficiency, however, drops rapidly as the motor mechanical power decreases to about 60% of its nominal value.



**Figure 2-10.** Motor efficiency as a function of the percentage of nominal mechanical power for a typical three-phase squirrel-cage induction motor.

### Relationship between reactive power, power factor, and motor efficiency in three-phase squirrel-cage induction motors

An important characteristic of three-phase squirrel-cage induction motors is that they always draw reactive power from the three-phase ac power source. In fact, the reactive power exchanged between the three-phase squirrel-cage induction motor and the three-phase ac power source exceeds the active power consumed by the motor during no-load operation. Reactive power is necessary to create the rotating magnetic field in three-phase squirrel-cage induction motors in the same way that an inductor needs reactive power to create the magnetic field that surrounds it.

The reactive power requirement of a three-phase squirrel-cage induction motor has a lot of impact on the motor operation. One of the most important effects is that the power factor of the motor decreases rapidly when working under the motor nominal mechanical power. This is due to the fact that a three-phase squirrel-cage induction motor requires about as much reactive power to produce a low mechanical power as to produce a mechanical power equal to the motor's nominal mechanical power. This relationship is illustrated in Figure 2-11. Since the necessary exchange of reactive power between the three-phase ac power source and the three-phase squirrel-cage induction motor increase the amount of power that flows in a system (and thus, the size and cost of the system), it is important to size the motor so that it operates as close as possible to its nominal mechanical power.

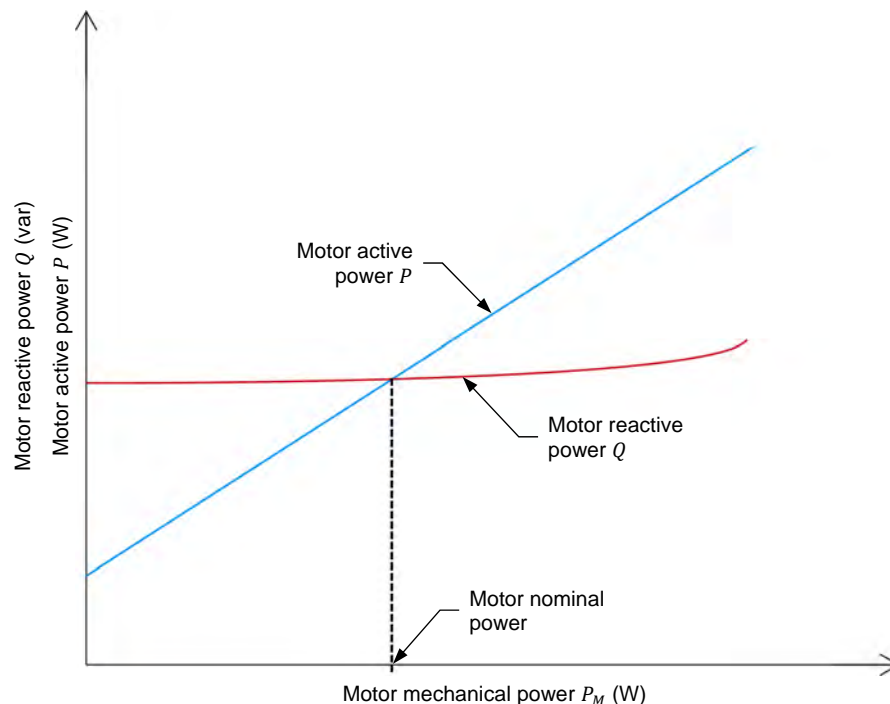


Figure 2-11. Active power  $P$  and reactive power  $Q$  as a function of the mechanical power  $P_M$  for a typical three-phase squirrel-cage induction motor.

The reactive power requirements of a three-phase squirrel-cage induction motor also have an impact on the motor efficiency. Since large motors require more reactive power (and thus, more current) to build the rotating magnetic field than small motors do, using an oversized motor for a given application means that

more current will flow in the system for the same mechanical power yield. Knowing that the equation for calculating power losses in a system is  $P = I^2 R$ , higher currents flowing in the motor result in higher power losses, thus reducing the motor efficiency. It is therefore very important when sizing a three-phase squirrel-cage induction motor for any application to ensure that the motor will operate close to its nominal mechanical power most of the time, as Figure 2-10 showed. Otherwise, it results in useless power and energy losses.

In order to maximize the power factor and the efficiency of squirrel-cage induction motors for a given application, it is therefore necessary to ensure that, first, the motor is correctly-sized for the application and, second, the motor is working within its specified nominal operation range during most of the time it is used in the application.

### High-efficiency motors

As mentioned earlier, the higher the mechanical power produced by the motor for a given amount of electrical power, the more efficient the motor. The efficiency of a motor is thus inversely proportional to the amount of energy losses occurring in the motor during the process of converting the electrical energy supplied to the motor into mechanical energy. Table 2-1 lists the different types of energy losses occurring in a typical three-phase squirrel-cage induction motor. No-load losses are losses that remain constant regardless of the motor load, while load losses vary depending on the motor load.

**Table 2-1. Types of energy losses in a typical three-phase squirrel-cage induction motor.**

No-load losses	Load losses
Iron losses in core	Stator copper losses
Windage and friction losses	Rotor losses
	Stray load losses

**High-efficiency motors** are motors that are designed to reduce to a certain extent any or all of the energy loss types listed in Table 2-1. Usual improvements designed to increase motor efficiency include a lengthening of the motor core, the use of higher quality steel, thinner motor laminations, a higher amount of copper in the motor windings (i.e., the use of larger conductors), and improved bearings. Due to these improvements, high-efficiency motors have a number of advantages over normal-efficiency motors, the most important of which are listed below:

- They consume less electrical power (typically up to 4% less) for the same mechanical power as normal-efficiency motors. This means that high-efficiency motors have lower operating costs than normal-efficiency motors.
- They maintain a high motor efficiency when operating at a mechanical power as low as 50% of the motor nominal mechanical power.
- They are more reliable and the motor components (e.g., bearings, windings) have a longer life.
- They better withstand high voltage fluctuations, short-term overloads, and phase imbalance.



High-efficiency motors are especially important in relation to renewable energies because they help in reducing the energy demand (and thus the carbon emission that results from the production of this energy) of any system where motors are used to perform work. Given that motors currently use roughly 65% of the energy consumed by industry worldwide, using high-efficiency motors is a very effective way of reducing the impact of large-scale energy consumption on the environment.



Figure 2-12. High-efficiency motors help in reducing electricity consumption by industry worldwide. The above motors are part of a new range of certified IE2 (high efficiency) and IE3 (premium efficiency) induction motors. IE2 and IE3 are certifications issued by the International Electrical Commission regarding the efficiency of electrical motors (© Siemens AG 2012, all rights reserved).

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Three-phase induction motor no-load and full-load operation
- Three-phase induction motor operation characteristics
- Three-phase induction motor direction of rotation

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections

*In this section, you will set up a circuit containing a three-phase induction machine coupled to a prime mover/brake. You will then set the measuring equipment required to study the three-phase induction machine operating as a motor.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Four-Pole Squirrel Cage Induction Motor](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

4. Turn the [Four-Quadrant Dynamometer/Power Supply](#) on, then set the [Operating Mode](#) switch to [Dynamometer](#). This setting allows the [Four-Quadrant Dynamometer/Power Supply](#) to operate as a prime mover, a brake, or both, depending on the selected function.

5. Turn the host computer on, then start the [LVDAC-EMS](#) software.

In the **LVDAC-EMS Start-Up** window, make sure the **Data Acquisition and Control Interface** and the **Four-Quadrant Dynamometer/Power Supply** are detected. Make sure the **Computer-Based Instrumentation** function is available for the **Data Acquisition and Control Interface**. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.

6. Connect the equipment as shown in Figure 2-13.

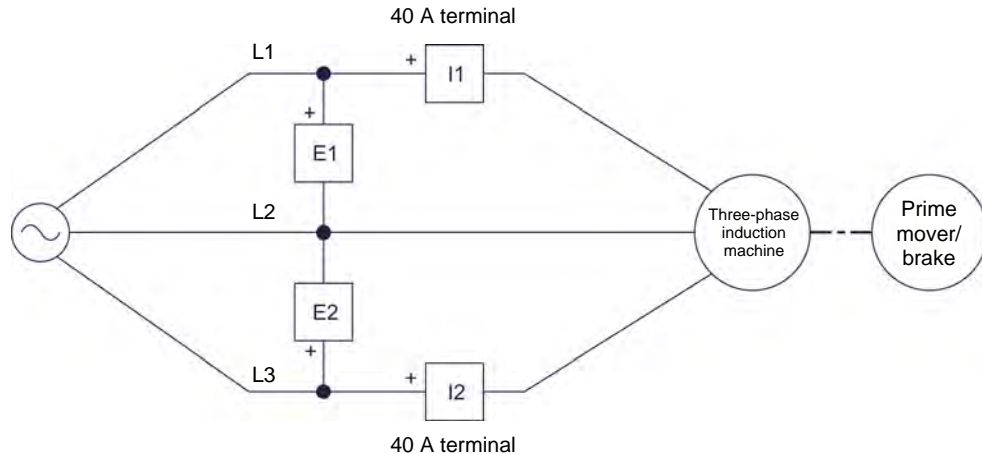


Figure 2-13. Three-phase induction machine coupled to a prime mover/brake.

7. In **LVDAC-EMS**, set the **Range** setting of current inputs **I1** and **I2** to **High**.
8. In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:

- Set the **Function** parameter to **CW Constant-Speed Prime Mover/Brake**. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a constant-speed prime mover/brake rotating in the clockwise direction. In this exercise, the **CW Constant-Speed Prime Mover/Brake function** will be used as a brake.
- Set the **Speed** parameter to the synchronous speed of the three-phase induction machine. This setting will cause the constant-speed prime mover/brake to make the three-phase induction machine rotate at the synchronous speed.



The synchronous speed of the **Four-Pole Squirrel Cage Induction Motor** is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.

- Set the **Pulley Ratio** parameter to 24:24.

9. In LVDAC-EMS, start the **Metering** application. Make the required settings in order to measure the rms values (ac) of the three-phase induction machine line voltage  $E_{Line}$  (input **E1**) and line current  $I_{Line}$  (input **I1**). Set two other meters to measure the machine active power  $P$  and reactive power  $Q$  using the two-wattmeter method (meter function **PQS1 + PQS2**). Finally, set a meter to measure the machine power factor  $PF$  from inputs **E1**, **I1**, **E2**, and **I2**.



The **PF (E1, I2)** function (accessible through the **Meter Settings** window of the **Metering** application) allows the calculation of the power factor using the power values measured from voltage and current inputs **E1** and **I1**, and **E2** and **I2**.

Click the **Continuous Refresh** button to enable continuous refresh of the values indicated by the various meters in the **Metering** application.

### Three-phase induction motor no-load and full-load operation



In the rest of this exercise, the three-phase induction machine is often referred to as the three-phase induction motor since it operates as a motor.

In this section, you will set the three-phase induction motor to rotate without load and measure the rotation speed and direction of rotation. You will verify that the measured speed is very close to the synchronous speed. You will then increase the three-phase induction motor mechanical power until the motor works at nominal power, and record the nominal motor speed, torque, and line current. You will verify that the measured nominal motor speed and line current are approximately equal to the specified nominal motor speed and line current.

10. On the **Power Supply**, turn the three-phase ac power source on to start the three-phase induction motor.

In the **Four-Quadrant Dynamometer/Power Supply** window, start the **CW Constant-Speed Prime Mover/Brake**. Adjust the **Speed** parameter until the torque produced by the three-phase induction motor is as close as possible to 0 N·m (0 lbf·in).

In the **Four-Quadrant Dynamometer/Power Supply** window, measure and record the no-load speed  $n$  of the three-phase induction motor.

Motor no-load speed  $n =$  \_\_\_\_\_ r/min

Record the direction of rotation of the three-phase induction motor.

Motor direction of rotation: \_\_\_\_\_

11. Is the motor no-load speed  $n$  you recorded in the previous step very close to the synchronous speed  $n_s$  of the three-phase induction motor (i.e., 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz)?

☐ Yes    ☐ No

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12. In the **Four-Quadrant Dynamometer/Power Supply** window, decrease the **Speed** parameter until the mechanical power  $P_M$  (indicated by the mechanical power meter in the **Four-Quadrant Dynamometer/Power Supply** window) produced by the three-phase induction motor is as close as possible to 200 W.

Measure and record the nominal value of the three-phase induction motor speed  $n$  and torque  $T$  indicated in the **Four-Quadrant Dynamometer/Power Supply** window, as well as the nominal value of the motor line current  $I_{Line}$  indicated in the **Metering** application.

Nominal motor speed  $n =$  \_\_\_\_\_ r/min

Nominal motor torque  $T =$  \_\_\_\_\_ N·m (lbf·in)

Nominal motor line current  $I_{Line} =$  \_\_\_\_\_ A

13. Are the measured nominal motor speed  $n$  and line current  $I_{Line}$  recorded in the previous step approximately equal to the nominal motor speed  $n$  and line current  $I_{Line}$  ratings of the **Four-Pole Squirrel Cage Induction Motor** indicated in Table 2-2 for your local ac power network voltage and frequency?

Table 2-2. Nominal motor speed  $n$  and line current  $I_{Line}$  at 200 W output power.

Local ac power network		Nominal motor speed $n$ (r/min)	Nominal motor line current $I_{Line}$ (A)
Voltage (V)	Frequency (Hz)		
120	60	1685	1.14
220	50	1364	0.55
240	50	1364	0.49
220	60	1633	0.55

☐ Yes    ☐ No

14. In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **CW Constant-Speed Prime Mover/Brake**.

On the **Power Supply**, turn the three-phase ac power source off to stop the three-phase induction motor.

### Three-phase induction motor operation characteristics

*In this section, you will make the three-phase induction motor speed decrease by step from the motor synchronous speed to 0 r/min, recording at each step in the Data Table the motor speed, torque, mechanical power, line voltage, line current, active power, reactive power, and power factor. You will calculate the motor efficiency using the recorded motor mechanical power and active power values. You will plot a graph of the three-phase induction motor torque as a function of the motor speed, and interpret the results. You will then plot a graph of the three-phase induction motor active power, reactive power, power factor, and efficiency as a function of the motor mechanical power, and interpret the results.*

**15.** In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

- Set the *Function* parameter to *Speed Sweep*. This function makes the **Four-Quadrant Dynamometer/Power Supply** operate as a constant-speed prime mover/brake whose speed varies over a range defined by the *Start Speed* and *Finish Speed* parameters in a specified number of steps (determined by the *Number of Steps* parameter) of equal time duration. The function also allows recording of the motor parameters in the **Data Table** at each step of the speed sweep.
- Set the *Start Speed* parameter to the synchronous speed of the three-phase induction motor. This sets the speed at which the constant-speed prime mover/brake makes the three-phase induction motor rotate during the first step of the speed sweep to the synchronous speed.
- Set the *Finish Speed* parameter to 200 r/min below the synchronous speed of the three-phase induction motor. This setting determines the speed at which the constant-speed prime mover/brake makes the three-phase induction motor rotate during the last step of the speed sweep.
- Set the *Number of Steps* parameter to 10 steps. This setting determines the number of steps that the constant-speed prime mover/brake takes while varying the speed at which it makes the three-phase induction motor rotate during the speed sweep.
- Set the *Step Duration* parameter to 7 s. This setting determines the time duration of each step of the speed sweep.
- Set the *Record Data to Table* parameter to *Yes*. This settings makes the **Data Table** record the various parameters (determined by the *Record Settings* of the **Data Table**) of the three-phase induction motor at the end of each step of the speed sweep.
- Make sure the *Pulley Ratio* parameter is set to 24:24.

16. In LVDAC-EMS, open the **Data Table** window.

Set the **Data Table** to record the three-phase induction motor speed  $n$ , torque  $T$ , and mechanical power  $P_M$  indicated in the **Four-Quadrant Dynamometer/Power Supply** window.

Also, set the **Data Table** to record the three-phase induction motor line voltage  $E_{Line}$  (input **E1**), line current  $I_{Line}$  (input **I1**), active power  $P$ , reactive power  $Q$ , and power factor  $PF$  indicated in the **Metering** application.

17. On the **Power Supply**, turn the three-phase ac power source on to start the three-phase induction motor.

In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Speed Sweep** function.

18. Wait for the **Speed Sweep** function to complete its sweep of the specified speed interval. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

- Set the **Start Speed** parameter to 40 r/min below the speed value at which you set the **Finish Speed** parameter in step 15.
- Set the **Finish Speed** parameter to 0 r/min.
- Set the **Number of Steps** parameter to between 13 and 16 steps.
- Set the **Step Duration** parameter to 7 s. This setting determines the time duration of each step of the speed sweep.

19. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Speed Sweep** function.

20. Wait for the **Speed Sweep** function to complete its sweep of the specified speed interval. Then, when all data has been recorded, turn the three-phase ac power source in the **Power Supply** off.

21. In the **Data Table** window, save the recorded data, then export it to a spreadsheet application.

In the spreadsheet application, add a new parameter to the results: the three-phase induction motor efficiency  $\eta$ . To calculate the motor efficiency  $\eta$ , divide each motor mechanical power  $P_M$  values by the corresponding motor active power  $P$  value, then multiply the result by 100 to express the efficiency  $\eta$  as a percentage.



22. Observe the recorded data. Does the three-phase induction motor line current  $I_{Line}$  increase as the torque  $T$  produced by the motor increases?

☐ Yes      ☐ No

23. Plot a graph of the three-phase induction motor torque  $T$  as a function of the motor speed  $n$  using the results you imported from the [Data Table](#).

Indicate on the graph the nominal motor speed  $n$  and nominal motor torque  $T$  recorded in step 12. Also, using the graph, estimate the value of the motor breakdown torque  $T_{Break.}$  and locked-rotor torque  $T_{Locked}$ , and indicate both torque values on the graph. Record the estimated value of the motor breakdown torque  $T_{Break.}$  and locked-rotor torque  $T_{Locked}$  below.

Motor breakdown torque  $T_{Break} = \underline{\hspace{2cm}}$  N·m (lbf·in)

Motor locked-rotor torque  $T_{Locked} = \underline{\hspace{2cm}}$  N·m (lbf·in)

Observe the graph you just plotted. Describe how the three-phase induction motor speed  $n$  varies as the motor torque  $T$  increases.

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24. Plot a graph of the three-phase induction motor active power  $P$  and reactive power  $Q$  as a function of the motor mechanical power  $P_M$  using the results you imported from the [Data Table](#). Do not plot on the graph the points recorded as the motor mechanical power  $P_M$  decreases after having reached its maximal value.

25. Does the graph you plotted in the previous step confirm that the three-phase induction motor draws a fairly constant amount of reactive power from the three-phase ac power source during most of the reactive power-versus-mechanical power curve?

☐ Yes      ☐ No



Observe the graph you plotted in the previous step. Briefly explain why it is not recommended to use a three-phase induction motor in applications requiring the motor to work at less than its nominal mechanical power.

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- 26.** Is the amount of motor reactive power  $Q$  higher than the amount of motor active power  $P$  when the three-phase induction motor operates without load?

☐ Yes      ☐ No

What does this indicate about three-phase induction motors operating without load?

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- 27.** Plot a graph of the three-phase induction motor power factor  $PF$  as a function of the motor mechanical power  $P_M$  using the results imported from the [Data Table](#). Do not plot on the graph the points recorded as the motor mechanical power  $P_M$  decreases after having reached its maximal value.

Plot a graph of the three-phase induction motor line current  $I_{Line}$  as a function of the motor mechanical power  $P_M$  using the results you imported from the [Data Table](#). Do not plot on the graph the points recorded as the motor mechanical power  $P_M$  decreases after having reached its maximal value.

Observe the graphs you just plotted. Describe how the three-phase induction motor power factor  $PF$  and line current  $I_{Line}$  vary as the motor mechanical power  $P_M$  increases.

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- 28.** Plot a graph of the three-phase induction motor efficiency  $\eta$  as a function of the motor mechanical power  $P_M$  using the results in the spreadsheet application.

Observe the graph you just plotted. Describe how the three-phase induction motor efficiency  $\eta$  varies as the motor mechanical power  $P_M$  increases.

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### Three-phase induction motor direction of rotation

*In this section, you will interchange the connections at two terminals of the three-phase induction motor. You will then start the motor and determine its direction of rotation. You will compare the result with the motor direction of rotation you recorded earlier in this exercise.*

- 29.** On the three-phase induction motor, interchange any two of the three leads connected to the stator windings.

On the **Power Supply**, turn the three-phase ac power source on.

- 30.** Record the direction of rotation of the three-phase induction motor.

Motor direction of rotation: \_\_\_\_\_

On the **Power Supply**, turn the three-phase ac power source off.

Is the motor direction of rotation you just recorded opposite to the motor direction of rotation you recorded in step 10?

☐ Yes      ☐ No

- 31.** Close **LVDAC-EMS**, then turn off all the equipment. Disconnect all leads and return them to their storage location.

## CONCLUSION

In this exercise, you familiarized yourself with the operation and the main characteristics of three-phase squirrel-cage induction motors. You learned what motor efficiency and high-efficiency motors are. You also learned the relationships between the different parameters related to the operation of three-phase squirrel-cage induction motors, such as the motor speed, torque, mechanical power, active power, reactive power, power factor, and efficiency.

## REVIEW QUESTIONS

1. Describe what the slip of a three-phase squirrel-cage induction motor is and how it varies as the load torque applied to the motor increases.

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2. Explain what the synchronous speed of a motor is. Which two parameters determine the synchronous speed of a motor?

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3. Describe what happens to the speed of a three-phase squirrel-cage induction motor as the torque produced by the motor increases.

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4. What is the main advantage of high-efficiency motors?

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5. Briefly describe how the virtually constant reactive power requirement of a three-phase squirrel-cage induction motor affects the motor power factor and efficiency?

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## Eddy-Current Brake and Asynchronous Generator

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the basic principles of operation of an eddy-current brake. You will know how a three-phase squirrel-cage induction machine can act as an eddy-current brake. You will also know how a three-phase squirrel-cage induction machine can act as an asynchronous generator.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Eddy-current brake operation
- Three-phase squirrel-cage induction machine operating as an asynchronous generator

### DISCUSSION

#### Eddy-current brake operation

Figure 2-14 illustrates the magnet and the conducting ladder shown previously in Figure 2-2. This time, however, it is the magnet that is fixed and the ladder that is displaced rapidly toward the right.

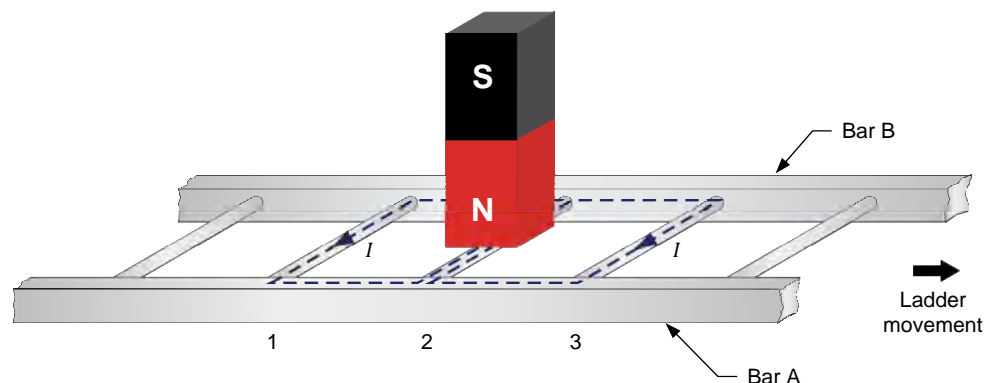
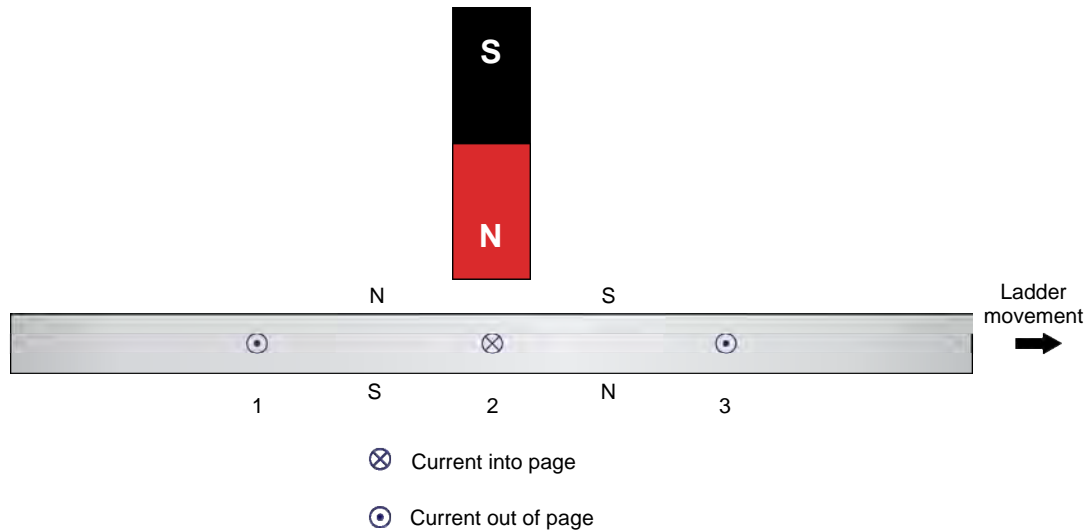


Figure 2-14. Conducting ladder moving below a magnet.

Moving the conducting ladder rapidly along the magnet causes an electrical current to flow in the loop formed by conductors 1 and 2, as well as in the loop formed by conductors 2 and 3. These currents create magnetic fields having north and south poles, as shown in Figure 2-15.



**Figure 2-15. Current in the conducting ladder creates magnetic fields.**

The interaction between the magnetic field produced by the magnet and the magnetic fields produced by the currents induced in the ladder creates a force between the fixed magnet and the moving electromagnet (i.e., the conducting ladder). This force causes the ladder to be pulled toward the fixed magnet and, therefore, tends to reduce the ladder speed. However, if the ladder stops moving, there will no longer be any variation in the magnetic flux. Consequently, no current will be induced in the wire loops and thus, no magnetic force will act on the ladder any longer. Therefore, a magnetic braking force acts on the ladder only as long as the ladder is moving. The greater the ladder speed (up to a certain limit), the greater the magnetic flux variation and, therefore, the greater the magnetic braking force acting on the conducting ladder.

This principle is used to advantage in the eddy-current brake, in which a fixed stator electromagnet creates a braking torque that acts on a squirrel-cage rotor obtained by closing a ladder similar to the ladder in Figure 2-14 upon itself. Figure 2-16 illustrates an eddy-current brake. Notice that a variable-voltage dc power source is used to make current flow in the stator electromagnet. Varying the dc power source voltage allows variation of the current in the electromagnet and thus, variation of the electromagnet strength. The greater the electromagnet strength, the greater the magnetic flux in the machine, the greater the currents induced in the squirrel-cage rotor as it turns, and ultimately, the greater the braking force acting on the squirrel-cage rotor.

The mechanical energy that is transferred from the driving machine to the eddy-current brake during braking is converted to electrical energy. This electrical energy is then dissipated as heat in the squirrel-cage rotor of the machine.

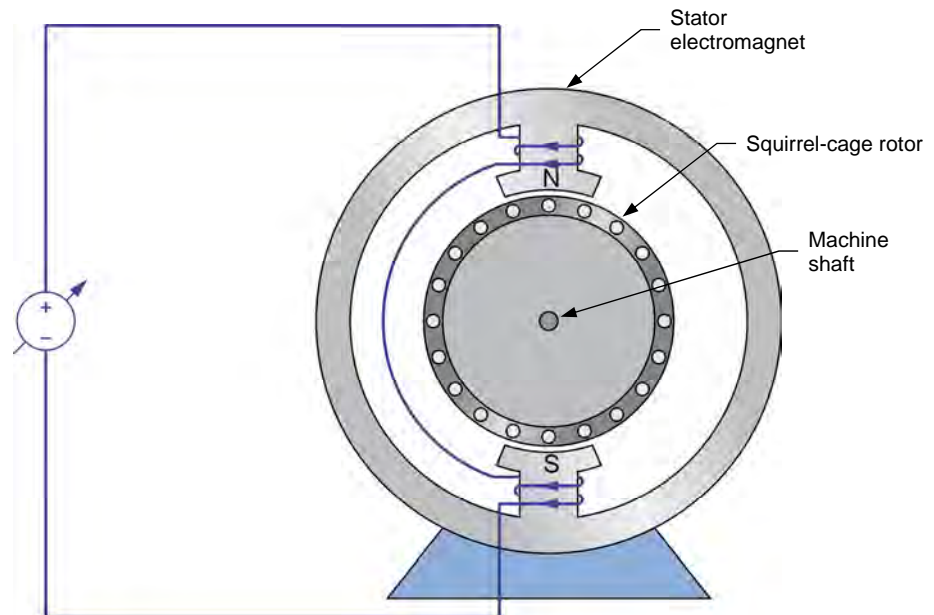


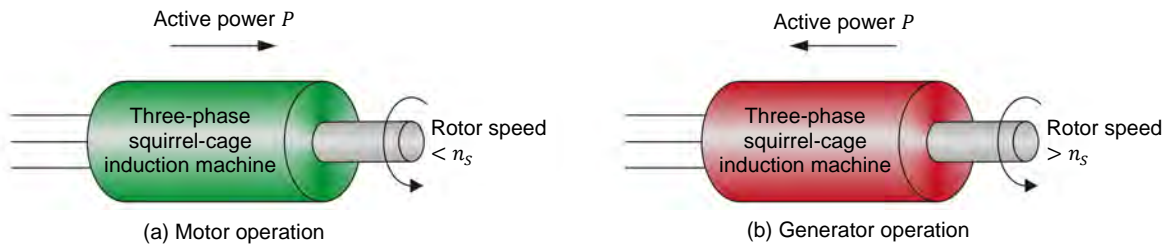
Figure 2-16. Eddy-current brake.

### Three-phase squirrel-cage induction machine operating as an asynchronous generator

A braking torque such as the one created in an eddy-current brake can be produced in three-phase squirrel-cage induction machines. This occurs when the rotor of the machine is made to rotate (by a prime mover driving the machine, for example) at a speed higher than that of the machine's rotating magnetic field (i.e., the machine synchronous speed). It results in the same forces acting on the rotor as when a conducting ladder moves along a fixed magnet, as shown in Figure 2-14. As in an eddy-current brake, mechanical energy is converted to electrical energy when the speed of the three-phase squirrel-cage induction machine is higher than the machine synchronous speed. However, most of this energy is not dissipated as heat in the rotor of the three-phase squirrel-cage induction machine. It is instead supplied to the three-phase ac power source connected to the stator windings of the machine. Therefore, a three-phase squirrel-cage induction machine connected to a three-phase ac power source operates as an asynchronous generator when the machine speed is higher than the machine synchronous speed.

To summarize, when the rotor of a three-phase squirrel-cage induction machine rotates slower than the machine synchronous speed, the machine operates as a motor because the interaction between the magnetic fields in the machine creates a force that tends to increase the rotor speed. Conversely, when the rotor of the machine turns at a speed higher than the machine synchronous speed, the interaction between the magnetic fields in the machine creates a force that tends to slow the rotor down. The machine thus operates as an asynchronous generator. Figure 2-17 illustrates the two operating modes.

