## Electricity and New Energy

# Single-Phase Induction Motors

## Student Manual

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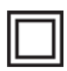
# Safety and Common Symbols

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

| Symbol | Description |
|---|---|
|   | **DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury. |
|   | **WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury. |
|   | **CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury. |
|   | **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 |
|  | Three-phase alternating current |
|  | Earth (ground) terminal |

# Safety and Common Symbols

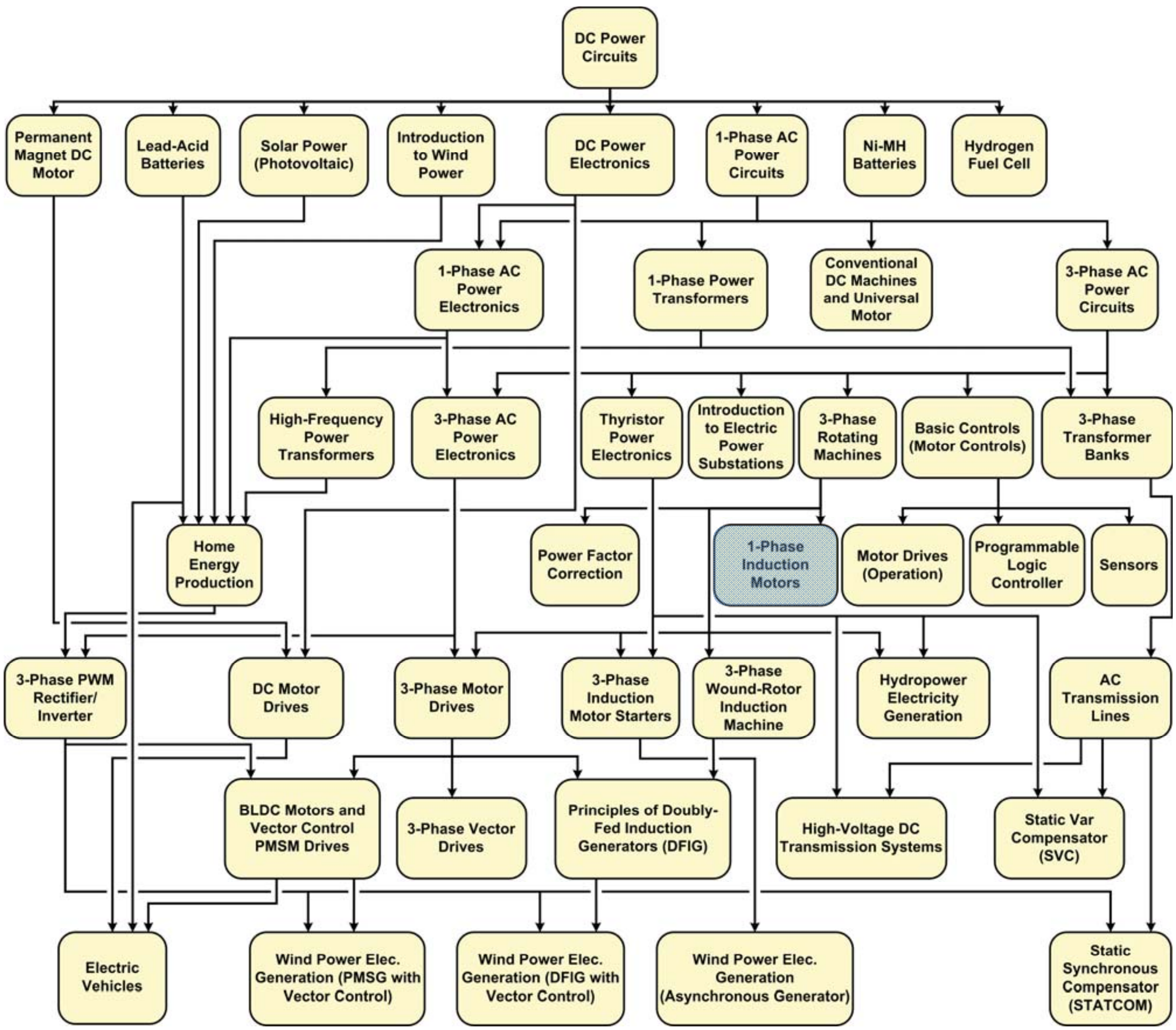
| Symbol | Description |
|---|---|
|  | Protective conductor terminal |
|  | Frame or chassis terminal |
|  | Equipotentiality |
|  | On (supply) |
|  | Off (supply) |
|  | Equipment protected throughout by double insulation or reinforced insulation |
|  | In position of a bi-stable push control |
|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

# Table of Contents

# 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.

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 present manual, *Single-Phase Induction Motors*, introduces the student to the operation and characteristics of the following two types of single-phase induction motor: capacitor-start induction motor and split-phase induction motor. These motors, although still in use in numerous applications today, are less common in modern applications where they are often replaced with three-phase induction motor drives (i.e., a three-phase squirrel-cage induction motor plus a variable-frequency, three-phase inverter) for added flexibility of operation and improved performance.

## 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 and *Single-Phase AC power Circuits*, part number 86358.

## Systems of units

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

# AC Induction Motors

**MANUAL OBJECTIVE**

When you have completed this manual, you will be able to demonstrate the main operating characteristics of single-phase induction motors.

**DISCUSSION OUTLINE**

The Discussion of Fundamentals covers the following points:

- Introduction to ac induction motors

**DISCUSSION OF FUNDAMENTALS**

## Introduction to ac induction motors

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

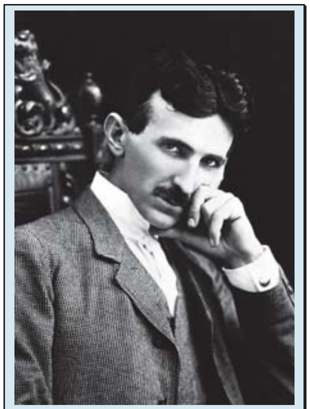


**Figure 1. The principles behind the operation of alternating-current motors are usually credited to scientist Nikola Tesla.**

