Electricity and New Energy

Three-Phase Rotating Machines

Courseware Sample

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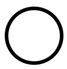
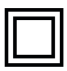
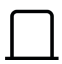
Safety and Common Symbols

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

Symbol	Description
⚠ 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
$\overline{\sim}$	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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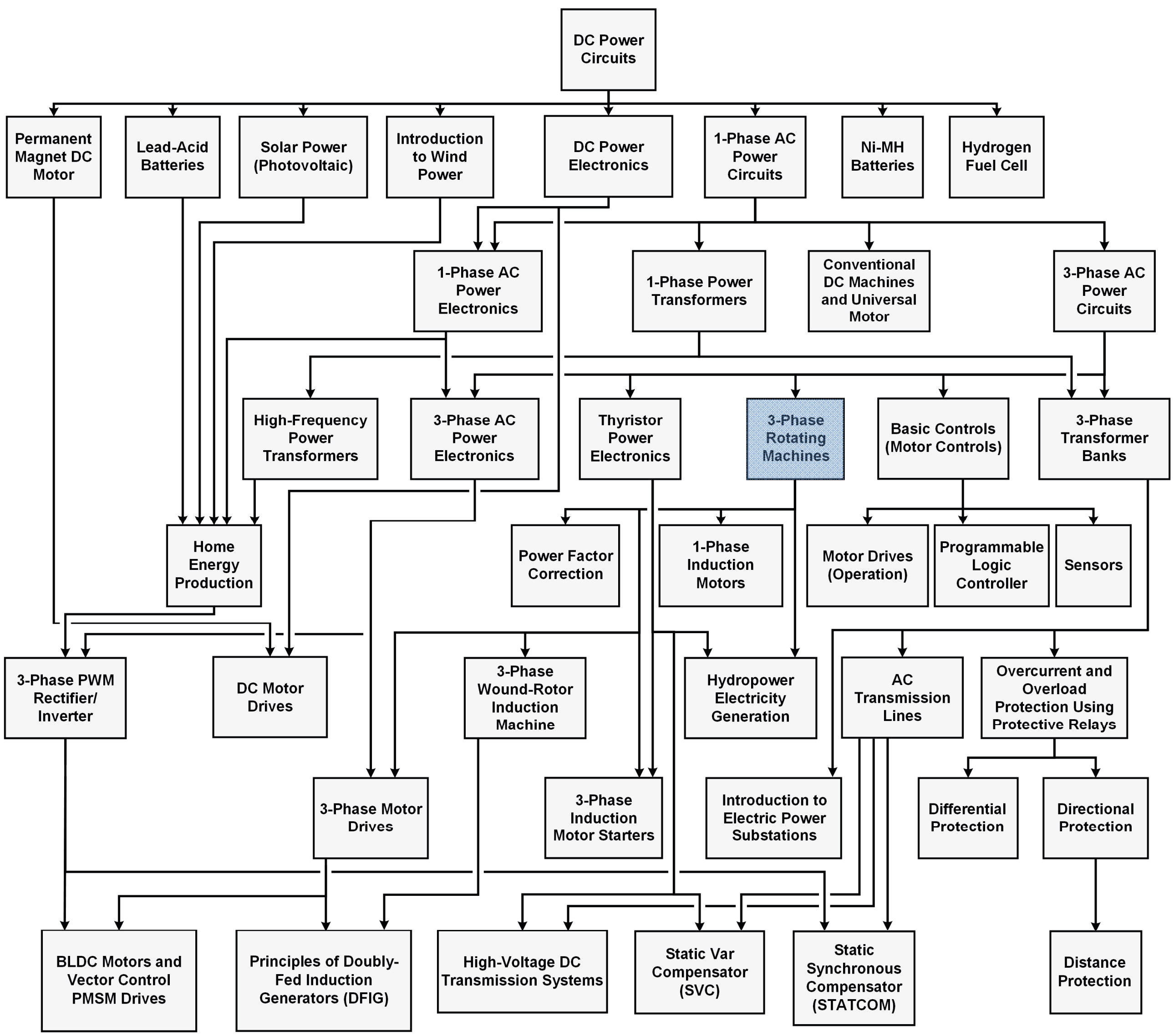
Preface

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.

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.

The authors and Festo Didactic look forward to your comments.

