Electricity and New Energy

AC/DC Motors and Generators

Courseware Sample

30329-F0

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By the staff of Festo Didactic

Safety and Common Symbols

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

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* 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
3∿	Three-phase alternating current
⏚	Earth (ground) terminal

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

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Preface

Computer-based teaching technologies are becoming more and more widespread in the field of education, and the Data Acquisition and Control for Electromechanical Systems (LVDAC-EMS), the Data Acquisition and Management for Electromechanical Systems (LVDAM-EMS), and the Simulation Software for Electromechanical Systems (LVSIM®-EMS) are witness to this new approach.

The LVDAC-EMS (or LVDAM-EMS) system is a complete set of measuring instruments that runs on a Pentium-type personal computer under the Microsoft® Windows® operating environment. Computer-based instruments (voltmeters, ammeters, power meters, an oscilloscope, a phasor analyzer, and an harmonic analyzer) provide instructors the opportunity to clearly demonstrate concepts related to electric power technology that, until now, could only be presented using traditional textbook methods and static drawings.

The LVDAC-EMS (or LVDAM-EMS) system uses a customized data acquisition module to interconnect modules of the Electromechanical System with the personal computer. Dedicated software routes the measured values from the data acquisition module to the computer-based instruments that provide all the standard measurements associated with voltage, current, power, and other electrical parameters. However, the system does much more: it provides built-in capabilities for waveform observation and phasor analysis, data storage and graphical representation, as well as programmable meter functions, thereby allowing unimagined possibilities for presenting courseware material.

LVSIM®-EMS is a software that faithfully simulates the Electromechanical System (EMS). Like the LVDAC-EMS (or LVDAM-EMS) system, LVSIM®-EMS runs on a PC-type computer under the Microsoft® Windows® operating environment.

LVSIM®-EMS recreates a three-dimensional classroom laboratory on a computer screen. Using the mouse, students can install an EMS training system in this virtual laboratory, make equipment setups, and perform exercises in the same way as if actual EMS equipment were used. The EMS equipment that can be installed in the virtual laboratory faithfully reproduces the actual EMS equipment included in the Computer-Assisted 0.2-kW Electromechanical Training System (Model 8006) in every detail. As for the actual EMS system, the operation and behaviour of the circuits simulated with LVSIM®-EMS can be observed by performing voltage, current, speed, and torque measurements, using the same computer-based instruments as for the LVDAC-EMS (or LVDAM-EMS) system.

The existing EMS courseware has been completely revised and adapted for the LVDAC-EMS (or LVDAM-EMS) system as well as LVSIM®-EMS, and the new series is titled Electrical Power Technology Using Data Acquisition. Exercises have been grouped in two separate manuals: manual 1, titled *Power Circuits and Transformers*, and manual 2, titled *AC/DC Motors and Generators*.

Each exercise approaches the subject matter from a practical point of view, and uses a hands-on approach to the study of electrical power technology. Students are guided through step-by-step exercise procedures that confirm concepts and theory presented in the exercise discussion. A conclusion and set of review questions complete each exercise, and a 10-question unit test helps evaluate knowledge gained in the courseware unit.

Preface

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

The 18 exercises in this manual, *AC/DC Motors and Generators*, provide a foundation for further study of rotating machines.

This manual is divided into six units:

–   Unit 1 provides a basic review of concepts and theory of rotating machines, torque, and speed, as well as highlighting specific details relating to power, losses, and efficiency of electric motors. It also describes the operation of the prime mover and brake used throughout the hands-on exercises. One exercise in Unit 1 focuses on the implementation of the prime mover and brake using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2. Another exercise in Unit 1 focuses on the implementation of the prime mover and brake using the Prime Mover/Dynamometer, Model 8960-1. The student performs either one of these two exercises, depending on whether he or she is using Model 8960-2 or 8960-1.

–   Units 2 and 3 deal with the basic operation and characteristics of direct current motors and generators, and explore some of the particularities of dc machines.

–   Units 4, 5, and 6 define and explain the concepts related to alternating current motors and generators. The operation of induction motors as well as that of synchronous motors and generators (alternators) are covered.

The hands-on exercises in this manual can be performed using either the Electromechanical System (EMS system) or the Electromechanical System using Virtual Laboratory Equipment (LVSIM®-EMS). When using the EMS system, you should turn on the computer and start Windows® before each exercise. On the other hand, when using LVSIM®-EMS, you should turn on the computer, start Windows®, and start LVSIM®-EMS before each exercise.

The hands-on exercises guide students through circuit setup and operation, and uses many of the measurement and observation capabilities of the virtual instrumentation system. Much detailed information about rotating machine parameters (voltages and currents, torque and speed, output power, and efficiency, etc.) can be visualized with the computer-based instruments, and students are encouraged to fully explore system capabilities.

Various symbols are used in many of the circuit diagrams given in the exercises. Each symbol is a functional representation of a device used in Electrical Power Technology. The use of these symbols greatly simplifies the circuit diagrams by reducing the number of interconnections shown, and makes it easier to understand circuit operation. Appendix A lists the symbols used, the name of the device which each symbol represents, and a diagram showing the equipment and connections required to obtain the device.

The exercises in this manual can be carried out with ac network voltages of 120 V, 220 V, and 240 V. The component values used in the different circuits often depend on the ac line voltage. For this reason, components in the circuit diagrams are identified where necessary with letters and subscripts. A table accompanying the circuit diagram indicates the component value required for each ac network voltage (120 V, 220 V, and 240 V).

About This Manual

Appendix A consists of diagrams showing the equipment and the connections required to obtain the devices used in the exercises.

Appendix B provides a table giving the usual impedance values that can be obtained with each of the 120-V, 220-V, and 240-V versions of the EMS load modules.

Appendix C provides a chart outlining the exact equipment required for each exercise.

Appendix D is a glossary of the new terms and words used in this manual.

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.

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Samples Exercises

Extracted from

the Student Manual

and the Instructor Guide

AC Induction Motors

UNIT OBJECTIVE

When you have completed this unit, you will be able to demonstrate and explain the operation of ac induction motors using the Squirrel-Cage Induction Motor module and the Capacitor-Start Motor module.

DISCUSSION OF FUNDAMENTALS

As you saw in Unit 1, a voltage is induced between the ends of a wire loop when the magnetic flux linking 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 4-1 shows a magnet that is displaced rapidly towards the right above a group of conductors. The conductors are short-circuited at their extremities by bars A and B and form a type of ladder.
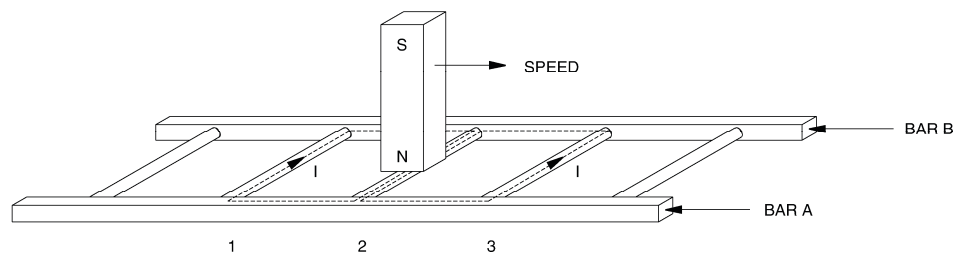
Figure 4-1. Magnet moving above a conducting ladder.

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 with north and south poles as shown in Figure 4-2.

⊗ CURRENT INTO PAGE

⊙ CURRENT OUT OF PAGE
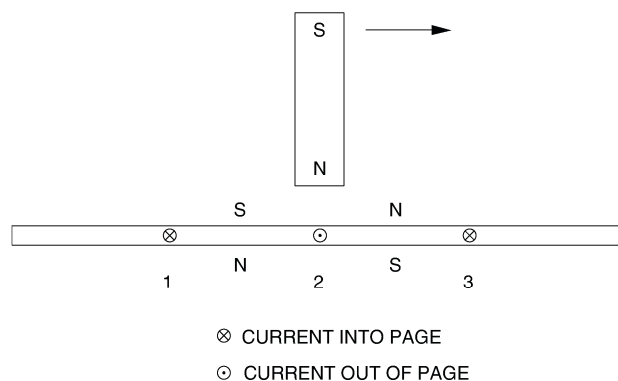
Figure 4-2. Current in the conductors creates magnetic fields.

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 electromagnet (the conducting 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 a variation in the magnetic flux. Consequently, there is no induced voltage to cause current flow in the wire loops, meaning that there is no longer a magnetic force acting on the ladder. Therefore, the ladder must move at a speed which is lower than that of the moving magnet for a magnetic force to pull the ladder in the direction of the moving magnet. The greater the speed difference between the two, the greater the variation in magnetic flux, and therefore, the greater the magnetic force acting on the conducting ladder.