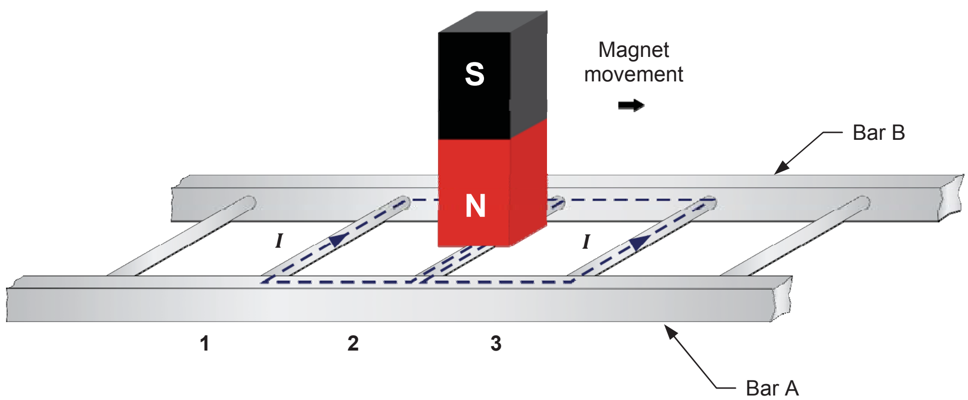



**Figure 2. Magnet moving above a conducting ladder.**

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

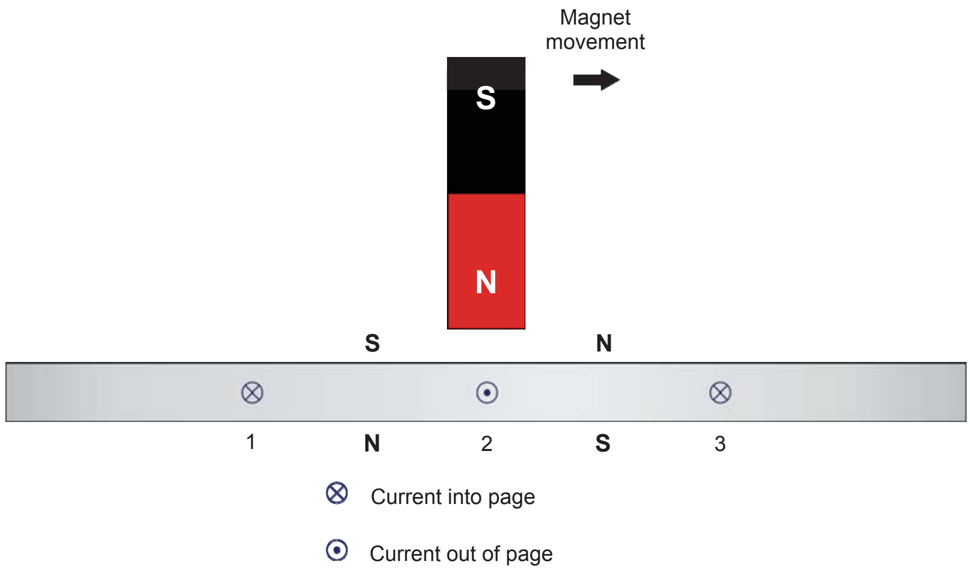



**Figure 3. Current in the conductors creates magnetic fields.**

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

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

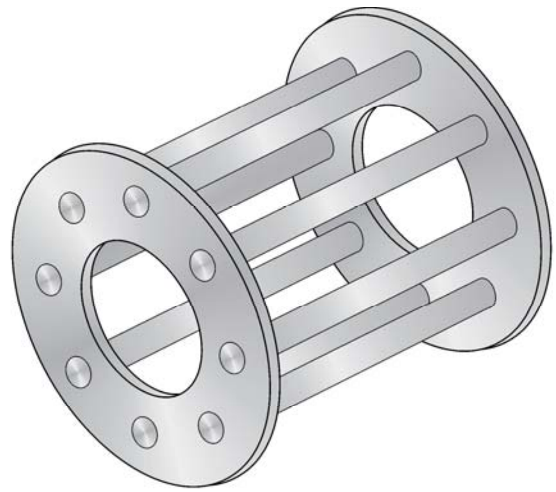


**Figure 4. Closing a ladder upon itself forms a squirrel cage.**

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

# Operation and Characteristics of Single-Phase Induction Motors

**EXERCISE OBJECTIVE**

When you have completed this exercise, you will be able to demonstrate the main operating characteristics of single-phase induction motors. You will start by studying what happens when a three-phase squirrel-cage induction motor is powered by the three phases, two phases, and one phase of the three-phase ac power source. You will know how to connect a capacitor and an auxiliary winding to a single-phase induction motor to allow this motor to start and rotate normally. Finally, you will know how to use a centrifugal switch to disconnect the auxiliary winding and capacitor of a single-phase induction motor once the motor starts rotating.

**DISCUSSION OUTLINE**

The Discussion of this exercise covers the following points:

- Simple single-phase squirrel-cage induction motor
- Adding a capacitor and an auxiliary winding to the single-phase induction motor
- Centrifugal switch

**DISCUSSION**

## Simple single-phase squirrel-cage induction motor

It is possible to obtain a single-phase squirrel-cage induction motor, using a simple electromagnet connected to a single-phase ac power source as shown in Figure 5.

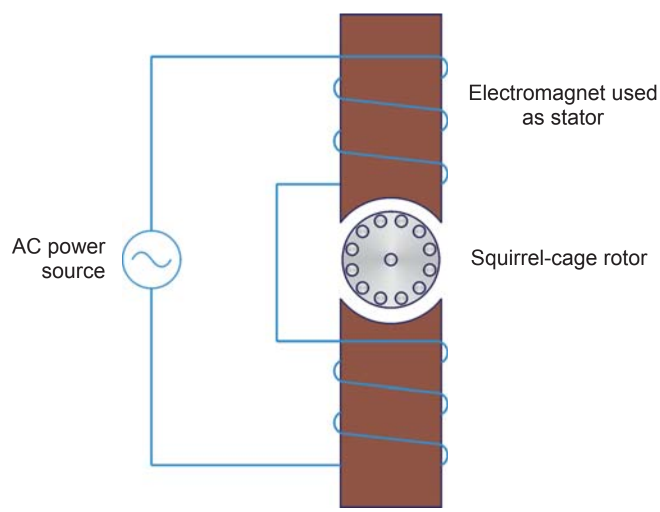



**Figure 5. Simple single-phase squirrel-cage induction motor.**

The operating principle of the **single-phase induction motor** is more complex than that of the three-phase squirrel-cage induction motor. The simple single-phase induction motor of Figure 5 can even be considered as an **eddy-current brake** that brakes in an intermittent manner since the sinusoidal current in the stator electromagnet continually passes from peaks to zeros. One could even wonder how this motor can turn since it seems to operate in a way similar to the eddy-current brake.

However, when the rotor of the simple single-phase induction motor of Figure 5 is turned manually, a torque which acts in the direction of rotation is produced, and the motor continues to turn as long as ac power is supplied to the stator electromagnet. This torque is due to a rotating magnetic field that results from the interaction of the magnetic field produced by the stator electromagnet and the magnetic field produced by the currents induced in the rotor. Figure 6 shows a graph of the torque versus rotation speed for this type of motor. The curve shows that the torque is very small at low speeds. It increases to a maximum value as the speed increases, and finally decreases toward zero again when the speed approaches the synchronous speed $n_S$.

