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FESTO

Student Manual

Three-Phase AC Power Circuits

Three-Phase AC Power Circuits

FESTO

Electricity and New Energy

LabVolt Series

Student Manual

Festo Didactic
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Electricity and New Energy

Three-Phase AC Power Circuits

Student Manual

579374

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Safety and Common Symbols

The following safety and common symbols may be used in this course 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. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
	Direct current

Safety and Common Symbols

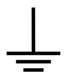
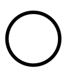
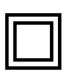
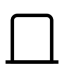
Symbol	Description
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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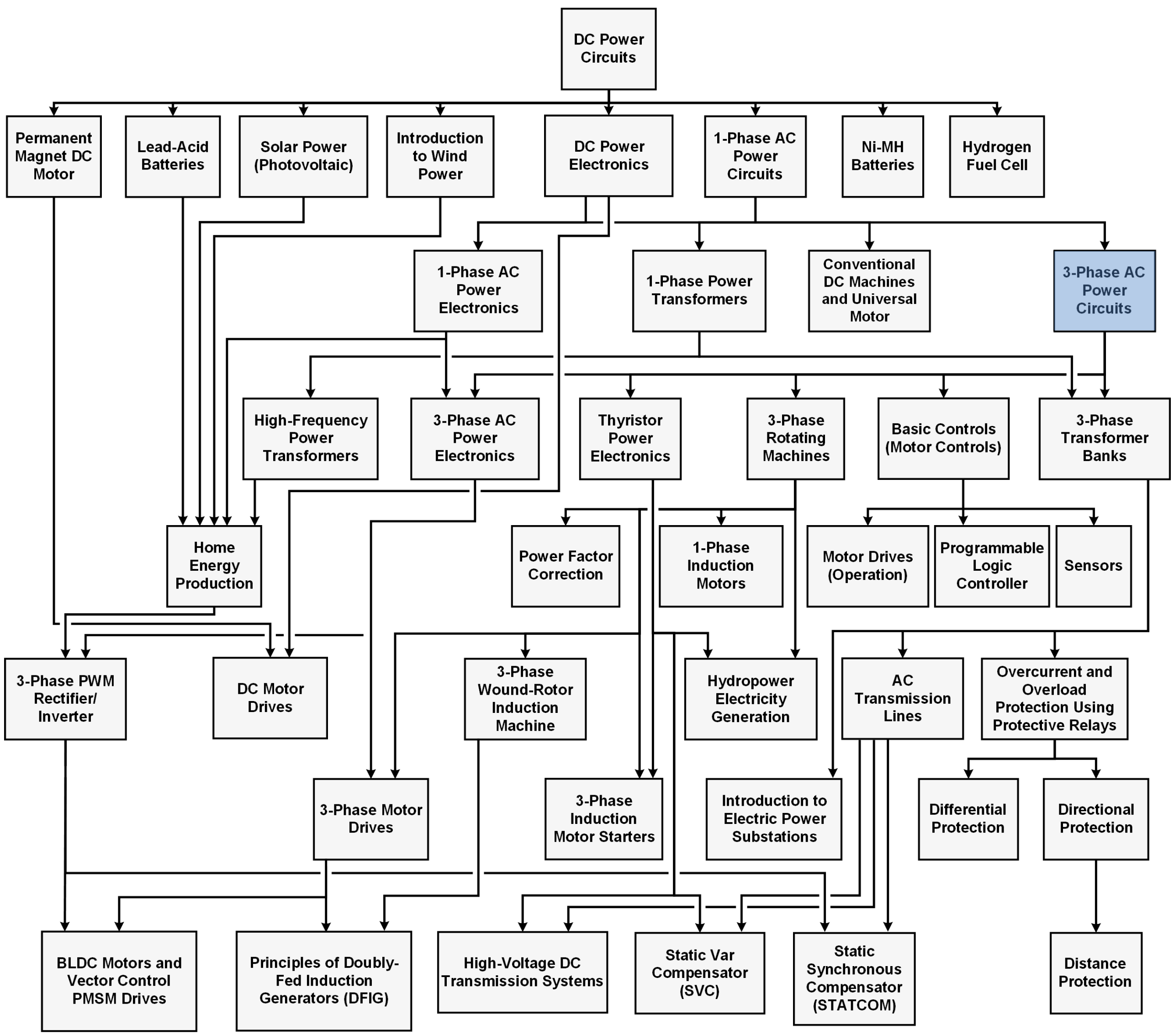
Table of Contents

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 motor starters and drives, storage of electrical energy in batteries, home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, protective relaying, and smart-grid technologies (SVC, STATCOM, HVDC transmission systems, etc.).