The rotor of an asynchronous induction motor is made by closing a ladder similar to that shown in Figure 4-1 upon itself to form a type of squirrel cage as shown in Figure 4-3. This is where the name squirrel-cage induction motor comes from.
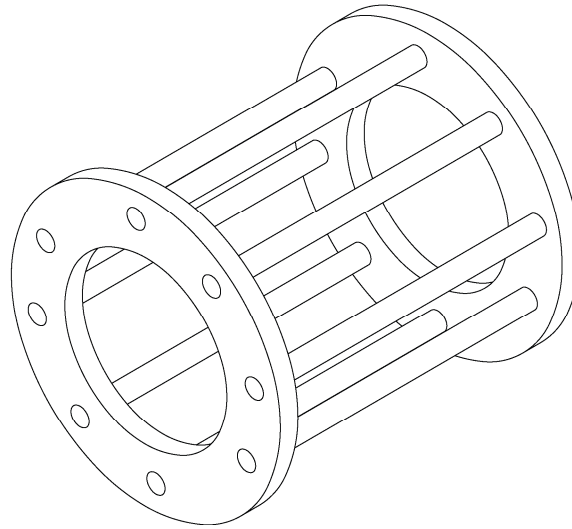
Figure 4-3. Closing a ladder upon itself forms a squirrel cage.

To make it easier for the magnetic flux to circulate, the rotor of a squirrel-cage induction motor is placed inside a laminated iron cylinder. The stator of the induction motor acts as a rotating electromagnet. The rotating electromagnet causes torque which pulls the rotor along in much the same manner as the moving magnet in Figure 4-1 pulls the ladder.

The Three-Phase Squirrel-Cage Induction Motor

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the operating characteristics of a three-phase induction motor using the Four-Pole Squirrel-Cage Induction Motor module.

DISCUSSION

One of the ways of creating a rotating electromagnet is to connect a three-phase power source to a stator made of three electromagnets A, B, and C, that are placed at 120° to one another as shown in Figure 4-4.
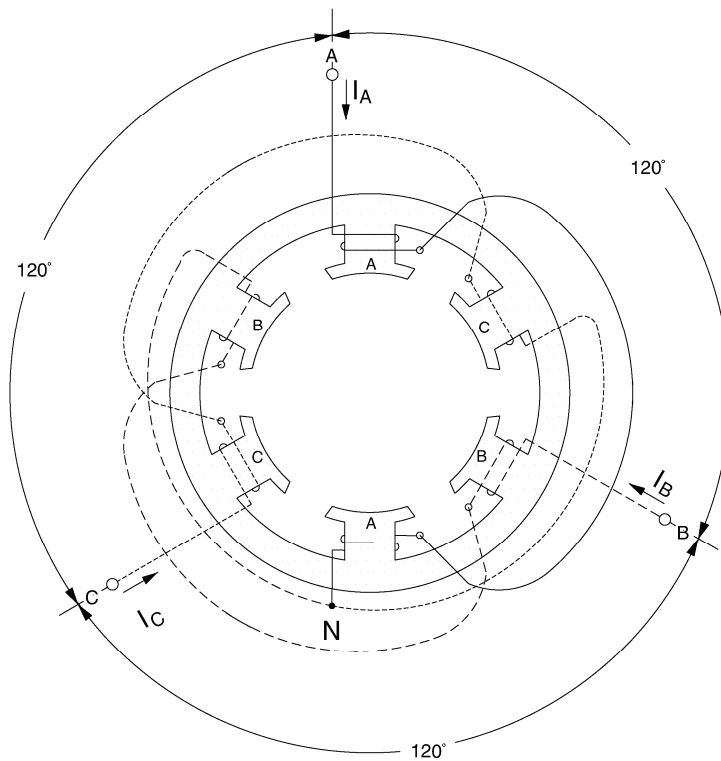
Figure 4-4. Three-phase stator windings.

When sine-wave currents that are phase shifted of 120° to each other, like those shown in Figure 4-5, are flowing in stator electromagnets A, B, and C, a magnetic field that rotates very regularly is obtained.
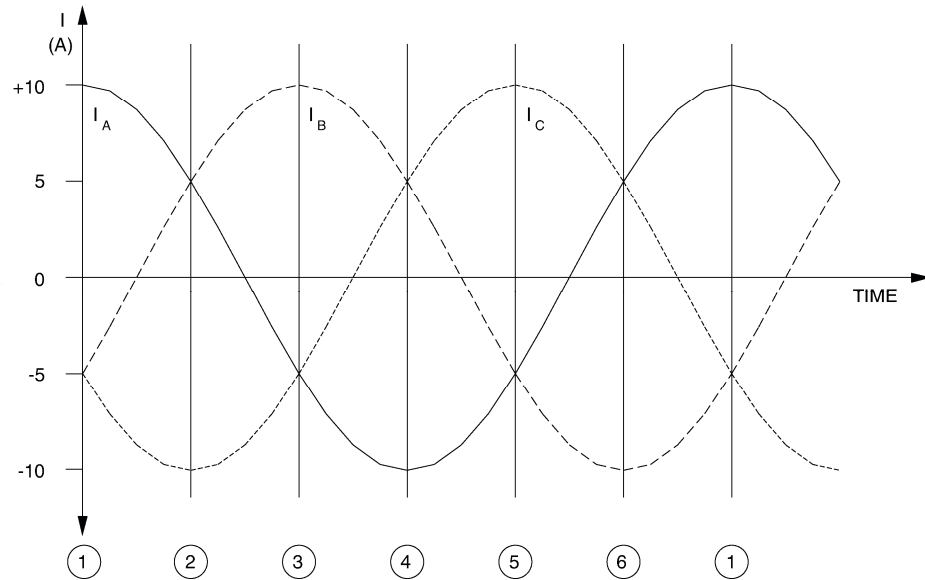
Figure 4-5. Three-phase sine-wave currents flowing in the stator windings.

Figure 4-6 illustrates the magnetic field created by stator electromagnets A, B, and C at instants numbered 1 to 6 in Figure 4-5. Notice that the magnetic lines of force exit at the north pole of each electromagnet and enter at the south pole. As can be seen, the magnetic field rotates clockwise.

The use of sine-wave currents produces 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 synchronous speed (n_S) and is proportional to the frequency of the ac power source. A rotating magnetic field can also be obtained using other combinations of sine-wave currents that are phase-shifted with respect to each other, but three-phase sine-wave currents are used more frequently.

When a squirrel-cage rotor is placed inside a rotating magnetic field, it is pulled around in the same direction as the rotating field. Interchanging the power connections to two of the stator windings (interchanging A with B for example) interchanges two of the three currents and reverses the phase sequence. This causes the rotating field to reverse direction. As a result, the direction of rotation of the motor is also reversed.
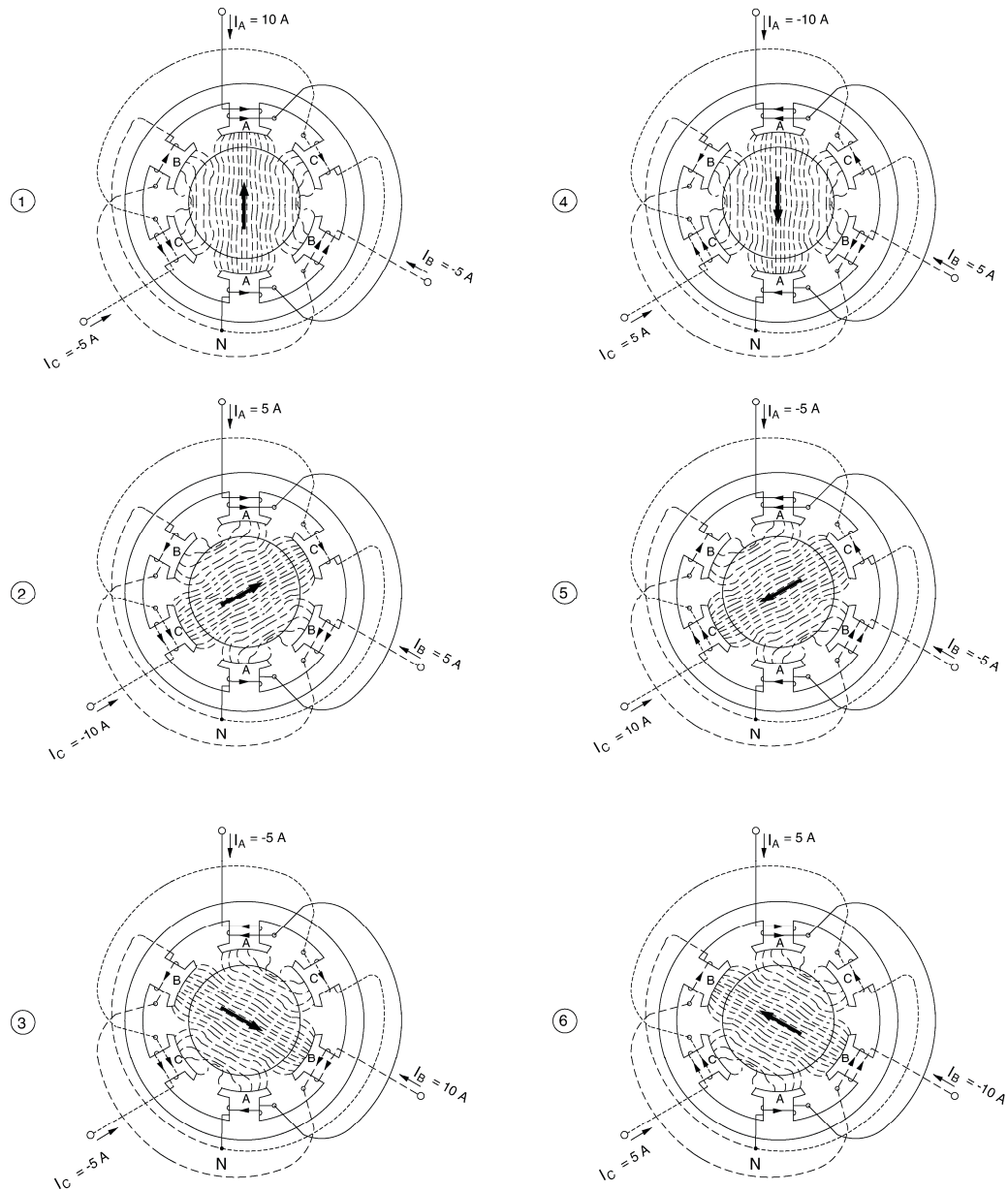
Figure 4-6. Position of the rotating magnetic field at various instants. (From Electrical Machines, Drives, and Power Systems by Theodore Wildi. Copyright © 1991, 1981 Sperika Enterprises Ltd. © Published by Prentice Hall. All rights reserved.).