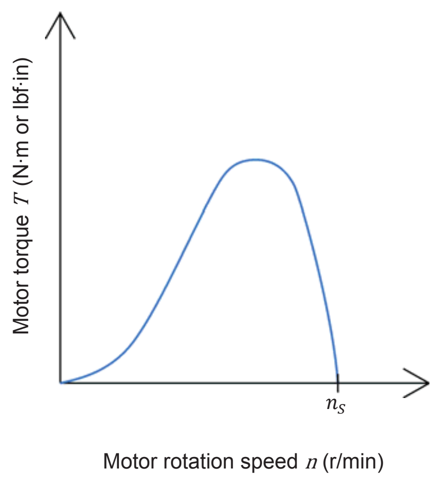



**Figure 6. Torque-versus-rotation speed curve of a single-phase induction motor.**

The low torque values at low speeds are due to the fact that the currents induced in the rotor produce magnetic fields that create forces which act on the rotor in various directions. Most of these forces cancel each other and the resulting force acting on the rotor is weak. This explains why the single-phase induction motor shown in Figure 5 must be started manually. To obtain torque at low speeds (starting torque), a rotating magnetic field must be produced in the stator when the motor is starting. A rotating magnetic field can be produced by using two alternating currents, $I_1$ and $I_2$, that are phase shifted 90° from one another, and two electromagnets placed at right angles to each other.

Figure 7 shows the simple single-phase induction motor of Figure 5 with the addition of a second electromagnet placed at right angle to the first electromagnet. The second electromagnet is identical to the first one and is connected to the same ac power source. The currents $I_1$ and $I_2$ in the electromagnets (winding currents) are in phase because the coils have the same impedance. However, because of the inductance of the coils of the electromagnets, there is a phase shift between the currents $I_1$ and $I_2$ and the ac source voltage $E_S$, as shown in the phasor diagram of Figure 7.

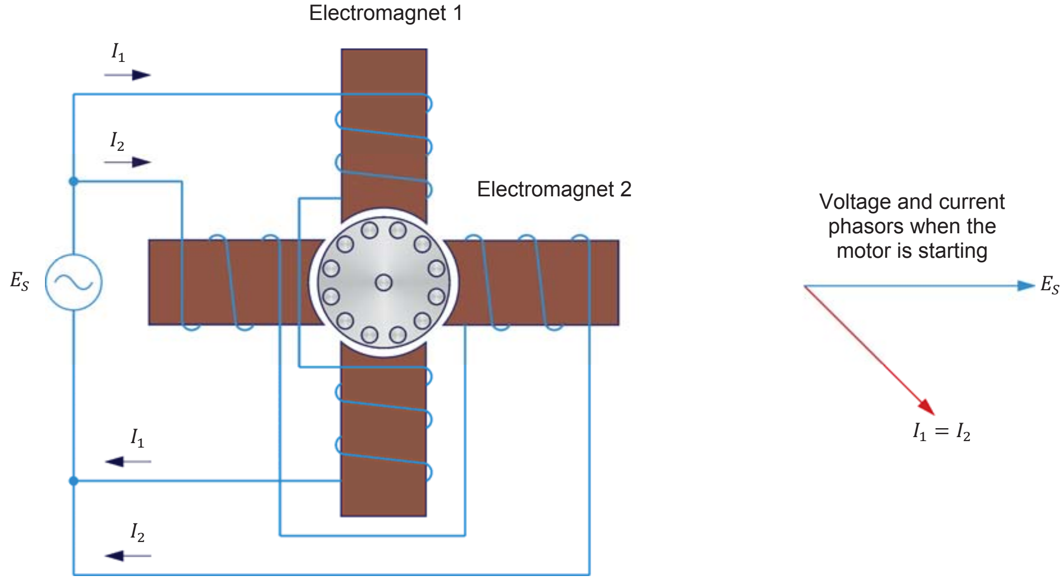
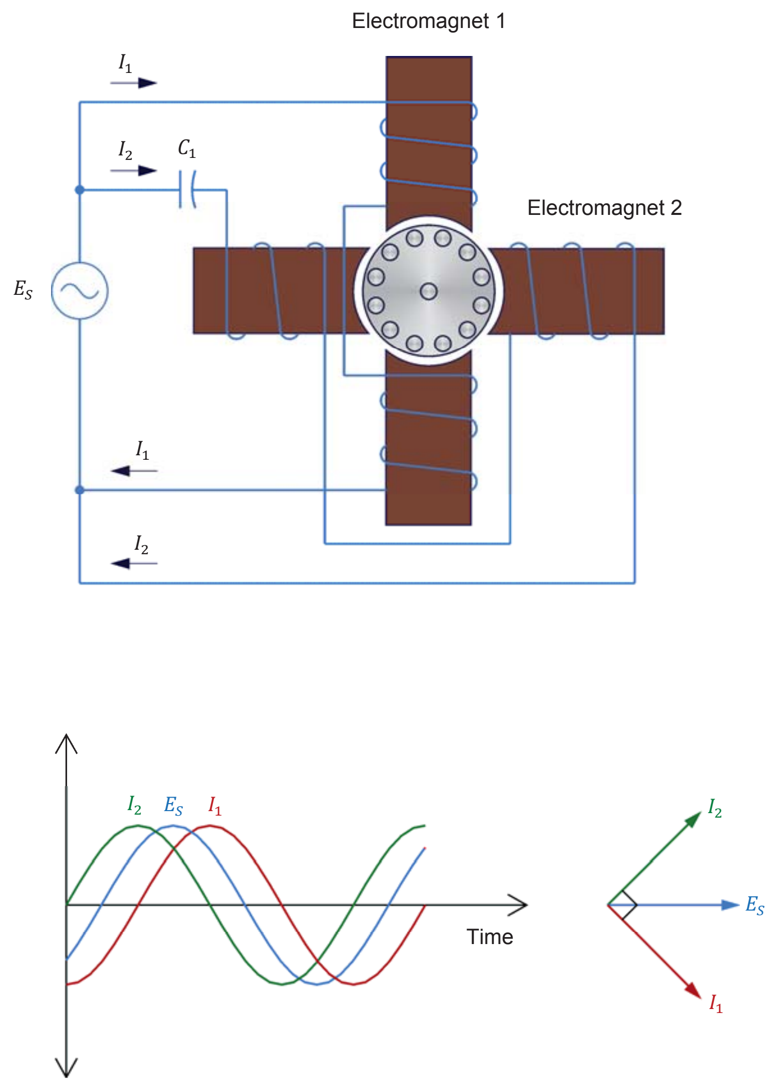



**Figure 7. Adding a second electromagnet to the single-phase induction motor of Figure 5.**

## Adding a capacitor and an auxiliary winding to the single-phase induction motor

Since currents $I_1$ and $I_2$ in the electromagnets (winding currents) of Figure 7 are in phase, there is no rotating magnetic field produced in the motor stator. However, it is possible to phase shift current $I_2$ by connecting a capacitor ($C_1$) in series with the winding of electromagnet 2 as shown in Figure 8. The capacitance of capacitor $C_1$ can be selected so that current $I_2$ leads current $I_1$ by 90° when the motor is starting. As a result, a rotating magnetic field is created when the motor is starting. The capacitor creates the equivalent of a two-phase ac power source and allows the motor to develop starting torque.