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

Three-phase ac power is one of the most common forms of electric power distribution worldwide. Many countries use three-phase ac power for power distribution since it is simpler, cheaper, and more efficient than single-phase ac power. Although most homes and small buildings are wired for single-phase ac power, they tap power off basic three-phase power distribution lines.

Three-phase ac power has several advantages over other means of power distribution. The main advantage is that, since the phase currents of three-phase power cancel each other out, it is possible to reduce the size of the neutral wire or to eliminate it altogether. This means that three-phase power lines can deliver more power for a given equipment weight and cost. Three-phase power systems also yield a more constant power transfer, which reduces the vibrations observed when motors and alternators (especially large ones) are connected to the system. Although it is possible for a polyphase power system to have more than three phases, three-phase power is the type of polyphase system having the lowest number of phases to exhibit the advantages mentioned above. Power distribution systems having a higher number of phases are for the moment simply too complex and costly to justify their common use.

This course, *Three-Phase AC Power Circuits*, teaches the basic concepts of three-phase ac power. The student is introduced to the two basic types of three-phase circuit connections: the wye (star) and delta configurations. The student learns how to calculate phase and line voltages, phase and line currents, phase balance, etc. The student then learns how to measure power in three-phase circuits using the two-wattmeter method as well as how to determine the power factor. Finally, the student learns what the phase sequence is and how to determine the phase sequence of a three-phase power system.

Safety considerations

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

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.

About This Course

Three-phase power distribution lines.[1]

Prerequisite

As a prerequisite to this course, you should have completed the following courses: *DC Power Circuits* and *Single-Phase AC Power Circuits*.

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).

[1] Photo byWing-Chi Poon, June 24, 2005 via Wikipedia: https://commons.wikimedia.org/wiki/File:Three_Phase_Electric_Power_Transmission.jpg. Available under a Creative Commons Attribution-Share Alike 2.5 Generic (CC BY-SA 2.5): https://creativecommons.org/licenses/by-sa/2.5.

Three-Phase Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will know what three-phase circuits are and how to solve balanced three-phase circuits connected in wye and delta configurations. You will also know the difference between line and phase voltages, and line and phase currents, as well as the relationship between line and phase parameter values in wye- and delta-connected three-phase circuits. You will know what the phase sequence of a three-phase circuit is. You will know how to calculate the active power dissipated in each phase of three-phase circuits, and how to calculate the total active power dissipated in a circuit. Finally, you will be able to use voltage and current measurements to verify the theory and calculations presented in this exercise.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to polyphase systems and three-phase circuits
- Wye and delta configurations
- Distinction between line and phase voltages, and line and phase currents
- Power in balanced three-phase circuits

DISCUSSION

Introduction to polyphase systems and three-phase circuits

A polyphase system is basically an ac system composed of a certain number of single-phase ac systems having the same frequency and operating in sequence. Each phase of a polyphase system (i.e., the phase of each single-phase ac system) is displaced from the next by a certain angular interval. In any polyphase system, the value of the angular interval between each phase depends on the number of phases in the system. This course covers the most common type of polyphase system: the three-phase system.

Three-phase systems, also referred to as three-phase circuits, are polyphase systems that have three phases, as their name implies. They are no more complicated to solve than single-phase circuits. In the majority of cases, three-phase circuits are symmetrical and they have identical impedances in each of their three branches (phases). Each branch can be treated exactly as a single-phase circuit, because a **balanced three-phase circuit** is simply a combination of three single-phase circuits. Therefore, voltage, current, and power relationships for three-phase circuits can be determined using the same basic equations and methods developed for single-phase circuits. Non-symmetrical, or unbalanced, three-phase circuits represent a special condition and their analysis is more complex. Unbalanced three-phase circuits are not covered in detail in this course.