Referring to what has been said in the Discussion of Fundamentals of this unit, one can easily deduce that the torque produced by a squirrel-cage induction motor increases as the difference in speed between the rotating magnetic field and the rotor increases. The difference in speed between the two is called slip. A plot of the speed versus torque characteristic for a squirrel-cage induction motor gives a curve similar to that shown in Figure 4-7. As can be seen, the motor speed (rotor speed) is always lower than the synchronous speed n_S because slip is necessary for the motor to develop torque. The synchronous speed for the motors is 1800 r/min for 60 Hz power, and 1500 r/min for 50-Hz power.
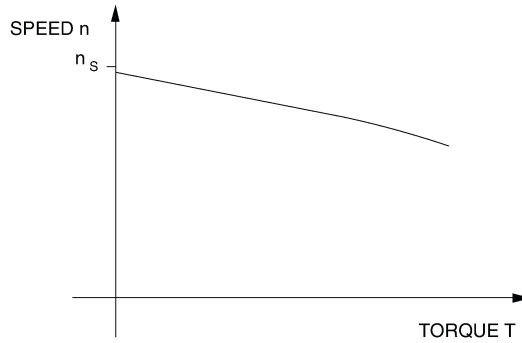
Figure 4-7. Speed versus torque characteristic of a squirrel-cage induction motor.

The speed versus torque characteristic of the squirrel-cage induction motor is very similar to that obtained previously for a separately-excited dc motor. However, the currents induced in the squirrel-cage rotor must change direction more and more rapidly as the slip increases. In other words, the frequency of the currents induced in the rotor increases as the slip increases. Since the rotor is made up of iron and coils of wire, it has an inductance that opposes rapid changes in current. As a result, the currents induced in the rotor are no longer directly proportional to the slip of the motor. This affects the speed versus torque characteristic as shown in Figure 4-8.
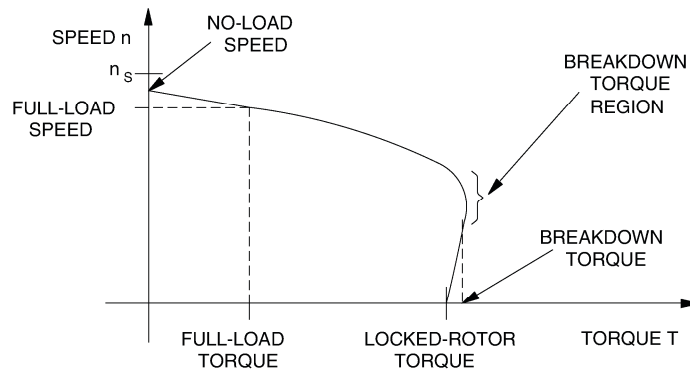
Figure 4-8. The motor inductance affects the speed versus torque characteristic.

As the curve shows, the no-load speed is slightly less than the synchronous speed n_S, but as the load torque increases, motor speed decreases. For the nominal value of motor torque (full-load torque) corresponds a nominal operating speed (full-load speed). Further increases in load torque lead to a point of instability, called breakdown torque, after which both motor speed and output torque decrease. The torque value at zero speed, called locked-rotor torque, is often less than the breakdown torque. At start-up, and at low speed, motor current is very high and the amount of power that is consumed is higher than during normal operation.

Another characteristic of three-phase squirrel-cage induction motors is the fact that they always draw reactive power from the ac power source. The reactive power even exceeds the active power when the squirrel-cage induction motor rotates without load. The reactive power is necessary to create the magnetic field in the machine in the same way that an inductor needs reactive power to create the magnetic field surrounding the inductor.

Procedure summary

In the first part of the exercise, you will set up the equipment in the Workstation, connect the equipment as shown in Figure 4-9, and make the appropriate settings on the equipment.

In the second part of the exercise, you will apply the nominal line voltage to the squirrel-cage induction motor, note the motor direction of rotation, and measure the motor no-load speed. You will then increase the mechanical load applied to the squirrel-cage induction motor by steps. For each step, you will record in the Data Table various electrical and mechanical parameters related to the motor. You will then use this data to plot various graphs and determine many of the characteristics of the squirrel-cage induction motor.

In the third part of the exercise, you will interchange two of the leads that supply power to the squirrel-cage induction motor and observe if this affects the direction of rotation.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart in Appendix C to obtain the list of equipment required for this exercise.

PROCEDURE

⚠ **WARNING**

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

Setting up the equipment

1. Install the equipment required in the EMS workstation.

Mechanically couple the prime mover/dynamometer module to the Four-Pole Squirrel-Cage Induction Motor.

2. On the Power Supply, make sure the main power switch is set to the O (off) position, and the voltage control knob is turned fully counterclockwise. Ensure the Power Supply is connected to a three-phase power source.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, connect its POWER INPUT to a wall receptacle.

3. Ensure that the data acquisition module is connected to a USB port of the computer.

Connect the POWER INPUT of the data acquisition module to the 24 V - AC output of the Power Supply.

If you are using the Prime Mover/Dynamometer, Model 8960-1, connect its LOW POWER INPUT to the 24 V - AC output of the Power Supply.

On the Power Supply, set the 24 V - AC power switch to the I (on) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it on by setting its POWER INPUT switch to the I (on) position. Press and hold the FUNCTION button 3 seconds to have uncorrected torque values on the display of the Four-Quadrant Dynamometer/Power Supply. The indication "NC" appears next to the function name on the display to indicate that the torque values are uncorrected.

4. Start the Data Acquisition software (LVDAC or LVDAM). Open setup configuration file ACMOTOR1.DAI.

If you are using LVSIM-EMS in LVVL, you must use the IMPORT option in the File menu to open the configuration file.

In the Metering window, select layout 2. Make sure that the continuous refresh mode is selected.

5. Connect the equipment as shown in Figure 4-9.
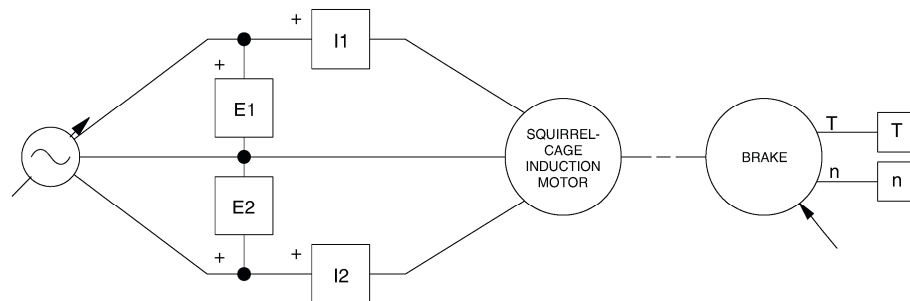
Figure 4-9. Squirrel-cage induction motor coupled to a brake.