Waveforms and phasors when the motor is starting

**Figure 8. Adding a capacitor to the single-phase induction motor allows the motor to develop starting torque.**

Another way to create a phase shift between currents $I_1$ and $I_2$ is to use a winding with fewer turns of smaller-sized wire. The resulting winding, which is called **auxiliary winding**, has more resistance and less inductance, and the winding current is almost in phase with the source voltage. Although the phase shift between the two currents is less than 90° when the motor is starting, as shown in Figure 9, a rotating magnetic field is created. The torque produced is sufficient for the motor to start rotating in applications not requiring high values of starting torque. Such a motor with an auxiliary winding is called a split-phase induction motor.

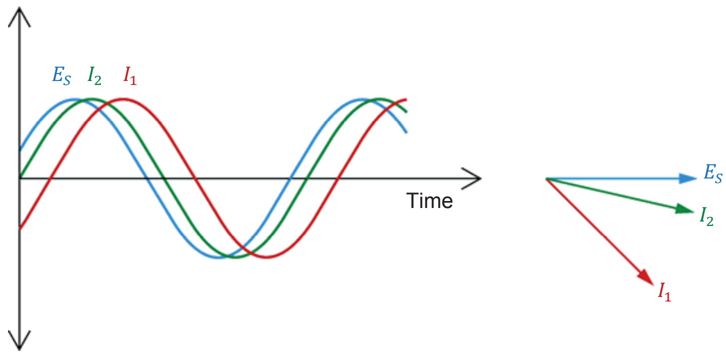



**Figure 9. Phase shift between the winding currents when an auxiliary winding is used.**

## Centrifugal switch

The auxiliary winding cannot support high currents for more than a few seconds without being damaged because it is made of fine wire. It is therefore connected through a **centrifugal switch** that opens and disconnects the winding from the motor circuit when the motor reaches about 75% of the normal speed. When the centrifugal switch opens, the rotating magnetic field is maintained by the interaction of the magnetic fields produced by the stator and the rotor.

**Figure 10. Single-phase induction motors are used in conventional washing machines, refrigerators, pumps, compressors, and air conditioners.**

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Three-phase, two-phase, and single-phase operation of a three-phase squirrel-cage induction motor
- Operation of a single-phase induction motor (split-phase and capacitor-start types)

## 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 squirrel-cage induction motor and the equipment required to measure the motor parameters.*

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

2. On the Power Supply, make sure that the main power switch and the 24-V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

3. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24-V ac power source of the Power Supply.

   Turn the 24-V ac power source of the Power Supply on.

4. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

5. Connect the equipment as shown in Figure 11. Use the variable, three-phase ac voltage output of the Power Supply to implement the variable-voltage ac power source. *E1*, *I1*, *I2*, and *I3* are voltage and current inputs of the Data Acquisition and Control Interface (DACI).

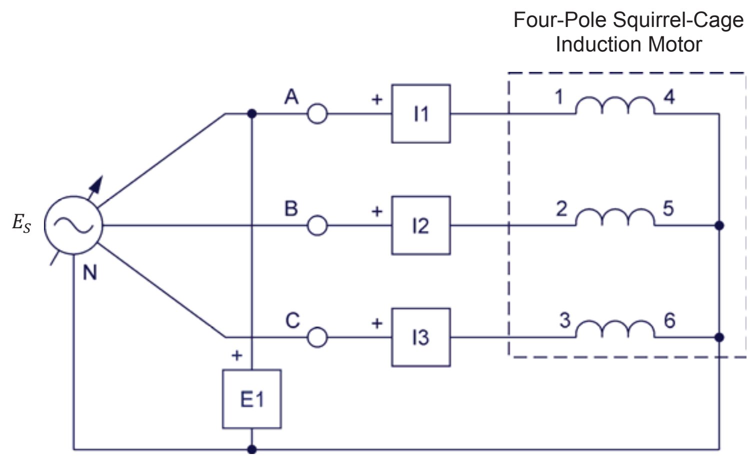



**Figure 11. Three-phase squirrel-cage induction motor.**

6. Turn the host computer on, then start the LVDAC-EMS software.

   In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface is detected. Make sure that the Computer-Based Instrumentation function for the Data Acquisition and Control Interface is available. Select the 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.

7. In LVDAC-EMS, open the Metering window. Set four meters to measure the rms values of the phase voltage $E_{1-N}$ (input *E1*) and line currents (inputs *I1*, *I2*, and *I3*) of the three-phase ac power source $E_S$.

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

## Three-phase, two-phase, and single-phase operation of a three-phase squirrel-cage induction motor

*In this section, you will observe the operation of a three-phase squirrel-cage induction motor when it is powered by the three phases, two phases, and one phase of the three-phase ac power source, using the Phasor Analyzer.*

8. Turn the Power Supply on by setting the main power switch to the **I** (on) position, then set the voltage control knob so that the voltage applied to each of the motor windings (indicated by meter *E1* in the Metering window) is equal to the nominal voltage of these windings.

   *The nominal voltage and current of the windings of the Four-Pole Squirrel-Cage Induction Motor are indicated on the module front panel.*

Does the Four-Pole Squirrel-Cage Induction Motor start readily and rotate normally?

❑ Yes ❑ No

**9.** In LVDAC-EMS, open the Phasor Analyzer. Set the phasor of voltage $E_{1-N}$ (*E1*) as the reference phasor, then make the appropriate settings in order to observe this phasor, as well as the phasors of the line currents measured using inputs *I1*, *I2*, and *I3* of the Data Acquisition and Control Interface (i.e., the currents in the three-phase squirrel-cage induction motor).

Are the line current phasors (*I1*, *I2*, and *I3*) all equal in magnitude and separated by a phase angle of 120°, thus confirming that they create a normal rotating magnetic field?

❑ Yes ❑ No

**10.** Turn the Power Supply off by setting the main power switch to the O (off) position. (Leave the 24-V ac power source of the Power Supply turned on.)

Open the circuit at point A shown in Figure 11. Make sure that voltage input *E1* of the Data Acquisition and Control Interface remains connected to the ac power source $E_S$.

**11.** Turn the Power Supply on by setting the main power switch to the I (on) position.

Does the Four-Pole Squirrel-Cage Induction Motor start readily and rotate normally?

❑ Yes ❑ No

In the Phasor Analyzer window, observe the current phasors of inputs *I2* and *I3*. Is there a phase shift between these phasors to create a rotating magnetic field?

❑ Yes ❑ No

**12.** Turn the Power Supply off by setting the main power switch to the O (off) position and the voltage control knob to 0%. (Leave the 24-V ac power source of the Power Supply turned on.)

Open the circuit at point B in Figure 11. Leave the circuit open at point A.