A three-phase ac circuit is powered by three voltage sine waves having the same frequency and magnitude and which are displaced from each other by 120°. The phase shift between each voltage waveform of a three-phase ac power source is therefore 120° (360°÷ 3 phases). Figure 1 shows an example of a simplified three-phase generator (alternator) producing three-phase ac power. A rotating magnetic field produced by a rotating magnet turns inside three identical coils of wire (windings) physically placed at a 120° angle from each other, thus producing three separate ac voltages (one per winding). Since the generator's rotating magnet turns at a fixed speed, the frequency of the ac power that is produced is constant, and the three separate voltages reach the maximal voltage value one after the other at phase intervals of 120°.

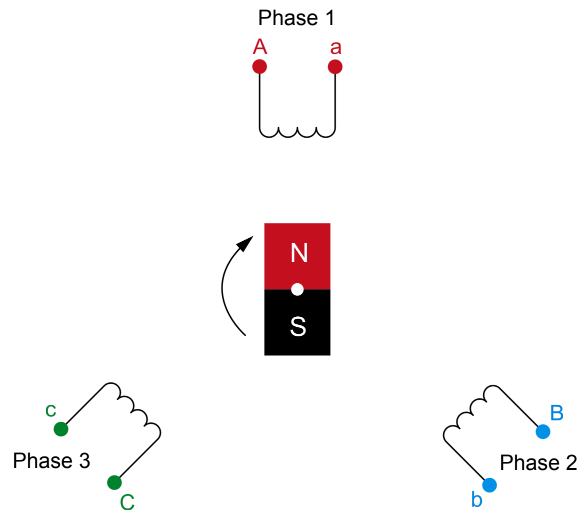
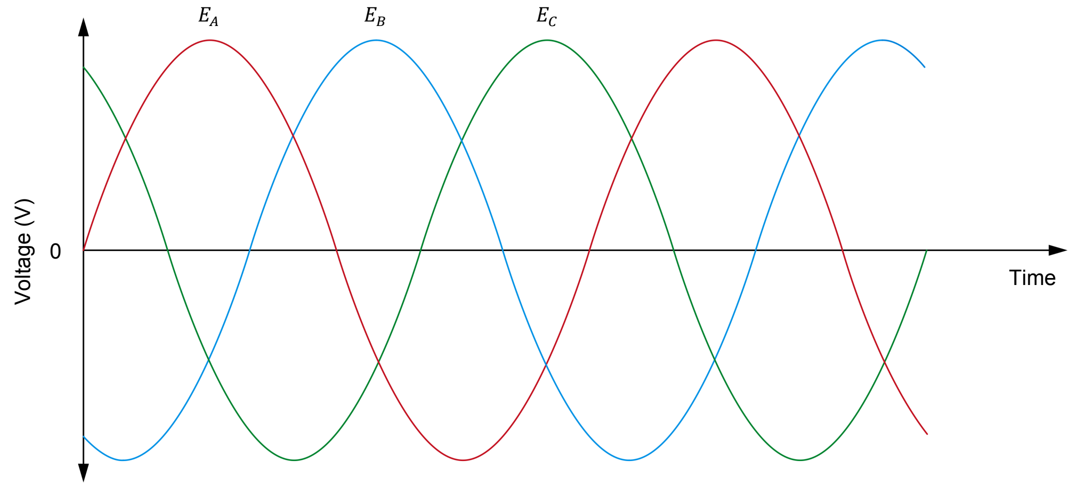


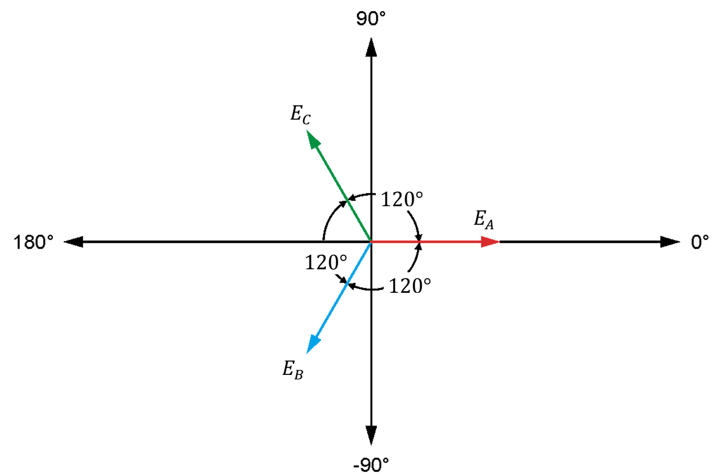
Figure 1. A simplified three-phase generator.