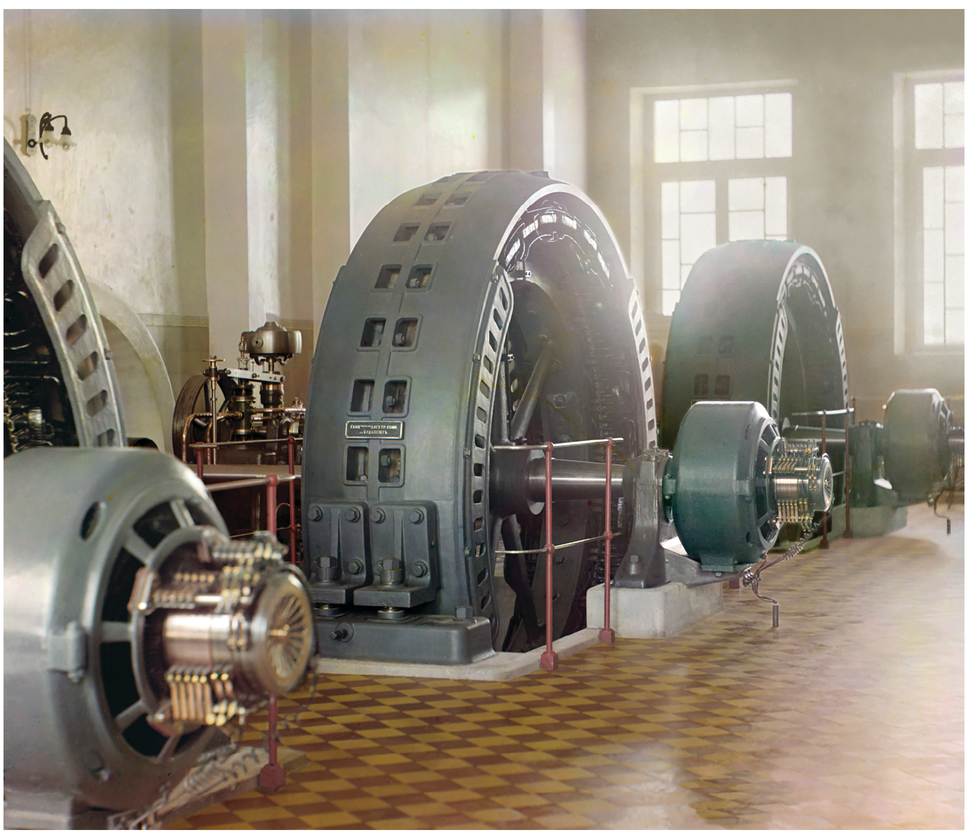
About This Manual

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.

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).

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.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

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° one to another, as shown in Figure 2-5.

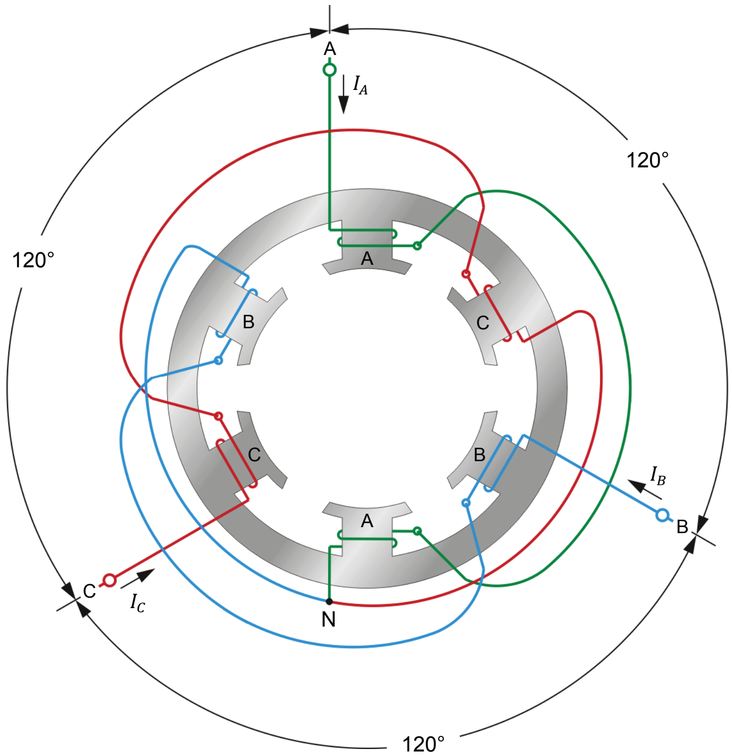


Figure 2-5. Three-phase stator windings (two poles per phase).

When sine-wave currents that are similarly phase shifted at an angle of 120° 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.

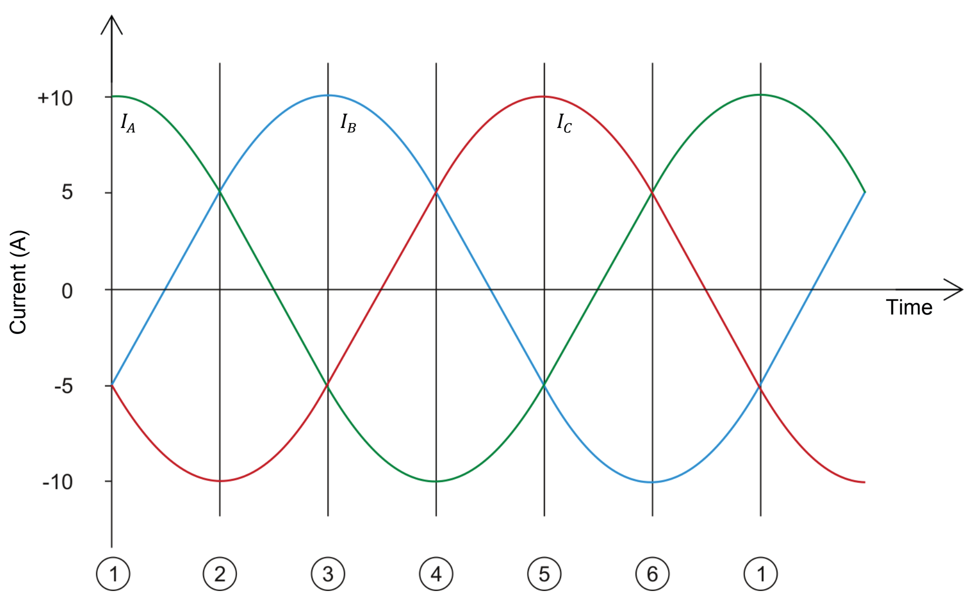


Figure 2-6. Three-phase sine wave currents flowing in the stator windings.

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.