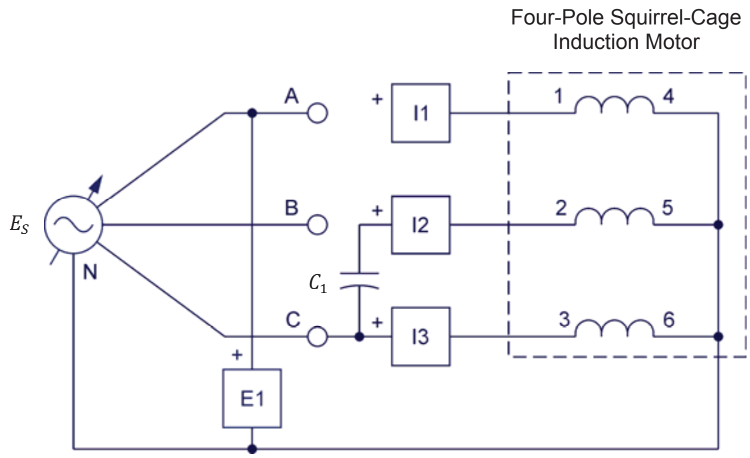
 

**13.** Turn the Power Supply on by setting the main power switch to the **I** (on) position, then set the voltage control knob to about 50% and wait approximately 5 seconds. Turn the Power Supply off by setting the main power switch to the **O** (off) position and the voltage control knob to 0%. (Leave the 24-V ac power source of the Power Supply turned on.)

Does the squirrel-cage induction motor start readily and rotate normally?

❑ Yes ❑ No

**14.** Connect a capacitor ($C_1$) to the motor circuit as shown in Figure 12. Use the Capacitive Load module to implement capacitor $C_1$. The capacitance value to be used for this capacitor depends on your local ac power network voltage and frequency (see table in the diagram).




| Local ac power network | | $C_1$ (µF) |
|---|---|---|
| **Voltage (V)** | **Frequency (Hz)** | |
| 120 | 60 | 15.4 |
| 220 | 50 | 3.6 |
| 240 | 50 | 3.3 |
| 220 | 60 | 3.0 |

**Figure 12. Adding a capacitor to the motor circuit.**

**15.** Turn the Power Supply on by setting the main power switch to the **I** (on) position, then slowly set the voltage control knob to 100%. While doing this, observe the current phasors of inputs *I2* and *I3* on the Phasor Analyzer as the voltage increases.

Does the Four-Pole Squirrel-Cage Induction Motor start rotating? Briefly explain why.

________________________________________________________________

________________________________________________________________

________________________________________________________________

**16.** On the Capacitive Load module, set the levers of all toggle switches to the O (off) position to disconnect the capacitor from the motor circuit and stop current flow in one of the two windings of the Four-Pole Squirrel-Cage Induction Motor.

Does the motor continue to rotate, thus showing that it can operate on single-phase ac power once it has started?

❑ Yes ❑ No

**17.** Turn the Power Supply off by setting the main power switch to the O (off) position and the voltage control knob to 0%. (Leave the 24-V ac power source of the Power Supply turned on.)

## Operation of a single-phase induction motor (split-phase and capacitor-start types)

*In this section, you will observe the operation of a single-phase induction motor using the Capacitor-Start Motor and the Phasor Analyzer.*

**18.** Remove all leads except the lead connecting the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24-V ac power source of the Power Supply.

Connect the capacitor-start motor circuit shown in Figure 13. Use one phase (terminals *4* and *N*) of the variable, three-phase ac voltage output of the Power Supply to implement the variable-voltage, single-phase ac power source. *E1* and *I1* are voltage and current inputs of the Data Acquisition and Control Interface (DACI).

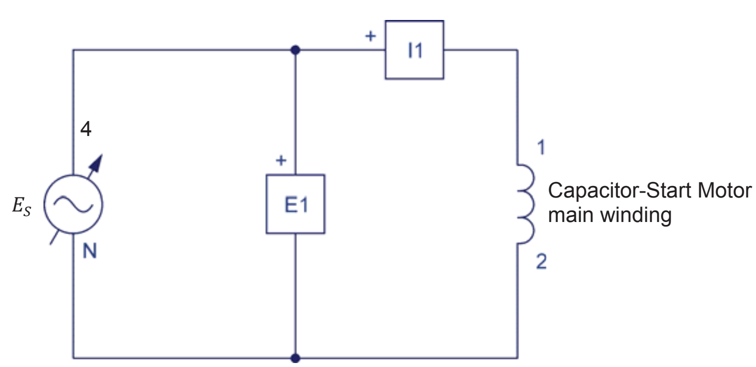



**Figure 13. Capacitor-start motor circuit.**

**19.** Turn the Power Supply on by setting the main power switch to the I (on) position, then set the voltage control knob to 10%.

In the Phasor Analyzer window, make the appropriate settings in order to observe the source voltage phasor (*E1*) and current phasor (*I1*). Observe that the current phasor (representing the main winding current) lags the source voltage phasor.

On the Power Supply, set the voltage control knob to 50%.

Does the Capacitor-Start Motor start rotating?

❑ Yes ❑ No

**20.** Turn the Power Supply off by setting the main power switch to the O (off) position and the voltage control knob to 0%. (Leave the 24 V ac power source of the Power Supply turned on.)

Connect the auxiliary winding of the Capacitor-Start Motor and input *I2* of the Data Acquisition and Control Interface as shown in Figure 14. Note that this setup, even though it uses the Capacitor-Start Motor, corresponds in fact to a split-phase induction motor.

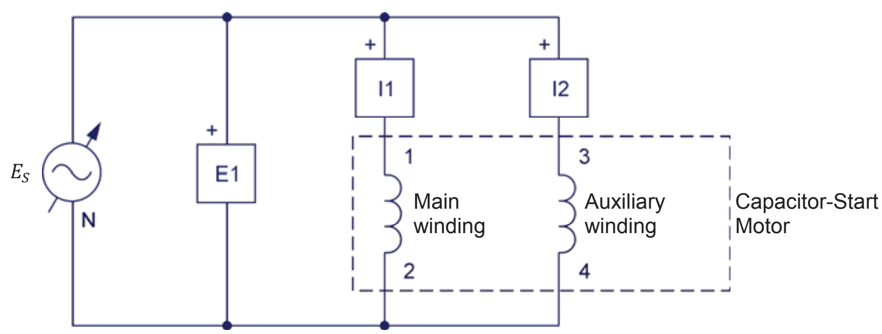



**Figure 14. Connecting the auxiliary winding to implement a split-phase induction motor.**

**21.** Turn the Power Supply on by setting the main power switch to the I (on) position, then slowly set the voltage control knob to about 10%.

On the Phasor Analyzer, observe the current phasors (*I1* and *I2*). These phasors represent the main winding current and the auxiliary winding current, respectively.

Is the phase shift of the auxiliary-winding current phasor (*I2*) with respect to the source voltage phasor (*E1*) less than that of the main-winding current phasor, thus confirming that the impedance of the auxiliary winding is more resistive and less inductive when the motor is starting?

❑ Yes ❑ No

Is the phase shift between the current phasors (*I1* and *I2*) less than 90°?

❑ Yes ❑ No

**22.** On the Power Supply, set the voltage control knob to 50%. Does the Capacitor-Start Motor start rotating?

❑ Yes ❑ No

Turn the Power Supply off by setting the main power switch to the O (off) position and the voltage control knob to 0%. (Leave the 24-V ac power source of the Power Supply turned on.)

**CAUTION**

The nominal current of the auxiliary winding of the Capacitor-Start Motor may be exceeded while performing this manipulation. Therefore, complete the manipulation within a time interval as short as possible. If the circuit breaker on the Capacitor-Start Motor trips, turn the Power Supply off, reset the breaker, turn the Power Supply on and continue the manipulation.