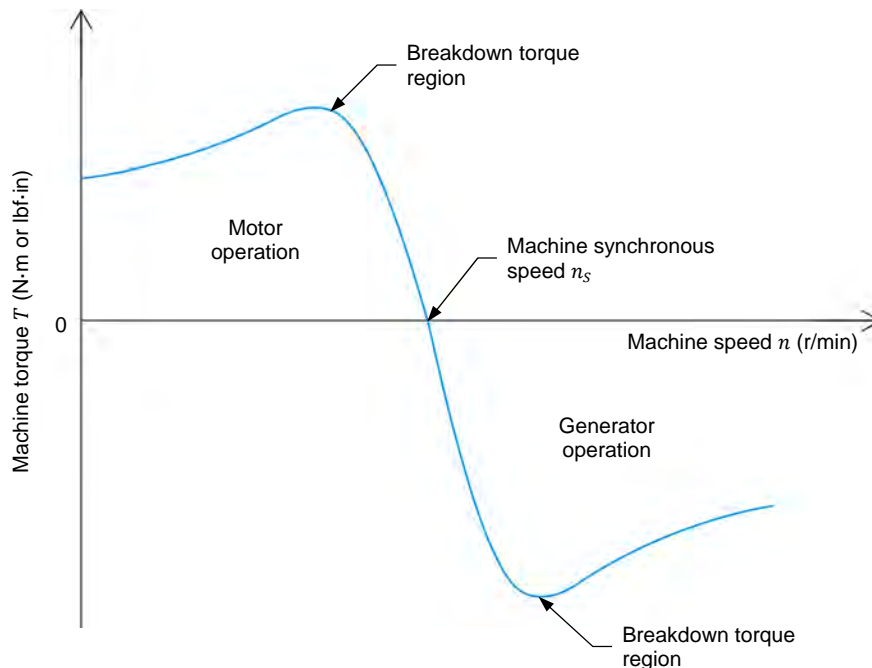




**Figure 2-17. Whether a three-phase squirrel-cage induction machine operates as a motor or as a generator depends on the rotor speed of the machine.**

As already mentioned, a three-phase squirrel-cage induction machine always draws reactive power from the three-phase ac power source to which the machine is connected. This constant supply of reactive power is used by the machine to create the rotating magnetic field necessary to the machine operation. This is true whether the machine is operating as a motor or as an asynchronous generator.

The torque  $T$  versus speed  $n$  curve in Figure 2-18 illustrates both motor and generator operation for a typical three-phase squirrel-cage induction machine. As you can see, the torque  $T$  versus speed  $n$  curve of a three-phase induction machine operating as an asynchronous generator is very similar to the torque  $T$  versus speed  $n$  curve of a three-phase induction machine operating as a motor. Note, however, that the breakdown torque of the machine operating as an asynchronous generator is always higher than the breakdown torque of the machine operating as a motor.



**Figure 2-18. Typical three-phase squirrel-cage induction machine torque  $T$  versus speed  $n$  curve for both motor and asynchronous generator operation.**

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Three-phase induction machine operating as an eddy-current brake
- Three-phase induction machine operating as a motor
- Three-phase induction machine operating as an asynchronous generator

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections

*In this section, you will set up a circuit containing a prime mover coupled to a three-phase induction machine. You will then set the measuring equipment required to study the three-phase induction machine operating as an eddy-current brake.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Four-Quadrant Dynamometer/Power Supply](#) to the [Four-Pole Squirrel Cage Induction Motor](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

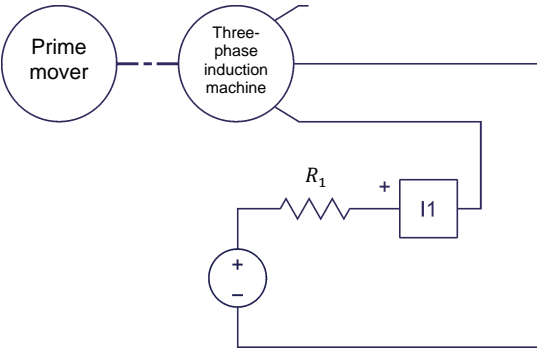
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4. Turn the **Four-Quadrant Dynamometer/Power Supply** on, then set the **Operating Mode** switch to **Dynamometer**. This setting allows the **Four-Quadrant Dynamometer/Power Supply** to operate as a prime mover, a brake, or both, depending on the selected function.
5. Turn the host computer on, then start the **LVDAC-EMS** software.

In the **LVDAC-EMS Start-Up** window, make sure the **Data Acquisition and Control Interface** and the **Four-Quadrant Dynamometer/Power Supply** are detected. Make sure the **Computer-Based Instrumentation** function is available for the **Data Acquisition and Control Interface**. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.

6. Connect the equipment as shown in Figure 2-19. Connect all three groups of resistors on the **Resistive Load** in parallel in order to implement resistor  $R_1$ .



Local ac power network		$R_1$ ( $\Omega$ )
Voltage (V)	Frequency (Hz)	
120	60	$\infty$
220	50	$\infty$
240	50	$\infty$
220	60	$\infty$

Figure 2-19. Prime mover coupled to a three-phase induction machine operating as an eddy-current brake.

7. Open all switches on the **Resistive Load** module so that the resistance of resistor  $R_1$  is infinite ( $\infty$ ).

8. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:
  - Set the *Function* parameter to *CW Prime Mover/Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a prime mover/brake rotating in the clockwise direction.
  - Set the *Speed* parameter to 150 r/min. This sets the no-load rotation speed of the prime mover/brake to 150 r/min.
  - Set the *Pulley Ratio* parameter to 24:24.
9. In LVDAC-EMS, start the *Metering* application. Make the required settings in order to measure the dc value of the stator electromagnet current  $I_{EM}$  (input *I1*).

Click the *Continuous Refresh* button to enable continuous refresh of the value indicated by the meter in the *Metering* application.

### Three-phase induction machine operating as an eddy-current brake

*In this section, you will set the prime mover to rotate in a clockwise direction, and observe the prime mover speed and the three-phase induction machine braking torque while varying the current in the stator electromagnet from a minimum to a maximum. Using the results, you will determine the relationship between the three-phase induction machine braking torque and stator electromagnet current when the prime mover rotates in a clockwise direction. You will then set the prime mover to rotate in a counterclockwise direction, and observe the prime mover speed and the three-phase induction machine braking torque while varying the current in the stator electromagnet from a minimum to a maximum. Using the results, you will confirm that the relationship between the three-phase induction machine braking torque and stator electromagnet current when the prime mover rotates in a counterclockwise direction is the same as when the prime mover rotates in a clockwise direction.*

10. On the *Power Supply*, turn the dc power source on.

In the *Four-Quadrant Dynamometer/Power Supply* window, start the prime mover.

Measure and record the prime mover speed  $n$  and the braking torque  $T_{Braking}$  produced by the three-phase induction machine. These are indicated in the *Four-Quadrant Dynamometer/Power Supply* window. Also, measure the stator electromagnet current  $I_{EM}$  indicated in the *Metering* application.

$n = \underline{\hspace{2cm}}$  r/min

$T_{Braking} = \underline{\hspace{2cm}}$  N·m (lbf·in)

$I_{EM} = \underline{\hspace{2cm}}$  A

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Record the direction of rotation of the three-phase induction machine.

Direction of rotation = \_\_\_\_\_

- 11.** Close the switches on the **Resistive Load** module one at a time in order to gradually increase the stator electromagnet current  $I_{EM}$ . While doing so, observe the prime mover speed  $n$  and the braking torque  $T_{Braking}$  produced by the three-phase induction machine.

When all switches on the **Resistive Load** module are closed, record the prime mover speed  $n$  and the braking torque  $T_{Braking}$  produced by the three-phase induction machine, as well as the stator electromagnet current  $I_{EM}$ .

$n$  = \_\_\_\_\_ r/min

$T_{Braking}$  = \_\_\_\_\_ N·m (lbf·in)

$I_{EM}$  = \_\_\_\_\_ A

Record the direction of rotation of the three-phase induction machine.

Direction of rotation = \_\_\_\_\_

When all measurements are performed, stop the prime mover then turn the dc power source in the **Power Supply** off.

- 12.** Describe how the braking torque  $T_{Braking}$  produced by the three-phase induction machine varies as the stator electromagnet current  $I_{EM}$  increases.

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- 13.** Do the results you obtained in step 11 confirm that the three-phase induction machine operates as an eddy-current brake?

☐ Yes      ☐ No

- 14.** Open all switches on the **Resistive Load** module so that the resistance of resistor  $R_1$  is infinite.

- 15.** In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

- Set the **Function** parameter to **CCW Prime Mover/Brake**. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a prime mover/brake rotating in the counterclockwise direction.

- Set the **Speed** parameter to -150 r/min. This sets the no-load rotation speed of the prime mover/brake to 150 r/min in the counterclockwise direction.

**16.** On the **Power Supply**, turn the dc power source on.

In the **Four-Quadrant Dynamometer/Power Supply** window, start the prime mover.

Measure and record the prime mover speed  $n$  and the braking torque  $T_{Braking}$  produced by the three-phase induction machine, as well as the stator electromagnet current  $I_{EM}$ .

$$n = \underline{\hspace{2cm}} \text{ r/min}$$

$$T_{Braking} = \underline{\hspace{2cm}} \text{ N}\cdot\text{m (lbf}\cdot\text{in)}$$

$$I_{EM} = \underline{\hspace{2cm}} \text{ A}$$

Record the direction of rotation of the three-phase induction machine.

Direction of rotation = \_\_\_\_\_

17. Close the switches on the **Resistive Load** module one at a time in order to gradually increase the stator electromagnet current  $I_{EM}$ . While doing so, observe the prime mover speed  $n$  and the braking torque  $T_{Braking}$  produced by the three-phase induction machine.

When all switches on the **Resistive Load** module are closed, record the prime mover speed  $n$  and the braking torque  $T_{Braking}$  produced by the three-phase induction machine, as well as the stator electromagnet current  $I_{EM}$ .

$$n = \text{_____ r/min}$$

$$T_{Braking} = \underline{\hspace{2cm}} \text{ N}\cdot\text{m (lbf}\cdot\text{in)}$$

$$I_{EM} = \underline{\hspace{2cm}} \text{ A}$$

Record the direction of rotation of the three-phase induction machine.

Direction of rotation =

When all measurements are performed, stop the prime mover then turn the dc power source in the **Power supply** off.

**18.** Describe how the braking torque  $T_{Braking}$  produced by the three-phase induction machine varies as the stator electromagnet current  $I_{EM}$  increases.

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19. Is the operation of the three-phase induction machine affected by the direction of rotation of the prime mover?

☐ Yes      ☐ No

### Three-phase induction machine operating as a motor

*In this section, you will set up a circuit containing a three-phase induction machine coupled to a constant-speed prime mover/brake. You will set the constant-speed prime mover/brake to rotate at a speed below the three-phase induction machine synchronous speed. You will measure the three-phase induction machine speed, torque, mechanical power, active power, and reactive power when the machine is turning at a speed below its synchronous speed (i.e., when the machine is operating as a motor). You will observe that active power is supplied by the three-phase ac power source to the machine. You will then set the constant-speed prime mover/brake to rotate at the three-phase induction machine synchronous speed. You will measure the three-phase induction machine speed, torque, mechanical power, active power, and reactive power when the machine is turning at synchronous speed. You will observe that virtually no active power is supplied by the three-phase ac power source to the machine.*

20. Connect the equipment as shown in Figure 2-20.

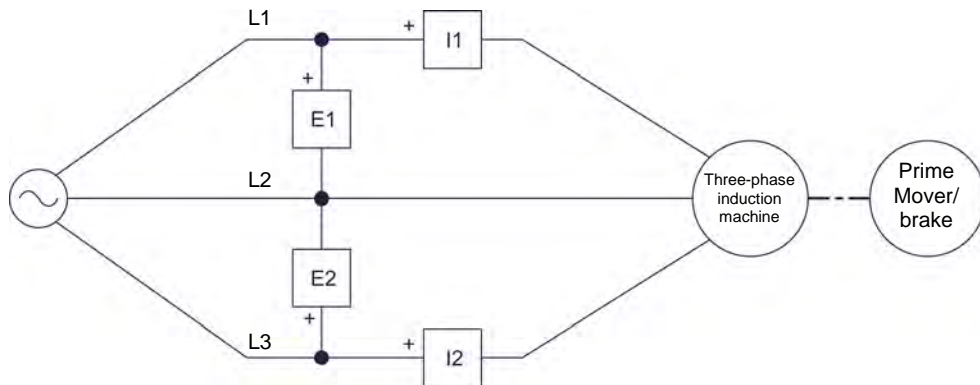


Figure 2-20. Three-phase induction machine coupled to a prime mover/brake.

21. In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

- Set the **Function** parameter to **CW Constant-Speed Prime Mover/Brake**. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a constant-speed prime mover/brake rotating in the clockwise direction.

- Set the *Speed* parameter to 100 r/min below the synchronous speed of the three-phase induction machine. This sets the speed of the *CW Constant-Speed Prime Mover/Brake* to the specified speed value.



The synchronous speed of the *Four-Pole Squirrel Cage Induction Motor* is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.

- 22.** In the *Metering* application, make the required settings in order to measure the rms values (ac) of the three-phase induction machine line voltage  $E_{Line}$  (input *E1*), and line current  $I_{Line}$  (input *I1*). Set two other meters to measure the machine active power  $P$  and reactive power  $Q$  using the two-wattmeter method (meter function *PQS1 + PQS2*).

In the *Metering* application, set the meter measuring the three-phase induction machine active power  $P$  so that it has a zero-center analog-type display.

In the *Four-Quadrant Dynamometer/Power Supply* window, set the meter measuring the three-phase induction machine mechanical power  $P_M$  so that it has a zero-center analog-type display.

- 23.** Before turning the three-phase ac power source in the *Power Supply* on and starting the *CW Constant-Speed Prime Mover/Brake*, make sure that both the three-phase induction machine and the prime mover/brake are set to rotate in the same direction (i.e., in the clockwise direction). To do so, start each machine separately and observe that the machine is rotating in the clockwise direction. Once you have confirmed the direction of rotation of either machine, turn it off.

- 24.** On the *Power Supply*, turn the three-phase ac power source on.

In the *Four-Quadrant Dynamometer/Power Supply* window, start the prime mover/brake.

Measure and record the machine speed  $n$ , torque  $T$ , and mechanical power  $P_M$  indicated in the *Four-Quadrant Dynamometer/Power Supply* window, as well as the machine active power  $P$  and reactive power  $Q$  indicated in the *Metering* application.

$n = \underline{\hspace{2cm}}$  r/min  $T = \underline{\hspace{2cm}}$  N·m (lbf·in)

$P = \underline{\hspace{2cm}}$  W  $Q = \underline{\hspace{2cm}}$  var

$P_M = \underline{\hspace{2cm}}$  W



25. Does the three-phase induction machine active power  $P$  measured in the previous step indicate that active power flows from the three-phase ac power source to the three-phase induction machine?

☐ Yes ☐ No

Does this confirm that the three-phase induction machine currently operates as a motor?

☐ Yes ☐ No

26. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Speed** parameter to the synchronous speed  $n_s$  of the three-phase induction machine.

Measure and record the machine speed  $n$ , torque  $T$ , and mechanical power  $P_M$  indicated in the **Four-Quadrant Dynamometer/Power Supply** window, as well as the machine active power  $P$  and reactive power  $Q$  indicated in the **Metering** application.

$n =$  \_\_\_\_\_ r/min

$T =$  \_\_\_\_\_ N·m (lbf·in)

$P =$  \_\_\_\_\_ W

$Q =$  \_\_\_\_\_ var

$P_M =$  \_\_\_\_\_ W

27. Does the three-phase induction machine active power  $P$  measured in the previous step indicate that a significant amount of active power flows from the three-phase ac power source to the three-phase induction machine?

☐ Yes ☐ No

### Three-phase induction machine operating as an asynchronous generator

*In this section, you will set the constant-speed prime mover/brake to rotate at a speed above the three-phase induction machine synchronous speed. You will measure the three-phase induction machine speed, torque, mechanical power, active power, and reactive power when the machine is turning at a speed above its synchronous speed (i.e., when the machine is operating as an asynchronous generator). You will observe that active power is supplied by the machine to the three-phase ac power source. Finally, you will disconnect the three-phase ac power source from the circuit, and verify that the machine line voltage is zero, thus confirming that the three-phase induction machine cannot operate as an asynchronous generator when the machine is not connected to an ac power source.*

28. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Speed** parameter to 100 r/min above the synchronous speed  $n_s$  of the three-phase induction machine.

Measure and record the machine speed  $n$ , torque  $T$ , and mechanical power  $P_M$  indicated in the [Four-Quadrant Dynamometer/Power Supply](#) window, as well as the machine active power  $P$  and reactive power  $Q$  indicated in the [Metering](#) application.

$n = \underline{\hspace{2cm}}$  r/min  $T = \underline{\hspace{2cm}}$  N·m (lbf·in)

$P = \underline{\hspace{2cm}}$  W  $Q = \underline{\hspace{2cm}}$  var

$P_M = \underline{\hspace{2cm}}$  W

- 29.** Does the three-phase induction machine active power  $P$  measured in the previous step indicate that active power flows from the three-phase induction machine to the three-phase ac power source?

☐ Yes ☐ No

Does this confirm that the three-phase induction machine currently operates as an asynchronous generator?

☐ Yes ☐ No

- 30.** In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the prime mover/brake, then set the [Speed](#) parameter to 1000 r/min.

On the [Power Supply](#), turn the three-phase ac power source off.

Disconnect the three-phase ac power source from the circuit by removing the leads connected to terminals [L1](#), [L2](#), and [L3](#) of the [Power Supply](#). Do not remove the leads used for circuit measurements (i.e., the leads connected to inputs [E1](#), [E2](#), [I1](#), and [I2](#) on the [Data Acquisition and Control Interface](#)).

- 31.** In the [Four-Quadrant Dynamometer/Power Supply](#) window, start the prime mover/brake.

In the [Metering](#) application, measure and record the line voltage  $E_{Line}$  produced by the three-phase induction machine.

$E_{Line} = \underline{\hspace{2cm}}$  V

In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the prime mover/brake.

- 32.** Does the line voltage  $E_{Line}$  measured in the previous step confirm that a three-phase induction machine cannot operate as an asynchronous generator when it is not connected to a three-phase ac power source?

☐ Yes ☐ No

- 33.** Close **LVDAC-EMS**, then turn off all the equipment. Disconnect all leads and return them to their storage location.

**CONCLUSION**

In this exercise, you saw the basic principles of operation of an eddy-current brake. You learned how a three-phase squirrel-cage induction machine can act as an eddy-current brake. You also learned how a three-phase squirrel-cage induction machine can act as an asynchronous generator.

**REVIEW QUESTIONS**

1. Explain how a three-phase squirrel-cage induction machine can act as an eddy-current brake.

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2. What is the relationship between the intensity of the current flowing in the stator electromagnet of an eddy-current brake and the magnitude of the braking torque produced by the eddy-current brake?

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3. What happens to the mechanical energy supplied by a driving machine to an eddy-current brake during braking?

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4. Explain the difference between a three-phase squirrel-cage induction machine operating as an eddy-current brake and a three-phase squirrel-cage induction machine operating as an asynchronous generator.

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5. Why is it necessary for a three-phase squirrel-cage induction machine to be connected to a three-phase ac power source, whether it is operating as a motor or as an asynchronous generator?

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## Unit Test

1. The speed of the rotating magnetic field created in a three-phase induction machine corresponds to the machine
  - a. no-load speed.
  - b. synchronous speed.
  - c. slip speed.
  - d. nominal speed.
2. The synchronous speed of a three-phase induction machine depends on the
  - a. number of magnetic poles in the machine and the frequency of the three-phase ac power source.
  - b. actual speed of the machine and the amount of active power supplied to it.
  - c. intensity of the machine's rotating magnetic field and the voltage of the three-phase ac power source.
  - d. the number of phases of the three-phase ac power source.
3. The difference between the actual speed and the synchronous speed of a three-phase induction machine is
  - a. known as the nominal machine speed.
  - b. zero.
  - c. known as the machine slip.
  - d. always constant.
4. Which of the following statements correctly describes what happens to the speed of a three-phase induction motor as the torque produced by the motor increases. Consider only the linear portion of the motor's torque versus speed curve.
  - a. The motor speed decreases until the breakdown torque region is reached.
  - b. The motor speed increases until the breakdown torque region is reached.
  - c. The motor speed remains constant.
  - d. The motor speed increases until the motor synchronous speed is reached.
5. The reactive power that a three-phase induction machine draws from a three-phase ac power source is used to
  - a. reduce the vibrations produced in the machine.
  - b. increase the power factor of the machine.
  - c. create the machine's rotating magnetic field.
  - d. maintain the machine slip constant.

6. A three-phase induction machine operating at a mechanical power lower than the machine's nominal mechanical power
  - a. has a higher power factor than if the machine would operate at its nominal mechanical power.
  - b. has a lower power factor than if the machine would operate at its nominal mechanical power.
  - c. consumes much more reactive power than if the machine would operate at its nominal mechanical power.
  - d. consumes much less reactive power than if the machine would operate at its nominal mechanical power.
7. Which of the following statements concerning high-efficiency motors is false? High-efficiency motors
  - a. consume less electrical power for the same mechanical power as normal-efficiency motors.
  - b. maintain a high motor efficiency even when operating at a mechanical power as low as 50% of the motor's nominal mechanical power.
  - c. are more reliable and have a longer life than normal-efficiency motors.
  - d. lower the amount of mechanical power needed to perform a given work.
8. When a three-phase induction machine turns at a speed that is faster than its synchronous speed, the machine
  - a. consumes active power and draws reactive power.
  - b. consumes active power and supplies reactive power.
  - c. supplies active power and draws reactive power.
  - d. supplies active power and reactive power.
9. The rotor speed of a three-phase induction machine operating as an asynchronous generator is
  - a. higher than the machine synchronous speed.
  - b. equal to the machine synchronous speed.
  - c. lower than the machine synchronous speed.
  - d. zero.
10. What is the output voltage of an asynchronous generator turning at a speed higher than the machine synchronous speed if the machine is not connected to a three-phase ac power source?
  - a. The machine output voltage is much higher than if the machine was connected to a three-phase ac power source.
  - b. The machine output voltage is equal to its nominal voltage rating.
  - c. The machine output voltage depends on the machine's direction of rotation.
  - d. The machine output voltage is virtually zero, except for the voltage produced by residual magnetism.

## Synchronous Motors

**UNIT OBJECTIVE**

When you have completed this unit, you will be familiar with the operation and the main characteristics of synchronous motors. You will also know what the pull-out torque of a synchronous motor is, and how the pull-out torque of a synchronous motor varies with the motor field current.

**DISCUSSION OUTLINE**

The Discussion of Fundamentals covers the following points:

- Introduction to synchronous motors

**DISCUSSION OF FUNDAMENTALS****Introduction to synchronous motors**

The principles of operation of a three-phase **synchronous motor** are very similar to those of a three-phase squirrel-cage induction motor. The motor stator is usually built in the same way (refer to Figure 2-5 in Unit 2), and it creates a rotating magnetic field identical to the one illustrated in Figure 2-7. The rotor of the synchronous motor, however, is not a squirrel-cage construction, but rather either a permanent magnet or an electromagnet installed on the motor shaft, as shown in Figure 3-1. The rotor of the synchronous motor is pulled along by the rotating magnetic field as explained in Unit 1.



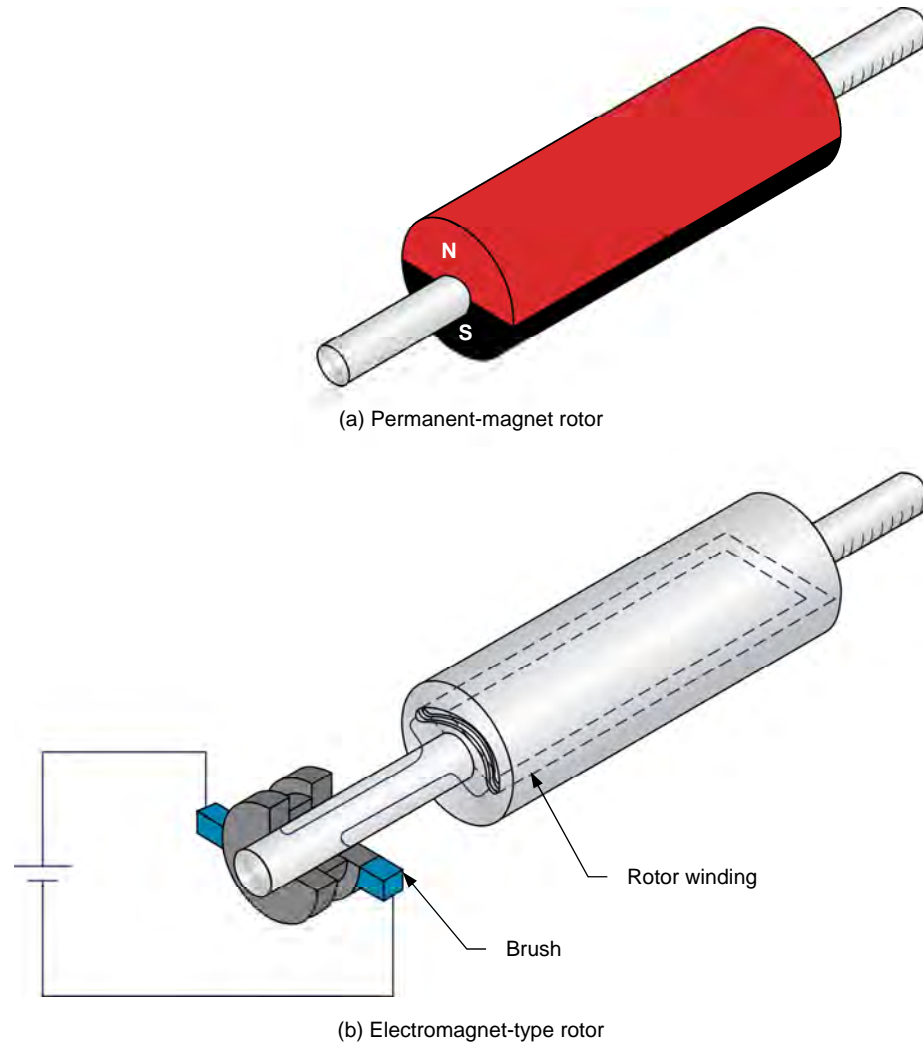


Figure 3-1. Different types of synchronous motor rotors.



Figure 3-2. Synchronous motors are commonly used in high-speed trains.

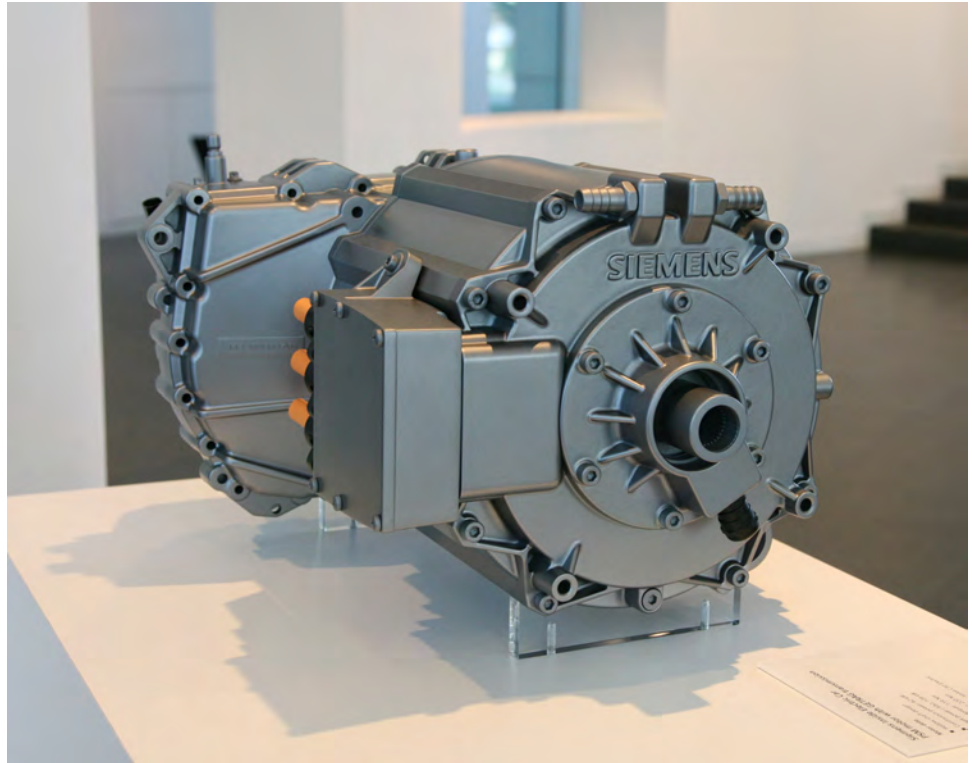
Synchronous motors have one major disadvantage when compared to other types of three-phase motors: synchronous motors are not self-starting motors, i.e., they necessitate assistance in order to start properly. This property is due to the inertia of the rotor. During motor start-up, when three-phase ac power is supplied to the stator windings, a magnetic field rotating at synchronous speed  $n_s$  is immediately created. Since the rotor is initially at rest, it cannot catch up with the rotating magnetic field, and the resulting torque acting on the rotor is fairly weak.

There are many existing methods designed to overcome the inertia of a synchronous motor rotor during start-up. One of the most common methods is to add a squirrel-cage to the rotor. During start-up, power is removed from the rotor electromagnet (thus removing the magnetic field generated in the electromagnet) and three-phase ac power is applied to the stator windings. A rotating magnetic field is created, currents are induced in the squirrel cage, and the motor starts to rotate like a conventional three-phase squirrel-cage induction motor. When the motor speed stabilizes, dc power is applied to the electromagnet, thus generating a magnetic field in the rotor electromagnet. This causes the rotor to pull into synchronization (i.e., to lock on the rotating magnetic field) and to turn exactly at synchronous speed  $n_s$ .

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The method described above can only be used when the rotor of the synchronous motor is an electromagnet, since it is impossible to remove the magnetic field generated in a permanent magnet rotor. In this case, a different method must be used. During start-up of a synchronous motor having a permanent magnet rotor, a variable-frequency ac power source is used to supply power to the stator windings of the permanent-magnet synchronous motor. The frequency of the ac power source is first set to a low value. This creates a stator magnetic field that rotates at a low speed, and thereby, allows the rotor to catch up with the field. The frequency of the ac power source is then increased gradually to increase the motor speed up to the desired value.



**Figure 3-3. Permanent-magnet synchronous motor found in a Volvo C30 electric vehicle (© Siemens AG 2012, all rights reserved).**



## The Three-Phase Synchronous Motor

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operation and the main characteristics of a three-phase synchronous motor. You will know the relationships between the line current, the field current, and the reactive power in a synchronous motor, and be able to plot a graph of these relationships.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Three-phase synchronous motor operation

### DISCUSSION

#### Three-phase synchronous motor operation

It is generally accepted that inductive components absorb reactive power and capacitive components supply reactive power, although reactive components in fact exchange reactive power and neither absorb nor supply reactive power.