The **phase sequence** of the voltage waveforms of a three-phase ac power source indicates the order in which they follow each other and reach the maximal voltage value. Figure 2 shows an example of the voltage waveforms produced in a three-phase ac power source, as well as the phasor diagram related to the voltage waveforms. The voltage waveforms and voltage phasors in Figure 2 follow the phase sequence E_A, E_B, E_C, which, when written in shorthand form, is the sequence A-B-C. This phase sequence is obtained when the magnet in the three-phase generator of Figure 1 rotates clockwise.

The phase sequence of a three-phase ac power source is important because it determines the direction of rotation of any three-phase motor connected to the power source. If the phases are connected out of sequence, the motor will turn in the opposite direction, and the consequences can be serious. For example, if a three-phase motor rotating in the clockwise direction causes an elevator to go up, connecting the phase wires incorrectly to the motor would cause the elevator to go down when it is supposed to go up, and vice-versa, which could result in a serious accident.



(a) Voltage waveforms produced in a three-phase ac power source

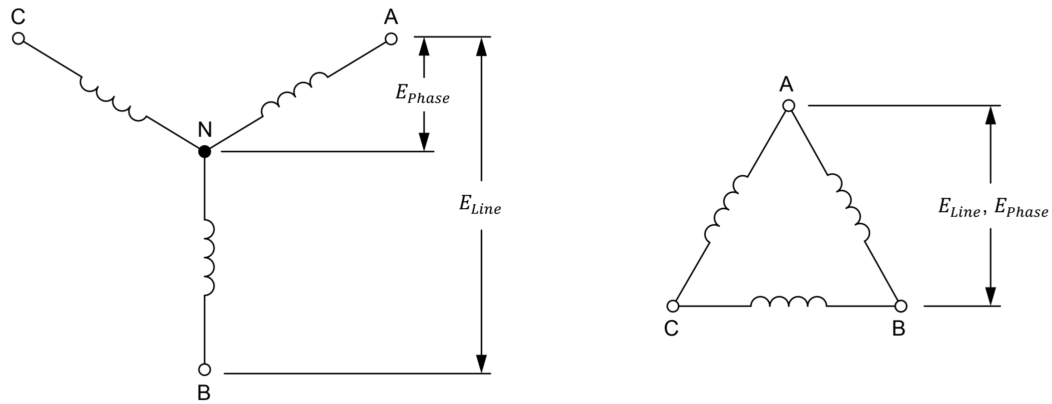


(b) Phasor diagram related to the voltage waveforms shown in part (a)

Figure 2. A-B-C phase sequence of a three-phase ac power source.

Wye and delta configurations

The windings of a three-phase ac power source (e.g., the generator in Figure 1) can be connected in either a **wye configuration**, or a **delta configuration**. The configuration names are derived from the appearance of the circuit drawings representing the configurations, i.e., the letter Y designates the wye configuration, while the Greek letter delta (Δ) designates the delta configuration. The connections for each configuration are shown in Figure 3. Each type of configuration has definite electrical characteristics.



(a) Three-phase wye configuration

(b) Three-phase delta configuration

Figure 3. Types of three-phase system configurations.

As Figure 3a shows, in a wye-connected circuit, one end of each of the three windings (or phases) of the three-phase ac power source is connected to a common point called the neutral. No current flows in the neutral because the currents flowing in the three windings (i.e., the phase currents) cancel each other out when the system is balanced. Wye connected systems typically consist of three or four wires (these wires are connected to points A, B, C, and N in Figure 3a), depending on whether or not the neutral line is present.

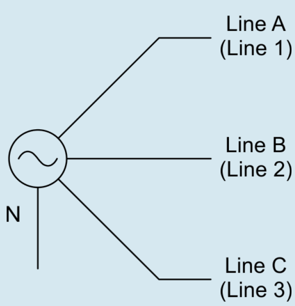
Figure 3b shows that, in a delta-connected circuit, the three windings of the three-phase ac power source are connected one to another, forming a triangle. The three line wires are connected to the three junction points of the circuit (points A, B, and C in Figure 3b). There is no point to which a neutral wire can be connected in a three-phase delta-connected circuit. Thus, delta-connected systems are typically three-wire systems.