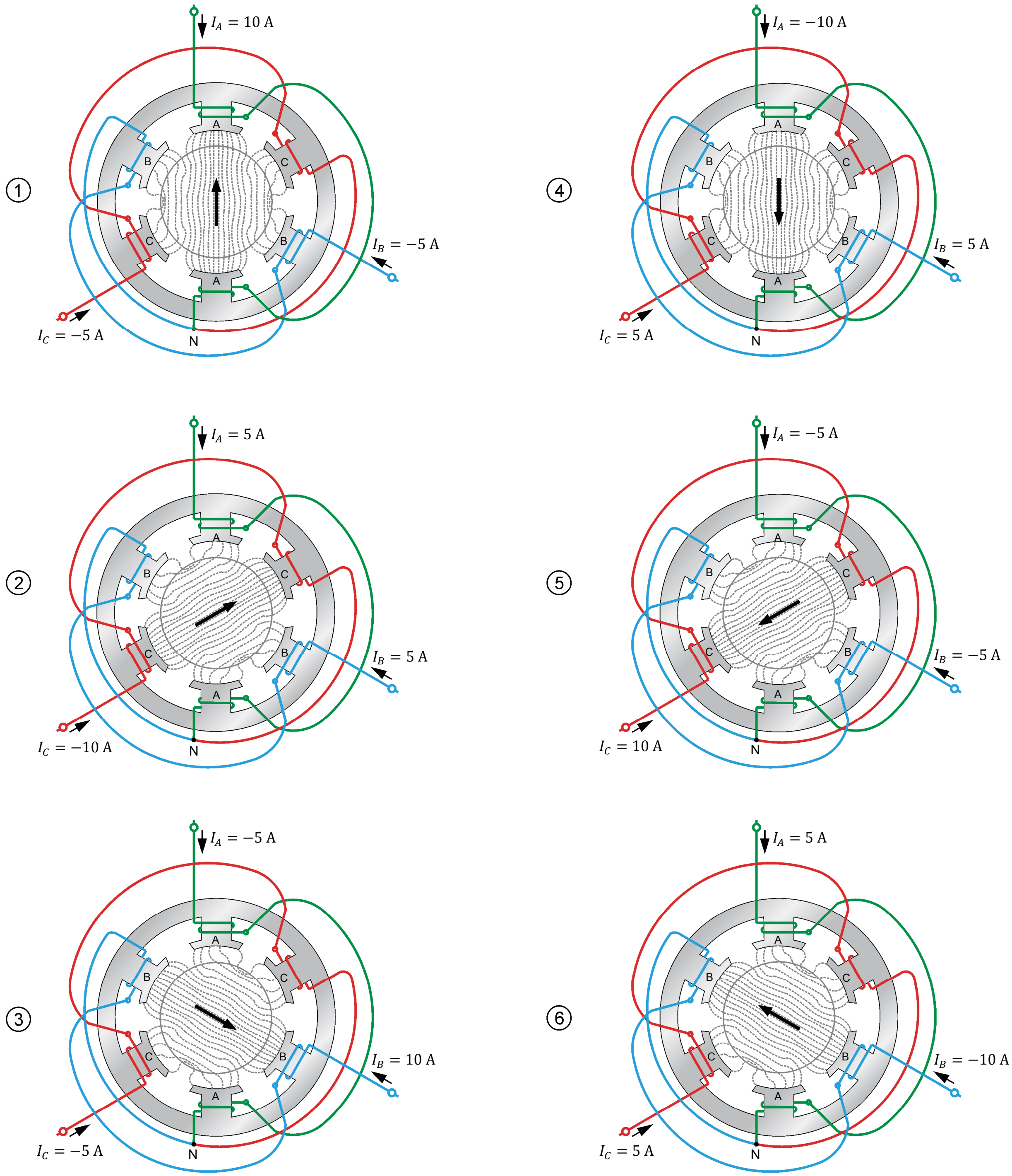


Figure 2-7. Position of the rotating magnetic field at various instants.

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:

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

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:

$$\text{Motor slip} = N_S - N_r \tag{2-2}$$

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:

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

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.

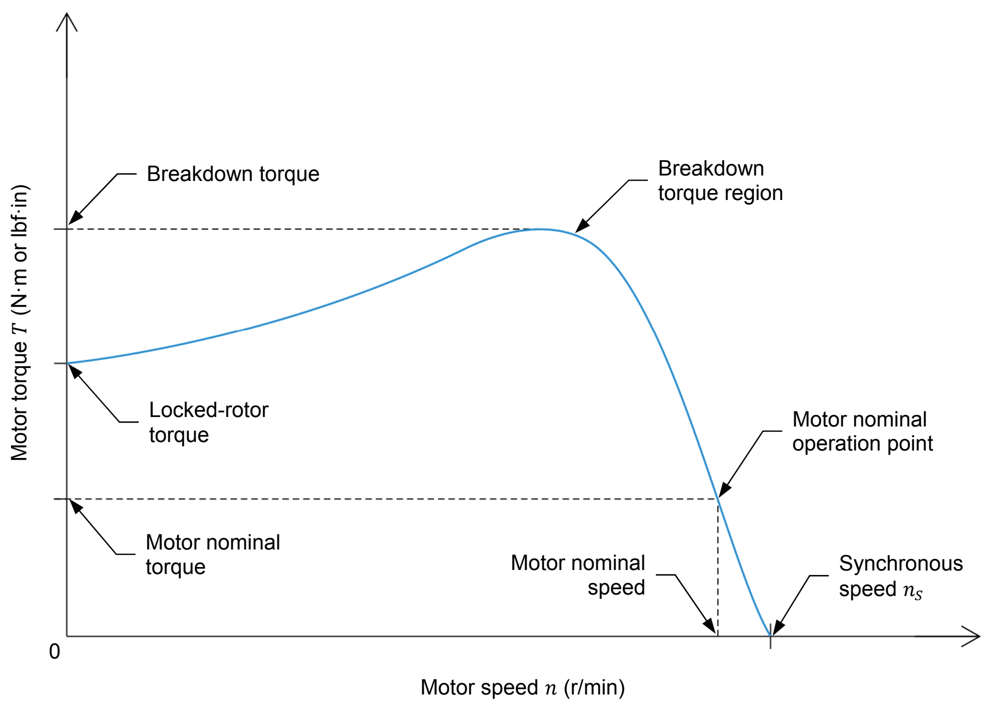


Figure 2-9. Typical three-phase squirrel-cage induction motor torque T versus speed n curve.