**23.** Modify the capacitor-start motor circuit so that the capacitor on the Capacitor-Start Motor is connected in series with the auxiliary winding as shown in Figure 15.

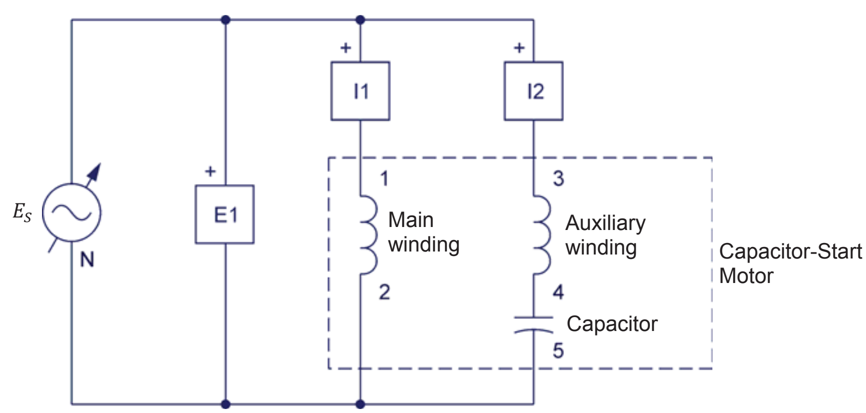



**Figure 15. Connecting a capacitor in series with the auxiliary winding.**

**24.** Turn the Power Supply on by setting the main power switch to the **I** (on) position, then slowly set the voltage control knob to about 10%.

Observe the current phasors (*I1* and *I2*) on the Phasor Analyzer.

Does connecting a capacitor in series with the auxiliary winding create a phase shift of approximately 90° between the current phasors?

❑ Yes ❑ No

On the Power Supply, set the voltage control knob to 50%. Does the Capacitor-Start Motor start rotating?

❑ Yes ❑ No

Let the motor operate during a few minutes while observing the current phasors (*I1* and *I2*) on the Phasor Analyzer.

Describe what happens.

______________________________________________

______________________________________________

______________________________________________

**25.** Turn the Power Supply off by setting the main power switch to the O (off) position and the voltage control knob to 0%. (Leave the 24-V ac power source of the Power Supply turned on.)

On the Capacitor-Start Motor, reset the tripped circuit breaker.

Modify the capacitor-start motor circuit by connecting the centrifugal switch on the Capacitor-Start Motor in series with the auxiliary winding and the capacitor as shown in Figure 16.

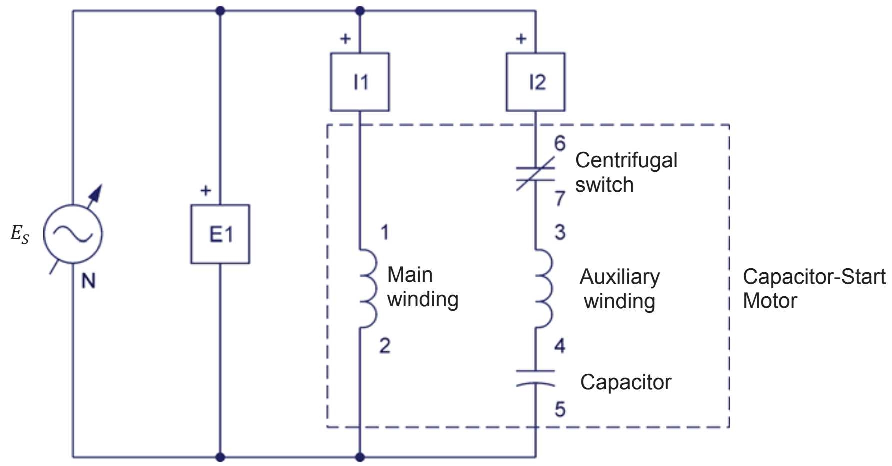



**Figure 16. Connecting a centrifugal switch in series with the auxiliary winding and capacitor.**

**26.** Turn the Power Supply on by setting the main power switch to the I (on) position and slowly set the voltage control knob to about 100%. While doing this, observe the current phasors (*I1* and *I2*) on the Phasor Analyzer as the voltage increases.

Does the Capacitor-Start Motor start rotating?

❑ Yes ❑ No

Briefly explain why the auxiliary-winding current phasor (*I2*) decreases to zero a little after the motor has started rotating.

______________________________________________

______________________________________________

______________________________________________

**27.** Turn the Power Supply off by setting the main power switch to the O (off) position and the voltage control knob to 0%, then turn the 24-V ac power source off. Close the LVDAC-EMS software. Disconnect all leads and return them to their storage location.

## Conclusion

In this exercise, you observed that a three-phase squirrel-cage induction motor starts and runs almost normally when powered by only two phases of a three-phase ac power source, because a rotating magnetic field is maintained. However, you saw that when only one phase is connected to the motor, there is no rotating magnetic field and the motor is not able to start rotating. You demonstrated that adding an auxiliary winding and a capacitor to an induction motor allows it to start and run normally when powered by a single-phase ac power source. You saw that this produces two currents (the main- and auxiliary-winding currents) that are phase shifted by approximately 90°, and that these currents produce the necessary rotating magnetic field when the motor is starting. Finally, you observed that a centrifugal switch is used to disconnect the auxiliary winding when the single-phase induction motor reaches sufficient speed to maintain the rotating magnetic field.

## Review Questions

1. When a three-phase squirrel-cage induction motor is powered by only two phases of the three-phase ac power source, how does the motor rotate?

_______________________________________________

_______________________________________________

2. When a three-phase squirrel-cage induction motor is powered by only one phase of the three-phase ac power source, does the motor rotate normally?

_______________________________________________

_______________________________________________

3. Why does adding an auxiliary winding and a capacitor to a single-phase induction motor help improve the operation of the motor?

_______________________________________________

_______________________________________________

4. Explain why single-phase induction motors of the capacitor-start type use a centrifugal switch.

_______________________________________________

_______________________________________________

_______________________________________________

_______________________________________________

5. Explain why the auxiliary winding has higher resistance and lower resistance.

_______________________________________________

_______________________________________________

# Equipment Utilization Chart

The following equipment is required to perform the exercise in this manual.

| Equipment | | Exercise 1 |
|---|---|---|
| Model | Description | |
| 8134-2[1] | Workstation | 1 |
| 8221-2[2] | Four-Pole Squirrel-Cage Induction Motor | 1 |
| 8251 | Capacitor-Start Motor | 1 |
| 8331 | Capacitive Load | 1 |
| 8821 | Power Supply | 1 |
| 8951-L | Connection Leads | 1 |
| 8990 | Personal Computer | 1 |
| 9063-B[3] | Data Acquisition and Control Interface | 1 |

[1] The Mobile Workstation, Model 8110-2, can also be used.
[2] Model 8221-0 can also be used.
[3] Model 9063-B consists of the Data Acquisition and Control Interface, Model 9063, with control function set 9069-1.