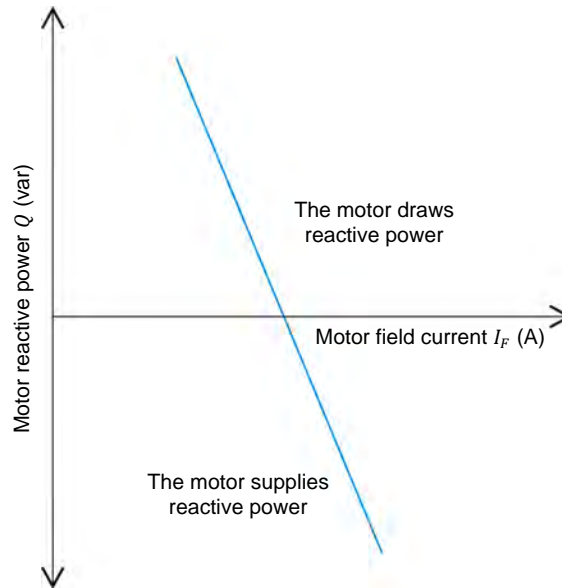
The most interesting features of a three-phase synchronous motor are the ability to operate at exactly the same speed as the rotating magnetic field (i.e., at the synchronous speed), the capability of running at unity power factor, and the ability to supply reactive power to an ac power source. As seen in Unit 2, an asynchronous motor always consumes reactive power, whether it operates as a motor or a generator. This is because the squirrel-cage induction motor requires reactive power to produce the rotating magnetic field. In the case of the three-phase synchronous motor, the rotating magnetic field is the sum of the magnetic fields produced by the stator and the rotor. If the rotor field is weak, the stator must contribute almost all the reactive power for the rotating magnetic field. The motor thus consumes reactive power like an inductor or an asynchronous motor. However, if the rotor field is strong, the stator acts to decrease the resulting field, and the motor thus supplies reactive power like a capacitor.

A graph of the reactive power  $Q$  versus the **field current**  $I_F$  (current in the rotor electromagnet) in a three-phase synchronous motor operating without load is shown in Figure 3-4. When the motor field current  $I_F$  is at a minimum, the magnetic field produced by the rotor is weak and the motor consumes a maximum of reactive power (reactive power  $Q$  is positive). The reactive power that is consumed decreases to zero as field current  $I_F$  increases because the strength of the magnetic field produced by the rotor increases. When the motor field current  $I_F$  exceeds a certain value, the rotor magnetic field is so strong that the motor starts to supply reactive power, i.e., reactive power  $Q$  becomes negative as illustrated in Figure 3-4. The value at which a particular synchronous motor begins to supply reactive power is specific to each motor and depends on the different motor characteristics.

The graph of the reactive power  $Q$  in a three-phase synchronous motor as a function of the motor field current  $I_F$  shows that a three-phase synchronous motor without load behaves like a three-phase reactive load whose nature (inductive or capacitive) and value depend on the motor field current  $I_F$ . This explains why three-phase synchronous motors without load are also known as synchronous condensers when used to control the power factor in three-phase power networks.

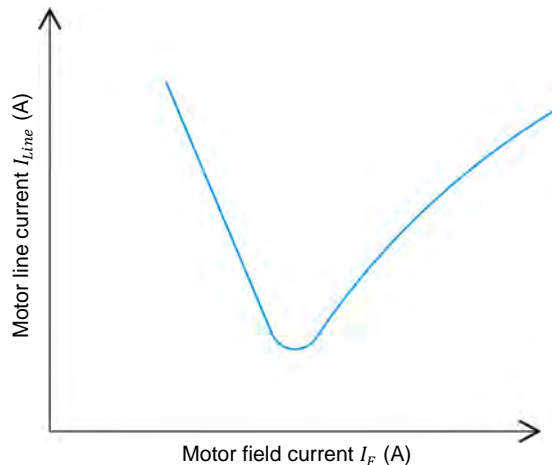
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**Figure 3-4.** Relationship between the reactive power  $Q$  and the field current  $I_F$  in a three-phase synchronous motor operating without load.

The graph of the line current  $I_{Line}$  in a three-phase synchronous motor as a function of the motor field current  $I_F$  is a "V" type curve (commonly referred to as a V-curve), as shown in Figure 3-5. The graph shows that the motor line current  $I_{Line}$  can be minimized by setting the motor field current  $I_F$  to the appropriate value. The field current  $I_F$  required to minimize the line current  $I_{Line}$  in a three-phase synchronous motor is the same as the field current  $I_F$  required to decrease the reactive power  $Q$  in the motor to zero. Therefore, the reactive power  $Q$  in a three-phase synchronous motor is zero when the line current  $I_{Line}$  in the motor is at a minimum.



**Figure 3-5.** Relationship between the line current  $I_{Line}$  and the field current  $I_F$  in a three-phase synchronous motor operating without load (synchronous motor V-curve).

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Starting a three-phase synchronous motor
- Characteristics of a three-phase synchronous motor

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections

*In this section, you will set up a circuit containing a synchronous motor mechanically coupled to a brake. You will then set the measuring equipment required to study the synchronous motor operation.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Synchronous Motor/Generator](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

4. Turn the **Four-Quadrant Dynamometer/Power Supply** on, then set the **Operating Mode** switch to **Dynamometer**. This setting allows the **Four-Quadrant Dynamometer/Power Supply** to operate as a prime mover, a brake, or both, depending on the selected function.
5. Turn the host computer on, then start the **LVDAC-EMS** software.

In the **LVDAC-EMS Start-Up** window, make sure the **Data Acquisition and Control Interface** and the **Four-Quadrant Dynamometer/Power Supply** are detected. Make sure the **Computer-Based Instrumentation** function is available for the **Data Acquisition and Control Interface**. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.

6. Connect the equipment as shown in Figure 3-6.

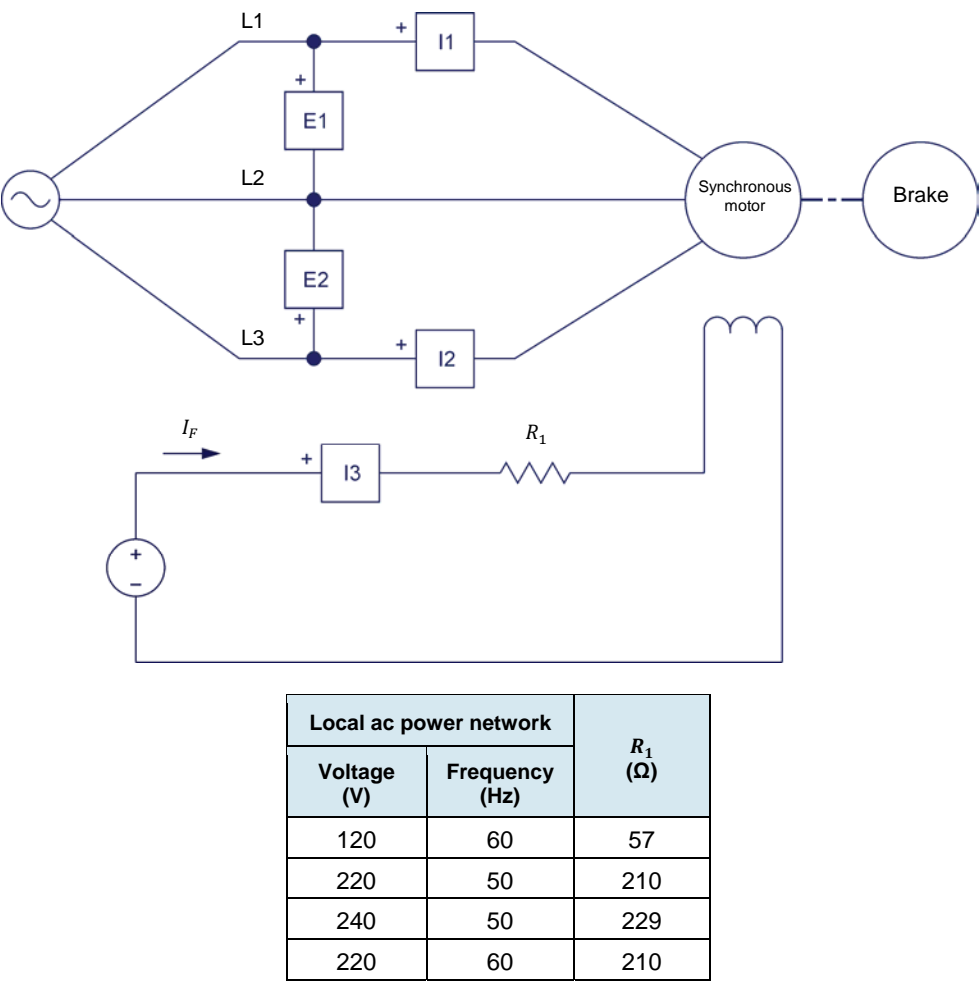


Figure 3-6. Synchronous motor coupled to a brake.

7. Make the necessary switch settings on the **Resistive Load** module in order to obtain the resistance value required.
8. In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
  - Set the **Function** parameter to **Two-Quadrant, Constant-Torque Brake**.
  - Set the **Torque** parameter to the maximum (i.e., 3.00 N·m or 26.55 lbf·in).
  - Set the **Pulley Ratio** parameter to 24:24.
9. In **LVDAC-EMS**, start the **Metering** application. Make the required settings in order to measure the rms values (ac) of the motor line voltage  $E_{Line}$  (input **E1**), and the motor line current  $I_{Line}$  (input **I1**). Set another meter to measure the dc value of the field current  $I_F$  (input **I3**) in the rotor electromagnet. Set two other meters to measure the motor active power  $P$  and reactive power  $Q$  using the two-wattmeter method (meter function **PQS1 + PQS2**).

Click the **Continuous Refresh** button to enable continuous refresh of the values indicated by the various meters in the **Metering** application.

### Starting a three-phase synchronous motor

*In this section, you will measure the synchronous motor starting torque when the load torque produced by the brake is at the maximum and current is flowing in the rotor electromagnet. You will then measure the synchronous motor starting torque when no current is flowing in the rotor electromagnet, and compare both starting torque values. You will set the load torque produced by the brake to the minimum and measure the synchronous motor speed when no current is flowing in the rotor electromagnet. You will then measure the synchronous motor speed when current is flowing in the rotor electromagnet, and compare both speed values. Finally, you will slowly vary the intensity of the field current to observe the relationship between the field current and the speed of the synchronous motor as well as the relationship between the field current and motor line current.*

10. On the **Synchronous Motor/Generator**, set the **Exciter** switch to the closed position (I), then turn the **Exciter** knob fully clockwise (i.e., set it to the **MAX.** position).



11. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Two-Quadrant, Constant-Torque Brake**.

On the **Power Supply**, turn the dc power source on, then turn the three-phase ac power source on to start the three-phase synchronous motor.



*If you are using the LVSIM-EMS software, skip the next manipulation and go directly to step 13.*

12. Wait a few seconds for the motor starting torque to stabilize then measure and record the motor starting torque  $T_{start,exc.}$  (indicated in the **Four-Quadrant Dynamometer/Power Supply** window) when current is flowing in the rotor electromagnet.

Motor starting torque  $T_{start,exc.} = \underline{\hspace{2cm}}$  N·m (lbf·in)

13. On the **Synchronous Motor/Generator**, make sure that the **Exciter** switch is set to the open (O) position.

Measure and record the motor starting torque  $T_{start}$  when no current is flowing in the rotor electromagnet.

Motor starting torque  $T_{start} = \underline{\hspace{2cm}}$  N·m (lbf·in)

14. On the **Power Supply**, turn the three-phase ac power source off, then turn the dc power source off.

15. Is the motor starting torque  $T_{start,exc.}$  obtained when current is flowing in the rotor electromagnet higher than the motor starting torque  $T_{start}$  obtained when no current is flowing in the rotor electromagnet?

☐ Yes      ☐ No

16. Does turning the rotor electromagnet off while starting the **Synchronous Motor/Generator** reduce vibrations in the motor?

☐ Yes      ☐ No

17. Do the results obtained so far indicate that it is desirable to turn the rotor electromagnet off before starting the **Synchronous Motor/Generator**?

☐ Yes      ☐ No

18. On the **Power Supply**, turn the dc power source on, then turn the three-phase ac power source on.

In the **Four-Quadrant Dynamometer/Power Supply** window, slowly lower the **Torque** parameter until the minimum value is reached (i.e., 0.0 N·m or 0.0 lbf·in).

Wait for the speed  $n$  of the **Synchronous Motor/Generator** to stabilize then record the motor speed  $n$  (indicated in the **Four-Quadrant Dynamometer/Power Supply** window) when no current is flowing in the rotor electromagnet.

Motor speed  $n = \underline{\hspace{2cm}}$  r/min

19. On the **Synchronous Motor/Generator**, set the **Exciter** knob to mid position, then set the **Exciter** switch to the closed (I) position.

Record the motor speed  $n_{Exc.}$  when current is flowing in the rotor electromagnet.

Motor speed  $n_{Exc.} = \underline{\hspace{2cm}}$  r/min

20. Compare the motor speed  $n_{Exc.}$  obtained when current is flowing in the rotor electromagnet with the motor speed  $n$  obtained when no current is flowing in the rotor electromagnet.

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21. Is the motor speed  $n_{Exc.}$  obtained when current is flowing in the rotor electromagnet approximately equal to the synchronous speed of the **Synchronous Motor/Generator**?

☐ Yes      ☐ No



The synchronous speed of the **Synchronous Motor/Generator** is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.

22. On the **Synchronous Motor/Generator**, slowly rotate the **Exciter** knob back and forth between the **MIN.** position and the **MAX.** position to vary the motor field current  $I_F$ . Observe the motor speed  $n$  (indicated in the **Four-Quadrant Dynamometer/Power Supply** window) and the motor line current  $I_{Line}$  (indicated in the **Metering** application) as you do so.

Does varying the motor field current  $I_F$  vary the motor speed  $n$ ?

☐ Yes      ☐ No

Does varying the motor field current  $I_F$  vary the motor line current  $I_{Line}$ ?

☐ Yes      ☐ No

- 23.** On the **Synchronous Motor/Generator**, set the **Exciter** knob to the **MIN.** position.

On the **Power Supply**, turn both power sources off.

In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **Two-Quadrant, Constant-Torque Brake**.

### Characteristics of a three-phase synchronous motor

*In this section, you will uncouple the three-phase synchronous motor from the Four-Quadrant Dynamometer/Power Supply. You will record in the Data Table the motor line voltage and current, field current, active power, and reactive power while varying the field current in the rotor electromagnet of the synchronous motor. You will use the recorded data to plot a graph of the motor line current as a function of the motor field current. You will use the graph to approximate the value of the motor field current for which the motor line current is at a minimum. You will then plot a graph of the motor active power and reactive power as a function of the motor field current, and determine the relationships between these parameters. You will use the graph to approximate the value of the motor field current for which the motor reactive power is zero. Finally, you will compare the value of the field current for which the motor line current is at a minimum with the value of the field current for which the motor reactive power is zero, and determine the relationship between these parameters.*

- 24.** Uncouple the **Synchronous Motor/Generator** from the **Four-Quadrant Dynamometer/Power Supply**.

On the **Power Supply**, turn the three-phase ac power source on, then turn the dc power source on.

- 25.** The range of field current  $I_F$  of the **Synchronous Motor/Generator** depends on the ac power network voltage and frequency as shown in Table 3-1.

**Table 3-1. Range of the motor field current  $I_F$ .**

Local ac power network		Range of motor field current $I_F$ (mA)
Voltage (V)	Frequency (Hz)	
120	60	360 to 780
220	50	140 to 460
240	50	140 to 460
220	60	140 to 460

Modify the resistance of resistor  $R_1$  and adjust the **Exciter** knob on the **Synchronous Motor/Generator** until the motor field current  $I_F$  is as close as possible to the minimum field current corresponding to your local ac power network voltage and frequency, as indicated in Table 3-1. For example, if your local ac power network voltage and frequency are 120 V and 60 Hz, respectively, set the motor field current  $I_F$  as close as possible to 360 mA.

26. In **LVDAC-EMS**, open the **Data Table** window.

Set the **Data Table** to record the motor line voltage  $E_{Line}$  (input **E1**), line current  $I_{Line}$  (input **I1**), field current  $I_F$ , active power  $P$ , and reactive power  $Q$  indicated in the **Metering** application.

In the **Data Table** window, click on the **Record Data** button to record the values of the motor line voltage  $E_{Line}$ , line current  $I_{Line}$ , field current  $I_F$ , active power  $P$ , and reactive power  $Q$ .

27. Modify the resistance of resistor  $R_1$  and adjust the **Exciter** knob on the **Synchronous Motor/Generator** to increase the motor field current  $I_F$  to the maximum field current value corresponding to your local ac power network voltage and frequency (see Table 3-1) in 7 or 8 equally distributed steps. For example, if your local ac power network voltage and frequency are 120 V and 60 Hz, respectively, increase the field current to 780 mA in 7 or 8 equally distributed steps. For each field current value, record the motor parameters in the **Data Table**.



*It may be necessary to short-circuit resistor  $R_1$  to obtain the maximum value of motor field current  $I_F$ .*

28. When all data has been recorded, turn both power sources in the **Power Supply** off.

29. In the **Data Table** window, save the recorded data.

30. Plot a graph of the motor line current  $I_{Line}$  as a function of the motor field current  $I_F$ .

Using the graph, approximate the value of the motor field current  $I_F$  that minimizes the motor line current  $I_{Line}$ . Record your result below.

Motor field current  $I_F$  = \_\_\_\_\_ mA

31. Plot a graph of the motor active power  $P$  and reactive power  $Q$  as a function of the motor field current  $I_F$ .

Does varying the motor field current  $I_F$  have a significant effect on the active power  $P$  consumed by the synchronous motor?

☐ Yes    ☐ No

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How does the motor reactive power  $Q$  vary as the field current  $I_F$  in the rotor electromagnet increases?

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- 32.** Could a synchronous motor operating without load be used to improve the power factor of a three-phase power network? Briefly explain why.

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- 33.** Use the graph you plotted in step 31 to approximate the value of the motor field current  $I_F$  for which the motor reactive power  $Q$  is equal to 0 var. Record your result below.

Motor field current  $I_F =$  \_\_\_\_\_ mA

- 34.** Compare the motor field current  $I_F$  for which the motor reactive power  $Q$  is equal to 0 var (recorded in the previous step) with the motor field current  $I_F$  for which the motor line current  $I_{Line}$  is at a minimum (recorded in step 30). What conclusions can you draw?

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- 35.** Based on the results you obtained in this exercise, can you conclude that the motor line current  $I_{Line}$  is at a minimum when the motor reactive power  $Q$  is zero?

☐ Yes      ☐ No

- 36.** Close **LVDAC-EMS**, then turn off all the equipment. Disconnect all leads and return them to their storage location.

**CONCLUSION**

In this exercise, you familiarized yourself with the operation and the main characteristics of a three-phase synchronous motor. You learned the relationships between the line current, the field current, and the reactive power in a synchronous motor, and how to plot a graph of these relationships.

**REVIEW QUESTIONS**

1. Which effect does turning the rotor electromagnet of a synchronous motor on have during motor start-up?

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2. Explain the relationship between the reactive power in a synchronous motor and the motor field current.

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3. When is the reactive power in a synchronous motor equal to 0 var, as related to the motor line current?

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4. What is the difference between a synchronous motor and an asynchronous motor, as related to the motor speed?

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5. How can a synchronous motor operating without load be used to improve the power factor of a three-phase power network?

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## Synchronous Motor Pull-Out Torque

### EXERCISE OBJECTIVE

When you have completed this exercise, you will know what the pull-out torque of a synchronous motor is, as well as the relationship between the pull-out torque of a synchronous motor and the field current in the rotor electromagnet.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Synchronous motor pull-out torque definition and characteristics

### DISCUSSION

#### Synchronous motor pull-out torque definition and characteristics

One of the most important characteristics of a three-phase synchronous motor is that the motor speed is exactly the same as the speed of the stator rotating magnetic field (i.e., the motor synchronous speed  $n_s$ ). When the synchronous motor operates without load torque, the electromagnet rotor is positioned so that its magnetic poles are aligned with the magnetic poles of the rotating magnetic field, as shown in Figure 3-7a. However, when load torque is applied to the synchronous motor, the electromagnet rotor changes position with respect to the rotating magnetic field, i.e., the rotor falls behind the rotating magnetic field. This is shown in Figure 3-7b.

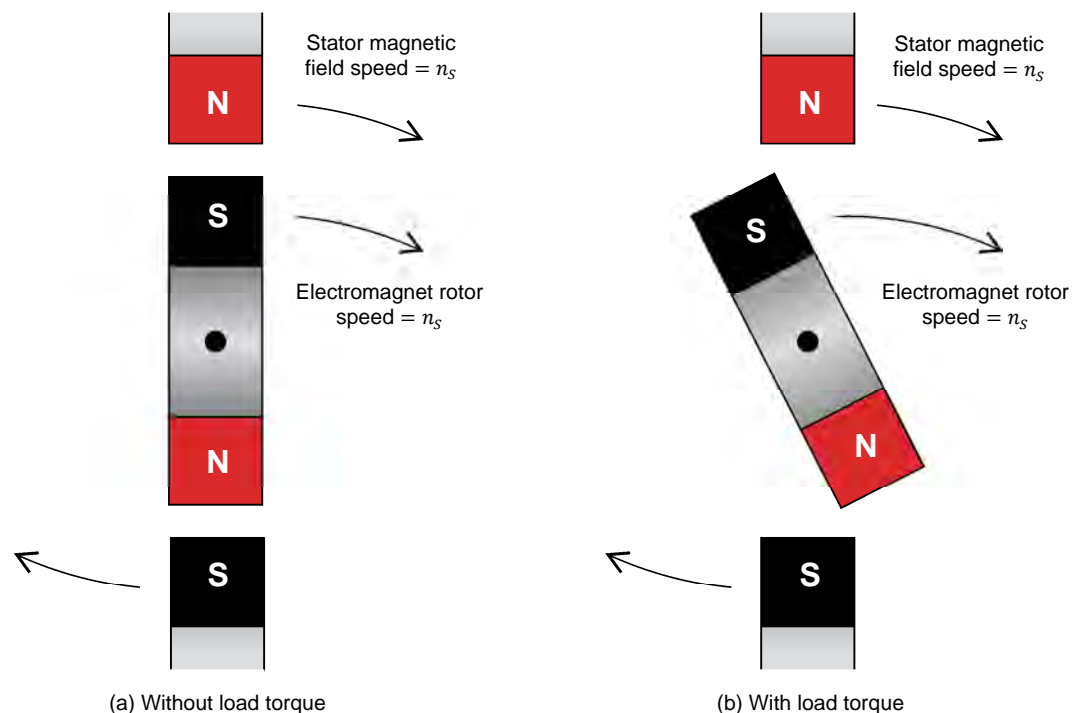


Figure 3-7. Effect of the load torque on the rotor position in a synchronous motor.



The lag of the rotor with respect to the rotating magnetic field of the stator is proportional to the load torque. Therefore, the higher the load torque, the further the rotor lags the rotating magnetic field. When the rotor lags the rotating magnetic field by  $90^\circ$ , it suddenly pulls out of synchronization with the rotating magnetic field. This causes the motor speed to decrease greatly, the motor line current to increase to high values, and the motor to begin vibrating. Protection devices are usually installed on synchronous motors to ensure that the motor suffers no damage when synchronization is lost. The load torque at which synchronization is lost is called pull-out torque.

As might be imagined, higher values of motor field current  $I_F$  allow the synchronous motor to sustain higher load torque values before pulling out of synchronization, thus increasing the pull-out torque of the motor. Figure 3-8 shows the graph of a synchronous motor pull-out torque as a function of the motor field current  $I_F$ . As the graph shows, the pull-out torque of a synchronous motor increases linearly as the motor field current  $I_F$  increases.

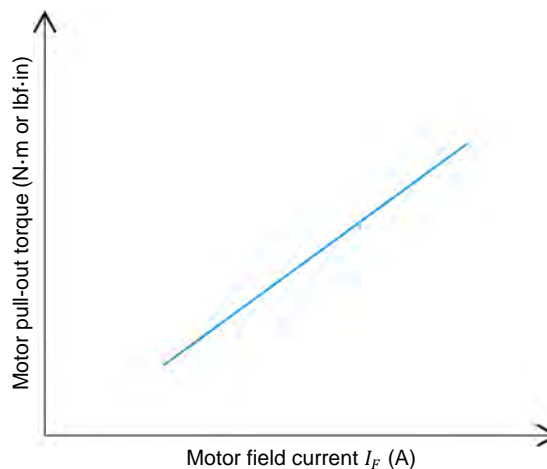


Figure 3-8. Synchronous motor pull-out torque as a function of the motor field current  $I_F$ .

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Synchronous motor pull-out torque

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections

*In this section, you will set up a circuit containing a synchronous motor mechanically coupled to a brake. You will then set the measuring equipment required to study the pull-out torque characteristics of the synchronous motor.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Synchronous Motor/Generator](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

4. Turn the [Four-Quadrant Dynamometer/Power Supply](#) on, then set the [Operating Mode](#) switch to [Dynamometer](#). This setting allows the [Four-Quadrant Dynamometer/Power Supply](#) to operate as a prime mover, a brake, or both, depending on the selected function.

5. Turn the host computer on, then start the [LVDAC-EMS](#) software.

In the [LVDAC-EMS Start-Up](#) window, make sure the [Data Acquisition and Control Interface](#) and the [Four-Quadrant Dynamometer/Power Supply](#) are detected. Make sure the [Computer-Based Instrumentation](#) function is available for the [Data Acquisition and Control Interface](#). Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the [LVDAC-EMS Start-Up](#) window.

6. Connect the equipment as shown in Figure 3-9.

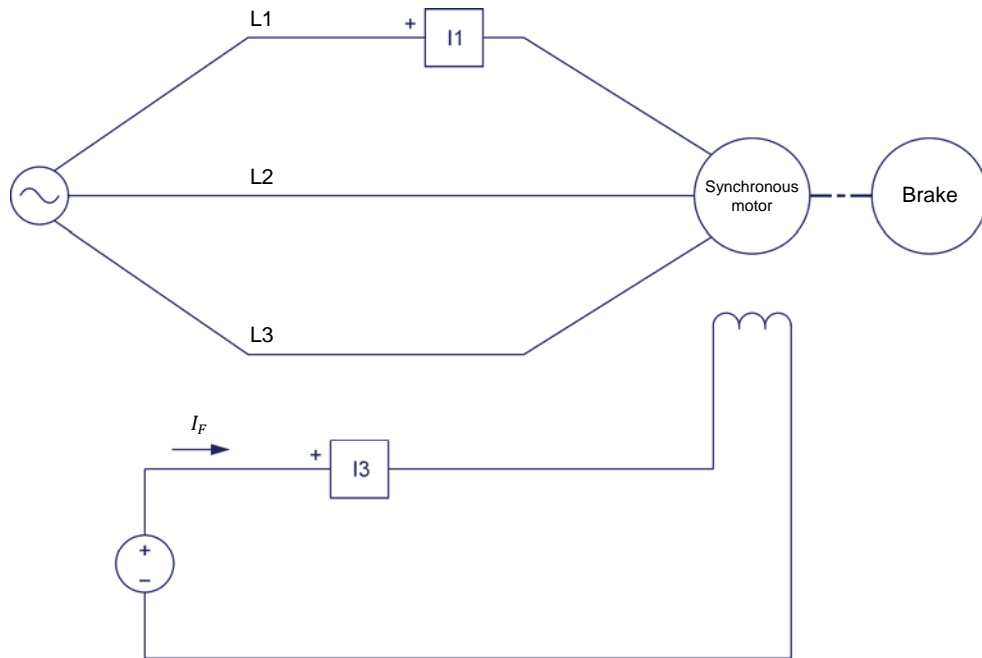


Figure 3-9. Synchronous motor coupled to a brake.

7. In LVDAC-EMS, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
- Set the **Function** parameter to **Two-Quadrant, Constant-Torque Brake**.
  - Set the **Torque** parameter to the minimum (i.e., 0.0 N·m or 0.0 lbf·in).
  - Set the **Pulley Ratio** parameter to 24:24.
8. In LVDAC-EMS, start the **Metering** application. Make the required settings in order to measure the rms value (ac) of the motor line current  $I_{Line\ 1}$  (input **I1**). Set another meter to measure the dc value of the field current  $I_F$  (input **I3**) in the rotor electromagnet.

Click the **Continuous Refresh** button to enable continuous refresh of the values indicated by the various meters in the **Metering** application.

### Synchronous motor pull-out torque

*In this section, you will turn the excitation on and set the Exciter knob on the synchronous motor to the minimum, and start the motor so that it turns at synchronous speed. You will measure the motor field current. You will increase the torque produced by the brake until the synchronous motor pull-out torque is reached. While doing this, you will measure the synchronous motor pull-out torque and line current just before the motor pulls out of synchronization, and the motor speed and line current when out of synchronization. You will then analyze the results. You will repeat the process for the following Exciter knob positions on the synchronous motor:  $\frac{1}{4}$ ,  $\frac{1}{2}$ ,  $\frac{3}{4}$ , and maximum. For each Exciter knob position, you will record the motor field current and pull-out torque. Using the results, you will plot a graph of the motor pull-out torque as a function of the motor field current, and analyze the resulting graph.*

9. On the **Synchronous Motor/Generator**, make sure that the **Exciter** switch is set to the open (O) position, then set the **Exciter** knob to the minimum position.

In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Two-Quadrant, Constant-Torque Brake**.

10. On the **Power Supply**, turn the dc power source on, then turn the three-phase ac power source on to start the three-phase synchronous motor.

Wait for the speed  $n$  of the synchronous motor to stabilize, then set the **Exciter** switch on the **Synchronous Motor/Generator** to the closed (I) position. The synchronous motor should rotate at synchronous speed.

11. In the **Metering** application, measure the motor field current  $I_F$  and record the value in the proper cell of the “Motor field current  $I_F$ ” column in Table 3-2. For example, if the **Exciter** knob on the **Synchronous Motor/Generator** is currently set to the minimum, record the value of the field current  $I_F$  in the uppermost cell of the “Motor field current  $I_F$ ” column in Table 3-2.

**Table 3-2. Measured synchronous motor field current  $I_F$  and pull-out torque  $T_{p-o}$  for different Exciter knob positions.**

Exciter knob position	Motor field current $I_F$ (A)	Motor pull-out torque $T_{p-o}$ (N·m or lbf·in)
Minimum		
$\frac{1}{4}$		
$\frac{1}{2}$		
$\frac{3}{4}$		
Maximum		

12. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly increase the torque produced by the **Two-Quadrant, Constant-Torque Brake** until the **Synchronous Motor/Generator** pulls out of synchronization. While doing so, observe attentively the synchronous motor torque, line current, and speed indicated in the **Four-Quadrant Dynamometer/Power Supply** window and the **Metering** application. Record the synchronous motor pull-out torque  $T_{P-O}$  in the proper cell of the “Motor pull-out torque  $T_{P-O}$ ” column in Table 3-2.

13. Record below the motor line current  $I_{Line,P-O}$  just before it pulls out of synchronization.

Motor line current  $I_{Line,P-O} = \underline{\hspace{2cm}}$  A

14. Measure and record below the synchronous motor speed  $n_{Async.}$  and line current  $I_{Line,async.}$  when the **Synchronous Motor/Generator** is out of synchronization.