Efficiency of three-phase squirrel-cage induction motors

Motor efficiency η 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.

$$\eta = \frac{P_M}{P} 100 \tag{2-4}$$

where η 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.

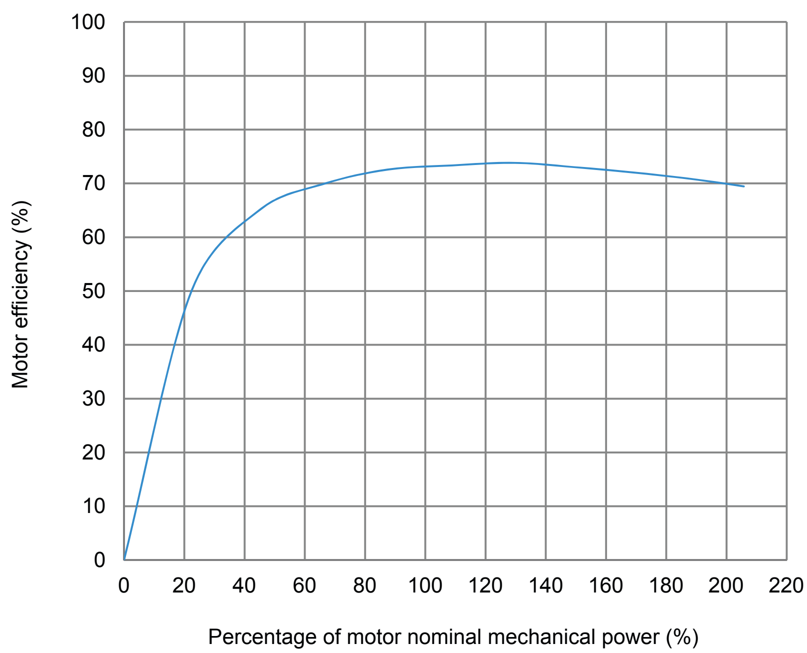


Figure 2-10. Motor efficiency as a function of the percentage of nominal mechanical power for a typical three-phase squirrel-cage induction motor.

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.

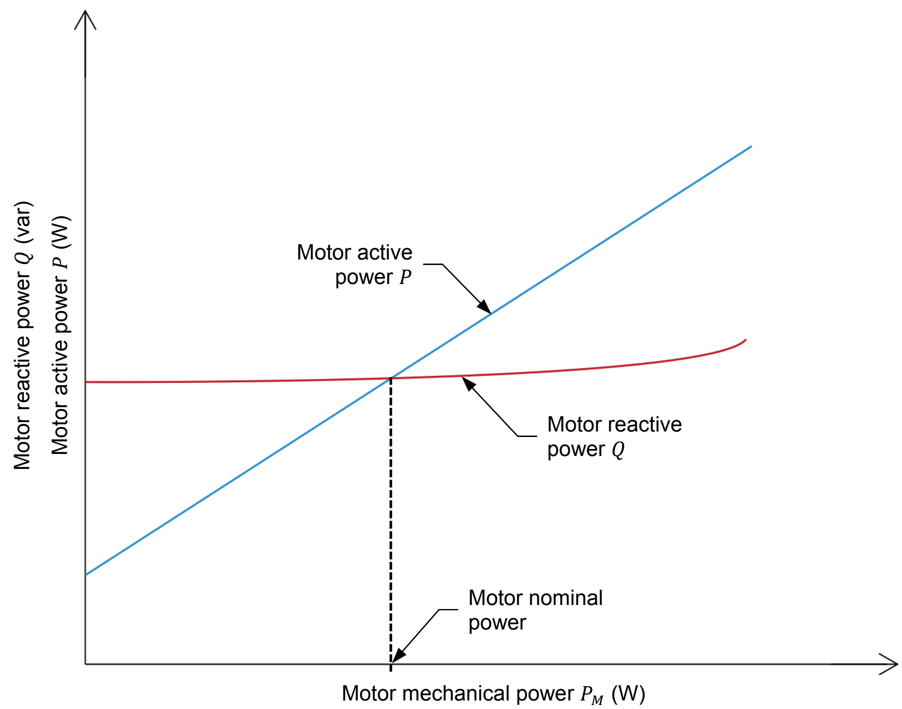


Figure 2-11. Active power P and reactive power Q as a function of the mechanical power P_M for a typical three-phase squirrel-cage induction motor.

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 $P = I^2R$, 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.