6. Set the Four-Quadrant Dynamometer/Power Supply or the Prime Mover/Dynamometer to operate as a brake, then set the brake torque control to minimum (fully counterclockwise position). To do this, refer to Exercise 1-1 or Exercise 1-2 if necessary.

If you are performing the exercise using LVSIM®-EMS, you can zoom in on the Prime Mover/Dynamometer before setting the controls in order to see additional front panels markings related to these controls.

Characteristics of a squirrel-cage induction motor

7. Turn the Power Supply on and set the voltage control knob so that the line voltage indicated by meter E line 1 is equal to the nominal line voltage of the squirrel-cage induction motor.

The rating of any of the machines is indicated in the lower left corner of the module front panel.

What is the direction of rotation of the squirrel-cage induction motor?

The motor rotates clockwise.

Record in the following blank space the motor speed indicated by the Speed meter in the Metering window.

$$n = \underline{\qquad} \text{ r/min}$$

$$n = 1768 \text{ r/min}$$

Is the no-load speed almost equal to the speed of the rotating magnetic field (synchronous speed) given in the Discussion?

❑ Yes   ❑ No

Yes

8. In the Metering window, make sure that the torque correction function of the Torque meter is enabled. The Torque meter indicates the output torque of the squirrel-cage induction motor.

On the brake, adjust the torque control so that the mechanical power developed by the squirrel-cage induction motor (indicated by meter Mech. Power in the Metering window) is equal to 175 W (nominal motor output power).

Record the nominal speed $n_{NOM.}$, torque $T_{NOM.}$, and line current $I_{NOM.}$ of the squirrel-cage induction motor in the following blank spaces. These parameters are indicated by meters Speed, Torque, and I line 1, respectively.

$$n_{NOM.} = \underline{\qquad} \text{ r/min}$$

$$T_{NOM.} = \underline{\qquad} \text{ N·m (lbf·in)}$$

$$I_{NOM.} = \underline{\qquad} \text{ A}$$

On the brake, set the torque control to minimum (fully counterclockwise position). The torque indicated by the brake's display should be 0 N·m (0 lbf·in).

$$n_{NOM.} = 1712 \text{ r/min}$$

$$T_{NOM.} = 0.98 \text{ N} \cdot \text{m (8.7 lbf} \cdot \text{in)}$$

$$I_{NOM.} = 0.97 \text{ A}$$

9. Record the motor line voltage E_{LINE}, line current I_{LINE}, active power P, reactive power Q, output torque T, and speed n in the Data Table. These parameters are indicated by meters E line 1, I line 1, Act. power, React. power, Speed, and Torque, respectively.

On the brake, carefully adjust the torque control so that the torque indicated by the Torque meter increases by 0.3 N·m (3.0 lbf·in) increments up to about 2.1 N·m (19 lbf·in). For each torque setting, record the data in the Data Table.

On the brake, continue to adjust the torque control so that the torque indicated by the Torque meter increases by 0.1 N·m (1.0 lbf·in) increments, until the motor speed starts to decrease fairly rapidly (breakdown torque region). For each torque setting, record the data in the Data Table.

Once the motor speed has stabilized, record the data in the Data Table.

The nominal line current of the Four-Pole Squirrel-Cage Induction Motor may be exceeded while performing this manipulation. It is, therefore, suggested to complete the manipulation within a time interval of 5 minutes or less.

10. When all data has been recorded, set the torque control knob on the brake to minimum (fully counterclockwise), turn the voltage control knob fully counterclockwise, and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT411, and print the Data Table.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to edit, entitle, and print a Data Table.

The results obtained are presented below. When the motor torque T is measured in N·m:

Motor line voltage, line current, active power, reactive power, torque, and speed (DT411).

Line voltage (E line 1) V	Line current (I line 1) A	Active power (Act. power) W	Reactive power (React. power) var	Torque (T) N·m	Speed (n) r/min
208.0	0.751	111	244	0.33	1768
207.6	0.843	168	244	0.63	1745
207.1	0.954	235	247	0.94	1716
206.7	1.106	303	252	1.23	1684
206.0	1.293	379	264	1.53	1645
205.4	1.519	463	279	1.83	1597
204.5	1.803	568	310	2.13	1498
204.5	2.018	598	317	2.22	1468
204.0	2.095	673	329	2.33	1421
203.6	2.292	718	346	2.42	1368
203.3	2.510	793	382	2.52	1275
200.6	3.921	1182	671	1.94	172

When the motor torque T is measured in lbf·in:

Motor line voltage, line current, active power, reactive power, torque, and speed (DT411).

Line voltage (E line 1) V	Line current (I line 1) A	Active power (Act. power) W	Reactive power (React. power) var	Torque (T) lbf·in	Speed (n) r/min
208.0	0.761	117	237	2.9	1771
207.3	0.860	184	239	5.9	1743
206.8	1.007	257	240	8.9	1714
206.2	1.186	337	259	11.9	1676
205.6	1.413	423	275	14.8	1632
205.2	1.691	522	298	17.9	1577
203.8	1.856	568	313	18.9	1543
204.7	2.012	593	327	19.8	1517
204.4	2.092	657	344	20.8	1483
204.0	2.273	707	364	21.8	1431
204.2	2.467	778	392	22.7	1359
204.2	2.772	863	424	23.6	1269
201.3	4.158	1240	733	17.9	180

Does the motor line current indicated in column I line 1 increase as the mechanical load applied to the squirrel-cage induction motor increases?

❑ Yes   ❑ No

Yes

11. In the Graph window, make the appropriate settings to obtain a graph of the motor speed (obtained from the Speed meter) as a function of the motor torque (obtained from the Torque meter). Entitle the graph as G411, name the x-axis as Squirrel-cage induction-motor torque, name the y-axis as Squirrel-cage induction-motor speed, and print the graph.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to use the Graph window of the Metering application to obtain a graph, entitle a graph, name the axes of a graph, and print a graph.

The resulting graph is shown below. When the motor torque T is expressed in N·m:
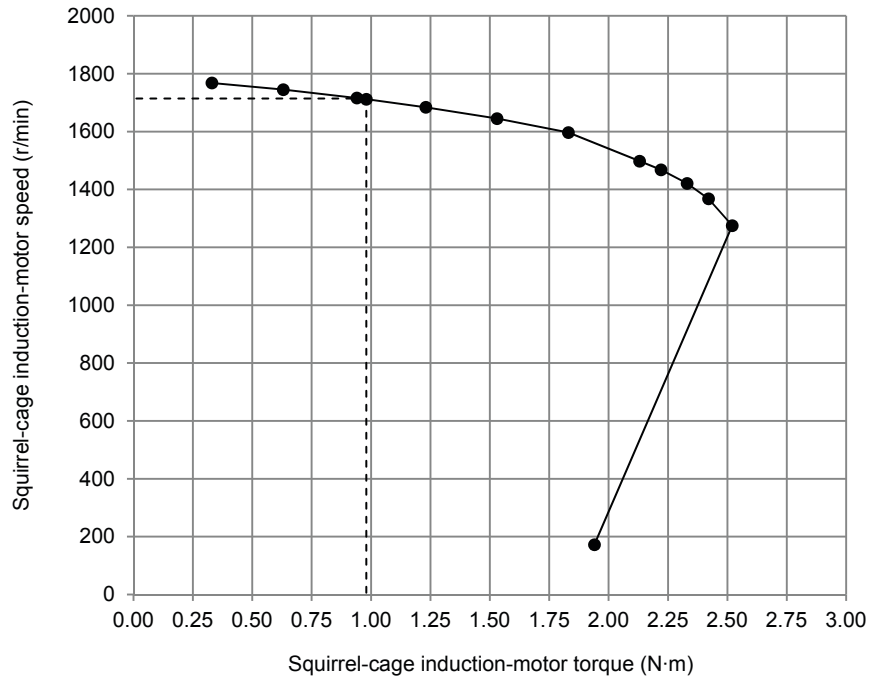
Squirrel-cage induction-motor speed versus torque (G411).