Motor speed  $n_{Async.} = \underline{\hspace{2cm}}$  r/min

Motor line current  $I_{Line,async.} = \underline{\hspace{2cm}}$  A

15. On the **Power Supply**, turn both power sources off.

On the **Synchronous Motor/Generator**, set the **Exciter** switch to the open (O) position.

In the **Four-Quadrant Dynamometer/Power Supply** window, set the torque produced by the **Two-Quadrant, Constant-Torque Brake** to the minimum (i.e., 0.0 N·m or 0.0 lbf·in).

16. Describe what happens to the motor speed when the **Synchronous Motor/Generator** pulls out of synchronization.

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17. Describe what happens to the motor line current when the **Synchronous Motor/Generator** pulls out of synchronization?

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18. Repeat steps 10, 11, 12, and 15 for each of the other four **Exciter** knob positions indicated in the “Exciter knob position” column of Table 3-2.

19. Using the values you recorded in Table 3-2, plot a graph of the synchronous motor pull-out torque  $T_{P-O}$  as a function of the motor field current  $I_F$ .

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20. Does the graph you plotted in the previous step confirm that the pull-out torque  $T_{P-O}$  of a synchronous motor increases linearly with the field current  $I_F$ ?

☐ Yes      ☐ No

21. Close **LVDAC-EMS**, then turn off all the equipment. Disconnect all leads and return them to their storage location.

### CONCLUSION

In this exercise, you learned what the pull-out torque of a synchronous motor is, as well as the relationship between the pull-out torque of a synchronous motor and the field current in the rotor electromagnet.

### REVIEW QUESTIONS

1. What happens to the rotor of a synchronous motor when load torque is applied to the motor?

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2. What is the pull-out torque of a synchronous motor?

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3. At which angle and relative position (leading or lagging) does the rotor of a synchronous motor pull out of synchronization with respect to the rotating magnetic field?

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4. What is the relationship between the pull-out torque of a synchronous motor and the motor field current?

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5. What happens to the speed and line current of a synchronous motor when the motor pulls out of synchronization?

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## Unit Test

1. The most interesting features of three-phase synchronous motors are
  - a. their ability to run at synchronous speed and to operate as asynchronous generators.
  - b. their ability to run at synchronous speed and to supply reactive power to an ac power source.
  - c. their ability to run at unity power factor and to produce a high starting torque.
  - d. Both b and c.
2. What is the main disadvantage of synchronous motors?
  - a. They are not self-starting motors.
  - b. They draw large amounts of reactive power.
  - c. They are hard to stop when started.
  - d. They have a low pull-out torque.
3. A three-phase synchronous motor draws reactive power from an ac power source. Decreasing the motor field current would
  - a. increase the reactive power which the motor draws from the ac power source.
  - b. decrease the reactive power which the motor draws from the ac power source.
  - c. decrease the power factor of the motor.
  - d. Both a and c.
4. A three-phase synchronous motor supplies reactive power to an ac power source. Decreasing the motor field current would
  - a. increase the reactive power which the motor supplies to the ac power source.
  - b. decrease the reactive power which the motor supplies to the ac power source.
  - c. decrease the power factor of the motor.
  - d. Both a and c.
5. It is desirable to turn the rotor electromagnet of a synchronous motor off during motor start-up in order to
  - a. increase the motor speed.
  - b. improve the power factor of the system to which the motor is connected.
  - c. reduce the vibrations produced in the motor.
  - d. increase the motor pull-out torque.



6. When the line current in a three-phase synchronous motor is at a minimum, the
  - a. motor neither draws nor supplies reactive power.
  - b. motor speed decreases rapidly.
  - c. motor field current is at a minimum.
  - d. motor functions as a generator.
  
7. A three-phase synchronous motor operating without load acts as
  - a. a resistive load whose value depends on the motor field current.
  - b. an asynchronous generator operating without load.
  - c. three independent single-phase power sources.
  - d. a reactive load whose nature (inductive or capacitive) and value depend on the motor field current.
  
8. The pull-out torque of a synchronous motor corresponds to
  - a. the minimum load torque value that causes the nominal line current of the motor to be exceeded.
  - b. the torque at which the motor pulls out of synchronization.
  - c. the maximum torque produced by the motor when the motor field current is at a minimum.
  - d. the minimum torque that the motor can supply.
  
9. The pull-out torque of a synchronous motor depends on
  - a. the power factor of the system to which is connected the motor.
  - b. the motor line current.
  - c. the motor field current.
  - d. None of the above.
  
10. When load torque is applied to a synchronous motor,
  - a. the motor slows down.
  - b. the motor speeds up.
  - c. the rotor position falls behind the rotating magnetic field.
  - d. the stator starts to rotate alongside the rotor.

## Synchronous Generators (Alternators)

### UNIT OBJECTIVE

When you have completed this unit, you will be familiar with the main characteristics and no-load operation of a three-phase synchronous generator. You will also be familiar with the simplified equivalent circuit of a three-phase synchronous generator, as well as with the voltage regulation characteristics of the generator when it supplies power to either a resistive, an inductive, or a capacitive load. You will know how to manually synchronize a three-phase synchronous generator to an ac power network, as well as how the generator operates after synchronization to the network.

### DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

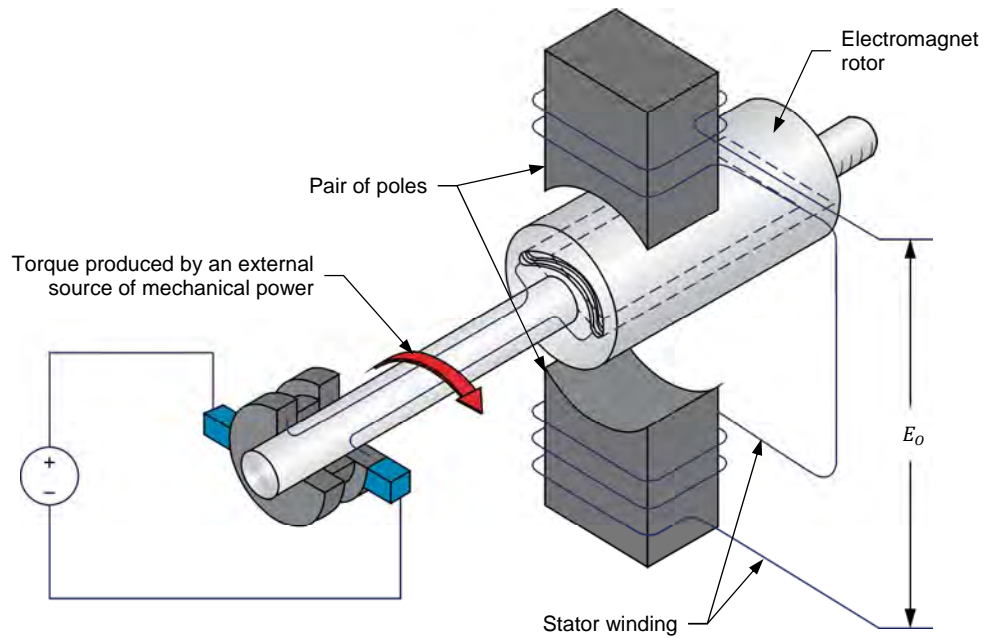
- Introduction to three-phase synchronous generators

### DISCUSSION OF FUNDAMENTALS

#### Introduction to three-phase synchronous generators

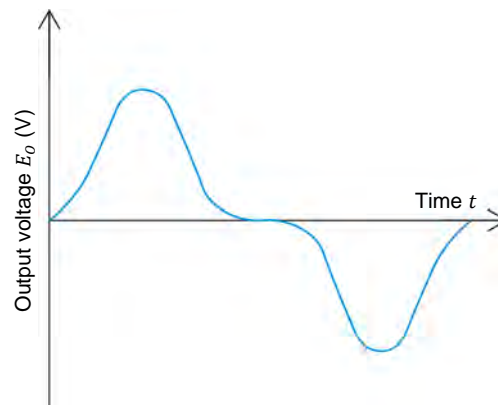
The three-phase **synchronous generator** (also called three-phase synchronous alternator) produces most of the electricity used today. It is found in all electrical-power generating stations, whether they are of the hydroelectric, diesel, coal-fired, wind turbine, or nuclear type. Three-phase synchronous generators (alternators) also produce the electricity used in motor vehicles such as cars and trucks.

The basic principle of operation of three-phase synchronous generators is quite simple and can be illustrated using the simplified single-phase synchronous generator shown in Figure 4-1.



**Figure 4-1. Simplified single-phase synchronous generator.**

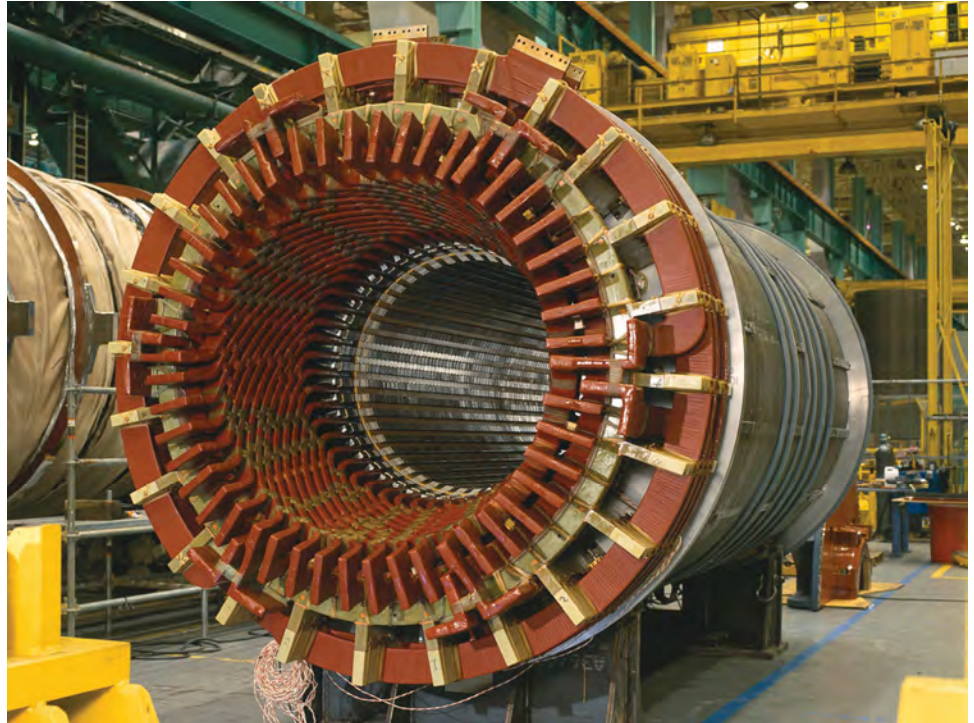
In this synchronous generator, an electromagnet creates a magnetic field in the rotor. The electromagnet rotor is coupled to an external source of mechanical power (e.g., a wind or water turbine) to make it rotate. As a result, a continually-changing magnetic flux passes through the stator winding as the rotor magnetic field rotates, inducing an alternating voltage across the stator winding. The synchronous generator has thus converted mechanical power from an external source to electrical power which can be supplied to any load connected to the generator. The output voltage  $E_o$  as a function of time  $t$  of the single-phase synchronous generator is shown in Figure 4-2.



**Figure 4-2. Output voltage  $E_o$  as a function of time  $t$  of the single-phase synchronous generator shown in Figure 4-1.**

The way the conductors are wound in the stator of any synchronous generator determines the waveform of the voltages induced across the stator windings. The stator-winding conductors in a three-phase synchronous generator are usually wound in such a way that the induced voltages have a sinusoidal waveform.

The stator in a three-phase synchronous generator consists of three windings located at  $120^\circ$  from one another. As a result, the three sine-wave voltages induced in the stator windings are also phase shifted by  $120^\circ$  with respect to each other. The stator of a three-phase synchronous generator is in fact very similar to the stator of the three-phase squirrel-cage induction motor shown in Figure 2-5.



**Figure 4-3.** Stator of a large three-phase synchronous generator with a power rating of 350 MVA. This generator is installed in a power plant in Charlotte, North Carolina, USA (© Siemens AG 2012, all rights reserved).



## Three-Phase Synchronous Generator No-Load Operation

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the main characteristics and no-load operation of a three-phase synchronous generator. You will know how the speed and field current of a three-phase synchronous generator affect the amplitude and frequency of the voltages produced by the generator.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Characteristics of a three-phase synchronous generator operating without load

### DISCUSSION

#### Characteristics of a three-phase synchronous generator operating without load

In three-phase synchronous generators, the stronger the rotor electromagnet (i.e., the stronger the generator field current  $I_F$ ), the greater the magnetic flux passing through the stator windings, and the greater the amplitude of the alternating voltages induced across the stator windings. Furthermore, the faster the rotor turns (i.e., the faster the generator speed  $n_{Gen.}$ ), the faster the rate of change in the magnetic flux passing through the stator windings, and thus, the higher the amplitude of the voltages induced across the stator windings. In brief, the amplitude of the voltages produced by a three-phase synchronous generator is proportional to the generator speed  $n_{Gen.}$  and field current  $I_F$ .

The frequency  $f_o$  of the voltages induced across the stator windings of a three-phase synchronous generator is also proportional to the generator speed  $n_{Gen.}$ . When the rotor of the synchronous generator shown in Figure 4-1 rotates at a speed of one revolution per second, the frequency of the induced voltage is 1 Hz. Since the speed  $n_{Gen.}$  of a synchronous generator is usually expressed in revolutions per minute, the expression is divided by 60 s. The resulting equation relating the speed  $n_{Gen.}$  of a three-phase synchronous generator to the output frequency  $f_o$  of the generator is given below. This equation is valid only if the generator has a single pair of magnetic poles per stator winding (like the synchronous generator shown in Figure 4-1).

$$f_o = \frac{n_{Gen.}}{60 \text{ s}} \quad (4-1)$$

where  $f_o$  is the frequency of the voltage waveform induced across each stator winding of the three-phase synchronous generator, expressed in hertz (Hz)

$n_{Gen.}$  is the rotor speed of the three-phase synchronous generator, expressed in revolutions per minute (r/min)

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Large, three-phase synchronous generators, however, usually have several north and south magnetic poles in each stator winding instead of just a single pair like the generator illustrated in Figure 4-1. The output frequency  $f_o$  which can be obtained for a given generator speed  $n_{Gen.}$  increases with the number of pairs of magnetic poles in each stator winding of the generator. This means that the output frequency  $f_o$  of a three-phase synchronous generator is proportional to the generator speed  $n_{Gen.}$  and to the number of pairs of magnetic poles  $N_{pairs}$  per stator winding in the generator. The resulting equation used to determine the output frequency  $f_o$  of any synchronous generator is given below.

The supplied Synchronous Motor/Generator has two pairs of magnetic poles per stator winding (i.e.,  $N_{pairs}$  equals 2).

$$f_o = \frac{n_{Gen.} \cdot N_{pairs}}{60 \text{ s}} \quad (4-2)$$

where  $N_{pairs}$  is the number of pairs of magnetic poles for each stator winding of the three-phase synchronous generator

Although small technical differences exist between a three-phase synchronous machine designed to operate as a motor and a three-phase synchronous machine designed to operate as a generator, both modes of operation can be demonstrated using the same three-phase synchronous machine.

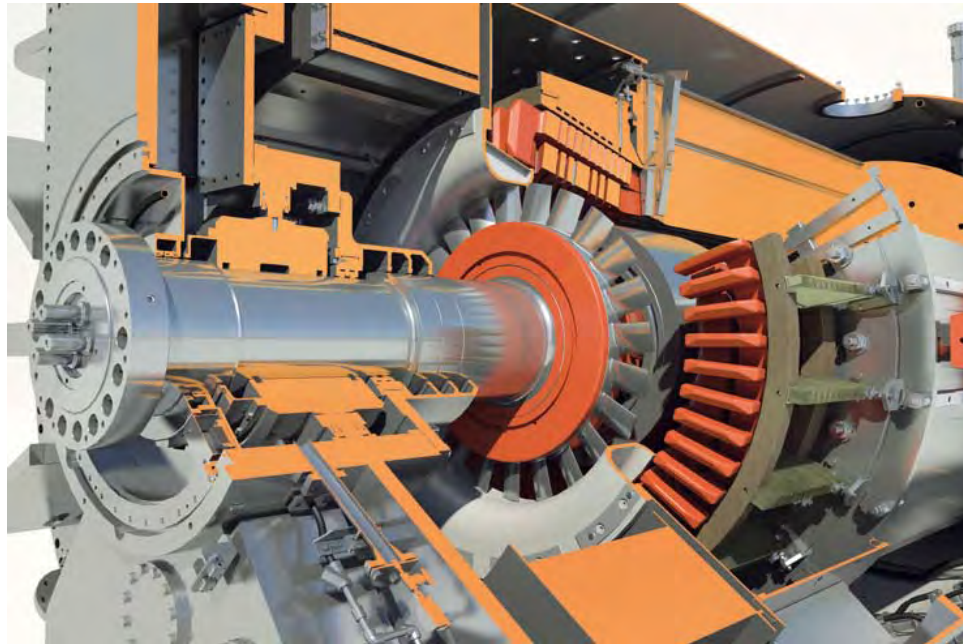


Figure 4-4. Sectional view of a 600 MVA hydrogen-cooled three-phase synchronous generator (© Siemens AG 2012, all rights reserved).

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Three-phase synchronous generator no-load operation
- Three-phase synchronous generator characteristics

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections

*In this section, you will set up a circuit containing a prime mover mechanically coupled to a synchronous generator. You will then set the measuring equipment required to study the synchronous generator no-load operation.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Synchronous Motor/Generator](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.



4. Turn the **Four-Quadrant Dynamometer/Power Supply** on, then set the **Operating Mode** switch to **Dynamometer**. This setting allows the **Four-Quadrant Dynamometer/Power Supply** to operate as a prime mover, a brake, or both, depending on the selected function.
5. Turn the host computer on, then start the **LVDAC-EMS** software.

In the **LVDAC-EMS Start-Up** window, make sure the **Data Acquisition and Control Interface** and the **Four-Quadrant Dynamometer/Power Supply** are detected. Make sure the **Computer-Based Instrumentation** function is available for the **Data Acquisition and Control Interface**. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.

6. Connect the equipment as shown in Figure 4-5.

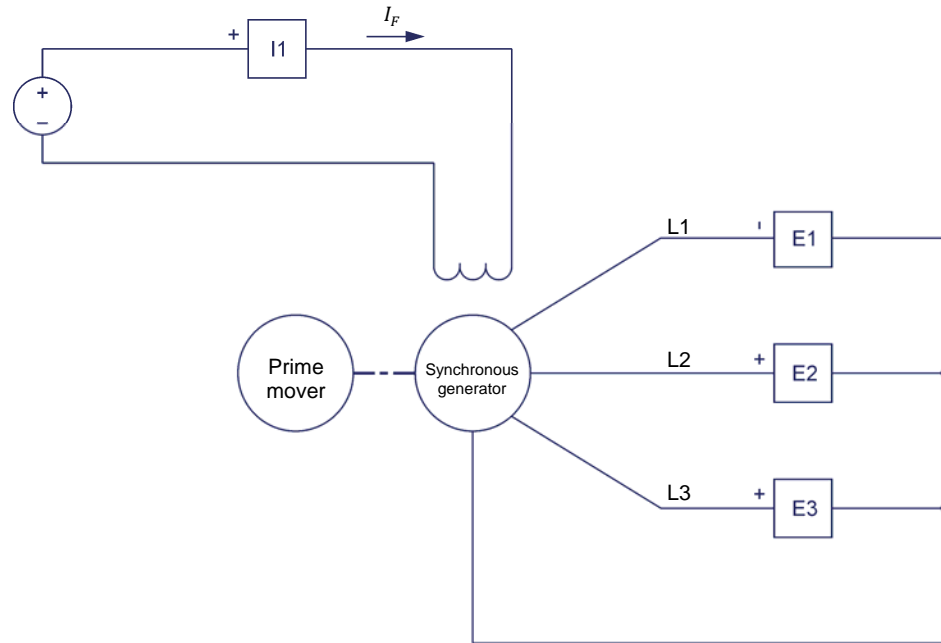


Figure 4-5. Prime mover coupled to a synchronous generator.

7. In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
  - Set the **Function** parameter to **CW Constant-Speed Prime Mover/Brake**.
  - Set the **Speed** parameter to the synchronous speed  $n_s$  of the **Synchronous Motor/Generator**.



The synchronous speed of the *Synchronous Motor/Generator* is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.

- Set the *Pulley Ratio* parameter to 24:24.

8. In *LVDAC-EMS*, start the *Metering* application. Make the required settings in order to measure the rms value (ac) of the three-phase synchronous generator output voltage  $E_o$  (input *E1*), as well as the generator output frequency  $f_o$  (input *E1*). Set another meter to measure the dc value of the field current  $I_F$  (input *I1*) in the rotor electromagnet.

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the *Metering* application.

9. On the *Synchronous Motor/Generator*, set the *Exciter* switch to the closed position (I), then adjust the *Exciter* knob to about  $\frac{3}{4}$  of the maximal excitation.



Maximal excitation is obtained when the *Exciter* knob of the *Synchronous Motor/Generator* is set to the fully-clockwise position.

### Three-phase synchronous generator no-load operation

*In this section, you will make the constant-speed prime mover rotate at the synchronous speed of the three-phase synchronous generator. You will observe on the Oscilloscope the waveforms of the voltages produced by the three-phase synchronous generator and determine the phase shift between the voltage waveforms. You will then vary the speed of the constant-speed prime mover and observe the effect on the generator output voltage waveforms. Finally, you will decrease the field current in the rotor electromagnet and observe the effect on the generator output voltage waveforms.*

10. In the *Four-Quadrant Dynamometer/Power Supply* window, start the prime mover.

On the *Power Supply*, turn the dc power source on.

11. In *LVDAC-EMS*, open the *Oscilloscope*, then make the appropriate settings in order to observe the voltage waveforms measured using inputs *E1*, *E2*, and *E3* (i.e., the waveforms of the voltages induced across each stator winding of the three-phase synchronous generator).



On the *Synchronous Motor/Generator*, readjust the *Exciter* knob so that the rms value of the voltages measured on the *Oscilloscope* is as close as possible to your local ac power network voltage.

Are all the voltage waveforms shown on the *Oscilloscope* sinusoidal?

- ☐ Yes      ☐ No

12. Using the [Oscilloscope](#), determine the phase shift  $\theta$  between the first and second voltage waveforms (voltages at inputs [E1](#) and [E2](#)).

$$\theta = \frac{\text{Time interval } d}{\text{Period } T} 360^\circ = \underline{\hspace{2cm}}^\circ$$

Is the phase shift  $\theta$  between the two voltage waveforms close to  $120^\circ$ ?

☐ Yes      ☐ No

13. Are the phase shifts  $\theta$  between the other voltage waveforms similar to the phase shift between the first and second waveforms you calculated in the previous step?

☐ Yes      ☐ No

Can you conclude that all three voltage waveforms produced by the three-phase synchronous generator are phase shifted  $120^\circ$  with respect to one another?

☐ Yes      ☐ No

14. In the [Four-Quadrant Dynamometer/Power Supply](#) window, slowly decrease the [Speed](#) parameter to 1000 r/min. While doing this, observe on the [Oscilloscope](#) the voltage waveforms at inputs [E1](#), [E2](#), and [E3](#).

How does the amplitude of the voltage waveforms produced by the three-phase synchronous generator vary as the speed  $n_{Gen.}$  of the generator decreases? Explain why.

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How does the frequency  $f_o$  of the voltage waveforms produced by the three-phase synchronous generator vary as the speed  $n_{Gen.}$  of the generator decreases? Explain why.

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15. Does varying the speed  $n_{gen.}$  of the three-phase synchronous generator affect the phase shift  $\theta$  between the voltage waveforms produced by the generator? Why?

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16. On the **Synchronous Motor/Generator**, slowly decrease the field current  $I_F$  by turning the **Exciter** knob counterclockwise. While doing this, observe on the **Oscilloscope** the voltage waveforms at inputs **E1**, **E2**, and **E3**.

How does the amplitude of the voltage waveforms produced by the three-phase synchronous generator vary as the generator field current  $I_F$  decreases? Explain why.

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17. Does varying the field current  $I_F$  of the three-phase synchronous generator affect the output frequency  $f_o$  and the phase shift  $\theta$  between the output voltage waveforms? Why?

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18. In the **Four-Quadrant Dynamometer/Power Supply** window, stop the prime mover.

On the **Power Supply**, turn the dc power source off.

### Three-phase synchronous generator characteristics

*In this section, you will modify the circuit of Figure 4-5 by adding a resistive load in series with the dc power source. You will set the constant-speed prime mover to rotate at the synchronous speed of the three-phase synchronous generator. You will then record in the Data Table the generator speed, output voltage, field current, and frequency for different field current values. You will calculate the theoretical frequency of the generator, and compare the result with the measured generator frequency. You will plot a graph of the generator output voltage as a function of the generator field current, and interpret the results. You will then set the prime mover speed to 0 r/min and the three-phase synchronous generator field current to a fixed value. You will record in the Data Table the generator*

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speed, output voltage, field current, and frequency while increasing the generator speed up to a certain value. You will plot a graph of the generator output voltage as a function of the generator speed, and interpret the results. Finally, you will plot a graph of the three-phase synchronous generator frequency as a function of the generator speed, and interpret the results.

19. Modify the circuit to the one shown in Figure 4-6.

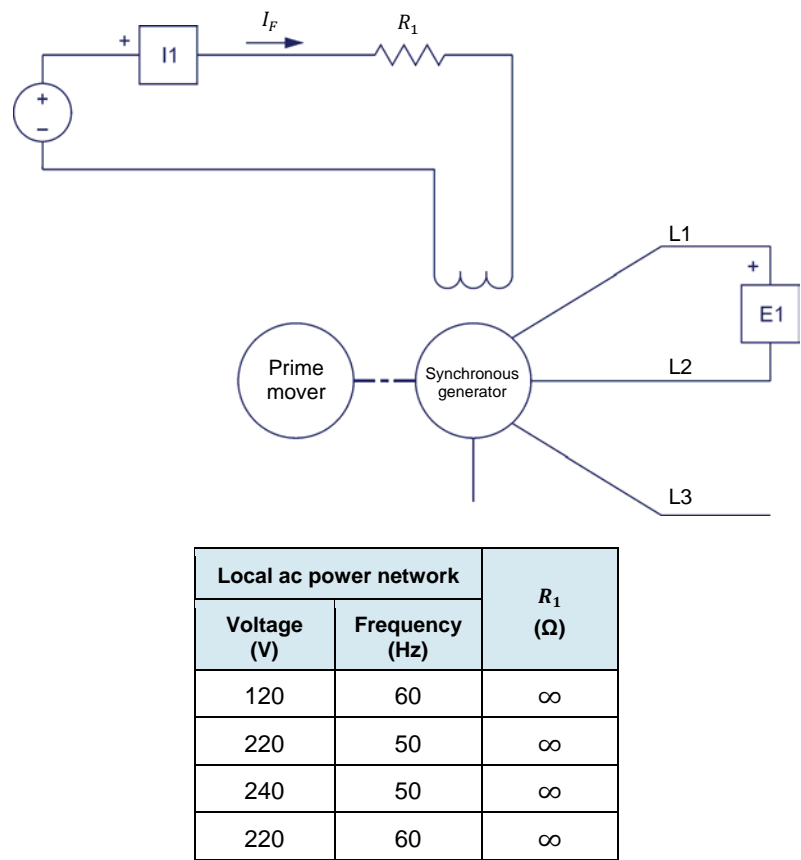


Figure 4-6. Prime mover coupled to a three-phase synchronous generator.

20. Open all switches on the **Resistive Load** module so that the resistance of resistor  $R_1$  is infinite.

21. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Speed** parameter to the synchronous speed  $n_s$  of the **Synchronous Motor/Generator**, then start the **CW Constant-Speed Prime Mover/Brake**.

On the **Power Supply**, turn the dc power source on.

**22.** In LVDAC-EMS, open the **Data Table** window.

Set the **Data Table** to record the three-phase synchronous generator speed  $n_{Gen.}$  indicated in the **Four-Quadrant Dynamometer/Power Supply** window.

Also, set the **Data Table** to record the three-phase synchronous generator output voltage  $E_O$  (input **E1**) and frequency  $f_O$  (input **E1**), as well as the generator field current  $I_F$  (input **I1**) indicated in the **Metering** application.

In the **Data Table** window, click on the **Record Data** button to record the values of the three-phase synchronous generator speed  $n_{Gen.}$ , output voltage  $E_O$ , output frequency  $f_O$ , and field current  $I_F$ .

**23.** Modify the resistance of resistor  $R_1$  and adjust the **Exciter** knob on the **Synchronous Motor/Generator** until the value of the field current  $I_F$  is as close as possible to the minimum field current  $I_F$  corresponding to your local ac power network voltage and frequency, as indicated in Table 4-1. For example, if your local ac power network voltage and frequency are 120 V and 60 Hz, respectively, set the generator field current  $I_F$  as close as possible to 200 mA.

**Table 4-1. Range of the three-phase synchronous generator field current  $I_F$ .**

Local ac power network		Range of generator field current $I_F$ (mA)
Voltage (V)	Frequency (Hz)	
120	60	200 to 780
220	50	80 to 460
240	50	80 to 460
220	60	80 to 460

**24.** In the **Data Table** window, click on the **Record Data** button to record the values of the three-phase synchronous generator speed  $n_{Gen.}$ , output voltage  $E_O$ , output frequency  $f_O$ , and field current  $I_F$ .

**25.** Modify the resistance of resistor  $R_1$  and adjust the **Exciter** knob on the **Synchronous Motor/Generator** to increase the generator field current  $I_F$  to the maximum field current value corresponding to your local ac power network voltage and frequency (see Table 4-1) in 11 or 12 equally distributed steps. For example, if your local ac power network voltage and frequency are 120 V and 60 Hz, respectively, increase the field current to 780 mA in 11 or 12 equally distributed steps. For each field current value, record the generator parameters in the **Data Table**.



*It may be necessary to short-circuit resistor  $R_1$  to obtain the maximum value of motor field current  $I_F$ .*

26. On the **Power Supply**, turn the dc power source off.

In the **Four-Quadrant Dynamometer/Power Supply** window, stop the prime mover.

27. In the **Data Table** window, save the recorded data.

28. Calculate the theoretical output frequency  $f_o$  of the **Synchronous Motor/Generator** using Equation (4-2).



*There are two pairs of magnetic poles in each stator winding of the Synchronous Motor/Generator.*

Theoretical output frequency  $f_o = \underline{\hspace{2cm}}$  Hz

29. Compare the theoretical output frequency  $f_o$  of the **Synchronous Motor/Generator** with the generator output frequency  $f_o$  you recorded in the **Data Table** window. Are both values approximately equal?

☐ Yes      ☐ No

30. Plot a graph of the three-phase synchronous generator output voltage  $E_o$  as a function of the generator field current  $I_F$  using the results you recorded to the **Data Table**.

Observe the graph you just plotted. Does the three-phase synchronous generator output voltage  $E_o$  increase with the field current  $I_F$ ?

☐ Yes      ☐ No

31. Does the relationship between the three-phase synchronous generator output voltage  $E_o$  and field current  $I_F$  become non-linear at high field current values, indicating that the stator windings are saturated?

☐ Yes      ☐ No

32. In the **Data Table** window, clear all data without clearing the record settings.

In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Speed** parameter to 0 r/min, then start the **CW Constant-Speed Prime Mover/Brake**.