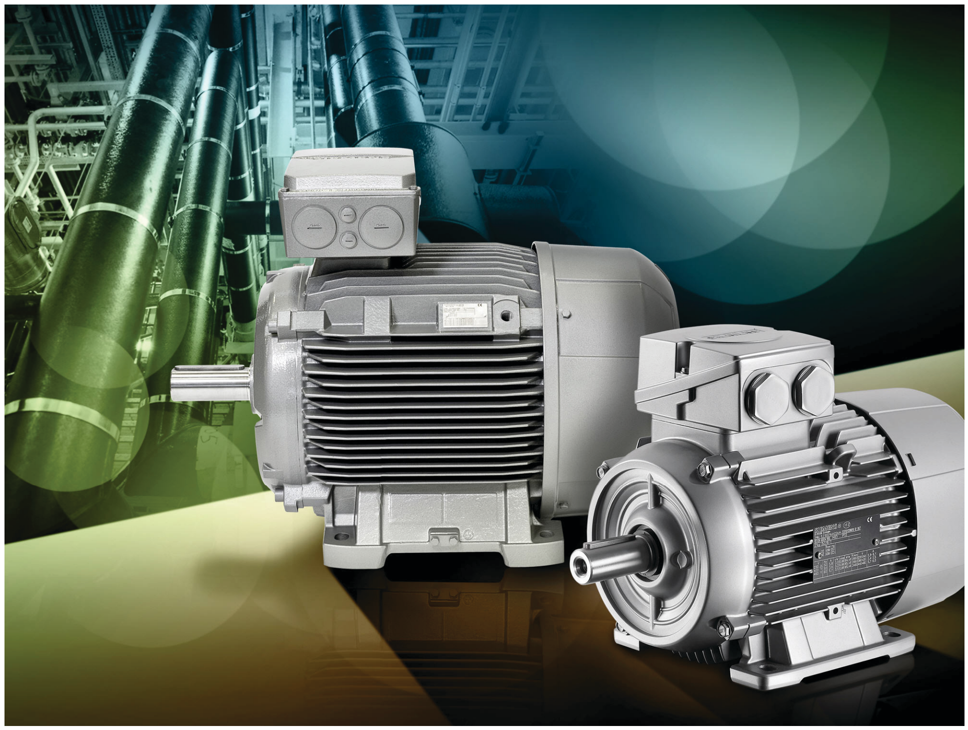


Figure 2-12. High-efficiency motors help in reducing electricity consumption by industry worldwide. The above motors are part of a new range of certified IE2 (high efficiency) and IE3 (premium efficiency) induction motors. IE2 and IE3 are certifications issued by the International Electrical Commission 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

⚠ 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.

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.

   ⚠ WARNING

   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.

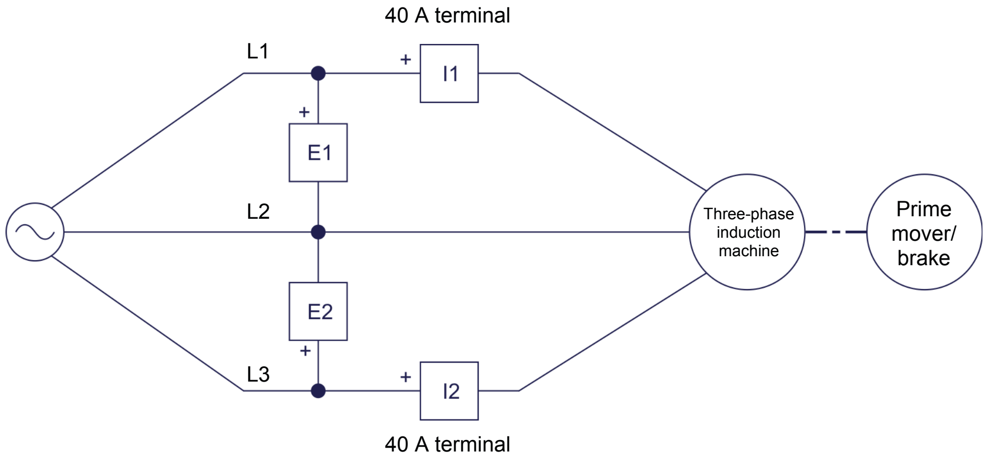


Figure 2-13. Three-phase induction machine coupled to a prime mover/brake.

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 (EI1, EI2) 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

    Motor no-load speed $n = 1796$ r/min

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

    Motor direction of rotation: _________________

    Motor direction of rotation: clockwise

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

Yes

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

Nominal motor speed $n = 1685$ r/min

Nominal motor torque $T = 1.14$ N·m (10.1 lbf·in)

Nominal motor line current $I_{Line} = 1.14$ 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

Yes

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 η. To calculate the motor efficiency η, 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 η as a percentage.

The results obtained are presented below.

Three-phase induction motor speed n, torque T, mechanical power P_M, line voltage E_{Line}, line current I_{Line}, active power P, reactive power Q, power factor PF, and efficiency η.

Speed n (r/min)	Torque T (N·m) [lbf·in]	Mechanical power P_M (W)	Line voltage E_{Line} (V)	Line current I_{Line} (A)	Active power P (W)	Reactive power Q (var)	Power factor PF	Efficiency η (%)
1794	0.02 [0.19]	4.14	210	0.74	50.1	269	0.18	8.27
1782	0.16 [1.37]	28.8	210	0.78	79.8	269	0.28	36.2
1764	0.38 [3.34]	69.6	210	0.84	125	268	0.42	55.8
1744	0.59 [5.20]	106	210	0.91	171	269	0.54	62.3
1724	0.79 [7.00]	143	210	1.00	217	272	0.62	65.9
1704	0.98 [8.69]	175	209	1.09	263	277	0.69	66.7
1683	1.16 [10.3]	205	209	1.19	304	281	0.73	67.4
1662	1.34 [11.8]	233	209	1.29	349	288	0.77	66.7
1642	1.48 [13.1]	254	209	1.38	386	294	0.80	65.9
1621	1.62 [14.3]	275	209	1.48	425	301	0.82	64.7
1601	1.75 [15.5]	293	209	1.58	461	309	0.83	63.7
1580	1.85 [16.4]	310	208	1.70	509	315	0.84	60.8
1470	2.27 [20.1]	349	208	2.07	633	359	0.87	55.1
1367	2.55 [22.5]	365	207	2.43	750	408	0.88	48.6
1268	2.69 [23.8]	357	207	2.72	839	455	0.88	42.6
1169	2.76 [24.4]	338	207	2.96	911	497	0.88	37.1
1070	2.78 [24.6]	311	207	3.16	970	536	0.88	32.1
972	2.76 [24.4]	281	206	3.32	1015	569	0.87	27.7
874	2.71 [24.0]	248	206	3.45	1052	598	0.87	23.6
776	2.63 [23.3]	214	206	3.56	1082	622	0.87	19.8
680	2.55 [22.6]	182	206	3.63	1105	640	0.87	16.4
582	2.47 [21.9]	151	206	3.71	1125	657	0.86	13.4
485	2.38 [21.0]	121	206	3.77	1143	672	0.86	10.6
387	2.27 [20.1]	92.1	206	3.82	1155	682	0.86	7.97
289	2.18 [19.3]	65.9	206	3.84	1163	690	0.86	5.66
192	2.08 [18.4]	41.8	206	3.87	1169	694	0.86	3.58
95	2.06 [18.2]	20.5	206	3.88	1175	700	0.86	1.74
0	1.93 [17.1]	0.00	206	3.89	1177	699	0.86	0.00

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?