Distinction between line and phase voltages, and line and phase currents

The voltage produced by a single winding of a three-phase circuit is called the line-to-neutral voltage, or simply the **phase voltage**, E_{Phase}. In a wye-connected three-phase ac power source, the phase voltage is measured between the neutral line and any one of points A, B, and C, as shown in Figure 3a. This results in the following three distinct phase voltages: E_{A-N}, E_{B-N}, and E_{C-N}.

The voltage between any two windings of a three-phase circuit is called the line-to-line voltage, or simply the **line voltage** E_{Line}. In a wye-connected three-phase ac power source, the line voltage is √3 (approximately 1.73) times greater than the phase voltage (i.e., $E_{Line} = \sqrt{3}\, E_{Phase}$). In a delta-connected three-phase ac power source, the voltage between any two windings is the same as the voltage across the third winding of the source (i.e., $E_{Line} = E_{Phase}$), as Figure 3b shows. With both configurations, this results in the following three distinct line voltages: E_{A-B}, E_{B-C}, and E_{C-A}.

The figure below shows the electrical symbol representing a three-phase ac power source. Note that lines A, B, and C are sometimes labeled lines 1, 2, and 3, respectively.



The three line wires (wires connected to points A, B, and C) and the neutral wire of a three-phase power system are usually available for connection to the load, which can be connected in either a wye configuration or a delta configuration. The two types of circuit connections are illustrated in Figure 4. Circuit analysis demonstrates that in a wye-connected load, the voltage (line voltage) between any two line wires, or lines, is √3 times greater than the voltage (phase voltage) across each load resistor. Furthermore, the **line current** I_{Line} flowing in each line of the power source is equal to the **phase current** I_{Phase} flowing in each load resistor. On the other hand, in a delta-connected load, the voltage (phase voltage) across each load resistor is equal to the line voltage of the source. Also, the line current is √3 times greater than the current (phase current) in each load resistor. The phase current in a delta-connected load is therefore √3 times smaller than the line current.

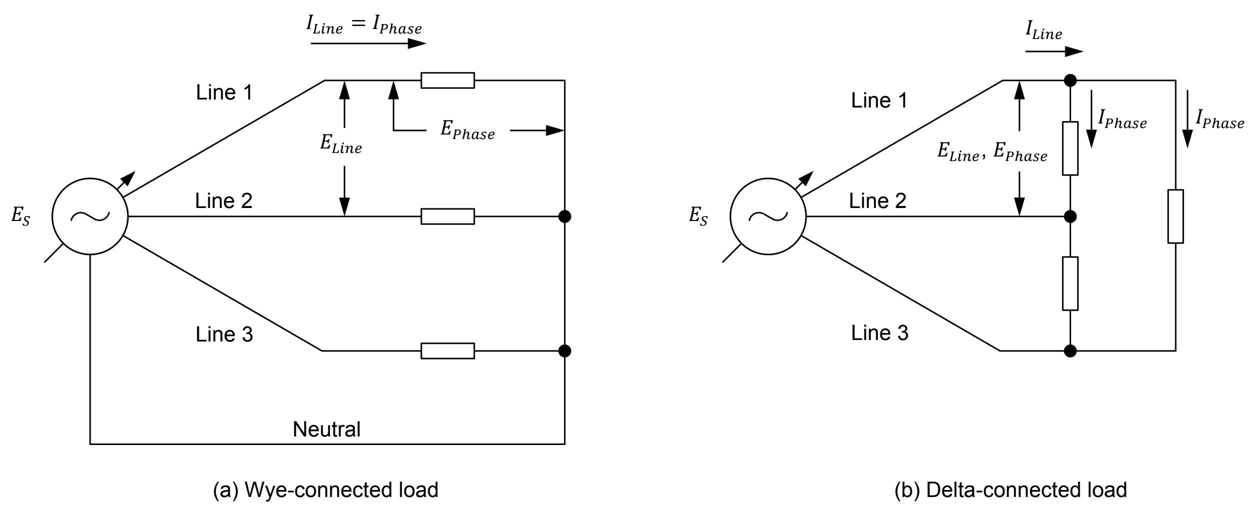


Figure 4. Types of load connections.

The relationships between the line and phase voltages and the line and phase currents simplify the analysis of balanced three-phase circuits. A shorthand way of writing these relationships is given below.