When the motor torque T is expressed in lbf·in:
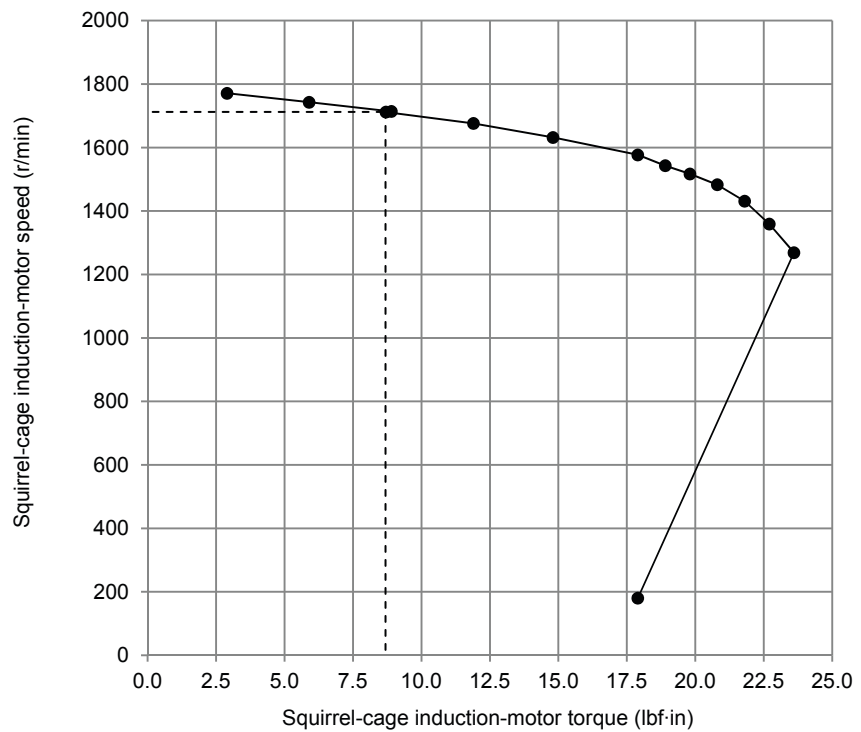
Squirrel-cage induction-motor speed versus torque (G411).

Briefly describe how the speed varies as the mechanical load applied to the squirrel-cage induction motor increases, i.e., as the motor torque increases.

The speed decreases when the mechanical load applied to the squirrel-cage induction motor increases.

12. Indicate on graph G411 the nominal speed and torque of the squirrel-cage induction motor measured previously.

Determine the breakdown torque of the squirrel-cage induction motor using graph G411.

$T_{BREAKDOWN}$ = _____ N·m (lbf·in)

$T_{BREAKDOWN}$ $= 2.52 \text{ N} \cdot \text{m} \ (23.6 \text{ lbf} \cdot \text{in})$

Determine the minimum-speed torque using graph G411. This torque is a good approximation of the locked-rotor torque of the squirrel-cage induction motor.

$T_{LOCKED\ ROTOR}$ = _____ N·m (lbf·in)

$T_{LOCKED\ ROTOR}$ $= 1.94 \text{ N} \cdot \text{m} \ (17.9 \text{ lbf} \cdot \text{in})$

Compare the breakdown torque and locked-rotor torque with the nominal torque of the squirrel-cage induction motor.

The breakdown and locked-rotor torques of the squirrel-cage induction motor are approximately 2.5 and 2 times the nominal torque, respectively.

13. In the Graph window, make the appropriate settings to obtain a graph of the motor active (P) and reactive (Q) power (obtained from meters Act. power and React. power, respectively) as a function of the motor speed (obtained from the Speed meter) using the data recorded previously in the Data Table (DT411). Entitle the graph as G411-1, name the x-axis as Squirrel-cage induction-motor speed, name the y-axis as Squirrel-cage induction-motor active power and reactive power, and print the graph.

The resulting graph is shown below.
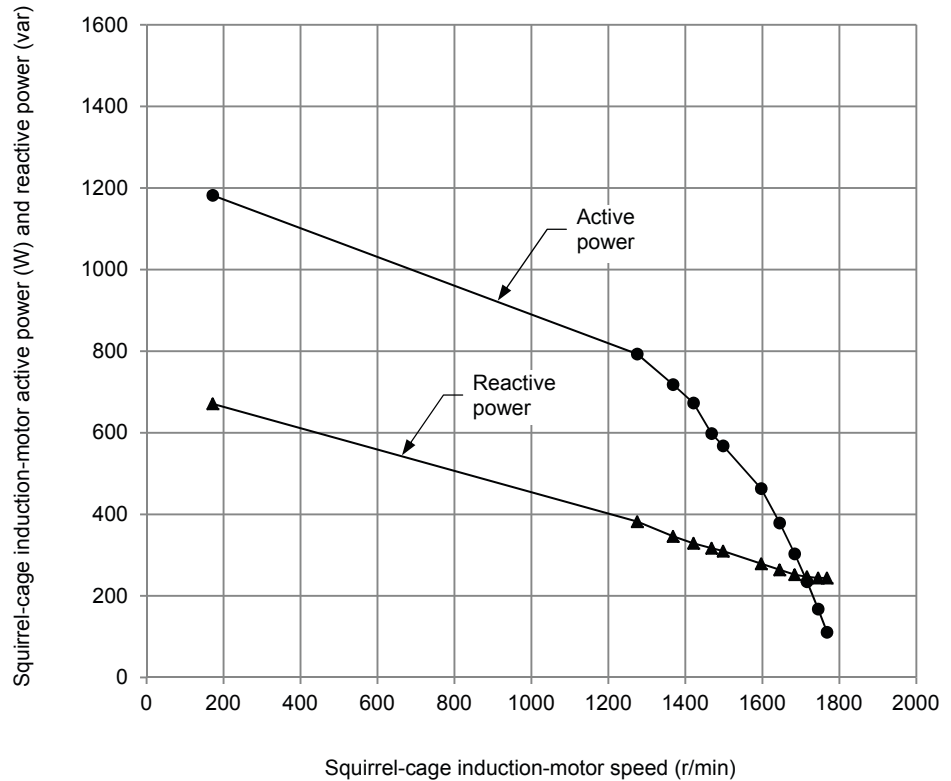
Squirrel-cage induction-motor active and reactive power versus speed (G411-1).

Does graph G411-1 confirm that the squirrel-cage induction motor always draws reactive power from the ac power source?

❑ Yes   ❑ No

Yes

Does graph G411-1 confirm that the squirrel-cage induction motor draws more electrical power from the ac power source as it drives an heavier load?

❑ Yes   ❑ No

Yes

Observe that when the squirrel-cage induction motor rotates without load, the reactive power exceeds the active power. What does this reveal?

This indicates that a squirrel-cage induction motor without load is similar to a reactive load (an inductor).

14. In the Graph window, make the appropriate settings to obtain a graph of the motor line current I_{LINE} (obtained from meter I line 1) as a function of the motor speed (obtained from the Speed meter) using the data recorded previously in the Data Table (DT411). Entitle the graph as G411-2, name the x-axis as Squirrel-cage induction-motor speed, name the y-axis as Squirrel-cage induction-motor line current, and print the graph.

The resulting graph is shown below.
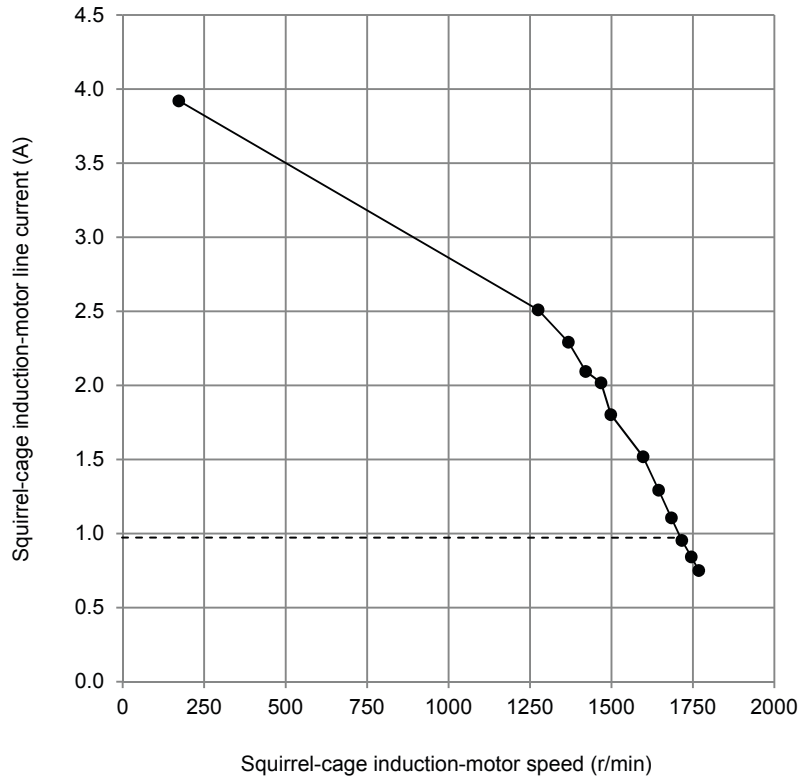
Squirrel-cage induction-motor line current versus speed (G411-2).

How does the line current vary as the motor speed decreases?

The line current increases when the motor speed decreases.