On the **Power Supply**, turn the dc power source on.

Modify the resistance of resistor  $R_1$  and adjust the **Exciter** knob on the **Synchronous Motor/Generator** until the three-phase synchronous generator field current  $I_F$  is as close as possible to the field current  $I_F$  corresponding to your local ac power network voltage and frequency indicated in the "Generator field current  $I_F$ " column of Table 4-2.

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Do not let the *Synchronous Motor/Generator* stop for a long time while current is flowing in the rotor electromagnet. Doing so could seriously damage the *Synchronous Motor/Generator*.

Table 4-2. Three-phase synchronous generator field current  $I_F$  and maximum speed  $n_{Max}$ .

Local ac power network		Generator field current $I_F$ (mA)	Generator maximum speed $n_{Max}$ (r/min)
Voltage (V)	Frequency (Hz)		
120	60	500	2400
220	50	300	2000
240	50	300	2000
220	60	300	2000

33. In the *Data Table* window, click on the *Record Data* button to record the values of the three-phase synchronous generator speed  $n_{Gen.}$ , output voltage  $E_O$ , output frequency  $f_O$ , and field current  $I_F$ .

34. In the *Four-Quadrant Dynamometer/Power Supply* window, increase the *Speed* parameter of the prime mover by 200 r/min.

In the *Data Table* window, click on the *Record Data* button to record the values of the three-phase synchronous generator speed  $n_{Gen.}$ , output voltage  $E_O$ , output frequency  $f_O$ , and field current  $I_F$ .

35. Repeat step 34 until you have recorded the generator parameters for the maximum speed  $n_{Max}$  corresponding to your local ac power network voltage and frequency, as indicated in the “Generator maximum speed  $n_{Max}$ ” column of Table 4-2.

36. On the *Power Supply*, turn the dc power source off.

In the *Four-Quadrant Dynamometer/Power Supply* window, stop the prime mover.

37. In the *Data Table* window, save the recorded data.

38. Plot a graph of the three-phase synchronous generator output voltage  $E_O$  as a function of the generator speed  $n_{Gen.}$  using the results you recorded to the *Data Table*.

Describe what happens to the three-phase synchronous generator output voltage  $E_O$  as the generator speed  $n_{Gen.}$  increases.

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39. Plot a graph of the three-phase synchronous generator output frequency  $f_o$  as a function of the generator speed  $n_{Gen.}$  using the results you recorded to the [Data Table](#).

Describe what happens to the three-phase synchronous generator output frequency  $f_o$  as the generator speed  $n_{Gen.}$  increases.

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40. Close [LVDAC-EMS](#), then turn off all the equipment. Disconnect all leads and return them to their storage location.

### CONCLUSION

In this exercise, you familiarized yourself with the main characteristics and no-load operation of a three-phase synchronous generator. You learned how the speed and field current of a three-phase synchronous generator affect the amplitude and frequency of the voltages produced by the generator.

### REVIEW QUESTIONS

1. Describe the operation of a three-phase synchronous generator.

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2. Explain why the output voltage  $E_o$  produced by a three-phase synchronous generator is necessarily an ac voltage.

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3. A three-phase synchronous generator having three pairs of magnetic poles in each stator winding rotates at a speed  $n_{Gen.}$  of 2000 r/min. Determine the generator output frequency  $f_o$ .

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4. Describe the relationship between the output voltage  $E_o$  produced by a three-phase synchronous generator operating without load and the generator field current  $I_F$ .

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5. Describe the relationship between the amplitude (i.e., the output voltage  $E_o$ ) and frequency  $f_o$  of the voltages produced by a three-phase synchronous generator operating without load and the generator speed  $n_{Gen}$ .

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## Voltage Regulation Characteristics

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the simplified equivalent circuit of a three-phase synchronous generator. You will also be familiar with the voltage regulation characteristic of a three-phase synchronous generator when the generator supplies power to either a resistive, an inductive, or a capacitive load.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Equivalent circuit of a three-phase synchronous generator
- Voltage regulation characteristics of three-phase synchronous generators

### DISCUSSION

#### Equivalent circuit of a three-phase synchronous generator

Figure 4-7 shows the simplified equivalent circuit representing one phase of a three-phase synchronous generator. A complete three-phase synchronous generator would be represented by three circuits like the one in Figure 4-7.

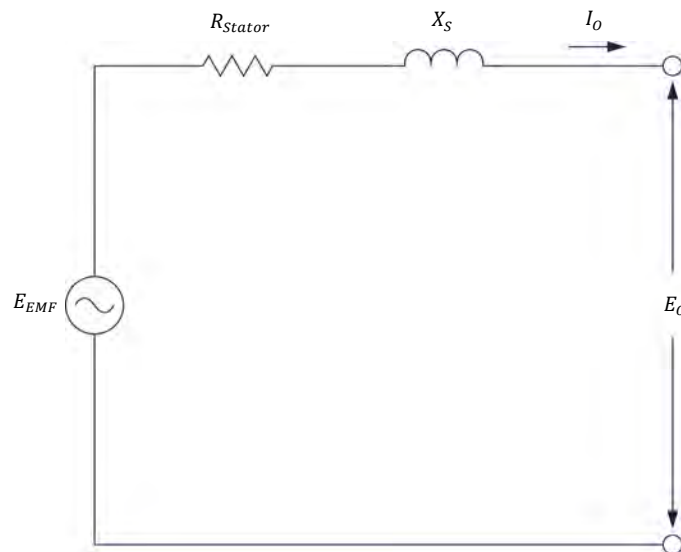


Figure 4-7. Simplified equivalent circuit representing one phase of a three-phase synchronous generator.

The equivalent circuit of the three-phase synchronous generator in Figure 4-7 consists of a resistor and an inductor connected in series with a sine wave voltage source. The resistor represents the resistance ( $R_{Stator}$ ) of the stator winding conductors. The inductor represents the inductive reactance of the stator winding conductors. The inductive reactance is known as the synchronous reactance  $X_s$  and is usually much greater than the resistance  $R_{Stator}$ .

Figure 4-7 reveals that a distinction must be made between the voltage  $E_{EMF}$  induced in the stator windings of a three-phase synchronous generator and the output voltage  $E_o$  across the load connected to the generator. The induced voltage  $E_{EMF}$  depends on the generator speed  $n_{Gen.}$  as well as on the strength of the electromagnet (i.e., the intensity of the field current  $I_F$ ). When the generator operates without load, the induced voltage  $E_{EMF}$  is equal to the output voltage  $E_o$  (this was assumed in Exercise 4-1 when studying the no-load operation of three-phase synchronous generators). When a load is connected to the generator, however, the output voltage  $E_o$  measured across the load is no longer equal to the induced voltage  $E_{EMF}$  and varies depending on the load type.

### Voltage regulation characteristics of three-phase synchronous generators

When a three-phase synchronous generator operates at a constant speed  $n_{Gen.}$  and with a fixed field current  $I_F$ , the voltage  $E_{EMF}$  induced in the stator windings of the generator is constant. Figure 4-8 shows voltage regulation characteristics (i.e., curves of the output voltage  $E_o$  as a function of the output current  $I_o$ ) of a three-phase synchronous generator for resistive, inductive, and capacitive loads. The curves show that when the load is either resistive or inductive, the generator output voltage  $E_o$  decreases when the generator output current  $I_o$  increases. Conversely, when the load is capacitive, the generator output voltage  $E_o$  increases when the generator output current  $I_o$  increases.

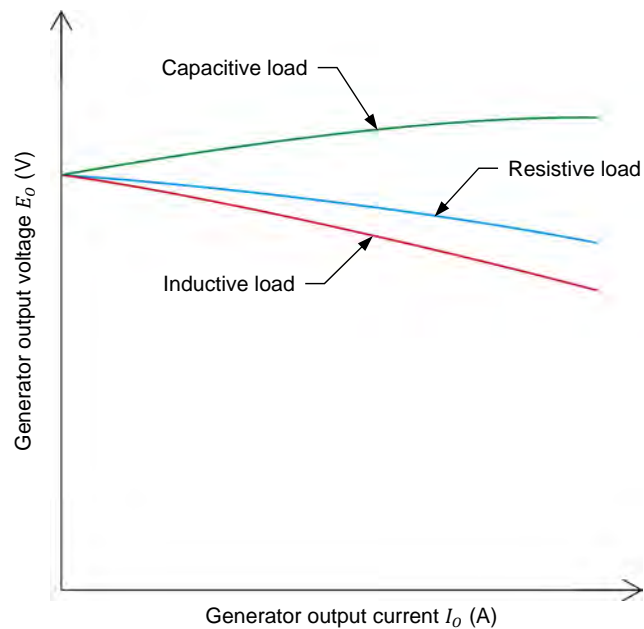


Figure 4-8. Typical voltage regulation characteristic curves of a three-phase synchronous generator.

The curves in Figure 4-8 can be obtained easily by resolving the circuits formed by a single phase of a three-phase synchronous generator connected to resistive, inductive, and capacitive loads. Consider for example that, in the diagram of Figure 4-7, the synchronous generator has an induced voltage  $E_{EMF}$  of 180 V, a stator resistance  $R_{Stator}$  of 5  $\Omega$ , and a synchronous reactance  $X_S$  of 20  $\Omega$ . In the following three cases, the three-phase synchronous generator is connected successively to a resistive load, an inductive load, and a capacitive load. The generator output voltage  $E_O$  is then calculated for each load type.

#### ***Voltage regulation calculations for a resistive load***

When the three-phase synchronous generator shown in Figure 4-7 is connected to a resistive load having a resistance  $R_{Load}$  of 1000  $\Omega$ , the voltage across the load can be calculated as follows:

$$R_T = R_{Stator} + R_{Load} = 5 \Omega + 1000 \Omega = 1005 \Omega$$

$$Z = \sqrt{R_T^2 + X_S^2} = \sqrt{(1005 \Omega)^2 + (20 \Omega)^2} = 1005 \Omega$$

$$I_O = E_{EMF}/Z = 180 \text{ V}/1005 \Omega = 0.18 \text{ A}$$

$$E_O = I_O \times R_{Load} = 0.18 \text{ A} \times 1000 \Omega = 180 \text{ V}$$

When the resistance  $R_{Load}$  of the resistive load is equal to 100  $\Omega$ , the voltage across the load can be calculated as follows:

$$R_T = R_{Stator} + R_{Load} = 5 \Omega + 100 \Omega = 105 \Omega$$

$$Z = \sqrt{R_T^2 + X_S^2} = \sqrt{(105 \Omega)^2 + (20 \Omega)^2} = 107 \Omega$$

$$I_O = E_{EMF}/Z = 180 \text{ V}/107 \Omega = 1.68 \text{ A}$$

$$E_O = I_O \times R_{Load} = 1.68 \text{ A} \times 100 \Omega = 168 \text{ V}$$

As you can see, the three-phase synchronous generator output voltage  $E_O$  measured across the resistive load has decreased by a value of 12 V (180 V-168 V) as the current flowing in the load increased from 0.18 A to 1.68 A. The generator output voltages and currents calculated for the resistive load are plotted on a graph in Figure 4-9.

**Voltage regulation calculations for an inductive load**

When the three-phase synchronous generator shown in Figure 4-7 is connected to an inductive load having an inductive reactance  $X_{L,Load}$  of 1000  $\Omega$ , the voltage across the load can be calculated as follows:

$$X_T = X_S + X_{L,Load} = 20 \Omega + 1000 \Omega = 1020 \Omega$$

$$Z = \sqrt{R_{Stator}^2 + X_T^2} = \sqrt{(5 \Omega)^2 + (1020 \Omega)^2} = 1020 \Omega$$

$$I_O = E_{EMF}/Z = 180 \text{ V}/1020 \Omega = 0.18 \text{ A}$$

$$E_O = I_O \times X_{L,Load} = 0.18 \text{ A} \times 1000 \Omega = 180 \text{ V}$$

When the inductive reactance  $X_{L,Load}$  of the inductive load is equal to 100  $\Omega$ , the voltage across the load can be calculated as follows:

$$X_T = X_S + X_{L,Load} = 20 \Omega + 100 \Omega = 120 \Omega$$

$$Z = \sqrt{R_{Stator}^2 + X_T^2} = \sqrt{(5 \Omega)^2 + (120 \Omega)^2} = 120 \Omega$$

$$I_O = E_{EMF}/Z = 180 \text{ V}/120 \Omega = 1.50 \text{ A}$$

$$E_O = I_O \times X_{L,Load} = 1.50 \text{ A} \times 100 \Omega = 150 \text{ V}$$

As you can see, the three-phase synchronous generator output voltage  $E_O$  measured across the inductive load has decreased by a value of 30 V (180 V-150 V) as the current flowing in the load increased from 0.18 A to 1.50 A. The output voltage  $E_O$  across the inductive load is thus significantly lower than the output voltage  $E_O$  across the resistive load for a comparable increase in the output current  $I_O$ . The generator output voltages and currents calculated for the inductive load are plotted on a graph in Figure 4-9.

**Voltage regulation calculations for a capacitive load**

When the three-phase synchronous generator shown in Figure 4-7 is connected to a capacitive load having a capacitive reactance  $X_{C,Load}$  of 1000  $\Omega$ , the voltage across the load can be calculated as follows:

$$X_T = X_L - X_C = X_S - X_{C,Load} = 20 \Omega - 1000 \Omega = -980 \Omega$$

$$Z = \sqrt{R_{Stator}^2 + X_T^2} = \sqrt{(5 \Omega)^2 + (-980 \Omega)^2} = 980 \Omega$$

$$I_O = E_{EMF}/Z = 180 \text{ V}/980 \Omega = 0.18 \text{ A}$$

$$E_O = I_O \times X_{C,Load} = 0.18 \text{ A} \times 1000 \Omega = 180 \text{ V}$$

When the capacitive reactance  $X_{C,Load}$  of the capacitive load is equal to  $100\ \Omega$ , the voltage across the load can be calculated as follows:

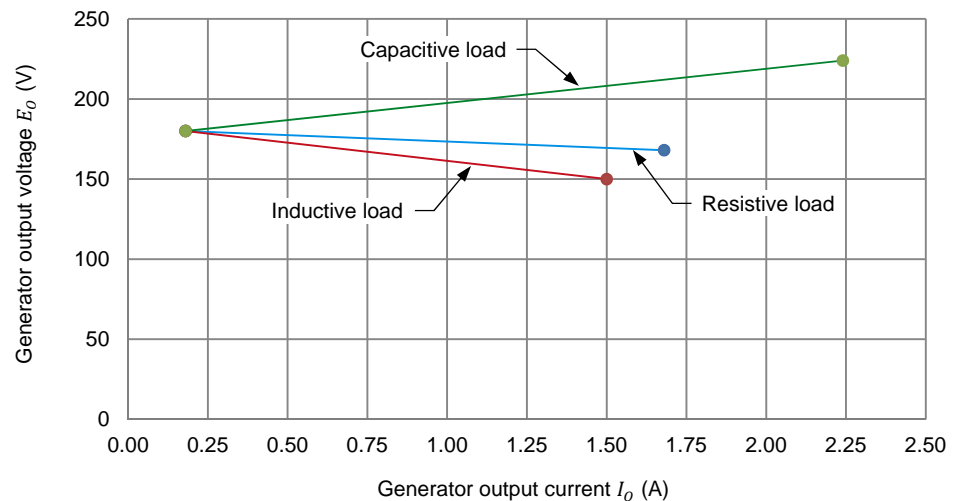
$$X_T = X_L - X_C = X_S - X_{C,Load} = 20\ \Omega - 100\ \Omega = -80\ \Omega$$

$$Z = \sqrt{R_{Stator}^2 + X_T^2} = \sqrt{(5\ \Omega)^2 + (-80\ \Omega)^2} = 80.2\ \Omega$$

$$I_O = E_{EMF}/Z = 180\text{ V}/80.2\ \Omega = 2.24\text{ A}$$

$$E_O = I_O \times X_{C,Load} = 2.24\text{ A} \times 100\ \Omega = 224\text{ V}$$

As you can see, the three-phase synchronous generator output voltage  $E_O$  measured across the capacitive load has increased by a value of  $44\text{ V}$  ( $224\text{ V} - 180\text{ V}$ ) as the current flowing in the load increased from  $0.18\text{ A}$  to  $2.24\text{ A}$ . The output voltage  $E_O$  across the capacitive load is thus significantly higher than the output voltage  $E_O$  across the resistive load as the generator output current  $I_O$  increases. The generator output voltages and currents calculated for the capacitive load are plotted on a graph in Figure 4-9.



**Figure 4-9.** Calculated three-phase synchronous generator output voltage  $E_O$  as a function of the generator output current  $I_O$  for resistive, inductive, and capacitive loads.

As you can see from Figure 4-9, when the three-phase synchronous generator output current  $I_O$  is equal to  $1.50\text{ A}$ , the resulting generator output voltage  $E_O$  is highest when the generator supplies power to a capacitive load (approximately  $209\text{ V}$ ). When the generator supplies power to a resistive load, the generator output voltage is closest to the generator induced voltage  $E_{EMF}$  (approximately  $170\text{ V}$ ). Finally, the generator output voltage  $E_O$  is lowest when the generator supplies power to an inductive load ( $150\text{ V}$ ).



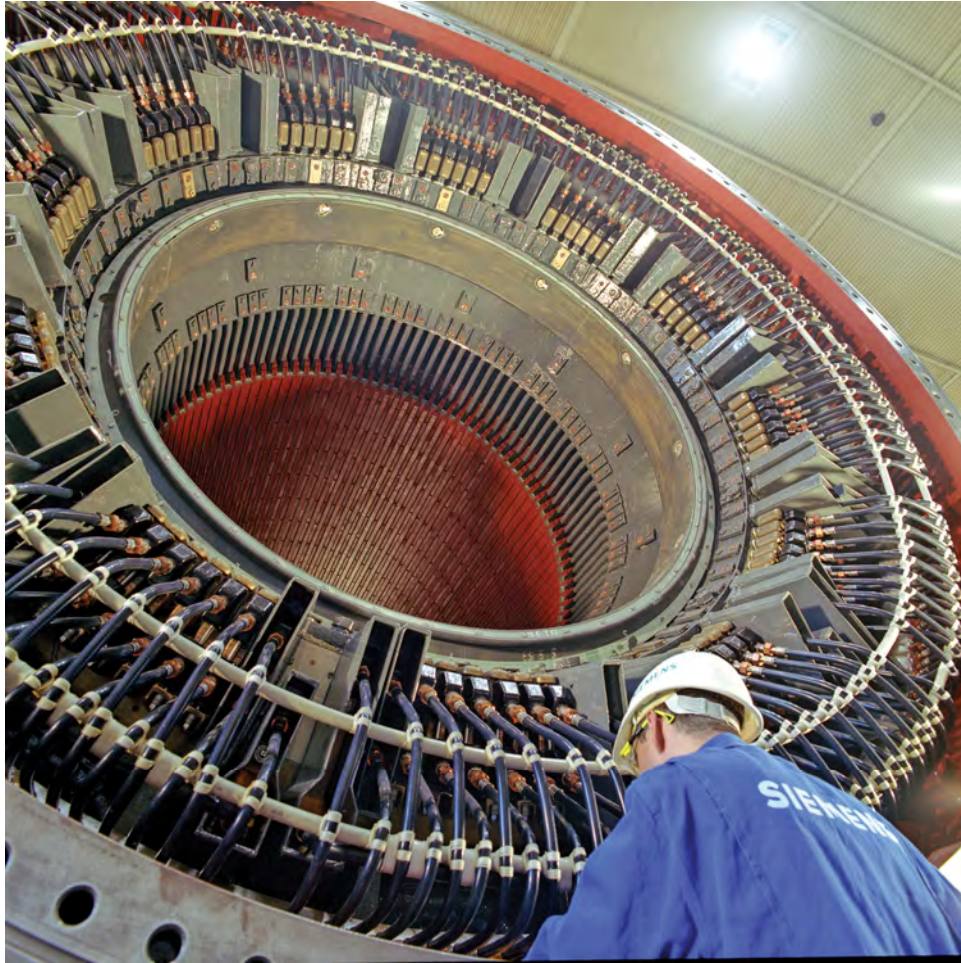


Figure 4-10. Water-cooled stator of a large three-phase synchronous generator in a manufacturing plant in Muelheim, Germany (© Siemens AG 2012, all rights reserved).

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Three-phase synchronous generator voltage regulation characteristic for resistive, inductive, and capacitive loads

## PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

### Set up and connections

*In this section, you will set up a circuit containing a prime mover mechanically coupled to a synchronous generator. You will then set the measuring equipment required to study the synchronous generator voltage regulation characteristics.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Synchronous Motor/Generator](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

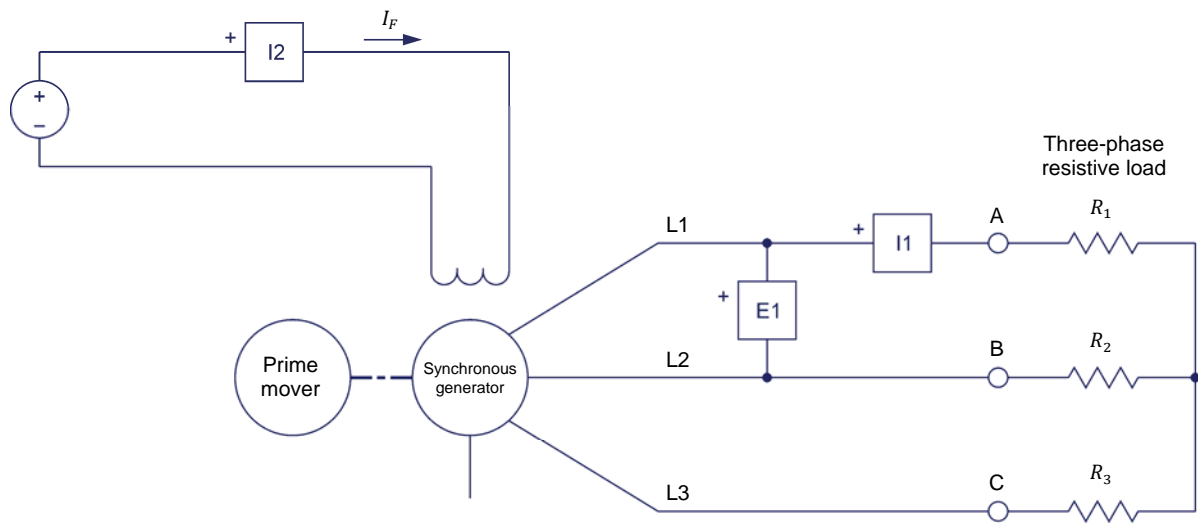
Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

4. Turn the [Four-Quadrant Dynamometer/Power Supply](#) on, then set the [Operating Mode](#) switch to [Dynamometer](#). This setting allows the [Four-Quadrant Dynamometer/Power Supply](#) to operate as a prime mover, a brake, or both, depending on the selected function.

5. Turn the host computer on, then start the [LVDAC-EMS](#) software.

In the [LVDAC-EMS Start-Up](#) window, make sure the [Data Acquisition and Control Interface](#) and the [Four-Quadrant Dynamometer/Power Supply](#) are detected. Make sure the [Computer-Based Instrumentation](#) function is available for the [Data Acquisition and Control Interface](#). Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the [LVDAC-EMS Start-Up](#) window.

6. Connect the equipment as shown in Figure 4-11.



Local ac power network		$R_1, R_2, R_3$ ( $\Omega$ )
Voltage (V)	Frequency (Hz)	
120	60	$\infty$
220	50	$\infty$
240	50	$\infty$
220	60	$\infty$

Figure 4-11. Prime mover coupled to a three-phase synchronous generator supplying power to a resistive load.

7. Open all switches on the **Resistive Load** module so that the resistance of resistors  $R_1$ ,  $R_2$ , and  $R_3$  is infinite.
8. In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
- Set the **Function** parameter to **CW Constant-Speed Prime Mover/Brake**.
  - Set the **Speed** parameter to the synchronous speed  $n_s$  of the **Synchronous Motor/Generator**.



The synchronous speed of the **Synchronous Motor/Generator** is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.

- Set the **Pulley Ratio** parameter to 24:24.

9. In LVDAC-EMS, start the [Metering](#) application. Make the required settings in order to measure the rms value (ac) of the three-phase synchronous generator output voltage  $E_o$  (input [E1](#)) and output current  $I_o$  (input [I1](#)). Set another meter to measure the dc value of the field current  $I_F$  (input [I2](#)) in the rotor electromagnet.

Click the [Continuous Refresh](#) button to enable continuous refresh of the values indicated by the various meters in the [Metering](#) application.

### Three-phase synchronous generator voltage regulation characteristic for resistive, inductive, and capacitive loads

*In this section, you will make the three-phase synchronous generator rotate at the synchronous speed and adjust the Exciter knob so that the generator output voltage is equal to its nominal value. You will record the generator speed, output voltage, output current, and field current while varying the resistance of the resistive load. You will then replace the resistive load with an inductive load, and record the generator speed, output voltage, output current, and field current while varying the reactance of the inductive load. Finally, you will replace the inductive load with a capacitive load, and record the generator speed, output voltage, output current, and field current while varying the reactance of the capacitive load. You will plot a graph of the generator output voltage when it is connected to a resistive load, an inductive load, and a capacitive load as a function of the output current. You will compare the resulting voltage regulation curves.*

#### **Voltage regulation characteristic when the three-phase synchronous generator supplies power to a resistive load**

10. In the [Four-Quadrant Dynamometer/Power Supply](#) window, start the [CW Constant-Speed Prime Mover/Brake](#).

On the [Power Supply](#), turn the dc power source on.

On the [Synchronous Motor/Generator](#), make sure that the [Exciter](#) switch is set to the closed (I) position, then adjust the [Exciter](#) knob so that the three-phase synchronous generator output voltage  $E_o$  is equal to the generator nominal voltage (value indicated on the front panel of the [Synchronous Motor/Generator](#)).

11. In LVDAC-EMS, open the [Data Table](#) window.

Set the [Data Table](#) to record the three-phase synchronous generator speed  $n_{Gen.}$  indicated in the [Four-Quadrant Dynamometer/Power Supply](#) window.

Also, set the [Data Table](#) to record the three-phase synchronous generator output voltage  $E_o$  (input [E1](#)), output current  $I_o$  (input [I1](#)), and field current  $I_F$  (input [I2](#)) indicated in the [Metering](#) application.

12. In the **Data Table** window, click on the **Record Data** button to record the values of the three-phase synchronous generator speed  $n_{Gen.}$ , output voltage  $E_O$ , output current  $I_O$ , and field current  $I_F$ .
13. Set the resistance of resistors  $R_1$ ,  $R_2$ , and  $R_3$  successively to each value indicated in Table 4-3 (the resistance values to be used depend on your local ac power network voltage and frequency). For each resistance value, record the three-phase synchronous generator parameters in the **Data Table**.

**Table 4-3. Resistance values used to study the three-phase synchronous generator voltage regulation characteristics.**

Local ac power network		$R_1, R_2, R_3$ ( $\Omega$ )	$R_1, R_2, R_3$ ( $\Omega$ )	$R_1, R_2, R_3$ ( $\Omega$ )	$R_1, R_2, R_3$ ( $\Omega$ )	$R_1, R_2, R_3$ ( $\Omega$ )	$R_1, R_2, R_3$ ( $\Omega$ )	$R_1, R_2, R_3$ ( $\Omega$ )
Voltage (V)	Frequency (Hz)							
120	60	1200	600	400	300	240	200	171
220	50	4400	2200	1467	1100	880	733	629
240	50	4800	2400	1600	1200	960	800	686
220	60	4400	2200	1467	1100	880	733	629

14. On the **Power Supply**, turn the dc power source off.

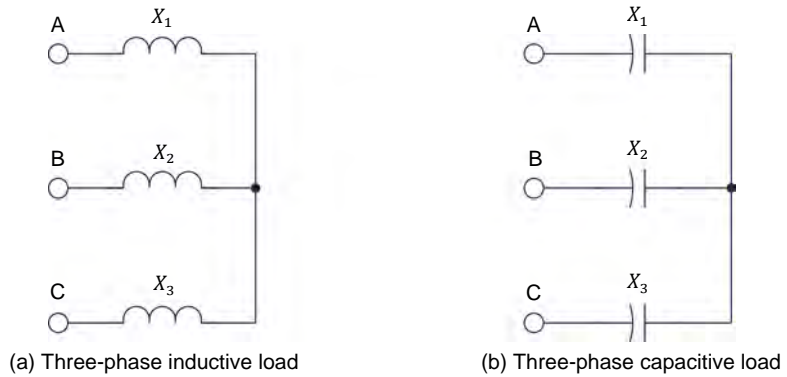
In the **Four-Quadrant Dynamometer/Power Supply** window, stop the prime mover.

15. In the **Data Table** window, save the recorded data.
16. In the **Data Table** window, clear the recorded data without clearing the record settings.

***Voltage regulation characteristic when the three-phase synchronous generator supplies power to an inductive load***

17. Remove the three-phase resistive load from the circuit in Figure 4-11 by disconnecting the load at points A, B, and C.

Add the three-phase inductive load shown in Figure 4-12a to the circuit by connecting points A, B, and C of the load to the corresponding points in the circuit.



Local ac power network		$X_1, X_2, X_3$ ( $\Omega$ )
Voltage (V)	Frequency (Hz)	
120	60	$\infty$
220	50	$\infty$
240	50	$\infty$
220	60	$\infty$

Figure 4-12. Three-phase inductive and capacitive loads used to study the three-phase synchronous generator voltage regulation characteristics.

18. Open all switches on the reactive load module so that the reactance of reactive components  $X_1$ ,  $X_2$ , and  $X_3$  is infinite.

19. In the [Four-Quadrant Dynamometer/Power Supply](#) window, start the prime mover.

On the [Power Supply](#), turn the dc power source on.

On the [Synchronous Motor/Generator](#), make sure that the [Exciter](#) switch is set to the closed (I) position, then adjust the [Exciter](#) knob so that the three-phase synchronous generator output voltage  $E_o$  is equal to the generator nominal voltage (value indicated on the front panel of the [Synchronous Motor/Generator](#)).

20. In the [Data Table](#) window, click on the [Record Data](#) button to record the values of the three-phase synchronous generator speed  $n_{Gen.}$ , output voltage  $E_o$ , output current  $I_o$ , and field current  $I_F$ .



21. Set the reactance of reactive components  $X_1$ ,  $X_2$ , and  $X_3$  successively to each value indicated in Table 4-4 (the reactance values to be used depend on your local ac power network voltage and frequency). For each reactance value, record the three-phase synchronous generator parameters in the [Data Table](#).

**Table 4-4. Reactance values used to study the three-phase synchronous generator voltage regulation characteristics.**

Local ac power network		$X_1, X_2, X_3$ ( $\Omega$ )	$X_1, X_2, X_3$ ( $\Omega$ )	$X_1, X_2, X_3$ ( $\Omega$ )	$X_1, X_2, X_3$ ( $\Omega$ )	$X_1, X_2, X_3$ ( $\Omega$ )	$X_1, X_2, X_3$ ( $\Omega$ )	$X_1, X_2, X_3$ ( $\Omega$ )
Voltage (V)	Frequency (Hz)							
120	60	1200	600	400	300	240	200	171
220	50	4400	2200	1467	1100	880	733	629
240	50	4800	2400	1600	1200	960	800	686
220	60	4400	2200	1467	1100	880	733	629

22. On the [Power Supply](#), turn the dc power source off.

When all data has been recorded, stop the prime mover in the [Four-Quadrant Dynamometer/Power Supply](#) window.