In wye-connected circuits:

$$E_{Line} = \sqrt{3} \times E_{Phase} \quad \text{and} \quad I_{Line} = I_{Phase}$$

In delta-connected circuits:

$$E_{Line} = E_{Phase} \quad \text{and} \quad I_{Line} = \sqrt{3} \times I_{Phase}$$

Power in balanced three-phase circuits

The formulas for calculating active, reactive, and apparent power in balanced three-phase circuits are the same as those used for single-phase circuits. Based on the formula for calculating power in a single-phase circuit, the active power dissipated in each phase of either a wye- or delta-connected load is equal to:

$$P_{Phase} = E_{Phase} \times I_{Phase} \times \cos\varphi \tag{1}$$

where P_{Phase} is the active power dissipated in each phase of a three-phase circuit, expressed in watts (W).
E_{Phase} is the phase voltage across each phase of a three-phase circuit, expressed in volts (V).
I_{Phase} is the phase current flowing in each phase of a three-phase circuit, expressed in amperes (A).
φ is the angle between the phase voltage and current in each phase of a three-phase circuit, expressed in degrees (°).

Therefore, the total active power P_T dissipated in a three-phase circuit is equal to:

$$P_T = 3 \times P_{Phase} = 3 \times E_{Phase} \times I_{Phase} \times \cos\varphi \tag{2}$$

where P_T is the total active power dissipated in a three-phase circuit, expressed in watts (W).

In purely resistive three-phase circuits, the voltage and current are in phase, which means that $\cos\varphi$ equals 1. Therefore, the total active power P_T dissipated in purely resistive three-phase circuits is equal to:

$$P_T = 3 \times E_{Phase} \times I_{Phase}$$

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Phase and line voltage measurements in the Power Supply
- Voltage, current, and power measurements in a wye-connected circuit
- Voltage, current, and power measurements in a delta-connected circuit

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.

Setup and connections

In this section, you will set up the equipment to measure the line-to-neutral (phase) and line-to-line (line) voltages of a three-phase ac power source.

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

2. Install the required equipment in the Workstation.

3. 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.

4. Connect the *Power Input* of the Data Acquisition and Control Interface to the *Power Output* of the 24 V AC Power Supply module. Turn the 24 V AC Power Supply module on.

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

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 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.

7. In LVDAC-EMS, open the Metering window. In this window, set meters to measure the rms (ac) values of the voltages at inputs *E1*, *E2*, and *E3* of the Data Acquisition and Control Interface. Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the meters in the Metering window.

8. Set up the circuit shown in Figure 5.

   Connect inputs *E1*, *E2*, and *E3* of the Data Acquisition and Control Interface (DACI) to first measure the Power Supply phase voltages E_{1-N}, E_{2-N}, and E_{3-N}, respectively. Later, you will modify the connections to inputs *E1*, *E2*, and *E3* of the DACI to measure the Power Supply line voltages E_{1-2}, E_{2-3}, and E_{3-1}, respectively.

   Make sure to connect voltage inputs E1, E2, and E3 of the Data Acquisition and Control Interface (DACI) with the polarity indicated in the figure.

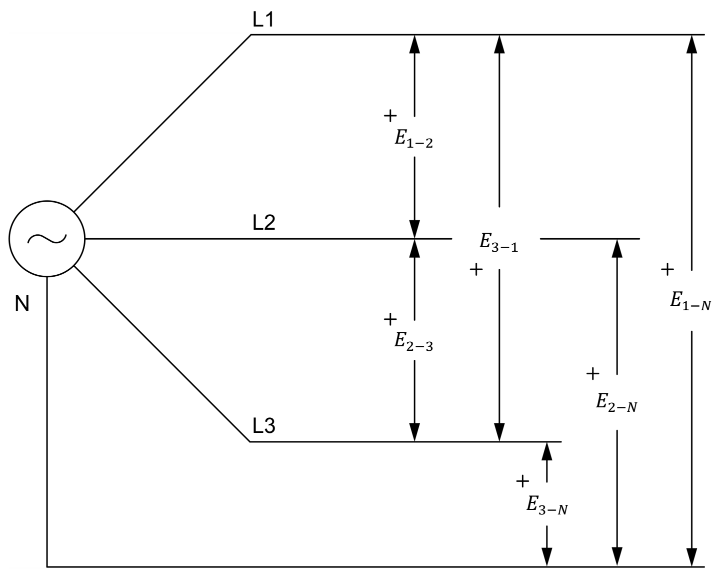


Figure 5. Phase and line voltage measurements.