15. Indicate on graph G411-2 the nominal line current of the squirrel-cage induction motor measured previously.

By how many times is the starting line current greater than the nominal line current? (Use the line current measured at minimum speed as the starting current.)

The starting line current is approximately four times greater than the nominal current.

Direction of rotation

16. On the Four-Pole Squirrel-Cage Induction Motor, interchange any two of the three leads connected to the stator windings.

Turn the Power Supply on and set the voltage control knob so that the line voltage indicated by meter E line 1 is approximately equal to the nominal line voltage of the squirrel-cage induction motor.

What is the direction of rotation of the squirrel-cage induction motor?

The motor rotates counterclockwise.

Does the squirrel-cage induction motor rotate opposite to the direction noted previously in this exercise?

❏ Yes   ❏ No

Yes

17. On the Power Supply, set the 24 V - AC power switch to the O (off) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it off by setting its POWER INPUT switch to the O (off) position.

Remove all leads and cables.

CONCLUSION

In this exercise, you observed that when the nominal line voltage is applied to the stator windings of a squirrel-cage induction motor without mechanical load, the rotor turns at approximately the same speed as the rotating magnetic field (synchronous speed). You saw that interchanging any two of the three leads supplying power to the stator windings reverses the phase sequence, and thereby, causes the motor to rotate in the opposite direction. You observed that the motor line currents increase as the mechanical load increases, thus showing that the squirrel-cage induction motor requires more electric power to drive heavier loads. You plotted a graph of speed versus torque and used it to determine the nominal, breakdown, and locked-rotor torques of the squirrel-cage induction motor. You also plotted a graph of the motor reactive power versus speed and observed that the squirrel-cage induction motor draws reactive power from the ac power source to create its magnetic field. Finally, you plotted a graph of the motor line current versus speed and observed that the starting current is many times greater than the nominal line current.

REVIEW QUESTIONS

1. The speed of the rotating magnetic field created by three-phase power is called

    a. no-load speed.
    b. synchronous speed.
    c. slip speed.
    d. nominal speed.

    b

2. The difference between the synchronous speed and the rotation speed of a squirrel-cage induction motor is

    a. known as slip.
    b. always greater than 10%.
    c. known as slip torque.
    d. always less than 1%.

    a

3. Reactive power is consumed by a squirrel-cage induction motor because

    a. it uses three-phase power.
    b. it does not require active power.
    c. it requires reactive power to create the rotating magnetic field.
    d. it has a squirrel-cage.

    c

4. Does the speed of a squirrel-cage induction motor increase or decrease when the motor load increases?

   a. It increases.
   b. It decreases.
   c. It stays the same because speed is independent of motor load.
   d. The speed oscillates around the original value.

   b

5. What happens when two of the three leads supplying power to a squirrel-cage induction motor are reversed?

   a. The motor does not start.
   b. Nothing.
   c. The motor reverses its direction of rotation.
   d. The motor consumes more reactive power.

   c

Synchronous Motors

After completing this unit, you will be able to demonstrate and explain the operating characteristics of synchronous motors using the Synchronous Motor/Generator module.

The principles of operation of the three-phase synchronous motor are very similar to those of the three-phase squirrel-cage induction motor. The stator is usually built in the same way (refer to Figure 4-4), and it creates a rotating magnetic field the same as illustrated in Figure 4-6. The rotor of the synchronous motor, however, is not a squirrel-cage construction, but rather a permanent magnet or an electromagnet installed on the motor shaft, as shown in Figure 5-1. This rotor is pulled along by the rotating magnetic field exactly as shown in Unit 1.
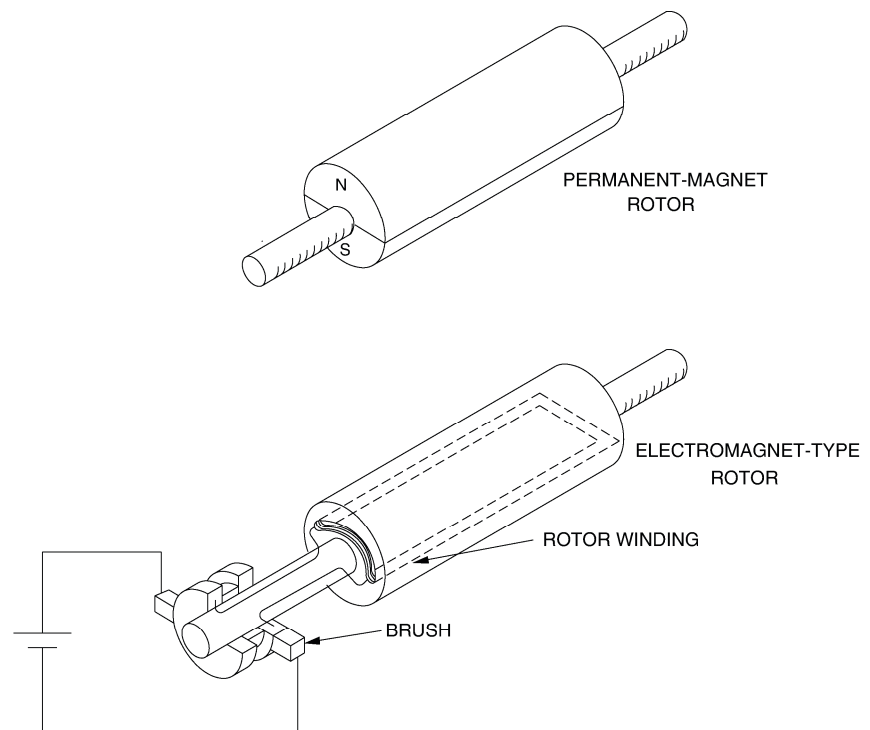
Figure 5-1. Rotor of a synchronous motor.

There is, however, a problem when starting a synchronous motor. When three-phase ac power is applied to the stator windings, a rotating magnetic field at synchronous speed n_S is immediately created. Since the rotor is at rest, it cannot catch up to the rotating magnetic field and the resulting torque acting on the rotor is fairly weak.

One way to aid in starting a synchronous motor having a rotor of the electromagnet type is to add a squirrel-cage to the rotor. During start-up, power is removed from the rotor 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 and the rotor locks to the rotating magnetic field and turns at exactly the synchronous speed n_S.

A synchronous motor with a permanent-magnet rotor cannot be started this way because the permanent magnet cannot be turned off. In this case, a variable-frequency ac source is used to supply power to the stator windings of the permanent-magnet synchronous motor. The frequency of the ac 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 to this field. The frequency of the ac source is then increased gradually to increase the speed to the desired value.

The Three-Phase Synchronous Motor

EXERCISE OBJECTIVE

When you have completed this exercise, you will you will be able to demonstrate how to start a synchronous motor as well as some characteristics of a synchronous motor using the Synchronous Motor/Generator module.

DISCUSSION

The most interesting features of the three-phase synchronous motor are its ability to operate at exactly the same speed as the rotating magnetic field, the capability of running at unity power factor, and to be able to supply reactive power to an ac power source. As seen in Unit 4, 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) of a three-phase synchronous motor operating without load is shown in Figure 5-2. When the field current I_f is minimum, the magnetic field produced by the rotor is weak and the motor consumes a maximum of reactive power (Q is positive). The reactive power that is consumed decreases to zero as current I_f increases because the strength of the magnetic field produced by the rotor increases. When current I_f exceeds a certain value that depends on the characteristics of the motor, the rotor magnetic field is so strong that the motor starts to supply reactive power, i.e., Q becomes negative as illustrated in Figure 5-2.

The graph of the reactive power Q versus the 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 field current I_f. Therefore, three-phase synchronous motors without load are also known as synchronous condensers when used to control the power factor on three-phase power networks.
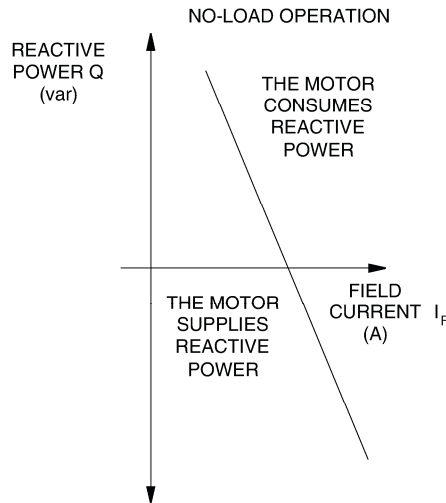
Figure 5-2. Reactive power Q versus field current I_f for a three-phase synchronous motor operating without load.