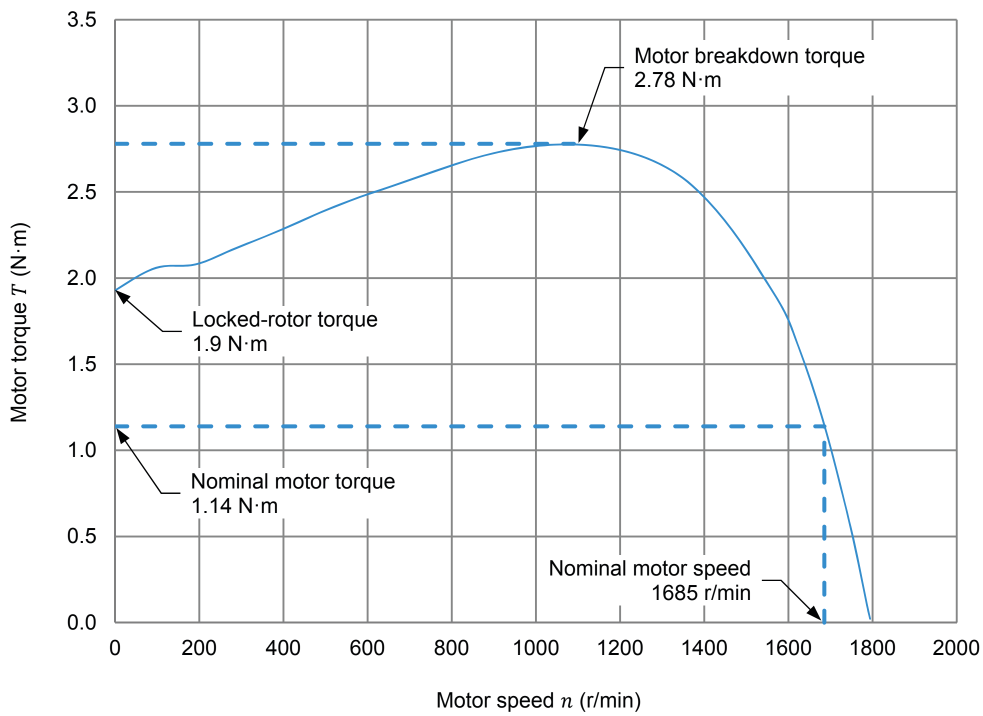
❑ Yes ❑ No

Yes

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.

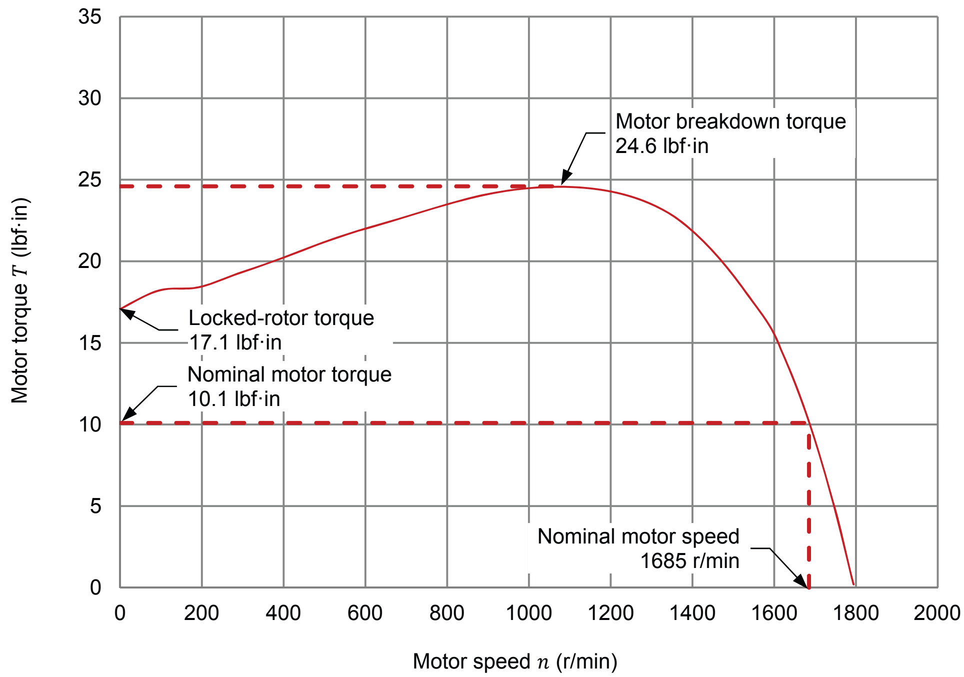
The resulting graphs are shown below.

When the motor torque T is expressed in N·m:



Three-phase induction motor torque T (expressed in N·m) as a function of the motor speed n.

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



Three-phase induction motor torque T (expressed in lbf·in) as a function of the motor speed n.