23. In the [Data Table](#) window, save the recorded data.

24. In the [Data Table](#) window, clear the recorded data without clearing the record settings.

***Voltage regulation characteristic when the three-phase synchronous generator supplies power to a capacitive load***

25. Remove the three-phase inductive load from the circuit in Figure 4-11 by disconnecting the load at points A, B, and C.

Add the three-phase capacitive load shown in Figure 4-12b to the circuit by connecting points A, B, and C of the load to the corresponding points in the circuit.

26. Repeat steps 18 to 22 to record the voltage regulation characteristics of the three-phase synchronous generator when the generator is supplying power to a capacitive load.

27. In the [Data Table](#) window, save the recorded data.

28. Plot a graph of the three-phase synchronous generator output voltage  $E_o$  measured when the generator is connected to a resistive load, an inductive load, and a capacitive load as a function of the generator output current  $I_o$ . Plot all three curves on the same graph.

- 29.** Compare the voltage regulation curves you plotted in the previous step for the different load types connected to the three-phase synchronous generator.

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- 30.** Close **LVDAC-EMS**, then turn off all the equipment. Disconnect all leads and return them to their storage location.

### CONCLUSION

In this exercise, you familiarized yourself with the simplified equivalent circuit of a three-phase synchronous generator. You also familiarized yourself with the voltage regulation characteristic of a three-phase synchronous generator when the generator supplies power to either a resistive, an inductive, or a capacitive load.

### REVIEW QUESTIONS

1. What are the two load components that make up the simplified equivalent circuit of a three-phase synchronous generator, and what do these load components represent?

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2. Explain the difference between the voltage  $E_{EMF}$  and the output voltage  $E_O$  of a three-phase synchronous generator.

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3. What happens to the output voltage  $E_o$  of a three-phase synchronous generator supplying power to a capacitive load as the output current  $I_o$  increases?

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4. What happens to the output voltage  $E_o$  of a three-phase synchronous generator supplying power to a resistive load as the output current  $I_o$  increases? What happens if the generator is connected to an inductive load instead?

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5. A three-phase synchronous generator supplying power to a capacitive load ( $X_{C,Load} = 150 \Omega$ ) has an induced voltage  $E_{EMF}$  of 140 V, a stator resistance  $R_{Stator}$  of  $2.5 \Omega$ , and a synchronous reactance  $X_s$  of  $30 \Omega$ . Determine the generator output voltage  $E_o$ .

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# Generator Synchronization

## EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the manual synchronization of a three-phase synchronous generator to an ac power network. You will also be familiar with the electrical transient that occurs when synchronizing a synchronous generator to an ac power network, as well as with the resulting mechanical stress on the generator shaft. You will know how the active power and reactive power of a synchronous generator can be controlled when the generator is synchronized to an ac power network.

## DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to generator synchronization
- Manual synchronization of a synchronous generator
- Electrical transient and mechanical stress at generator synchronization
- Generator operation after synchronization to an ac power network

## DISCUSSION

### Introduction to generator synchronization

Most of the electrical energy consumed today is produced by three-phase synchronous generators. Since a huge amount of electrical energy is consumed every day, ac power networks are generally made up of a large number of synchronous generators all connected in parallel and operating at the same frequency. When the electrical power demand increases, additional generators must be connected to the ac power network. This process of connecting generators to the ac power network is called generator **synchronization**. Before synchronizing a three-phase synchronous generator to an ac power network, it is important to ensure that the following synchronization conditions are met:

- The phase sequence of the synchronous generator must be the same as that of the ac power network.
- The synchronous generator output frequency  $f_{Gen.}$  must be equal to the ac power network frequency  $f_{Net.}$
- The synchronous generator voltage  $E_{Gen.}$  must be equal to the ac power network voltage  $E_{Net.}$
- The synchronous generator voltage must be in phase with the ac power network voltage.

A synchronous generator can be synchronized to the ac power network (i.e., connected to the ac power network) only when all these conditions are met. A synchronous generator must never be connected to an ac power network before verifying synchronization. Connecting a synchronous generator to the ac power network when the above synchronization conditions are not met

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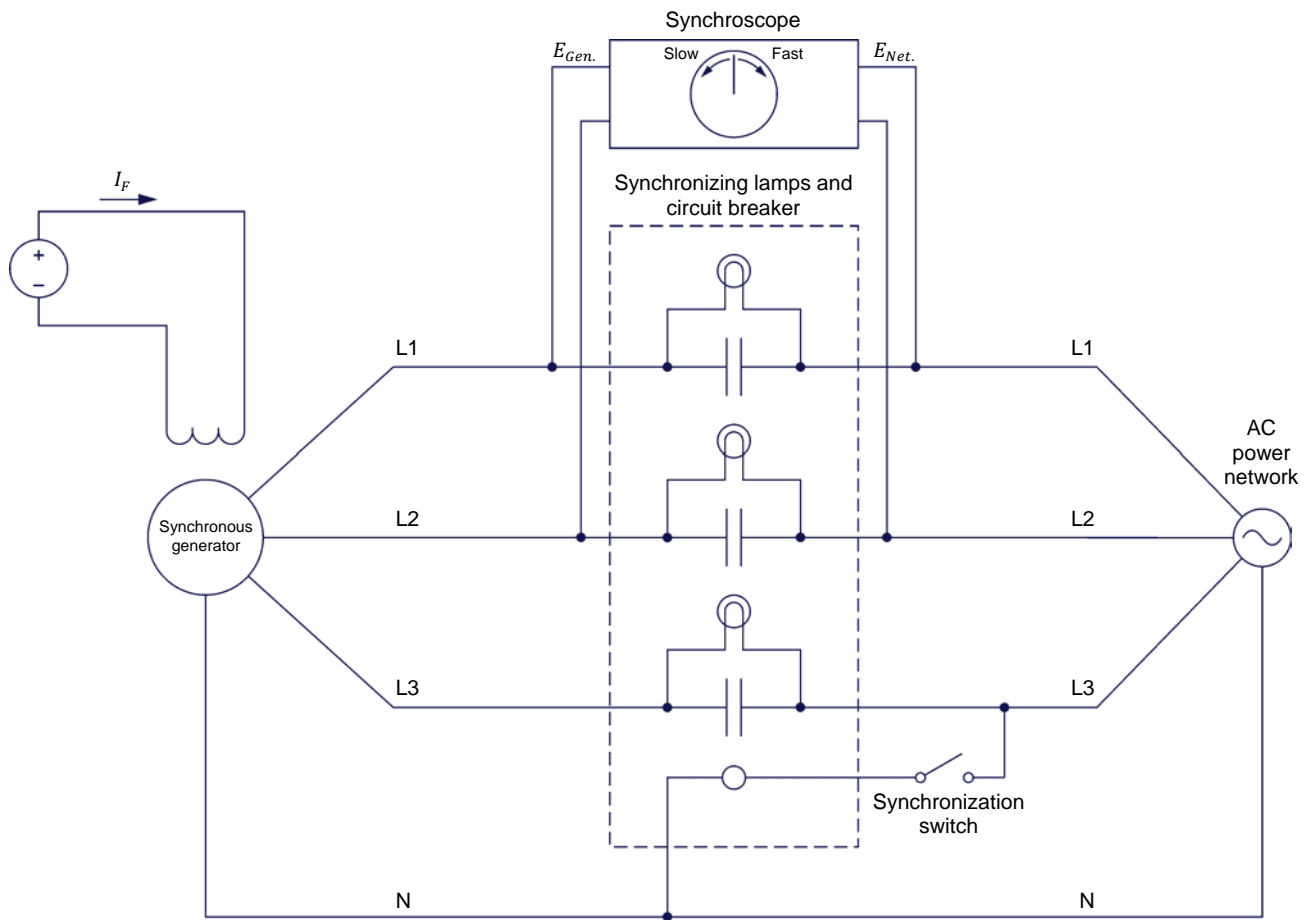
produces very high current and power **transients**. These transients impose a severe electrical and mechanical stress on the generator and can cause serious damage to both the generator and the generating station. Furthermore, large current and power transients at generator synchronization can produce instability in the ac power network. Current and power transients, as well as the mechanical stress imposed on the generator, are discussed in more detail later in this exercise.

### Manual synchronization of a synchronous generator

Figure 4-13 shows the typical circuit used for manual synchronization of a synchronous generator to an ac power network. In this circuit, the synchronous generator is connected to the ac power network (represented by a three-phase ac power source) through a circuit breaker consisting of a three-phase contactor which is energized by closing a switch (synchronization switch). Three synchronizing lamps (one for each phase) are connected in parallel with the circuit breaker contacts. A **synchroscope** is connected to measure the generator voltage  $E_{Gen.}$  (voltage  $E_{1-2}$  in the example of Figure 4-13) and the network voltage  $E_{Net.}$ . The synchronizing lamps are used to ensure that the phase sequence of the generator is the same as that of the network. On the other hand, the synchroscope is used to ensure that the frequency and phase angle of the generator voltage are the same as the frequency and phase angle of the network voltage. The use of the synchronizing lamps and the synchroscope is described in more detail below.

The first step for synchronizing a three-phase synchronous generator to an ac power network is to adjust the generator speed  $n_{Gen.}$  and field current  $I_F$  so that the generator frequency  $f_{Gen.}$  and voltage  $E_{Gen.}$  are close to the network frequency  $f_{Net.}$  and voltage  $E_{Net.}$ , respectively. The generator speed  $n_{Gen.}$  is usually adjusted before the generator field current  $I_F$ . This is because adjusting the generator speed  $n_{Gen.}$  to set the generator frequency  $f_{Gen.}$  also modifies the generator voltage  $E_{Gen.}$ . On the other hand, adjusting the generator field current  $I_F$  to set the generator voltage  $E_{Gen.}$  has no effect on the generator frequency  $f_{Gen.}$ . It is also recommended to set the initial field current  $I_F$  of the synchronous generator to a low value, since increasing the generator speed  $n_{Gen.}$  to increase the generator frequency  $f_{Gen.}$  up to the nominal value also increases the generator voltage  $E_{Gen.}$  and, thus, can cause the nominal voltage value to be exceeded significantly.

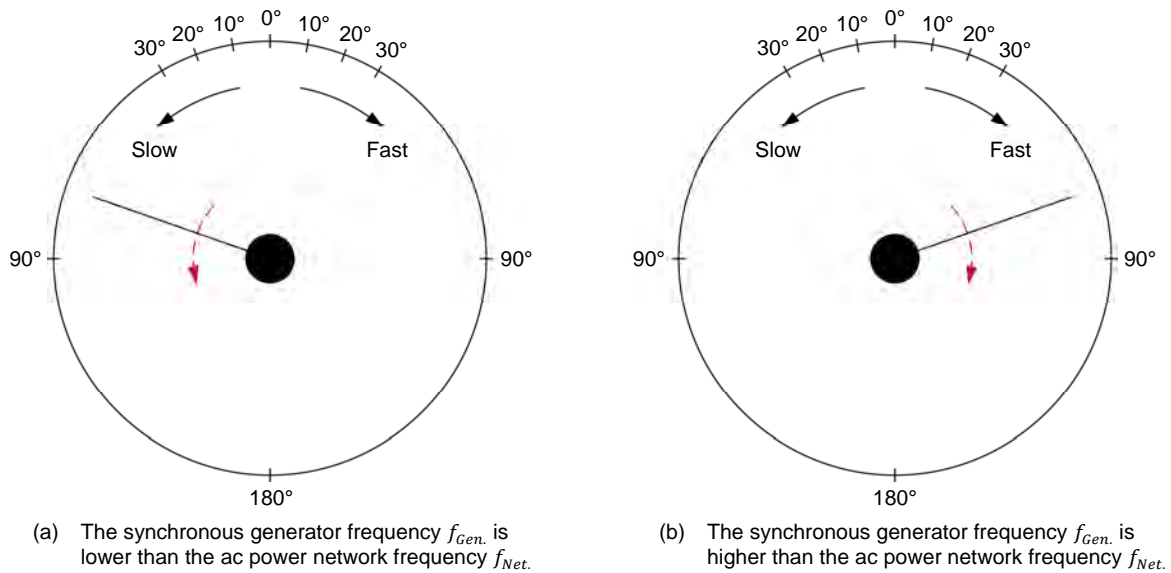
The second step for synchronizing a synchronous generator to an ac power network is to ensure that the phase sequence of the generator is the same as that of the network. This can be determined by observing whether or not the synchronizing lamps in the circuit diagram of Figure 4-13 blink in synchronism. When so, the phase sequence of the generator is the same as that of the ac power network. On the other hand, when the synchronizing lamps do not blink in synchronism, the phase sequence of the generator differs from that of the ac power network. In that case, it is necessary to stop the synchronous generator, interchange the connections at two of the three generator line wires, and restart the synchronous generator. This reverses the phase sequence of the generator and ensures that it is now the same as that of the ac power network.



**Figure 4-13. Circuit for manually synchronizing a generator to an ac power network using synchronizing lamps and a synchroscope.**

The third step for synchronizing a synchronous generator to an ac power network is to carefully adjust the generator speed  $n_{Gen.}$  so that the generator frequency  $f_{Gen.}$  is very close to the ac power network frequency  $f_{Net.}$ . This is achieved using the synchroscope connected as shown in Figure 4-13. The synchroscope indicates whether the generator frequency  $f_{Gen.}$  is lower (the synchroscope needle rotates in the slow or counterclockwise direction) or higher (the synchroscope needle rotates in the fast or clockwise direction) than the network frequency  $f_{Net.}$ . Both cases are illustrated in the following figure.

The rotation speed of the synchroscope needle is proportional to the difference between the generator frequency  $f_{Gen.}$  and the network frequency  $f_{Net.}$ . In order to adjust the generator frequency  $f_{Gen.}$  so that it is very close to the network frequency  $f_{Net.}$ , it is necessary to adjust the generator speed  $n_{Gen.}$  so that the synchroscope needle rotates as slowly as possible. When the synchroscope needle rotates very slowly, it means that the generator frequency  $f_{Gen.}$  is very close to the network frequency  $f_{Net.}$ . The field current  $I_F$  of the synchronous generator is then adjusted so that the generator voltage  $E_{Gen.}$  is virtually equal to the network voltage  $E_{Net.}$ .



**Figure 4-14. Synchroscope indicating whether the frequency  $f_{Gen.}$  of a synchronous generator is lower or higher than the ac power network frequency  $f_{Net.}$**

The fourth and last step for synchronizing a synchronous generator to an ac power network is to close the circuit breaker (by energizing the three-phase contactor) at the moment when the generator voltage is in phase with the network voltage. This is achieved using the synchroscope. The orientation of the synchroscope needle indicates the phase angle difference (i.e., the phase shift) between the generator voltage and the network voltage. Therefore, to synchronize the generator to the network, the circuit breaker must be closed at the moment when the synchroscope needle points toward the  $0^\circ$  phase shift (i.e., toward the top of the synchroscope). This ensures that the phase shift between the generator voltage and the ac power network voltage is virtually null.

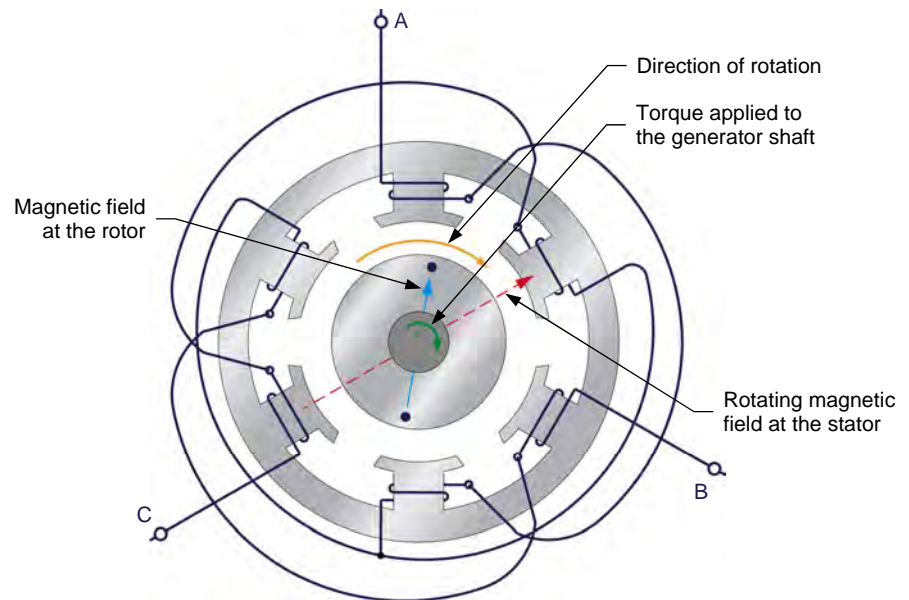
When the circuit breaker is closed, the synchronous generator is synchronized to the ac power network. Once the generator has been synchronized, it can now supply power to the network (i.e., the generator can take its share of the load imposed on the network). The operation of a synchronous generator after synchronization to the network is covered in detail later in this exercise.

### Electrical transient and mechanical stress at generator synchronization

Synchronizing a synchronous generator to an ac power network inevitably produces current and power transients, i.e., momentary exchanges of power between the generator and the network that cause large currents to flow temporarily between the generator and the network. This is due to the great difficulty of perfectly synchronizing a generator to an ac power network. It is possible, however, to minimize the current and power transients produced at the instant of synchronization by ensuring that the frequency and phase angle of the generator voltage are as close as possible to the frequency and phase angle of the network voltage. In other words, it is necessary to make sure that the generator voltage is in phase with the network voltage at the instant of synchronization (i.e., that the synchroscope indicates  $0^\circ$  at the instant of synchronization).

When synchronizing a synchronous generator to an ac power network, if the generator voltage is not perfectly in phase with the network voltage, it results that the magnetic field at the rotor of the generator is not aligned with the rotating magnetic field at the stator. When this happens, a very high torque is applied to the generator shaft at the instant of synchronization so that the magnetic field at the rotor aligns itself with the rotating magnetic field at the stator. The direction of the torque applied to the generator shaft depends on whether the generator voltage lags or leads the network voltage  $E_{Net.}$  at the instant of synchronization, as well as on the generator design characteristics.

On the one hand, if the synchronous generator voltage lags behind the ac power network voltage at the instant of synchronization, as shown in Figure 4-15, the magnetic field at the rotor also lags behind the rotating magnetic field at the stator. Therefore, a very high torque is applied to the generator shaft in order to speed up the rotor until the magnetic field at the rotor catches up with the rotating magnetic field at the stator. This causes the generator to momentarily operate as a motor, i.e., to consume active power.

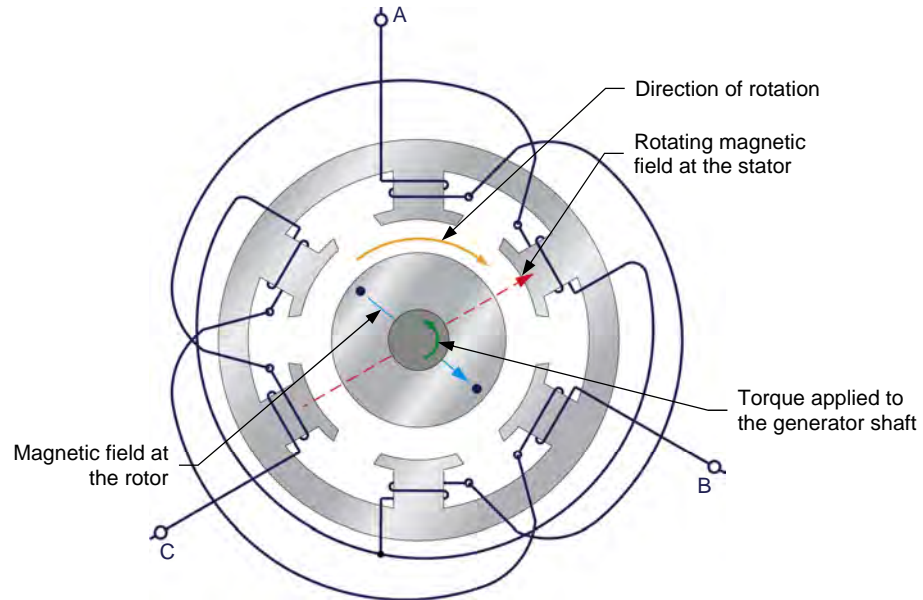


**Figure 4-15. Orientation of the magnetic field at the rotor relative to the rotating magnetic field at the stator when the synchronous generator voltage lags behind the ac power network voltage at the instant of synchronization.**

On the other hand, if the synchronous generator voltage leads the ac power network voltage at the instant of synchronization, as shown in Figure 4-16, the magnetic field at the rotor also leads the rotating magnetic field at the stator. Therefore, a very high torque is applied to the generator shaft in order to brake the rotor until the rotating magnetic field at the stator catches up with the magnetic field at the rotor. This causes the generator to momentarily operate as a loaded generator (i.e., to momentarily supply active power to the network).

At the instant of synchronization, the sudden increase in torque acting on the generator shaft due to the error of alignment between the magnetic field at the rotor and the rotating magnetic field at the stator imposes a great mechanical stress on the generator shaft. The greater the difference in position between the

magnetic field at the rotor and the rotating magnetic field at the stator (i.e., the greater the phase shift between the generator voltage and the ac power network voltage), the greater the torque applied to the generator shaft and, thus, the greater the mechanical stress imposed on the shaft.



**Figure 4-16.** Orientation of the magnetic field at the rotor relative to the rotating magnetic field at the stator when the synchronous generator voltage leads the ac power network voltage at the instant of synchronization.

In any large generating station containing several high-power synchronous generators, such mechanical stress due to improper generator synchronization can result in serious damage to both the generator and the generating station. It is therefore very important to minimize the mechanical stress imposed on a synchronous generator at the instant of synchronization by making sure that the generator is properly synchronized to the ac power network before closing the circuit breaker and allowing synchronization.

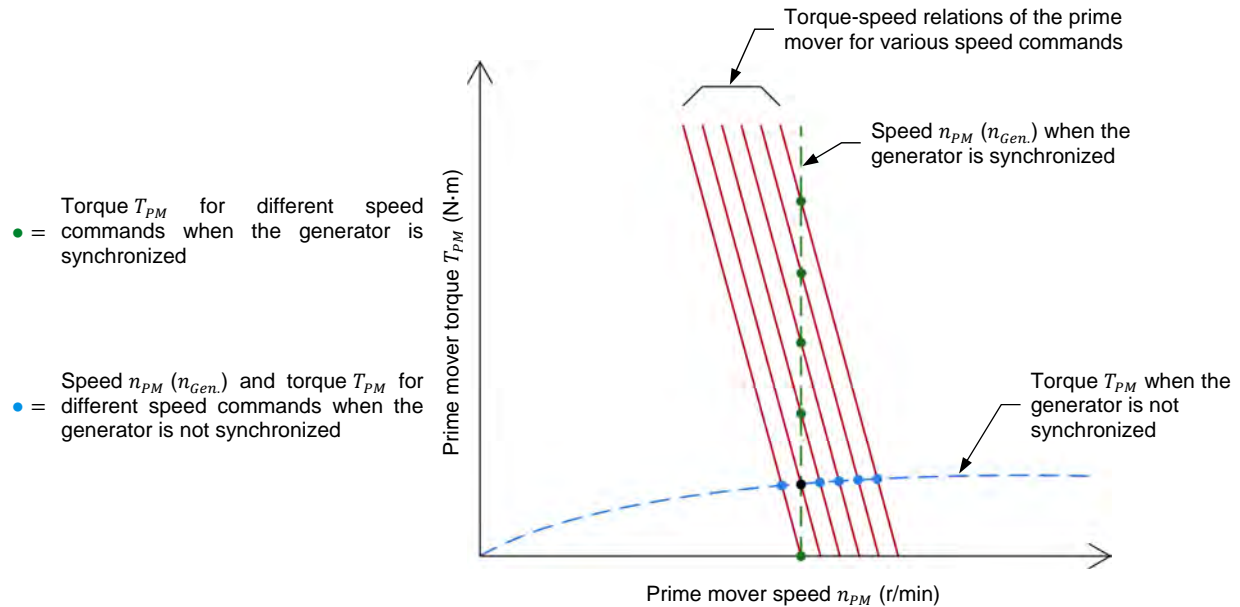
### Generator operation after synchronization to an ac power network

When a synchronous generator is properly synchronized to an ac power network, i.e., when all synchronization conditions are met within close tolerance before connection of the generator to the ac power network, virtually no current flows between the generator and the ac power network after the synchronization because both the generator and the network produce voltages having the same amplitude and phase angle. As a result, the generator neither supplies active power to nor exchanges reactive power with the ac power network. When this occurs, the generator is said to be floating. The control of a synchronous generator active power  $P_{Gen.}$  and reactive power  $Q_{Gen.}$  after synchronization to an ac power network is covered in detail in the following two subsections.



**Synchronous generator active power control after synchronization**

When a synchronous generator is connected to an ac power network, varying the speed command of the prime mover driving the generator modifies the amount of active power  $P_{Gen.}$  supplied by the generator. This can be explained using the typical torque-versus-speed relations of a prime mover shown in Figure 4-17.



**Figure 4-17. Operating points of a prime mover driving a synchronous generator before and after synchronization.**

When the synchronous generator is not synchronized to the ac power network, the prime mover speed  $n_{PM}$  and, thus, the generator speed  $n_{Gen.}$ , can be varied by modifying the prime mover speed command. When the prime mover speed command increases, the prime mover speed  $n_{PM}$  increases in direct proportion and the prime mover torque  $T_{PM}$  increases slightly because the torque opposing rotation increases with speed (as shown by the blue dotted line in Figure 4-17). This is illustrated by the operating points shown in blue in Figure 4-17.

When the generator is synchronized to the ac power network, however, the prime mover speed  $n_{PM}$ , as well as the synchronous generator speed  $n_{Gen.}$ , can no longer be varied by modifying the prime mover speed command. This is because the generator speed  $n_{Gen.}$  and, consequently, the prime mover speed  $n_{PM}$ , are imposed by the network, and are thus maintained virtually constant, as shown by the green curve in Figure 4-17.

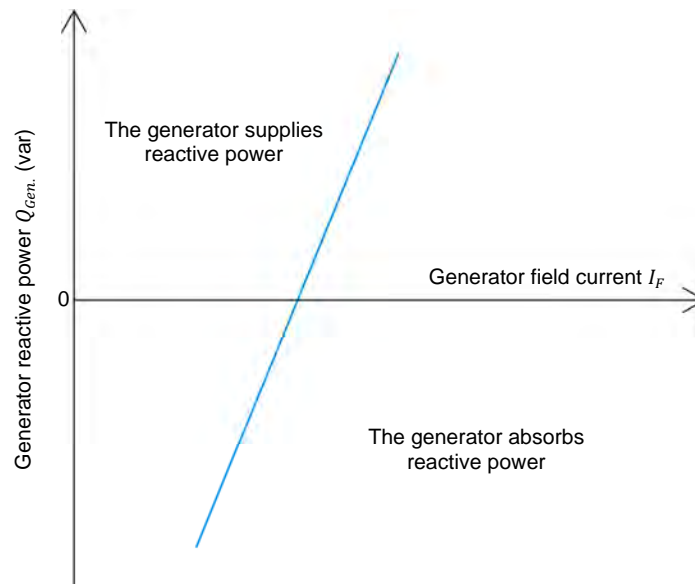
Instead, varying the prime mover speed command varies the prime mover torque  $T_{PM}$ . The higher the prime mover speed command, the higher the prime mover torque  $T_{PM}$  developed at the imposed prime mover speed  $n_{PM}$ . This is illustrated by the operating points shown in green in Figure 4-17. The higher the prime mover torque  $T_{PM}$ , the higher the mechanical power  $P_M$  supplied to the generator and, thus, the amount of active power  $P_{Gen.}$  supplied to the network by the generator. Because of this, when a synchronous generator is synchronized to an ac power network, varying the prime mover speed command (and, by extension, the mechanical power  $P_M$ ) varies the generator active power  $P_{Gen.}$ .



Note that varying the prime mover speed command to adjust the amount of active power  $P_{Gen.}$  which the generator supplies to the network also slightly modifies the amount of reactive power  $Q_{Gen.}$  which the generator exchanges with the network. This is due to reasons which are beyond the scope of this manual.

### ***Synchronous generator reactive power control after synchronization***

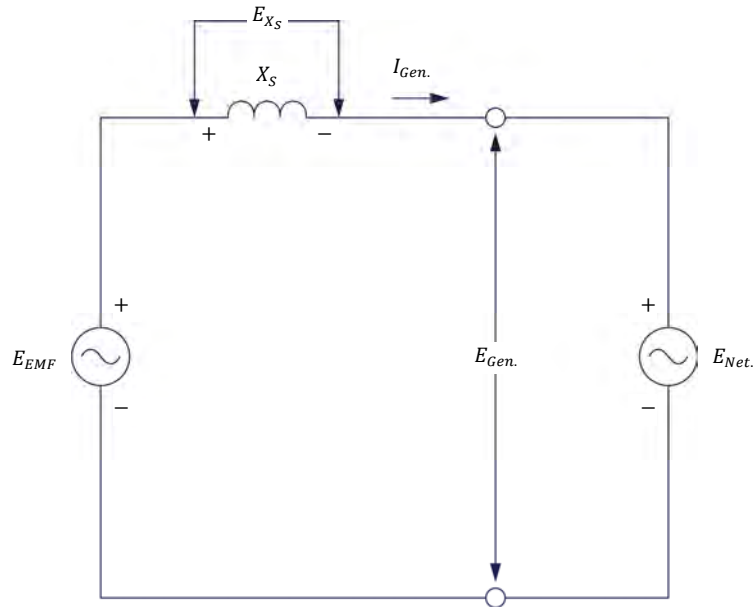
When a synchronous generator is connected to an ac power network, varying the intensity of the generator field current  $I_F$  modifies the amount of reactive power  $Q_{Gen.}$  which the generator exchanges with the network. The higher the intensity of the generator field current  $I_F$ , the higher the amount of reactive power  $Q_{Gen.}$  which the generator supplies to the network ( $Q_{Gen.}$  is positive). However, when the generator field current  $I_F$  is decreased below a certain point, the generator rather absorbs reactive power coming from the ac power network ( $Q_{Gen.}$  becomes negative). This is illustrated in the following figure.



**Figure 4-18. Synchronous generator reactive power  $Q_{Gen.}$  as a function of the field current  $I_F$  when the generator is synchronized to the ac power network.**

The relationship between the reactive power  $Q_{Gen.}$  of a synchronous generator synchronized to an ac power network and the intensity of the generator field current  $I_F$  can be understood by considering the simplified equivalent circuit of one phase of a three-phase synchronous generator connected to an ac power network, as shown in Figure 4-19. As you can see, this circuit is the same as the simplified equivalent circuit of a synchronous generator seen in the previous exercise, with the addition of an ac power source representing the network. Note also that the stator resistance  $R_{Stator}$  is not included in the circuit as it is considered negligible.

In Figure 4-19, the voltage  $E_{EMF}$  represents the voltage induced across the stator windings of the generator. The voltage  $E_{Gen.}$  and current  $I_{Gen.}$  correspond to the generator voltage and current, respectively. The inductance  $X_S$  represents the generator synchronous reactance (i.e., the inductive reactance of the generator stator windings), while the voltage  $E_{X_S}$  represents the voltage drop across the synchronous reactance. Finally, the voltage  $E_{Net.}$  represents the ac power network voltage.