The graph of the line current I_L versus the field current I_f for a three-phase synchronous motor is a "V" type curve like that shown in Figure 5-3. This graph shows that the line current to the motor can be minimized by setting the field current I_f to the appropriate value. The field current required to minimize the line current is the same as that required to decrease the reactive power to zero. Therefore, the motor reactive power is zero when the line current is minimum.
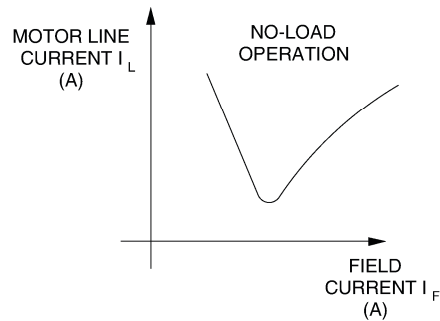
Figure 5-3. Line current I_L versus field current I_f for a three-phase synchronous motor operating without load.

The most inconvenient aspect of a three-phase synchronous motor is that it does not start easily, as is explained earlier in this unit.

Procedure summary

In the first part of the exercise, you will set up the equipment in the Workstation, connect the equipment as shown in Figure 5-4, and make the appropriate settings on the equipment.

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In the second part of the exercise, you will see how to start a three-phase synchronous motor with a rotor of the electromagnet type. You will also vary the field current to see if this affects the motor speed and line current.

In the third part of the exercise, you will vary the field current by steps. For each step, you will record in the Data Table various electrical parameters related to the three-phase synchronous motor. You will then use this data to plot various graphs and determine many of the characteristics of the three-phase synchronous motor.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart in Appendix C to obtain the list of equipment required for this exercise.

PROCEDURE

⚠ **WARNING**

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

Setting up the equipment

1. Install the equipment required in the EMS workstation.

    Mechanically couple the prime mover/dynamometer module to the Synchronous Motor/Generator.

2. On the Power Supply, make sure the main power switch is set to the O (off) position, and the voltage control knob is turned fully counterclockwise. Ensure the Power Supply is connected to a three-phase power source.

    If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, connect its POWER INPUT to a wall receptacle.

3. Ensure that the data acquisition module is connected to a USB port of the computer.

    Connect the POWER INPUT of the data acquisition module to the 24 V - AC output of the Power Supply.

    If you are using the Prime Mover/Dynamometer, Model 8960-1, connect its LOW POWER INPUT to the 24 V - AC output of the Power Supply.

    On the Power Supply, set the 24 V - AC power switch to the I (on) position.

    If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it on by setting its POWER INPUT switch to the I (on) position. Press and hold the FUNCTION button 3 seconds to have uncorrected torque values on the display of the Four-Quadrant Dynamometer/Power Supply. The indication "NC" appears next to the function name on the display to indicate that the torque values are uncorrected.

4. Start the Data Acquisition software (LVDAC or LVDAM). Open setup configuration file ACMOTOR1.DAI.

In the Metering window, select layout 2. Make sure that the continuous refresh mode is selected.

5. Connect the equipment as shown in Figure 5-4. Connect the three resistor sections on the Resistive Load module in parallel to implement resistor R_1.
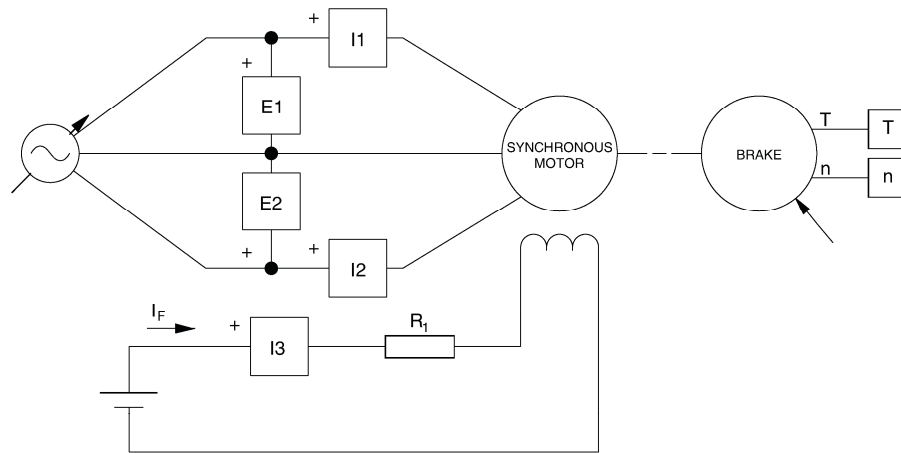
Local ac power network		R_1 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	57
220	50	210
220	60	210
240	50	229

Figure 5-4. Synchronous motor coupled to a brake.

6. Set the Four-Quadrant Dynamometer/Power Supply or the Prime Mover/Dynamometer to operate as a brake, then set the brake torque control to maximum (fully clockwise position). To do this, refer to Exercise 1-1 or Exercise 1-2 if necessary.

If you are performing the exercise using LVSIM®-EMS, you can zoom in the Prime Mover/Dynamometer module before setting the controls in order to see additional front panel markings related to these controls.

Starting a three-phase synchronous motor

7. In the Metering window, make sure that the torque correction function of the Torque meter is enabled.

On the Synchronous Motor/Generator, set the EXCITER switch to the I (closed) position and turn the EXCITER knob fully clockwise.

Turn the Power Supply on and set the voltage control knob so that the line voltage indicated by meter E line 1 is equal to the nominal line voltage of the synchronous motor.

The rating of any of the machines is indicated in the lower left corner of the module front panel.

Record the starting torque T_{START} of the synchronous motor (indicated by the Torque meter in the Metering window).

$$T_{START} \ = \ \underline{\qquad} \ \text{N} \cdot \text{m} \ (\text{lbf} \cdot \text{in}) \qquad \text{(rotor electromagnet turned on)}$$

$T_{START} \ = 1.22 \ \text{N} \cdot \text{m} \ (10.8 \ \text{lbf} \cdot \text{in}) \qquad \text{(rotor electromagnet turned on)}$

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

Record the starting torque T_{START} of the synchronous motor in the following blank space.

$$T_{START} \ = \ \underline{\qquad} \ \text{N} \cdot \text{m} \ (\text{lbf} \cdot \text{in}) \qquad \text{(rotor electromagnet turned off)}$$

$T_{START} \ = 2.45 \ \text{N} \cdot \text{m} \ (21.7 \ \text{lbf} \cdot \text{in}) \qquad \text{(rotor electromagnet turned off)}$

Compare the starting torque obtained when the rotor electromagnet is turned off to that obtained when the rotor electromagnet is turned on.

The starting torque obtained when the rotor electromagnet is turned off is higher than that obtained when it is turned on.

From the results obtained so far, would you conclude that it is desirable to turn the rotor electromagnet off before starting the synchronous motor? Briefly explain.

Yes, because when the rotor electromagnet is turned off, the starting torque is high.

9. On the brake, slowly set the torque control to minimum (fully counterclockwise), wait until the synchronous motor speed stabilizes, and record the motor speed n (indicated by the Speed meter) in the following blank space.

$n = $ _____ r/min

$n = 1748\,\text{r/min}$

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

Does the motor speed n change?

❏ Yes ❏ No

Yes

Record the motor speed n in the following blank space.

$n = $ _____ r/min

$n = 1800\,\text{r/min}$

Is the motor speed now approximately equal to the nominal speed of the Synchronous Motor/Generator (synchronous speed n_S)?

❏ Yes ❏ No

Yes

10. On the Synchronous Motor/Generator, slowly vary the setting of the EXCITER knob between the MIN. and MAX. positions to vary the field current I_f [indicated by meter I field (I_f)]. While doing this, observe the motor speed n and the motor line current I_{LINE} indicated by the Speed meter and meter I line 1, respectively.

Does varying the field current I_f vary the motor speed n?

❏ Yes ❏ No

No

Does the motor line current I_{LINE} vary when the field current I_f is varied?

❑ Yes   ❑ No

Yes

On the Synchronous Motor/Generator, set the EXCITER knob to the MIN. position.

Characteristics of a three-phase synchronous motor

11. Change the value of resistor R_1 and vary the setting of the EXCITER knob on the Synchronous Motor/Generator so that the field current I_f [indicated by meter I field (I_f)] passes from the minimum current to the maximum current indicated in Table 5-1, in ten steps that are spaced as equally as possible. Note that it may be necessary to short circuit resistor R_1 to increase the field current to the maximum value indicated in the table. For each current setting, record the motor line voltage E_{LINE}, line current I_{LINE}, field current I_f, active power P, and reactive power Q in the Data Table. These parameters are indicated by meters E line 1, I line 1, I field (I_f), Act. power, and React. power, respectively.

Table 5-1. Range of field current.

Local ac power network		I_f (mA)
Voltage (V)	Frequency (Hz)	
120	60	300 to 900
220	50	100 to 500
220	60	100 to 500
240	50	100 to 500

12. When all data has been recorded, turn the voltage control knob fully counterclockwise, and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT511, and print the Data Table.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to edit, entitle, and print a Data Table.