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} = _______ N·m (lbf·in)

Motor locked-rotor torque T_{Locked} = _______ N·m (lbf·in)

Motor breakdown torque $T_{Break} = 2.78 \text{ N} \cdot \text{m} \ (24.6 \text{ lbf} \cdot \text{in})$

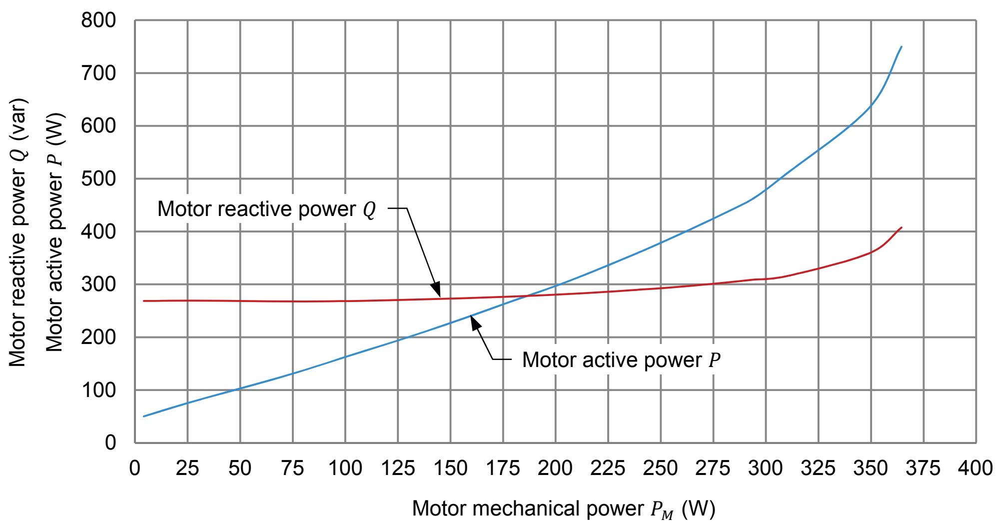
Motor locked-rotor torque $T_{Locked} = 1.90 \text{ N} \cdot \text{m} \ (17.1 \text{ lbf} \cdot \text{in})$

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

The speed n of the three-phase induction motor decreases more and more rapidly as the motor torque T increases until the motor torque T reaches the breakdown torque region. At this point, the motor torque stops increasing and begins decreasing. After the breakdown torque region, the motor speed n decreases rapidly as the motor torque T decreases.

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.

The resulting graph is shown below.



Three-phase induction motor active power P and reactive power Q as a function of the motor mechanical power P_M.

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

Yes

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.

As the graph of the motor active power P and reactive power Q as a function of the motor mechanical power P_M shows, the amount of reactive power required by the three-phase induction motor does not vary much with the motor mechanical power for most of the motor reactive power-versus-mechanical power curve. Thus, even when the motor is operating under its nominal mechanical power, it draws virtually the same amount of reactive power. This reduces the motor efficiency (due to large copper losses) and increases the size and cost of the equipment needed to supply power to the motor.

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

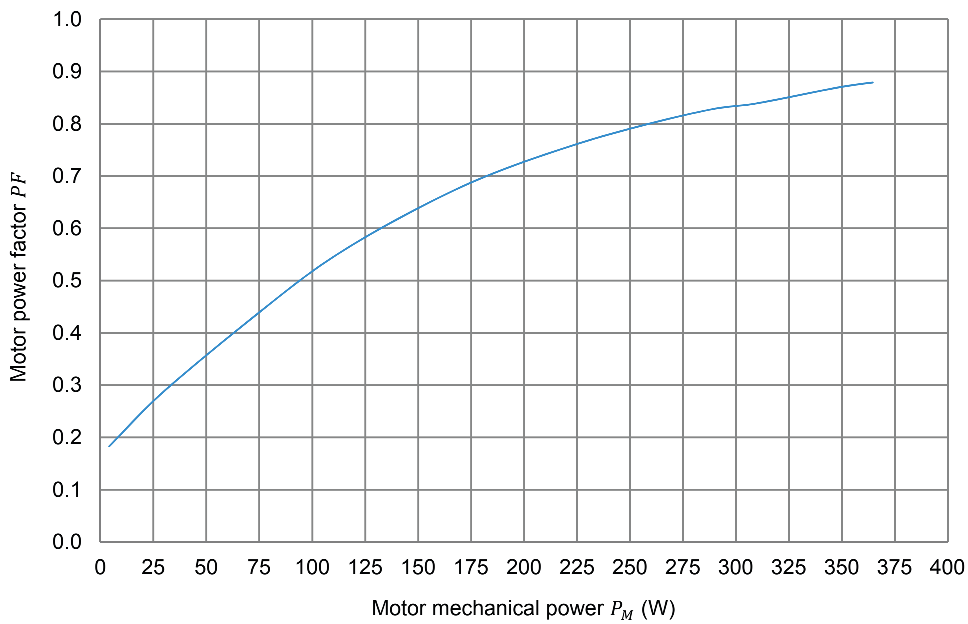
Yes

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

This indicates that a three-phase induction motor operating without load is similar to an inductive load (i.e., it absorbs reactive power and draws very little active power).

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.