**Figure 4-19. Simplified equivalent circuit of one phase of a three-phase synchronous generator connected to an ac power network.**

As the figure shows, the synchronous generator voltage  $E_{Gen.}$  is equal to the ac power network voltage  $E_{Net.}$ . This is as expected because the network imposes its voltage to the generator. The generator voltage  $E_{EMF}$ , on the other hand, is proportional to the generator speed  $n_{Gen.}$  and field excitation. At any given generator speed  $n_{Gen.}$ , the greater the generator excitation (i.e., the greater the generator field current  $I_F$ ), the greater the value of the voltage  $E_{EMF}$ .

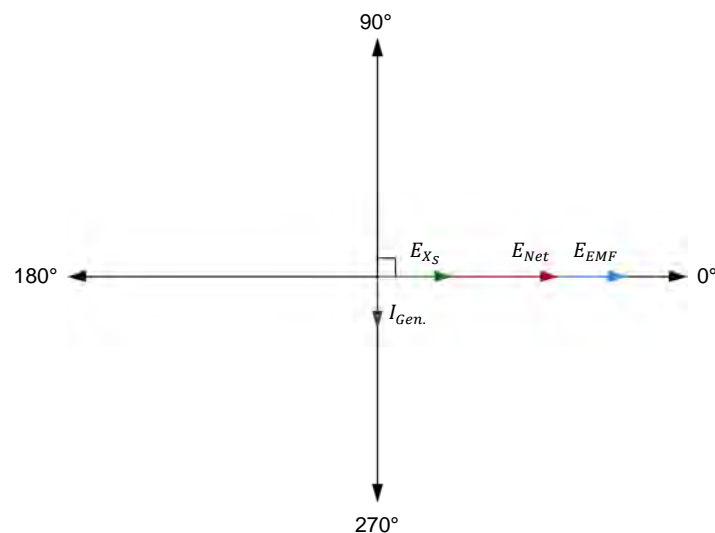
The voltage drop  $E_{X_S}$  across the synchronous reactance is equal to the difference between the voltage  $E_{EMF}$  induced across the stator windings of the generator and the network voltage  $E_{Net.}$  (i.e., the generator voltage  $E_{Gen.}$ ), and can be calculated using the following equation:

$$E_{X_S} = E_{EMF} - E_{Net.} \quad (4-3)$$

where  $E_{X_S}$  is the voltage drop across the synchronous reactance of the synchronous generator, expressed in volts (V).  
 $E_{EMF}$  is the voltage induced across the stator windings of the synchronous generator, expressed in volts (V).  
 $E_{Net.}$  is the ac power network voltage, expressed in volts (V).

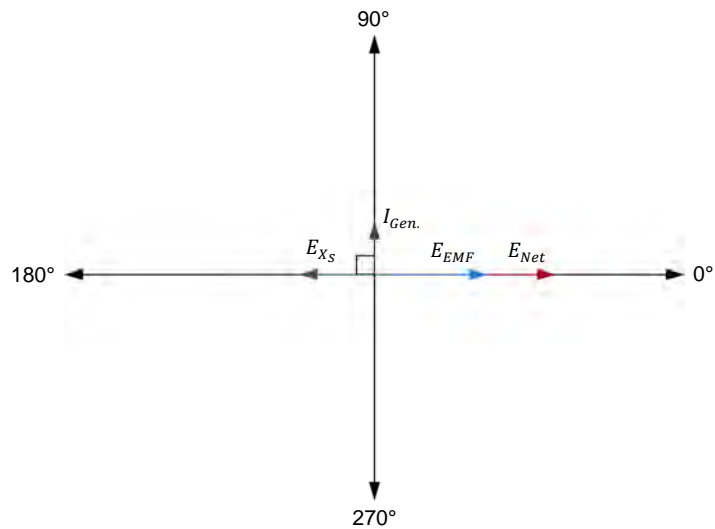
Thus, using Equation (4-3), it is possible to determine that when the voltage  $E_{EMF}$  induced across the generator is equal to the network voltage  $E_{Net.}$ , the voltage drop  $E_{X_S}$  across the synchronous reactance is equal to 0 V. Therefore, no current flows between the generator and the network ( $I_{Gen.}$  is equal to 0 A), and the generator reactive power  $Q_{Gen.}$  is null.

When the voltage  $E_{EMF}$  is higher than the ac power network voltage  $E_{Net.}$  (i.e., when the generator is over-excited), the voltage drop  $E_{X_S}$  calculated using Equation (4-3) is of positive polarity. Consequently, the voltage drop  $E_{X_S}$  is in phase with the generator voltage  $E_{EMF}$  and the network voltage  $E_{Net.}$ . Since the synchronous reactance is inductive, the generator current  $I_{Gen.}$  lags 90° behind the voltage drop  $E_{X_S}$ , the voltage  $E_{EMF}$ , and the network voltage  $E_{Net.}$ . This is illustrated in the phasor diagram of Figure 4-20. In this case (i.e., when the generator is over-excited), the ac power network acts as an inductor since current  $I_{Gen.}$  lags 90° behind voltage  $E_{Net.}$  (i.e., it absorbs reactive power) and, thus, the synchronous generator acts as a capacitor (i.e., it supplies reactive power).



**Figure 4-20.** Phasor diagram representing the voltages and currents in the circuit of Figure 4-19 when the generator is over-excited ( $E_{EMF} > E_{Net.}$ ).

On the other hand, when the voltage  $E_{EMF}$  induced across the generator is lower than the ac power network voltage  $E_{Net.}$  (i.e., when the generator is under-excited), the voltage drop  $E_{X_S}$  calculated using Equation (4-3) is of negative polarity. Consequently, the voltage drop  $E_{X_S}$  is 180° out of phase with respect to the voltage  $E_{EMF}$  and the network voltage  $E_{Net.}$ . Since the synchronous reactance is inductive, the generator current  $I_{Gen.}$  lags 90° behind the voltage drop  $E_{X_S}$ , but leads by 90° the voltage  $E_{EMF}$  and the network voltage  $E_{Net.}$ . This is illustrated in the phasor diagram of Figure 4-21. In this case (i.e., when the generator is under-excited), the ac power network acts as a capacitor since current  $I_{Gen.}$  leads voltage  $E_{Net.}$  by 90° (i.e., it supplies reactive power) and, thus, the synchronous generator acts as an inductor (i.e., it absorbs reactive power).



**Figure 4-21.** Phasor diagram representing the voltages and currents in the circuit of Figure 4-19 when the generator is under-excited ( $E_{EMF} < E_{Net}$ ).

As the above demonstration shows, it is possible to effectively control the amount of reactive power  $Q_{Gen.}$  which a synchronous generator exchanges with the ac power network by adjusting the field excitation of the generator. Over-excitation causes the synchronous generator to supply reactive power to the network, while under-excitation causes the synchronous generator to absorb reactive power from the network. Note that varying the field excitation of a synchronous generator also slightly modifies the amount of active power  $P_{Gen.}$  which the generator supplies to the network. This is due to reasons which are beyond the scope of this manual.

In actual ac power networks, the field excitation of each synchronous generator connected to the network is usually adjusted so that no reactive power is exchanged between the generator and the ac power network, i.e., so that the power factor of the generator is unity. This minimizes the value of the line currents when the generator supplies the maximum amount of active power to the network and, thus, allows the size of the conductors connecting the generator to the ac power network to be reduced to a minimum.

#### PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Generator manual synchronization
- Generator transients and mechanical stress at synchronization
- Generator operation after synchronization to the ac power network

#### PROCEDURE



High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

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## Set up and connections

*In this section, you will set up a circuit containing a prime mover mechanically coupled to a synchronous generator which is connected to the ac power network through a three-phase contactor. You will then set the measuring equipment required to study the behavior of the synchronous generator during manual synchronization.*

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

Install the required equipment in the [Workstation](#).



Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the [Synchronous Motor/Generator](#) to the [Four-Quadrant Dynamometer/Power Supply](#) using a timing belt.

2. Make sure that the ac and dc power switches on the [Power Supply](#) are set to the **O** (off) position, then connect the [Power Supply](#) to a three-phase ac power outlet.

Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.

Connect the [Power Input](#) of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

4. Turn the [Four-Quadrant Dynamometer/Power Supply](#) on, then set the [Operating Mode](#) switch to [Dynamometer](#). This setting allows the [Four-Quadrant Dynamometer/Power Supply](#) to operate as a prime mover, a brake, or both, depending on the selected function.

5. Turn the host computer on, then start the [LVDAC-EMS](#) software.

In the [LVDAC-EMS Start-Up](#) window, make sure that the [Data Acquisition and Control Interface](#) and the [Four-Quadrant Dynamometer/Power Supply](#) are detected. Make sure that the [Computer-Based Instrumentation](#) and [Synchroscope](#) functions for the [Data Acquisition and Control Interface](#) are

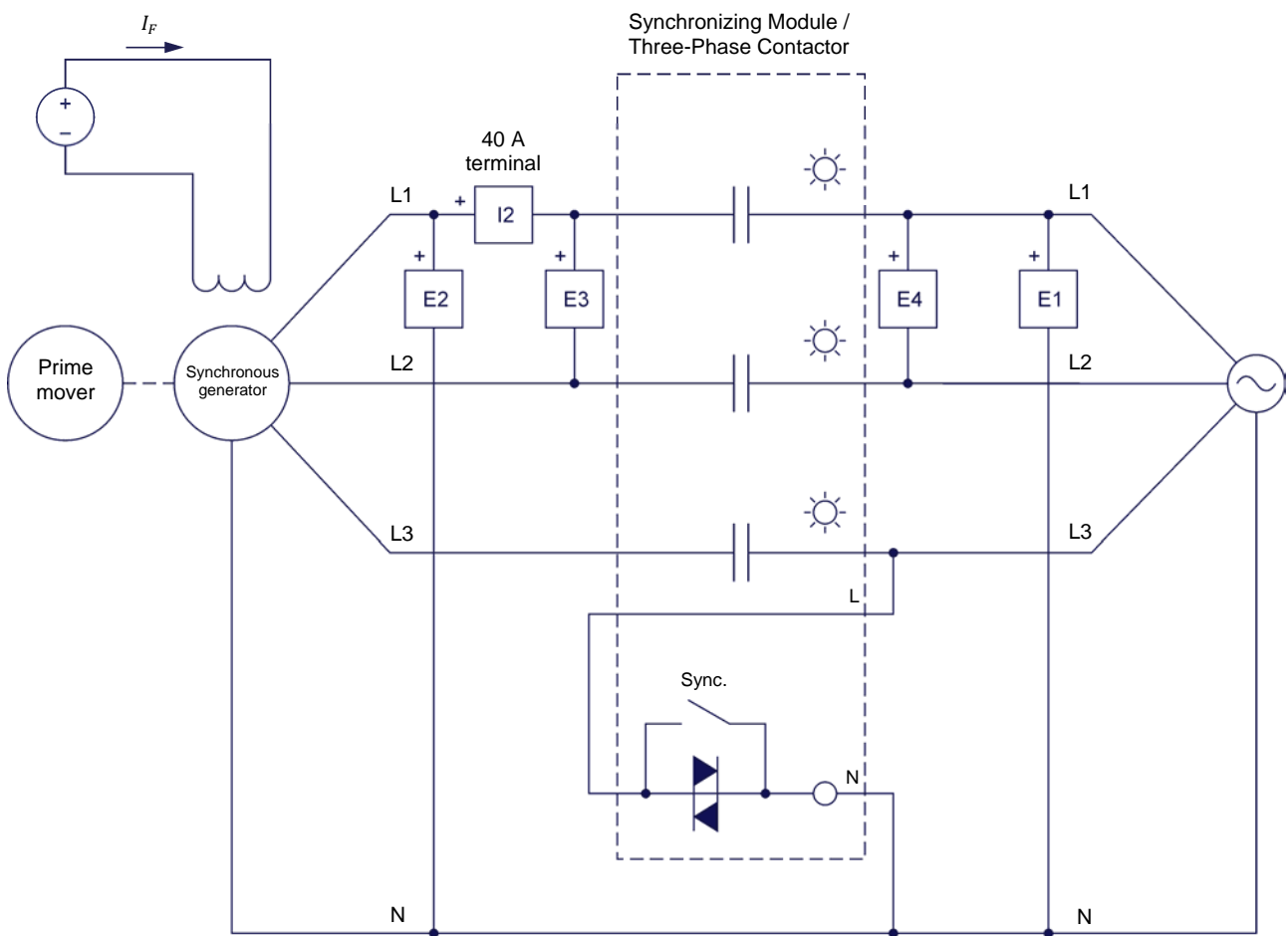
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available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.

6. Connect the equipment as shown in Figure 4-22. This circuit represents a synchronous generator connected to an ac power network through a circuit breaker (three-phase contactor).



*In the circuit of Figure 4-22, voltage inputs **E3** and **E4** are used to measure the generator voltage  $E_{Gen.}$  and ac power network voltage  $E_{Net.}$ , respectively. Measuring these voltages is necessary for the operation of the synchroscope in **LVDAC-EMS**. Because of this, voltage inputs **E3** and **E4** are not available in this exercise to measure and observe circuit parameters using the other instruments in **LVDAC-EMS**.*



**Figure 4-22.** Three-phase synchronous generator connected to an ac power network through a circuit breaker (three-phase contactor).

7. In **LVDAC-EMS**, set the **Range** setting of current input **I2** to High.

8. Connect *Analog Output T* of the *Four-Quadrant Dynamometer/Power Supply* to *Analog Input 7/T* of the *Data Acquisition and Control Interface* using a miniature banana plug lead.

Connect the common (white) terminal of the *Analog Outputs* on the *Four-Quadrant Dynamometer/Power Supply* to one of the two analog common (white) terminals on the *Data Acquisition and Control Interface* using a miniature banana plug lead.

9. In *LVDAC-EMS*, open the *Four-Quadrant Dynamometer/Power Supply* window, then make the following settings:

- Set the *Function* parameter to *CW Prime Mover/Brake*.
- Set the *Speed* parameter to the synchronous speed  $n_s$  of the *Synchronous Motor/Generator*.



*The synchronous speed of the *Synchronous Motor/Generator* is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.*

- Set the *Pulley Ratio* parameter to 24:24.

10. In *LVDAC-EMS*, open the *Metering* window. Make the required settings in order to measure the active power supplied by one phase of the generator, as well as the reactive power exchanged by one phase of the generator [metering function *PQS2 (E2, I2)*]. Also, turn off all meters measuring the voltages at inputs *E3* and *E4*.

In the *Metering* window, make sure that the *Single Refresh* mode is selected.

11. In *LVDAC-EMS*, open the *Synchroscope* window. Start the synchroscope.



*In addition to emulating the operation of an actual synchroscope, the *Synchroscope* window also measures the synchronous generator voltage  $E_{Gen.}$  and frequency  $f_{Gen.}$ , the ac power network voltage  $E_{Net.}$  and frequency  $f_{Net.}$ , as well as the voltage difference between the generator voltage  $E_{Gen.}$  and the network voltage  $E_{Net.}$ . The values of these parameters are indicated in meters at the bottom of the window.*

12. On the *Synchronous Motor/Generator*, set the *Exciter* switch to the closed (I) position, then adjust the *Exciter* knob to about  $\frac{1}{4}$  of the maximal excitation.



*Maximal excitation is obtained when the *Exciter* knob of the *Synchronous Motor/Generator* is set to the fully-clockwise position.*

On the *Synchronizing Module/Three-Phase Contactor*, make sure that the *Lamps* switch is set to the I position. This ensures that the synchronizing lamps on the module are operational.

On the [Synchronizing Module/Three-Phase Contactor](#), make sure that the [Sync.](#) switch is set to the open (O) position. This ensures that the synchronous generator is not connected to the ac power network.

### Generator manual synchronization

*In this section, you will interchange two connections at the stator windings of the synchronous generator. You will start the prime mover and adjust the rotation speed so that it is just below the synchronous speed. You will adjust the generator voltage so that it is equal to the network voltage. You will determine if the phase sequence of the generator is the same as that of the ac power network. You will then interchange again two connections at the stator windings of the synchronous generator, and determine if the phase sequence of the generator is the same as that of the network. You will observe the indicator needle on the Synchroscope, as well as the waveforms of the generator voltage and network voltage on the Oscilloscope. You will increase the generator speed so that it is a little above the synchronous speed, and observe the results on the Synchroscope and the Oscilloscope. You will adjust the generator frequency so that it is very close to the network frequency, and observe the results on the Synchroscope and the Oscilloscope. You will set the Oscilloscope to record the generator current and power transients, as well as the generator torque fluctuations, at the instant of synchronization. You will synchronize the generator to the network when the generator voltage is virtually in phase with the network voltage, and analyse the results.*

13. On the [Synchronous Motor/Generator](#), interchange the connections at output terminals 2 and 3 of the generator.
14. In the [Four-Quadrant Dynamometer/Power Supply](#) window, start the prime mover.

On the [Power Supply](#), turn the dc power source on, then turn the three-phase ac power source on.

15. In the [Four-Quadrant Dynamometer/Power Supply](#) window, increase the [Speed](#) parameter of the prime mover until the generator speed  $n_{Gen.}$  is about 25 r/min below the synchronous speed  $n_s$  of the [Synchronous Motor/Generator](#). While doing so, observe the synchroscope needle in the [Synchroscope](#) window.

On the [Synchronous Motor/Generator](#), adjust the [Exciter](#) knob so that the synchronous generator voltage  $E_{Gen.}$  is as close as possible to the ac power network voltage  $E_{Net.}$  (both voltage values are indicated in the [Synchroscope](#) window).



- 16.** On the [Synchronizing Module/Three-Phase Contactor](#), observe the synchronizing lamps. What can you conclude?

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Can the synchronous generator be synchronized to the network in these conditions?

☐ Yes    ☐ No

- 17.** On the [Power Supply](#), turn the three-phase ac power source off, then turn the dc power source off.

In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the prime mover.

- 18.** On the [Synchronous Motor/Generator](#), interchange the connections at output terminals 2 and 3 of the generator.

- 19.** In the [Four-Quadrant Dynamometer/Power Supply](#) window, start the prime mover.

On the [Power Supply](#), turn the dc power source on, then turn the three-phase ac power source on.

- 20.** On the [Synchronizing Module/Three-Phase Contactor](#), observe the synchronizing lamps. What can you conclude?

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- 21.** In the [Synchroscope](#) window, observe the direction of rotation of the synchroscope needle. In which direction does the indicator needle rotate?

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Is this direction coherent with the synchronous generator frequency  $f_{Gen.}$  and ac power network frequency  $f_{Net.}$  indicated in the **Synchroscope** window? Explain briefly.

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- 22.** In **LVDAC-EMS**, open the **Oscilloscope**, then make the appropriate settings in order to observe the waveforms of the ac power network voltage  $E_{Net.}$  (input **E1**) and the synchronous generator voltage  $E_{Gen.}$  (input **E2**). Select the ac power network voltage  $E_{Net.}$  (input **E1**) as the trigger source of the **Oscilloscope**.

Observe the waveforms of the ac power network voltage  $E_{Net.}$  and the synchronous generator voltage  $E_{Gen.}$ . Describe and explain briefly what you observe.

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- 23.** In the **Four-Quadrant Dynamometer/Power Supply** window, increase the **Speed** parameter of the prime mover until the generator speed  $n_{Gen.}$  is about 25 r/min above the synchronous speed  $n_s$  of the **Synchronous Motor/Generator**. While doing so, observe the synchroscope needle in the **Synchroscope** window.

- 24.** In the **Synchroscope** window, observe the direction of rotation of the synchroscope needle. In which direction does the indicator needle rotates?

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Is this direction coherent with the synchronous generator frequency  $f_{Gen.}$  and ac power network frequency  $f_{Net.}$  indicated in the **Synchroscope** window? Explain briefly.

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25. On the **Oscilloscope**, observe the waveforms of the ac power network voltage  $E_{Net.}$  and the synchronous generator voltage  $E_{Gen.}$ . Describe and explain briefly what you observe.

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26. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly decrease the **Speed** parameter of the prime mover until the generator speed  $n_{Gen.}$  is about 5 r/min above the synchronous speed  $n_s$  of the **Synchronous Motor/Generator**. While doing so, observe the synchroscope needle and meters in the **Synchroscope** window as well as the voltage waveforms on the **Oscilloscope**. Describe and explain briefly what you observe.

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27. In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Speed** parameter of the prime mover until the synchroscope needle rotates very slowly in the Fast direction.

Is the synchronous generator frequency  $f_{Gen.}$  very close to the ac power network frequency  $f_{Net.}$ ?

☐ Yes    ☐ No

On the **Oscilloscope**, do the waveform of the synchronous generator voltage  $E_{Gen.}$  and that of the ac power network voltage  $E_{Net.}$  slide very slowly with respect to each other?

☐ Yes    ☐ No

28. On the **Synchronous Motor/Generator**, adjust the **Exciter** knob so that the synchronous generator voltage  $E_{Gen.}$  is as close as possible to the ac power network voltage  $E_{Net.}$ .

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29. Observe the synchroscope needle, the voltage waveforms on the [Oscilloscope](#), and the synchronizing lamps on the [Synchronizing Module/Three-Phase Contactor](#). Describe what you observe whenever the synchroscope needle passes by the  $0^\circ$  position.

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Is it possible to synchronize the synchronous generator to the ac power network at that instant (i.e., when the synchroscope needle passes by the  $0^\circ$  position)? Explain briefly why.

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30. On the [Oscilloscope](#), make the appropriate settings in order to observe the waveforms of the synchronous generator current  $I_{Gen.}$  (input [I2](#)), power (from inputs [E2](#) and [I2](#)), and torque  $T_{Gen.}$  (measured using [Analog Input 7/T](#)).



*It is recommended to set the sensitivity of the channel used to observe the generator current waveform to 5 A/div, the sensitivity of the channel used to observe the generator power waveform to 500 W/div, the sensitivity of the channel used to observe the generator torque signal to 0.1 N·m/div, and the time base to 50 ms/div. You can adjust these settings as needed during the course of this exercise in order to decrease or increase the sensitivity of the displayed signals.*

On the **Oscilloscope**, set the trigger type to **Hardware**, the trigger source to the channel used to observe the waveform of the generator current  $I_{Gen.}$ , and the trigger level to 0.5 A (or 0.3 A if your ac power network voltage is higher than 120 V). Adjust the horizontal position of the trigger point to about 2 divisions of the left-hand side of the oscilloscope screen.



*These settings ensure that the **Oscilloscope** begins to record data only when the synchronous generator current  $I_{Gen.}$  reaches a value of 0.5 A (or 0.3 A), i.e., when the generator is synchronizing to the ac power network.*

On the **Oscilloscope**, click the **Single Refresh** button.

31. In the **Synchroscope** window, wait for the synchronous generator voltage  $E_{Gen.}$  and the ac power network voltage  $E_{Net.}$  to be in phase (i.e., when the synchroscope needle points toward  $0^\circ$ ), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.
32. In the **Metering** window, measure the synchronous generator active power and reactive power by clicking the **Single Refresh** button, then multiply each power value by three to obtain the generator three-phase active power  $P_{Gen.}$  and reactive power  $Q_{Gen.}$ . Measure also the generator torque  $T_{Gen.}$  indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Record the values below.

Generator three-phase active power  $P_{Gen.} = \underline{\hspace{2cm}}$  W

Generator three-phase reactive power  $Q_{Gen.} = \underline{\hspace{2cm}}$  var

Generator torque  $T_{Gen.} = \underline{\hspace{2cm}}$  N·m

Explain briefly why the power values you just recorded are obtained.

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33. On the [Oscilloscope](#), observe the recorded waveforms of the synchronous generator current  $I_{Gen.}$ , power, and torque  $T_{Gen.}$ . Describe what happened at the instant of synchronization and explain briefly.

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Save all signals recorded on the [Oscilloscope](#) by making a screen capture of the [Oscilloscope](#) window and saving it to a file. You will use these signals for comparison purposes in the next part of this exercise.

### Generator transients and mechanical stress at synchronization

*In this section, you will record on the Oscilloscope the synchronous generator current and power transients, as well as the generator torque fluctuations, when the generator is synchronized to the network with various phase shifts between the generator voltage and the ac power network voltage, as well as when the generator voltage value is different from the network voltage value. You will analyse the recorded signals, and determine which factors affect the generator current and power transients, as well as the generator torque fluctuations, at the instant of synchronization.*

34. On the [Synchronizing Module/Three-Phase Contactor](#), set the [Sync.](#) switch to the open (O) position to disconnect the synchronous generator from the ac power network.

On the [Oscilloscope](#), click the [Single Refresh](#) button.

35. In the [Synchroscope](#) window, wait for the synchronous generator voltage  $E_{Gen.}$  to lag by  $30^\circ$  behind the ac power network voltage  $E_{Net.}$  (i.e., when the synchroscope needle points toward  $30^\circ$  in the Slow half of the dial), then set the [Sync.](#) switch on the [Synchronizing Module/Three-Phase Contactor](#) to the closed (I) position to synchronize the generator to the network.

Save all signals recorded on the [Oscilloscope](#) by making a screen capture of the [Oscilloscope](#) window and saving it to a file, then repeat step 34.

36. In the **Synchroscope** window, wait for the synchronous generator voltage  $E_{Gen.}$  to lag by about  $60^\circ$  behind the ac power network voltage  $E_{Net.}$  (i.e., when the indicator needle points toward  $60^\circ$  in the Slow half of the dial), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.

Save all signals recorded on the **Oscilloscope** by making a screen capture of the **Oscilloscope** window and saving it to a file, then repeat step 34.

37. In the **Synchroscope** window, wait for the synchronous generator voltage  $E_{Gen.}$  to lead by  $30^\circ$  the ac power network voltage  $E_{Net.}$  (i.e., when the indicator needle points toward  $30^\circ$  in the Fast half of the dial), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.

Save all signals recorded on the **Oscilloscope** by making a screen capture of the **Oscilloscope** window and saving it to a file, then repeat step 34.

38. In the **Synchroscope** window, wait for the synchronous generator voltage  $E_{Gen.}$  to lead by about  $60^\circ$  the ac power network voltage  $E_{Net.}$  (i.e., when the indicator needle points toward  $60^\circ$  in the Fast half of the dial), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.

Save all signals recorded on the **Oscilloscope** by making a screen capture of the **Oscilloscope** window and saving it to a file, then repeat step 34.

39. In the **Synchroscope** window, wait for the synchronous generator voltage  $E_{Gen.}$  to be about  $180^\circ$  out of phase with respect to the ac power network voltage  $E_{Net.}$  (i.e., when the indicator needle points toward  $180^\circ$  on the dial), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.

Is there a loud noise at the instant of synchronization when the synchronous generator voltage is  $180^\circ$  out of phase with respect to the ac power network voltage? Explain briefly why.

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Save all signals recorded on the **Oscilloscope** by making a screen capture of the **Oscilloscope** window and saving it to a file, then repeat step 34.

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40. On the **Synchronous Motor/Generator**, set the **Exciter** knob to the **MIN.** position. This ensures that the synchronous generator voltage  $E_{Gen.}$  is significantly lower than the ac power network voltage  $E_{Net.}$ .

In the **Synchroscope** window, wait for the synchronous generator voltage  $E_{Gen.}$  and the ac power network voltage  $E_{Net.}$  to be in phase (i.e., when the indicator needle points toward  $0^\circ$ ), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.

Save all signals recorded on the **Oscilloscope** by making a screen capture of the **Oscilloscope** window and saving it to a file, then close the **Oscilloscope**.

41. In the **Metering** window, measure the synchronous generator active power and reactive power by clicking the **Single Refresh** button, then multiply each power value by three to obtain the generator three-phase active power  $P_{Gen.}$  and reactive power  $Q_{Gen.}$ . Measure also the generator torque  $T_{Gen.}$  indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Record the values below.

Generator three-phase active power  $P_{Gen.} = \underline{\hspace{2cm}}$  W

Generator three-phase reactive power  $Q_{Gen.} = \underline{\hspace{2cm}}$  var

Generator torque  $T_{Gen.} = \underline{\hspace{2cm}}$  N·m

Compare the synchronous generator three-phase active power  $P_{Gen.}$  and reactive power  $Q_{Gen.}$  values you just recorded when the generator is synchronized while voltage  $E_{Gen.}$  is significantly lower than the ac power network voltage  $E_{Net.}$  to the power values you recorded in step 32 when the generator is synchronized while voltage  $E_{Gen.}$  is equal to the network voltage  $E_{Net.}$ . What can you conclude?

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42. On the **Synchronizing Module/Three-Phase Contactor**, set the **Sync.** switch to the open (O) position to disconnect the synchronous generator from the ac power network.



- 43.** On the **Power Supply**, turn the three-phase ac power source off, then turn the dc power source off.

In the **Four-Quadrant Dynamometer/Power Supply** window, stop the prime mover.

- 44.** Using the screen captures of the **Oscilloscope** window you saved to files, compare the magnitude of the current and power transients recorded at the instant of synchronization for the various phase angle differences between the synchronous generator voltage and the ac power network voltage. What do you observe?

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Explain briefly your observations.

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45. Using the screen captures of the **Oscilloscope** window you saved to files, compare the magnitude of the increase in the synchronous generator torque  $T_{Gen.}$  recorded at the instant of synchronization for the various phase angle differences between the synchronous generator voltage and the ac power network voltage. What do you observe?

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46. Does the synchronous generator torque  $T_{Gen.}$  at the instant of synchronization become momentarily positive when the generator voltage lags behind the ac power network voltage, indicating that the generator momentarily operates as a motor?

☐ Yes      ☐ No

Does the synchronous generator torque  $T_{Gen.}$  at the instant of synchronization become momentarily negative when the generator voltage leads the ac power network voltage, indicating that the generator momentarily operates as a generator?

☐ Yes      ☐ No

47. Considering the observations about the synchronous generator torque  $T_{Gen.}$  you made so far, is it acceptable in actual generating stations to synchronize a synchronous generator to the ac power network while the generator voltage and the network voltage are out of phase? Explain briefly.

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48. Considering your observations, what is the optimal phase angle difference between the synchronous generator voltage and the ac power network voltage at the instant of synchronization for minimizing the magnitude of the current and power transients, as well as the mechanical stress on the generator shaft (i.e., the large increase in the generator torque  $T_{Gen.}$ ). Explain briefly.

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49. Using the screen captures of the [Oscilloscope](#) window you saved to files at steps 33 and 40, compare the current and power transients recorded at the instant of synchronization when the synchronous generator voltage  $E_{Gen.}$  is in phase but significantly lower than the ac power network voltage  $E_{Net.}$  to those recorded when the generator voltage  $E_{Gen.}$  is in phase with and equal to the network voltage  $E_{Net.}$ . What do you observe? Explain briefly.

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### Generator operation after synchronization to the ac power network

*In this section, you will synchronize the synchronous generator to the ac power network. You will then vary the prime mover speed, and observe the effects on the generator speed, frequency, and active power. You will analyze the results. You will adjust the generator active power so that it is equal to 0 W. You will then vary the field excitation of the generator, and observe the effects on the generator voltage and reactive power. You will analyze the results.*

50. In the **Four-Quadrant Dynamometer/Power Supply** window, start the prime mover.

On the **Power Supply**, turn the dc power source on, then turn the three-phase ac power source on.