Phase and line voltage measurements in the Power Supply

In this section, you will measure the phase voltages of the three-phase ac power source in the Power Supply, and observe the phase voltage waveforms of the three-phase ac power source using the Oscilloscope, as well as the phase voltage phasors of the three-phase ac power source using the Phasor Analyzer. You will measure the line voltages of the three-phase ac power source in the Power Supply. You will then calculate the ratio of the average line voltage to the average phase voltage and confirm that the ratio is equal to √3.

9. Turn the three-phase ac power source on.

10. Measure and record below the phase voltages of the three-phase ac power source.

$E_{1-N} =$ _______ V

$E_{2-N} =$ _______ V

$E_{3-N} =$ _______ V

Determine the average value of the phase voltages.

$$\text{Average } E_{Phase} = \frac{E_{1-N} + E_{2-N} + E_{3-N}}{3} = \text{\_\_\_\_\_\_\_ V}$$

11. In LVDAC-EMS, open the Oscilloscope, then make the appropriate settings to observe the phase voltage waveforms related to inputs *E1*, *E2*, and *E3* of the DACI.

Is the phase shift between each voltage sine wave of the three-phase ac power source equal to 120°?

❑ Yes ❑ No

12. In LVDAC-EMS, open the Phasor Analyzer, then make the appropriate settings to observe the phase voltage phasors related to inputs *E1*, *E2*, and *E3* of the DACI.

Is the phase shift between each voltage phasor of the three-phase ac power source equal to 120°?

❑ Yes ❑ No

13. Turn the three-phase ac power source off.

14. On the DACI, modify the connections to voltage inputs *E1*, *E2*, and *E3* to measure the line voltages (E_{1-2}, E_{2-3}, and E_{3-1}, respectively) of the three-phase ac power source (see Figure 5).

Make sure to connect voltage inputs E1, E2, and E3 of the Data Acquisition and Control Interface (DACI) with the polarity indicated in Figure 5.

15. Turn the three-phase ac power source on.

16. Measure and record below the line voltages of the three-phase ac power source.

$E_{1-2} =$ _______ V

$E_{2-3} =$ _______ V

$E_{3-1} =$ _______ V

17. Turn the three-phase ac power source off.

18. Determine the average value of the line voltages.

$$\text{Average } E_{Line} = \frac{E_{1-2} + E_{2-3} + E_{3-1}}{3} = \_\_\_\_\_\_\_ \text{ V}$$

19. Calculate the ratio of the average line voltage E_{Line} to the average phase voltage E_{Phase}.

$$\frac{\text{Average } E_{Line}}{\text{Average } E_{Phase}} = \_\_\_\_\_\_$$

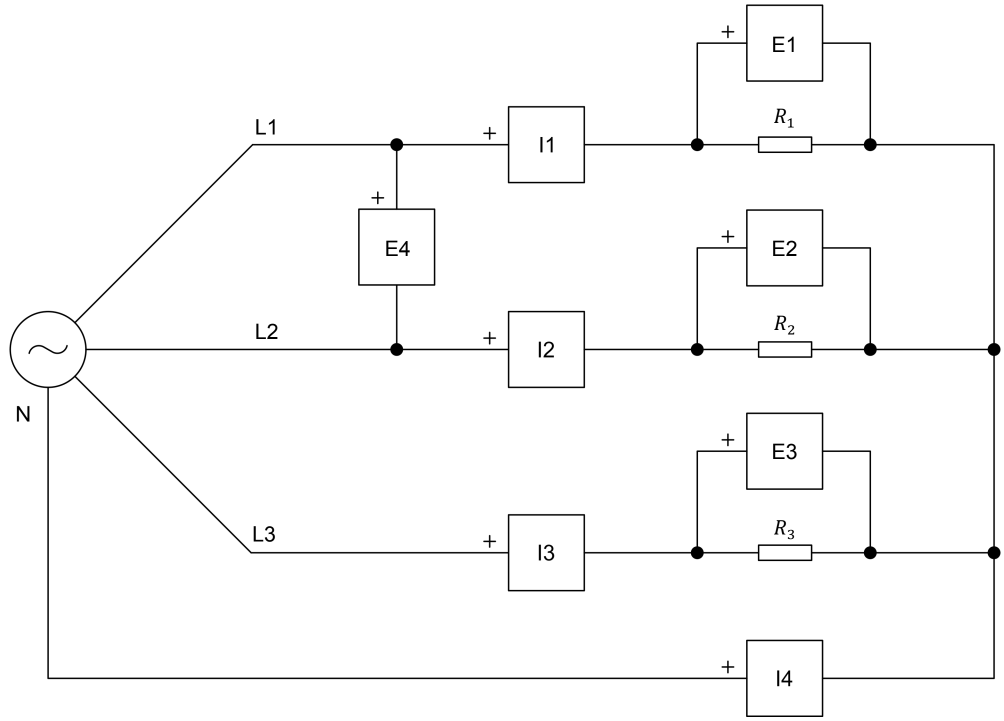
20. Is the ratio of the average line voltage E_{Line} to average phase voltage E_{Phase} calculated in the previous step approximately equal to 1.73 (i.e., √3)?