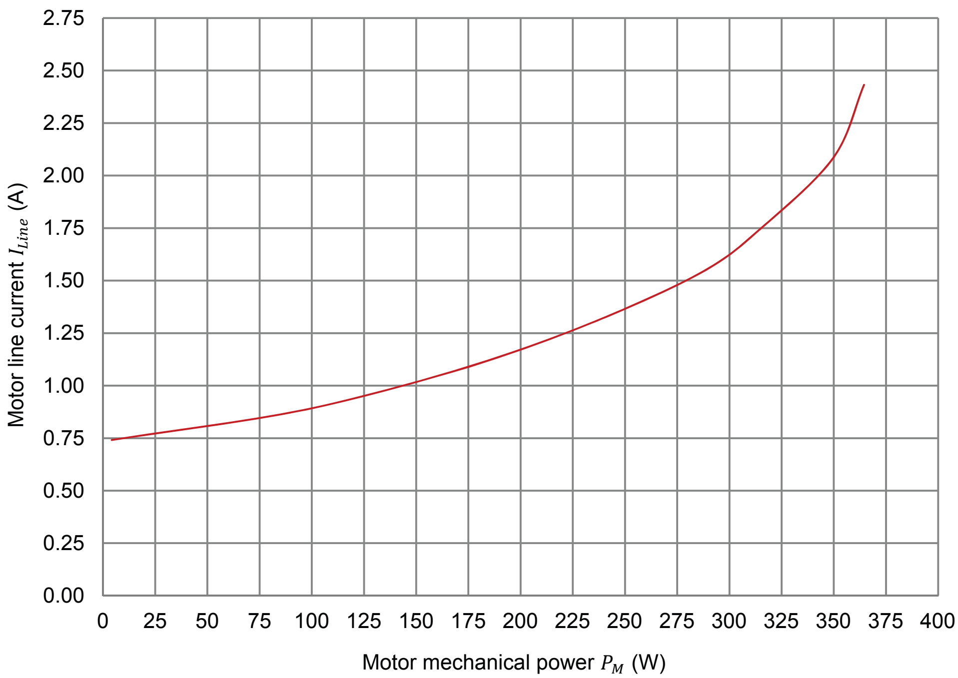
The resulting graph is shown below.



Three-phase induction motor power factor PF as a function of the motor mechanical power P_M.

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.

The resulting graph is shown below.



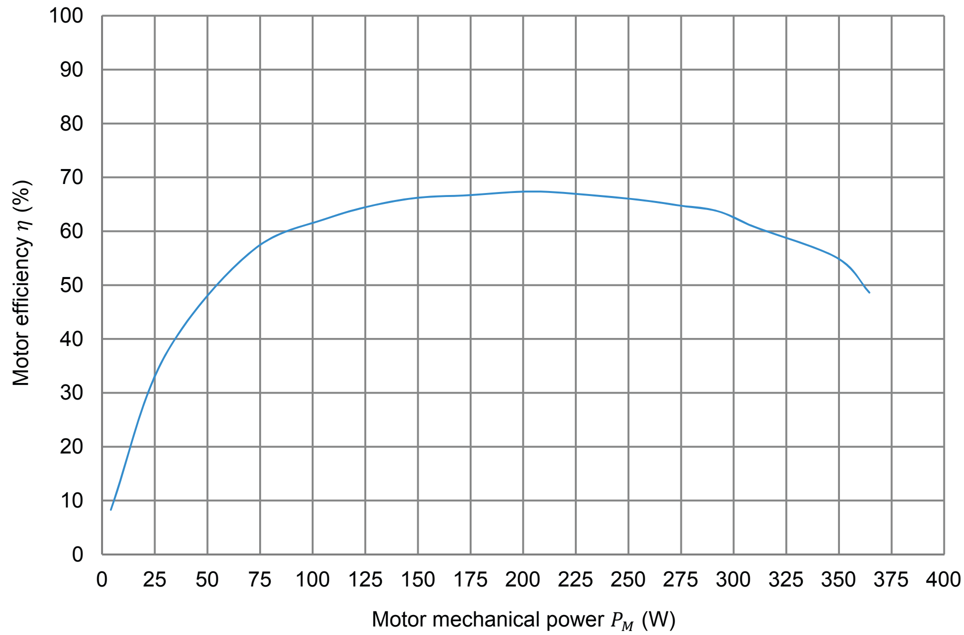
Three-phase induction motor line current I_{Line} as a function of the motor mechanical power P_M.

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.

Both the power factor PF and the line current I_{Line} of the three-phase induction motor increase with the motor mechanical power P_M. The motor power factor PF starts at a low value, increases substantially, then begins to stabilize at around the motor nominal mechanical power, although it continues to increase at a lower rate as the motor mechanical power continues to increase. On the other hand, the motor line current I_{Line} starts at a relatively high value, increases a little until the motor nominal mechanical power is reached, then increases more and more rapidly as the motor mechanical power continues to increase.

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

The resulting graph is shown below.



Three-phase induction motor efficiency η as a function of the motor mechanical power P_M.

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

The three-phase induction motor efficiency η increases rapidly with the motor mechanical power P_M, until the motor mechanical power P_M reaches the motor nominal power. At this point, the motor efficiency η stabilizes then begins to decrease.

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: _______________

Motor direction of rotation: counterclockwise

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

Yes

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.

The slip of a three-phase squirrel-cage induction motor corresponds to the difference between the speed of the motor rotating magnetic field and the speed of the rotor. The slip of a motor is directly proportional to the load torque applied to the motor (i.e., the slip increases with the load torque).

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

A motor synchronous speed corresponds to the speed of the rotating magnetic field produced in the motor. The synchronous speed of a motor is determined by the number of magnetic poles in the motor and the frequency of the ac power source to which the motor is connected.

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

As the torque produced by a three-phase squirrel-cage induction motor increases, the motor speed decreases slightly. After the torque produced by the motor reaches the breakdown torque region, both the torque produced by the motor and the motor speed begin to decrease rapidly. When the motor speed reaches about 0 r/min, the torque produced by the motor stabilizes at a point called the locked-rotor torque.

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

High efficiency motors consume less electrical power to produce the same mechanical power as normal-efficiency motors, which reduces the motor energy consumption and operating costs.

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?

The virtually constant reactive power requirement of a three-phase squirrel-cage induction motor causes the motor power factor to rapidly decrease when the motor works under its nominal mechanical power. It also causes the motor line current to remain close to the nominal value even when the motor is operating under its nominal mechanical power, which results in high energy losses in the motor and, consequently, reduced motor efficiency.

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