51. In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Speed** parameter of the prime mover until the generator frequency  $f_{Gen.}$  is very close to the ac power network frequency  $f_{Net.}$

On the **Synchronous Motor/Generator**, adjust the **Exciter** knob so that the synchronous generator voltage  $E_{Gen.}$  is as close as possible to the ac power network voltage  $E_{Net.}$

52. In the **Synchroscope** window, wait for the synchronous generator voltage and the ac power network voltage to be in phase (i.e., when the synchroscope needle points toward  $0^\circ$ ), then set the **Sync.** switch on the **Synchronizing Module/Three-Phase Contactor** to the closed (I) position to synchronize the generator to the network.

53. In the **Metering** window, click the **Continuous Refresh** button to enable continuous refresh of the values indicated by the various meters in the window.

54. In the **Four-Quadrant Dynamometer/Power Supply** window, vary the **Speed** parameter of the prime mover. Observe what happens to the synchronous generator parameters (indicated in the **Metering** window and the **Synchroscope** window) as you do so.

What happens to the synchronous generator speed  $n_{Gen.}$ , frequency  $f_{Gen.}$ , and torque  $T_{Gen.}$  as you vary the **Speed** parameter (i.e., the speed control setting) of the prime mover? Explain briefly why.

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What happens to the synchronous generator active power  $P_{Gen.}$  as you vary the speed control setting of the prime mover? Explain briefly why.

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55. In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Speed** parameter of the prime mover so that the generator active power  $P_{Gen.}$  is as close as possible to 0 W.

56. On the **Synchronous Motor/Generator**, vary the setting of the **Exciter** knob. Observe what happens to the synchronous generator parameters (indicated in the **Metering** window and the **Synchroscope** window) as you do so.

What happens to the synchronous generator voltage  $E_{Gen.}$  as you vary the setting of the **Exciter** knob on the **Synchronous Motor/Generator**? Explain briefly why.

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What happens to the synchronous generator reactive power  $Q_{Gen.}$  as you vary the setting of the **Exciter** knob on the **Synchronous Motor/Generator**?

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- 57.** Considering your observations, can you conclude that adjusting the speed of the prime mover driving a synchronous generator is a good means of controlling the generator active power  $P_{Gen.}$  when it is connected to an ac power network?

☐ Yes      ☐ No

Considering your observations, can you conclude that adjusting the field excitation of a synchronous generator is a good means of controlling the generator reactive power  $Q_{Gen.}$  when it is connected to an ac power network?

☐ Yes      ☐ No

- 58.** Close **LVDAC-EMS**, then turn off all the equipment. Disconnect all leads and return them to their storage location.

### CONCLUSION

In this exercise, you familiarized yourself with the manual synchronization of a three-phase synchronous generator to an ac power network. You also became familiar with the electrical transient that occurs when synchronizing a synchronous generator to an ac power network, as well as with the mechanical stress imposed on the generator shaft. You learned how the active power and reactive power of a synchronous generator can be controlled when the generator is synchronized to an ac power network.

### REVIEW QUESTIONS

1. What are the synchronization conditions that must be met before synchronizing a three-phase synchronous generator to an ac power network?

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2. What are the synchronizing lamps and the synchroscope used for when synchronizing a synchronous generator to an ac power network?

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3. When synchronizing a synchronous generator to the ac power network, what does the rotation of the synchroscope needle in the Slow (counterclockwise) direction indicate? What does the rotation of the synchroscope needle in the Fast (clockwise) direction indicate?

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4. What are the main negative effects of improperly synchronizing a synchronous generator to an ac power network?

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5. Is it possible to vary the frequency  $f_{Gen.}$  and voltage  $E_{Gen.}$  of a synchronous generator after it has been synchronized to an ac power network? Explain briefly why.

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## Unit Test

1. Complete the following sentence: A three-phase synchronous generator
  - a. is equivalent to an eddy-current brake.
  - b. functions in the same way as an asynchronous generator.
  - c. consists of three electromagnets located at  $120^\circ$  from each other that induce voltages in the stator windings as they rotate.
  - d. is basically an electromagnet that induces voltages in the stator windings as it rotates.
  
2. Complete the following sentence: The speed  $n_{Gen.}$  of a three-phase synchronous generator determines
  - a. the frequency and amplitude of the generator output voltage  $E_O$ .
  - b. only the frequency of the generator output voltage  $E_O$ .
  - c. only the amplitude of the generator output voltage  $E_O$ .
  - d. neither the frequency nor the amplitude of the generator output voltage  $E_O$ .
  
3. A three-phase synchronous generator having 30 pairs of poles per stator windings produces voltages whose frequency  $f$  is 60 Hz when the generator rotates at the nominal speed. What is the nominal speed of the synchronous generator?
  - a. 3600 r/min
  - b. 360 r/min
  - c. 120 r/min
  - d. 1800 r/min
  
4. How can the output voltage  $E_O$  of a three-phase synchronous generator be varied without modifying the output frequency  $f$  of the generator?
  - a. By varying the generator speed  $n_{Gen.}$
  - b. By varying the way the conductors are wound in the stator windings of the generator
  - c. By varying the torque  $T$  applied to the shaft of the generator
  - d. By varying the field current  $I_F$  of the generator
  
5. In the simplified equivalent circuit of a three-phase synchronous generator, the value of the generator synchronous reactance  $X_{L,Stator}$  is
  - a. much lower than the value of the stator resistance  $R_{Stator}$ .
  - b. much greater than the value of the stator resistance  $R_{Stator}$ .
  - c. equal to the value of the stator resistance  $R_{Stator}$ .
  - d. virtually zero.



6. When a three-phase synchronous generator supplies power to a capacitive load, the generator output voltage  $E_O$ 
  - a. decreases as the field current  $I_F$  increases.
  - b. increases with the output current  $I_O$ .
  - c. remains constant as the output current  $I_O$  increases.
  - d. decreases as the output current  $I_O$  increases.
  
7. When a three-phase synchronous generator supplies power to either a resistive load or an inductive load, the generator output voltage  $E_O$ 
  - a. decreases as the field current  $I_F$  increases.
  - b. increases as the output current  $I_O$  increases.
  - c. remains constant as the output current  $I_O$  increases.
  - d. decreases as the output current  $I_O$  increases.
  
8. A three-phase synchronous generator supplying power to an inductive load ( $X_{L,Load} = 80 \, \Omega$ ) has an induced voltage  $E_{EMF}$  of 160 V, a stator resistance  $R_{Stator}$  of 5  $\Omega$ , and a synchronous reactance  $X_{L,Stator}$  of 25  $\Omega$ . Determine the generator output voltage  $E_O$ .
  - a.  $E_O = 232 \, \text{V}$
  - b.  $E_O = 160 \, \text{V}$
  - c.  $E_O = 122 \, \text{V}$
  - d.  $E_O = 152 \, \text{V}$
  
9. Which of the following statements is not a synchronization condition that must be met before synchronizing a synchronous generator to an ac power network?
  - a. The synchronous generator frequency  $f_{Gen.}$  must be equal to the ac power network frequency  $f_{Net.}$
  - b. The synchronous generator voltage  $E_{Gen.}$  must be equal to the ac power network voltage  $E_{Net.}$
  - c. The generator output voltage must be in phase with the ac power network voltage.
  - d. None of the above
  
10. Complete the following sentence: After synchronization to an ac power network, it is possible to control the active power  $P_{Gen.}$  and the reactive power  $Q_{Gen.}$  of a synchronous generator by adjusting, respectively, the generator
  - a. speed  $n_{Gen.}$  and field current  $I_F$ .
  - b. voltage  $E_{Gen.}$  and mechanical power  $P_M$ .
  - c. field current  $I_F$  and speed  $n_{Gen.}$ .
  - d. voltage  $E_{Gen.}$  and speed  $n_{Gen.}$ .

## Equipment Utilization Chart

The following equipment is required to perform the exercises in this manual.

Equipment									
Model	Description	1-1	2-1	2-2	3-1	3-2	4-1	4-2	4-3
8134 <sup>(1)</sup>	Workstation	1	1	1	1	1	1	1	1
8221-2 <sup>(2)</sup>	Four-Pole Squirrel Cage Induction Motor		1	1					
8241-2	Synchronous Motor/Generator	1			1	1	1	1	1
8311 <sup>(3)</sup>	Resistive Load			1	1		1	1	
8321	Inductive Load							1	
8331	Capacitive Load							1	
8621-A	Synchronizing Module/Three-Phase Contactor								1
8823	Power Supply	1	1	1	1	1	1	1	1
8942	Timing Belt	1	1	1	1	1	1	1	1
8951-L	Connection Leads	1	1	1	1	1	1	1	1
8960-C <sup>(4)</sup>	Four-Quadrant Dynamometer/Power Supply	1	1	1	1	1	1	1	1
8990	Host Computer	1	1	1	1	1	1	1	1
9063-B <sup>(5)</sup>	Data Acquisition and Control Interface		1	1	1	1	1	1	1
9069-C	Synchroscope								1
30004-2	24 V AC Power Supply		1	1	1	1	1	1	1
<p>(1) Workstation model 8110 can also be used.</p> <p>(2) Resistive Load unit with voltage rating corresponding to your local ac power network voltage. Use model variant -00, -01, -02, -05, -06, -07, or -0A.</p> <p>(3) Model 8221-0 can also be used.</p> <p>(4) Model 8960-C consists of the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, with the Standard Functions (manual control) set, Model 8968-1, and the Standard Functions (computer-based control) set, Model 8968-2.</p> <p>(5) Model 9063-B consists of the Data Acquisition and Control Interface, Model 9063, with the Computer-Based Instrumentation function set, Model 9069-1.</p>									



## Glossary of New Terms

<b>ac motor</b>	An ac motor is an electric motor whose power is supplied by an alternating current power source.
<b>dc motor</b>	A dc motor is an electric motor whose power is supplied by a direct current power source.
<b>dynamometer</b>	A dynamometer is a device used to measure the torque produced by a rotating machine.
<b>electric generator</b>	An electric generator is a rotating machine that converts mechanical energy into electrical energy through the process of electromagnetic induction.
<b>electric motor</b>	An electric motor is a rotating machine that converts electrical energy into mechanical energy through the process of electromagnetic induction and interacting magnetic fields.
<b>electromagnet</b>	An electromagnet is a device that produces a magnetic field when an electric current flows through it. A coil of wire wound around an iron core is a common example of an electromagnet.
<b>electromagnetic induction</b>	Electromagnetic induction consists in the production of an electromotive force (i.e., an induced voltage $E_{EMF}$ ) in a circuit resulting from a change in the magnetic flux passing through that circuit.
<b>field current</b>	The field current of a three-phase synchronous machine corresponds to the dc current flowing in the rotor electromagnet. The field current is necessary in order to produce the magnetic field in the rotor electromagnet required for synchronous operation.
<b>high-efficiency motor</b>	High-efficiency motors are motors that are designed to reduce to a certain extent the energy losses occurring in the motor. Due to this fact, high-efficiency motors consume less electrical power (as much as 4% less) than normal motors and can maintain a high efficiency even when operating at mechanical power values as low as 50% of the motor nominal power.
<b>magnetic force</b>	A magnetic force corresponds to the force of attraction or repulsion that exists between magnetic fields. Magnetic fields with poles having the same polarity repel each other, while magnetic fields with poles of different polarities attract each other.
<b>magnetic poles</b>	Magnetic poles are the part of a magnet where the magnetic lines of force exit or enter, and where the lines of force are the most concentrated. By convention, magnetic lines of force exit from the north magnetic pole and enter at the south magnetic pole.

<b>motor efficiency</b>	The efficiency $\eta$ of a motor is the ratio between the mechanical power $P_M$ produced by the motor and the active power $P$ supplied to the motor. The resulting equation for motor efficiency is thus: $\eta = P_M/P$ .
<b>prime mover</b>	A prime mover is a device that is used to drive a rotating machine (i.e., to make the machine rotate with the prime mover). Prime movers are mainly used to study the operation of generators.
<b>rotor</b>	A rotor corresponds to the rotating part of a rotating machine. The rotor is the motor component that produces the mechanical work.
<b>slip</b>	The slip of an induction motor corresponds to the ratio between the speed of the rotor and the speed of the rotating magnetic field (i.e., the synchronous speed $n_s$ ). It can be expressed either as a percentage (%) of the synchronous speed or in revolutions per minute (r/min).
<b>speed</b>	The speed $n$ of a rotating machine is the number of turns per unit of time at which the machine rotates. Speed is usually expressed in revolutions per minute (r/min).
<b>squirrel-cage induction machine</b>	A three-phase squirrel-cage induction machine is a type of motor having a squirrel-cage rotor (i.e., a rotor that is made of conducting bars short-circuited by two metal rings). Squirrel-cage induction machines are asynchronous, as the speed $n$ of the rotor never catches up with the speed of the rotating magnetic field (i.e., the synchronous speed $n_s$ ).
<b>stator</b>	A stator corresponds to the stationary part of a rotating machine. The stator of three-phase machines is the machine component that produces the rotating magnetic field.
<b>synchronization</b>	The synchronization of a three-phase synchronous generator is the process of connecting the generator to an ac power network. In order to achieve a smooth synchronization, a number of synchronization conditions must be met. Proper synchronization of a synchronous generator to an ac power network is necessary in order to minimize the current and power transients produced at the instant of synchronization, as well as the mechanical stress on the generator shaft.
<b>synchronous generator</b>	A three-phase synchronous generator is a three-phase electric generator that rotates at the synchronous speed, i.e., at the speed of the rotating magnetic field. Three-phase synchronous generators are used widely to produce ac power. The rotor of a synchronous generator is either a permanent magnet or an electromagnet.
<b>synchronous motor</b>	A synchronous motor is a type of three-phase motor whose rotor usually rotates at the same speed $n$ as the rotating magnetic field (i.e., the synchronous speed $n_s$ ). The rotor of a synchronous motor is either a permanent magnet or an electromagnet. Synchronous motors necessitate assistance in order to start properly.

<b>synchronous speed</b>	A motor's synchronous speed is the speed of the rotating magnetic field produced by the sine-wave currents flowing through the stator of that motor. Synchronous speed is proportional to the frequency of the three-phase ac power source, and inversely proportional to the number of magnetic poles in the motor per phase.
<b>synchroscope</b>	A synchroscope is a device used during the synchronization of a synchronous generator to an ac power network in order to ensure that the frequency and phase angle of the generator voltage are the same as the frequency and phase angle of the network voltage. A synchroscope is connected in parallel with the contacts of the generator circuit breaker and indicates (through the means of a dial and a needle) the difference both in frequency and in phase angle between the generator voltage and the ac power network voltage.
<b>torque</b>	The torque $T$ produced by a rotating machine indicates the magnitude of the twisting force that the machine applies to an object in rotation. Torque can be expressed in newton-meters (N·m) or in pound force-inches (lbf·in). A motor rotates due to the torque produced by the motor when electrical power is supplied to it, while a generator rotates due to the torque applied to the generator shaft by an external force (e.g., a prime mover).
<b>transient</b>	A transient is a momentary increase in the magnitude of a system parameter occurring due to a change of state in the system. When synchronizing a three-phase synchronous generator to an ac power network, current and power transients, i.e., momentary exchanges of power between the generator and the network that cause large currents to flow temporarily between the generator and the network, are produced due to the alignment of the magnetic field at the rotor with the rotating magnetic field at the stator.



## 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 C-1 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

Table C-1. Impedance table for the load modules.

Impedance ( $\Omega$ )			Position of the switches								
120 V 60 Hz	220/230 V 50 Hz/60 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



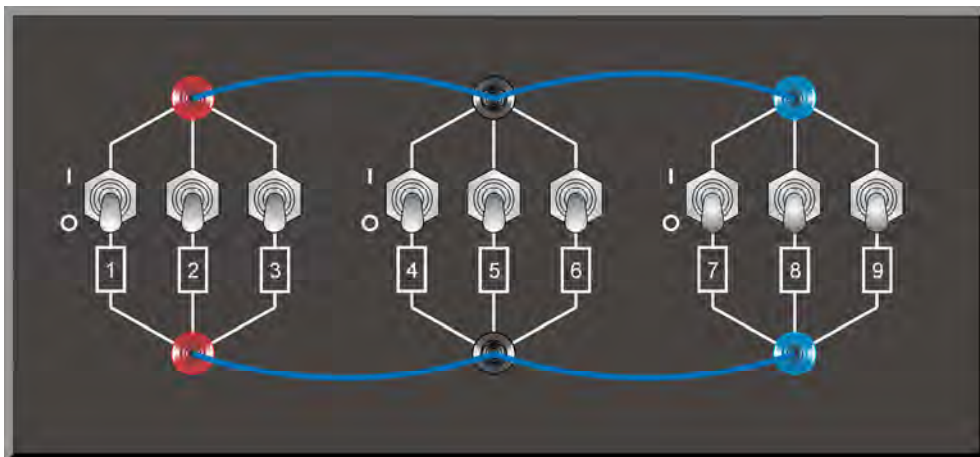
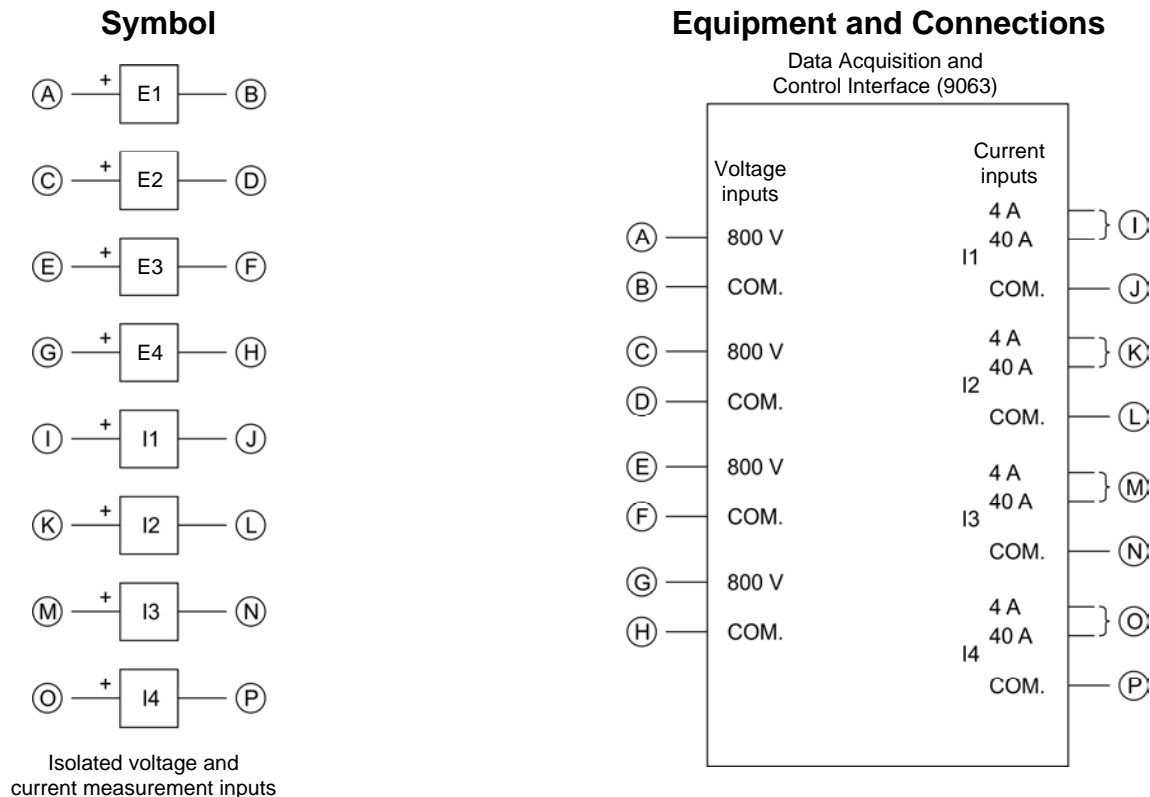


Figure C-1. Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

## Circuit Diagram Symbols

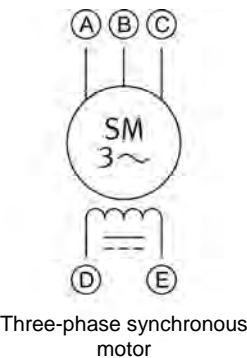
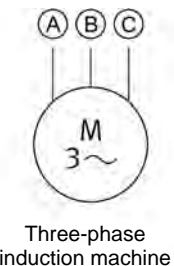
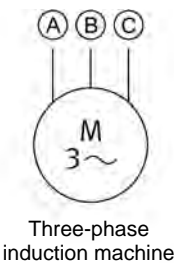
Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using the equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown on the circuit diagram, and thus, makes it easier to understand the circuit operation.

For each symbol other than those of power sources, resistors, inductors, and capacitors, this appendix gives the name of the device which the symbol represents, as well as the equipment and the connections required to properly connect the device to a circuit. Notice that the terminals of each symbol are identified using circled letters. The same circled letters identify the corresponding terminals in the Equipment and Connections diagram. Also notice that the numbers (when present) in the Equipment and Connections diagrams correspond to terminal numbering used on the actual equipment.

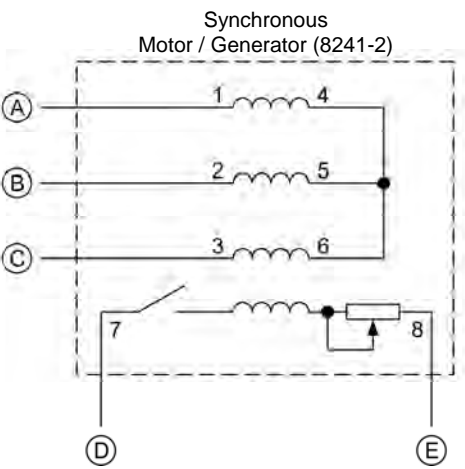
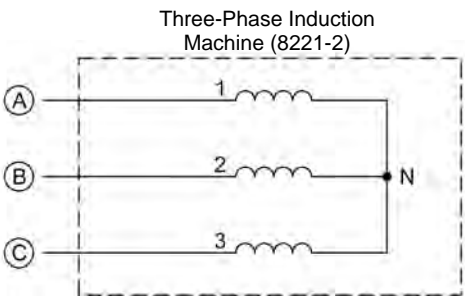
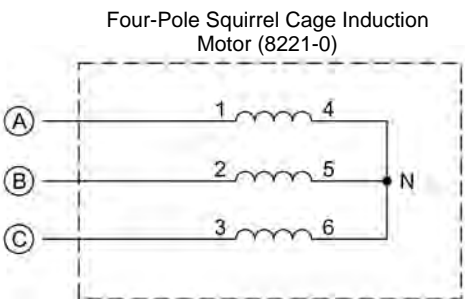


When a current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.

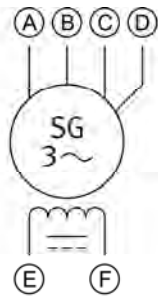
Symbol



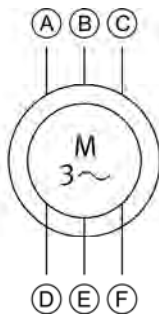
Equipment and Connections



### Symbol

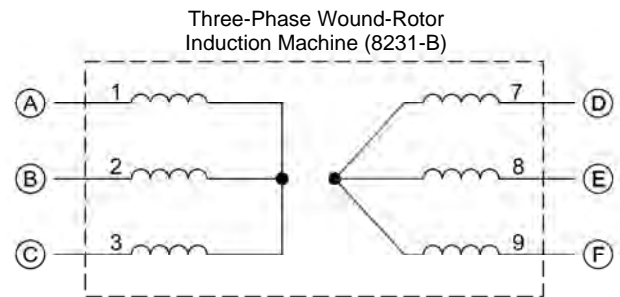
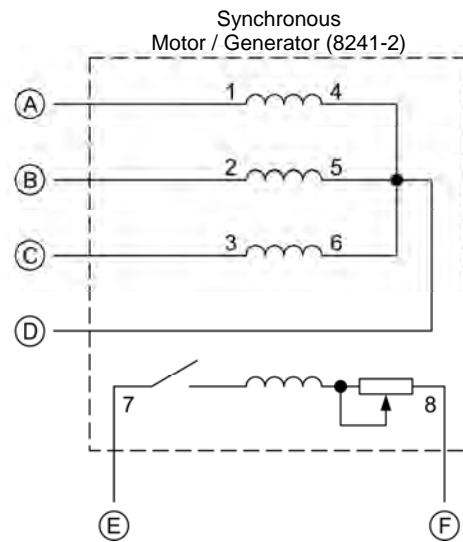


Three-phase synchronous generator

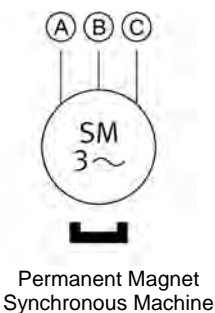


Three-phase wound-rotor induction machine

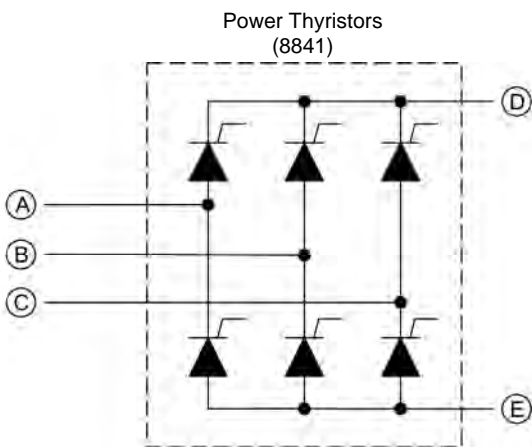
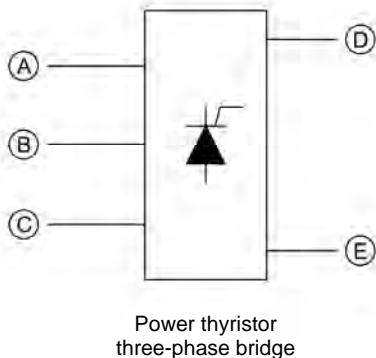
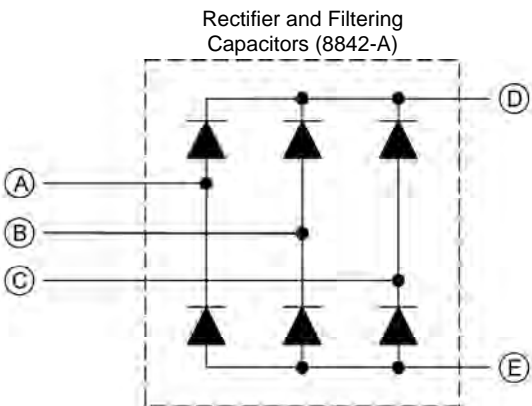
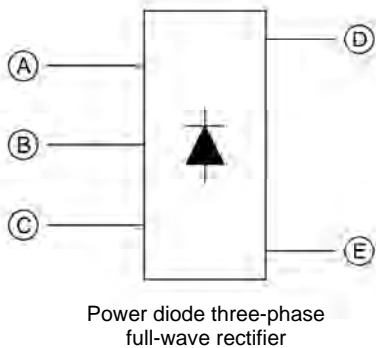
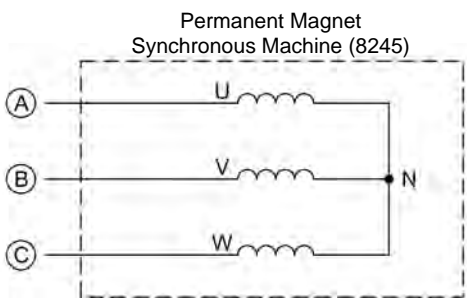
### Equipment and Connections



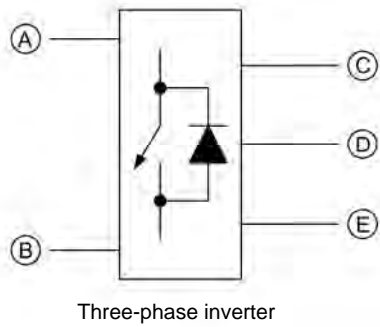
Symbol



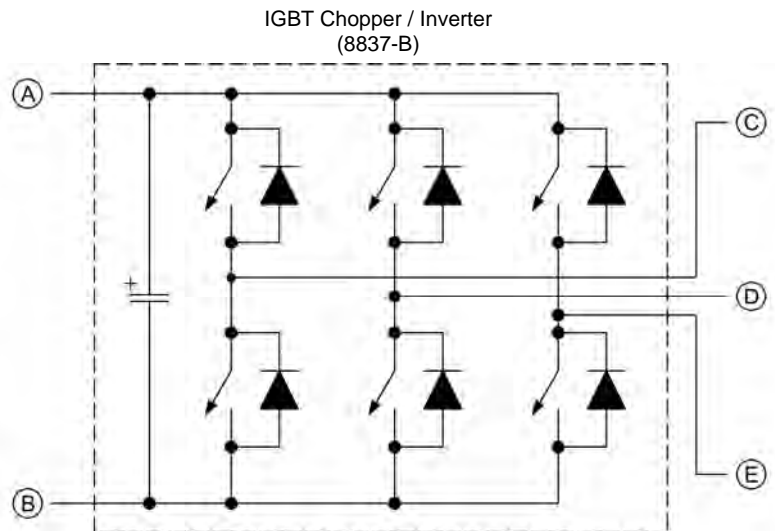
Equipment and Connections



## Symbol



## Equipment and Connections



The electronic switch symbol in the three-phase inverter above replaces MOSFET or IGBT symbols. It is not an IEC or ANSI symbol.



# Index of New Terms



*The bold page number indicates the main entry. Refer to the Glossary of New Terms above for definitions of new terms.*

ac motor .....	<b>1</b>
dc motor .....	<b>1</b> , 13
dynamometer .....	<b>13</b>
electric generators.....	<b>7</b>
electric motor.....	<b>1</b>
electromagnet .....	<b>3</b> , 4, 7, 8, 33, 35, 37, 58, 75, 76, 77, 79, 91, 102, 105, 120
electromagnetic induction .....	<b>7</b> , 8
field current .....	<b>79</b> , 80, 92, 105, 120, 134, 140
high-efficiency motors .....	<b>43</b> , 44
magnetic force.....	<b>1</b> , 32, 58
magnetic pole.....	<b>3</b>
motor efficiency .....	<b>41</b>
prime mover .....	<b>13</b> , 14, 15, 16, 139, 144
rotor.....	<b>7</b> , 8, 32, 33, 38, 39, 40, 58, 59, 75, 76, 77, 79, 91, 92, 102, 105
slip.....	<b>39</b> , 40
speed .....	<b>11</b> , 12, 13, 15, 16, 39, 40, 59, 60, 76, 77, 79, 91, 105, 120, 134, 139
squirrel-cage induction machine .....	<b>32</b> , 33, 59, 60
stator .....	<b>7</b> , 8, 9, 33, 35, 38, 59, 75, 76, 79, 91, 102, 105, 106, 120
synchronization .....	<b>133</b> , 134, 136, 137, 138, 139, 140
synchronous generator ....	<b>101</b> , 105, 106, 119, 120, 122, 133, 134, 136, 138, 140, 144
synchronous motor.....	<b>75</b> , 76, 77, 79, 80, 91, 92
synchronous speed.....	<b>38</b> , 40, 59, 76, 79, 91
synchroscope .....	<b>134</b> , 135
torque .....	<b>11</b> , 12, 13, 14, 15, 16, 33, 39, 40, 58, 60, 76, 91, 92, 137, 139
transient .....	<b>134</b> , 136





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