# Glossary of New Terms

**auxiliary winding** — Winding used to create a phase shift between currents in the stator of the single-phase induction motor. This increases the starting torque and helps the motor start. The auxiliary winding has fewer turns of smaller-sized wire than the main winding, and thus has more resistance and less inductance than the main winding.

**centrifugal switch** — Switch operating by centrifugal force that disconnects the auxiliary winding once the single-phase induction motor starts rotating. This is necessary because the auxiliary winding cannot support high currents for more than a few seconds without being damaged since it is made of fine wire.

**eddy-current brake** — A fixed electromagnet that creates braking torque which acts on a squirrel-cage rotor.

**electromagnetic induction** — Electromagnetic induction consists in the production of an electromotive force (i.e., an induced voltage) in a circuit resulting from a change in the magnetic flux passing through that circuit. For example, a voltage is induced between the ends of a wire loop when the magnetic flux passing through the loop varies as a function of time

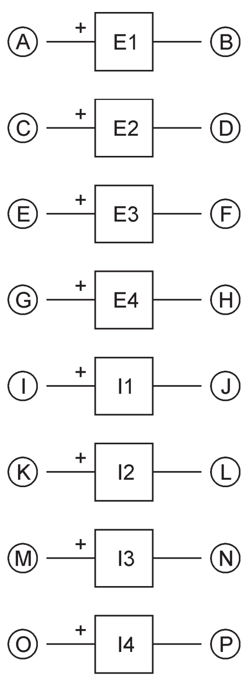
**single-phase induction motor** — Induction motor powered by a single-phase ac power source. The following two types of single-phase induction motor are commonly used: capacitor-start induction motor and split-phase induction motor.

# Circuit Diagram Symbols

Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using the equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown on the circuit diagram, and thus, makes it easier to understand the circuit operation.

For each symbol other than those of power sources, resistors, inductors, and capacitors, this appendix gives the name of the device which the symbol represents, as well as the equipment and the connections required to properly connect the device to a circuit. Notice that the terminals of each symbol are identified using circled letters. The same circled letters identify the corresponding terminals in the Equipment and Connections diagram. Also notice that the numbers (when present) in the Equipment and Connections diagrams correspond to terminal numbering used on the actual equipment.

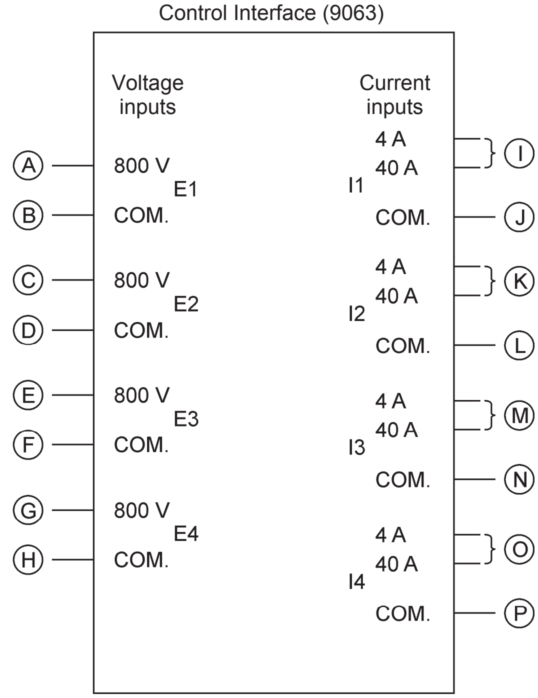
**Symbol**




Isolated voltage and current measurement inputs

**Equipment and Connections**

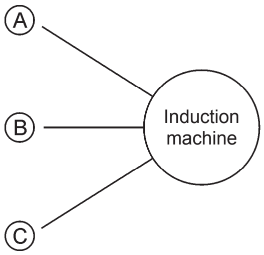
Data Acquisition and Control Interface (9063)




*When a current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.*

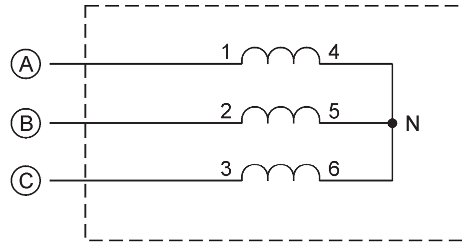
## Symbol

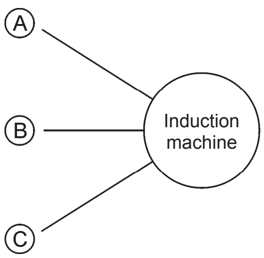
## Equipment and Connections




Three-phase induction machine

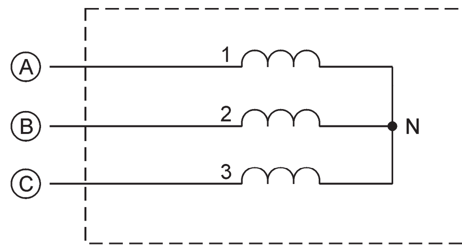
Four-Pole Squirrel Cage Induction Motor (8221-0)

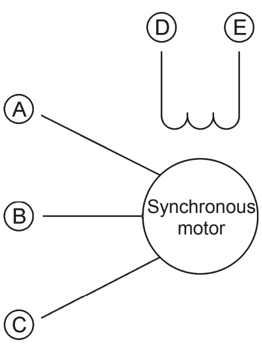



Three-phase induction machine

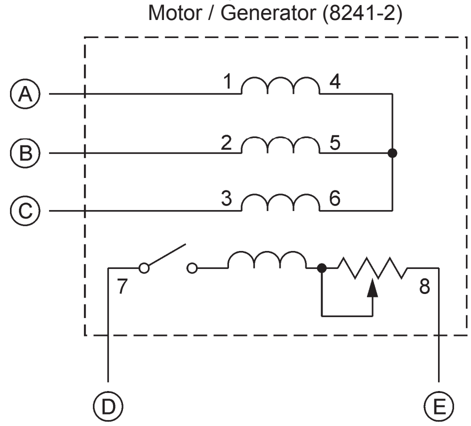
Three-Phase Induction Machine (8221-2)



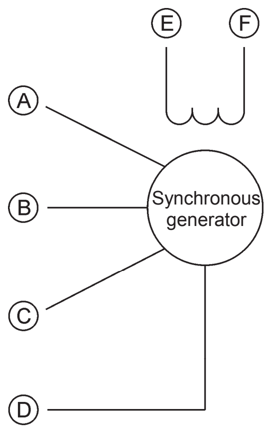




Three-phase synchronous motor

Synchronous Motor / Generator (8241-2)