The results obtained are presented below.

Synchronous motor line voltage, line current, field current, active power, and reactive power (DT511).

Line voltage (E line 1) V	Line current (I line 1) A	Field current [I field (I_f)] A	Active power (W)	Reactive power (var)
208.4	0.461	0.300	94.3	145
207.5	0.351	0.367	91.3	101
208.5	0.276	0.434	88.0	63.7
208.4	0.224	0.500	87.6	25.7
208.5	0.215	0.566	87.4	-8.9
208.3	0.254	0.632	89.3	-44.7
208.0	0.324	0.700	90.4	-84.2
208.2	0.396	0.765	94.5	-116
208.2	0.472	0.832	95.4	-148
208.7	0.547	0.899	101	-179

13. In the Graph window, make the appropriate settings to obtain a graph of the motor line current I_{LINE} (obtained from meter I line 1) as a function of the field current I_f [obtained from meter I field (I_f)]. Entitle the graph as G511, name the x-axis as Synchronous motor field current, name the y-axis as Synchronous motor line current, and print the graph.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to use the Graph window of the Metering application to obtain a graph, entitle a graph, name the axes of a graph, and print a graph.

The resulting graph is shown below.

y-axis: Synchronous motor line current (A)
x-axis: Synchronous motor field current (A)
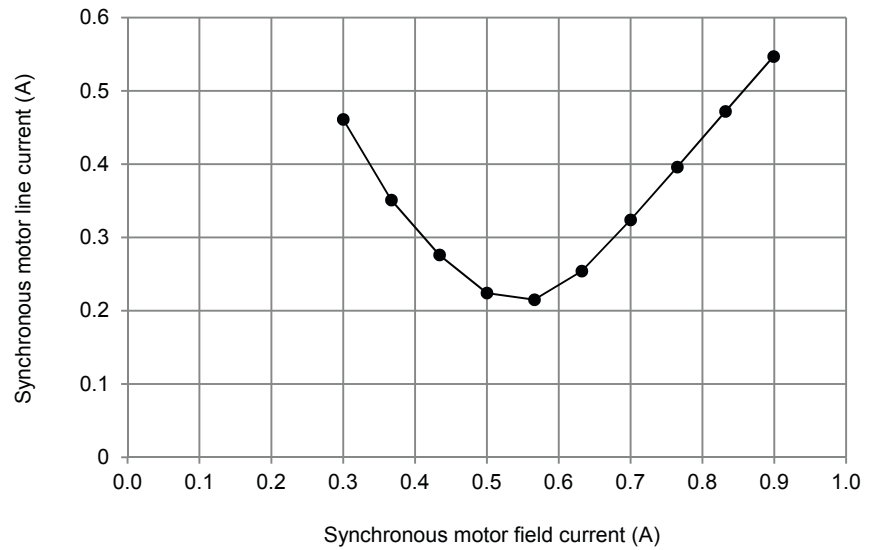
Synchronous motor line current versus field current (G511).

Approximate the field current I_f that minimizes the motor line current I_{LINE} using graph G511. Record your result in the following blank space.

I_f = _____ A (for reducing the motor line current to minimum)

I_f = 0.56 A (for reducing the motor line current to minimum)

14. In the Graph window, make the appropriate settings to obtain a graph of the motor active power P and reactive power Q (obtained from meters Act. power and React. power, respectively) as a function of the field current I_f [obtained from meter I field (I_f)], using the data recorded previously in the Data Table. Entitle the graph as G511-1, name the x-axis as Synchronous motor field current, name the y-axis as Synchronous motor active power and reactive power, and print the graph.

The resulting graph is shown below.
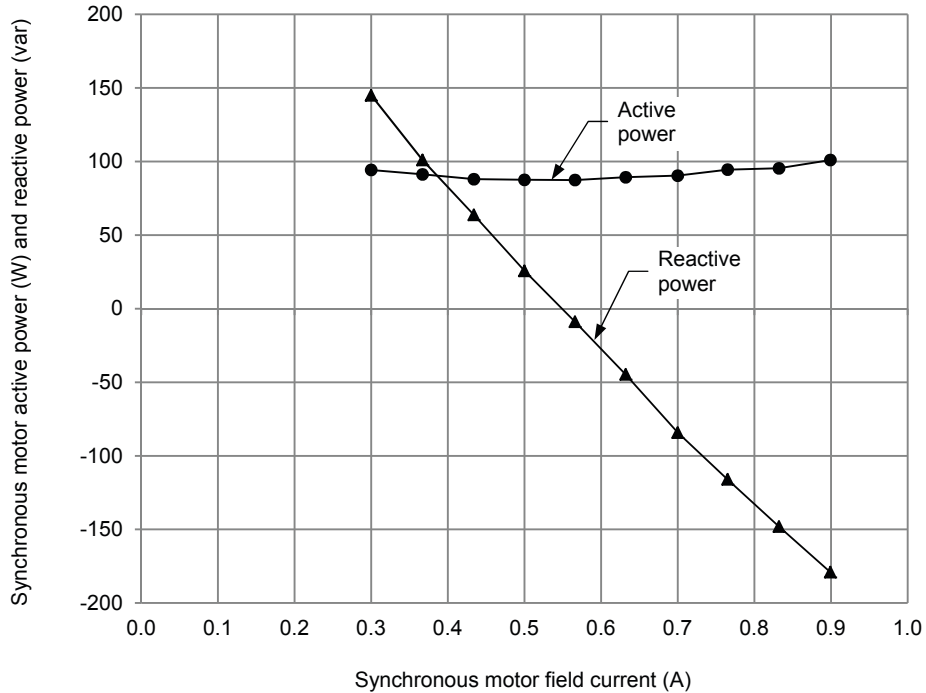
Synchronous motor active and reactive power versus field current (G511-1).

Does varying the field current I_f vary the active power consumed by the synchronous motor significantly?

❑ Yes   ❑ No

No

How does the motor reactive power Q vary when the field current I_f increases?

When the field current increases, the motor reactive power decreases linearly to zero, changes polarity, and increases linearly.

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

Yes, because the synchronous motor acts as either an inductor or a capacitor depending on the value of field current.

15. Determine the field current I_f for which the reactive power Q is zero using graph G511-1. Record your result in the following blank space.

I_f = _____ A (for reducing the motor reactive power to zero)

I_f = 0.56 A (for reducing the motor reactive power to zero)

Compare the field current that sets the reactive power Q to zero with the field current that minimizes the motor line current I_{LINE}.

The field current that sets the reactive power Q to zero equals the field current that minimizes the motor line current.

From the results obtained so far, can you conclude that the motor line current is minimum when the reactive power is zero?

❑ Yes   ❑ No

Yes

16. On the Power Supply, set the 24 V - AC power switch to the O (off) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it off by setting its POWER INPUT switch to the O (off) position.

Remove all leads and cables.

CONCLUSION

In this exercise, you saw that the rotor electromagnet must be turned off when starting a synchronous motor, to obtain a higher torque. You observed that once a synchronous motor rotates at a fairly high speed, the rotor electromagnet can be turned on to make the motor turn at the synchronous speed n_S. You found that varying the field current I_f of a synchronous motor (current in the rotor electromagnet) varies the motor line current I_{LINE} as well as the motor reactive power Q. You plotted graphs of the motor line current, active power P, and reactive power Q versus the field current. You found that the synchronous motor line current can be minimized by adjusting the field current. You observed that the synchronous motor can either sink or source reactive power depending on the value of the field current. You saw that this allows a three-phase synchronous motor to be used as a synchronous condenser to improve the power factor of a three-phase power network.

REVIEW QUESTIONS

1. The starting torque of a three-phase synchronous motor is increased when

    a. the rotor electromagnet is turned on.
    b. the rotor electromagnet is turned off.
    c. the power factor of the ac power network is unity.
    d. dc power is applied to one of the stator windings.

    b

2. When a synchronous motor without load is connected to a three-phase ac power network, the resulting power factor depends on

    a. the speed of the motor.
    b. the active power consumed by the motor.
    c. the amount of field current.
    d. the line current.

    c

3. Reactive power in a synchronous motor without load is minimum when the

    a. line current is maximum.
    b. line current is minimum.
    c. line current equals the field current.
    d. field current is minimum.

    b

4. Synchronous condenser is another name for

    a. an asynchronous motor.
    b. a squirrel-cage motor.
    c. a split-phase motor.
    d. a synchronous motor operating without load.

    d

5. The squirrel cage in a synchronous motor with a rotor of the electromagnet type

    a. minimizes the motor line current.
    b. prevents saturation of the rotor electromagnet.
    c. allows the motor to start when ac power is applied to the stator windings.
    d. makes the motor operate as a synchronous condenser.

    c

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