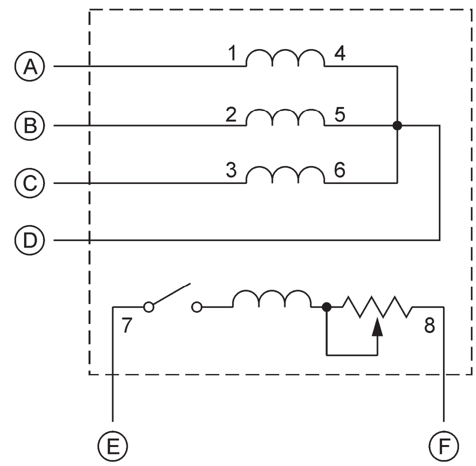
## Symbol

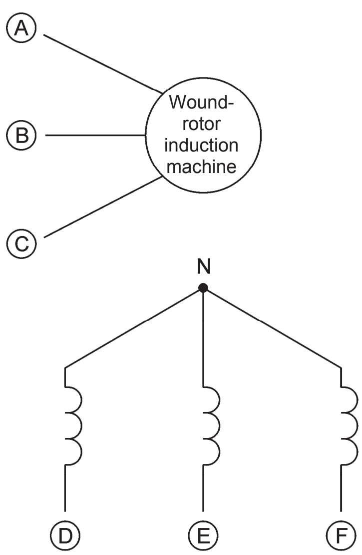



Three-phase synchronous generator

## Equipment and Connections

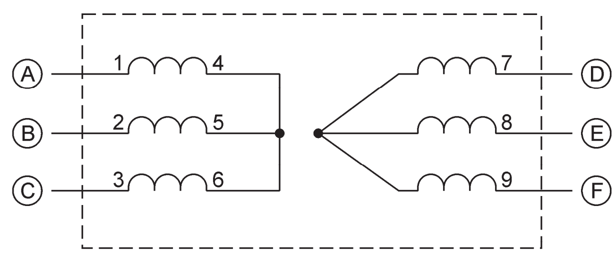
Synchronous Motor / Generator (8241-2)



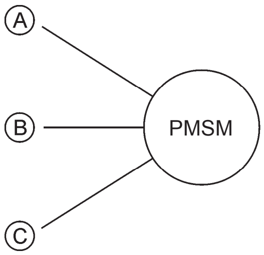

Three-phase wound-rotor induction machine

Three-Phase Wound-Rotor Induction Machine (8231-B)



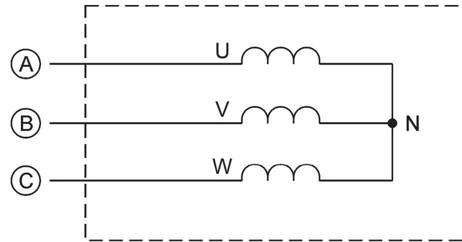
## Symbol

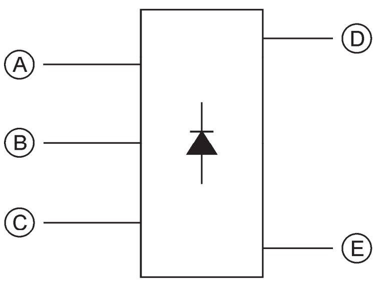
## Equipment and Connections




Permanent Magnet Synchronous Machine

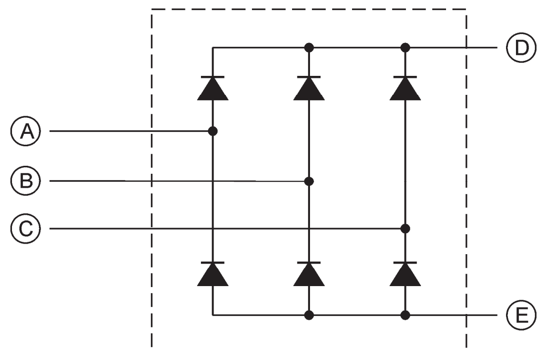
Permanent Magnet Synchronous Machine (8245)

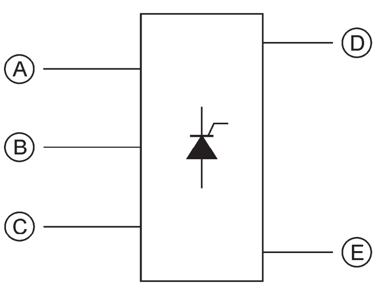



Power diode three-phase full-wave rectifier

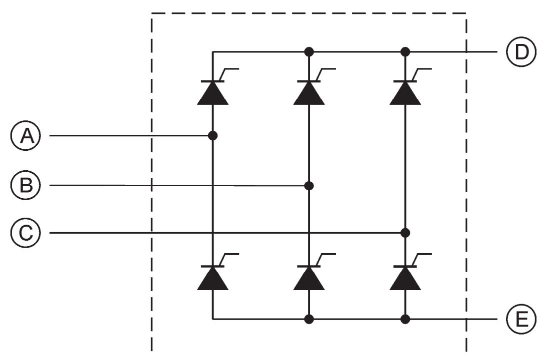
Rectifier and Filtering Capacitors (8842-A)

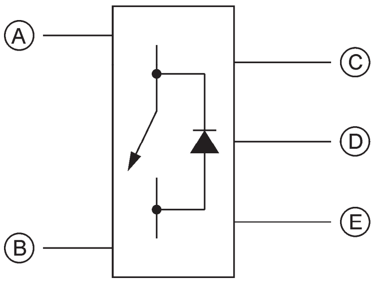
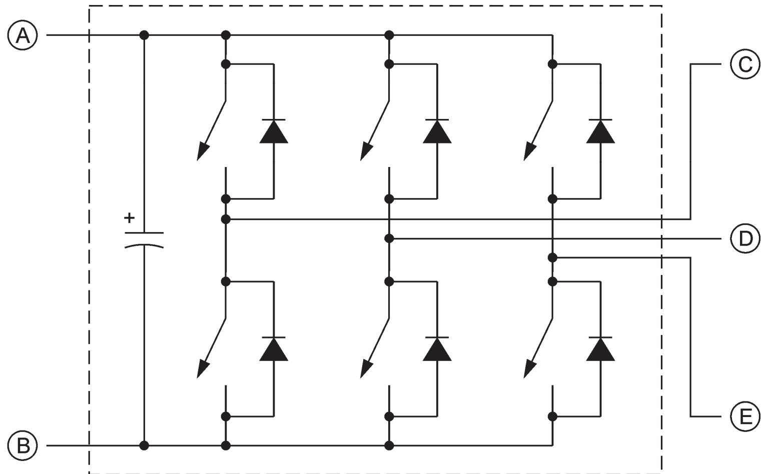



Power thyristor three-phase bridge

Power Thyristors (8841)



| **Symbol** | **Equipment and Connections** |
| --- | --- |
| <br>Three-phase inverter | IGBT Chopper / Inverter<br>(8837-B)<br> |

# Index of New Terms

*The bold page number indicates the main entry. Refer to the Glossary of New Terms for definitions of new terms.*

# Bibliography

Boylestad, Robert L., *Introductory Circuit Analysis*, 11th Edition, Upper Saddle River: Prentice Hall, 2006, ISBN 978-0131730441.

Wildi, Theodore, *Electrical Machines, Drives, and Power Systems*, 6th Edition, Upper Saddle River: Prentice Hall, 2005, ISBN 978-0131776913.