❑ Yes ❑ No

Voltage, current, and power measurements in a wye-connected circuit

In this section, you will set up a wye-connected, three-phase circuit using three load resistors. You will measure the phase voltages and currents in the circuit, as well as the circuit line voltage and neutral line current. You will confirm that the load is balanced and that the ratio between the line voltage and the average phase voltage in the circuit is equal to √3. You will verify that the current flowing in the neutral line is equal to zero and that removing the neutral line does not affect the measured voltages and currents. You will then calculate the active power dissipated in each phase of the circuit and the total active power dissipated in the circuit, using the measured phase voltages and currents. Finally, you will calculate the total active power dissipated in the circuit, using the measured average phase voltage and current, and compare the two calculated total active power values.

21. Set up the wye-connected, resistive, three-phase circuit shown in Figure 6.



Local ac power network		R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
Voltage (V)	Frequency (Hz)			
120	60	300	300	300
220	50	1100	1100	1100
240	50	1200	1200	1200
220	60	1100	1100	1100

Figure 6. Wye-connected, three-phase circuit supplying power to a three-phase resistive load.

The values of certain components (e.g., resistors, capacitors) used in the circuits of this manual depend on your local ac power network voltage and frequency. Whenever necessary, a table below the circuit diagram indicates the value of each component for ac power network voltages of 120 V, 220 V, and 240 V, and for ac power network frequencies of 50 Hz and 60 Hz. Make sure to use the component values corresponding to your local ac power network voltage and frequency.

22. Make the necessary switch settings on the Resistive Load module to obtain the resistance values required.

Appendix C lists the switch settings required on the Resistive Load module to obtain various resistance values.

23. In the Metering window, make the required settings in order to measure the rms (ac) values of voltages E_{R1}, E_{R2}, E_{R3}, and E_{Line} (inputs *E1*, *E2*, *E3*, and *E4*, respectively, of the DACI), as well as currents I_{R1}, I_{R2}, I_{R3}, and I_N (inputs *I1*, *I2*, *I3*, and *I4*, respectively, of the DACI).

24. Turn the three-phase ac power source on.

25. Measure and record below the voltages and currents in the circuit of Figure 6.

E_{R1} = _______ V

E_{R2} = _______ V

E_{R3} = _______ V

E_{Line} = _______ V

I_{R1} = _______ A

I_{R2} = _______ A

I_{R3} = _______ A

I_N = _______ A

26. Turn the three-phase ac power source off.

27. Compare the individual load voltages E_{R1}, E_{R2}, and E_{R3} measured in step 25. Are they approximately equal?

❑ Yes ❑ No

Compare the individual load currents I_{R1}, I_{R2}, and I_{R3} measured in step 25. Are they approximately equal?

❑ Yes ❑ No

Does this mean that the three-phase load is balanced?

❑ Yes ❑ No

28. Calculate the average phase voltage E_{Phase} using the phase voltages recorded in step 25.

$$\text{Average } E_{Phase} = \frac{E_{R1} + E_{R2} + E_{R3}}{3} = \underline{\qquad\qquad}\ \text{V}$$

29. Is the ratio of the line voltage E_{Line} measured in step 25 to the average phase voltage E_{Phase} obtained in the previous step approximately equal to √3?

❑ Yes ❑ No

30. Is the current I_N flowing in the neutral line approximately equal to zero?

❑ Yes ❑ No

31. Disconnect the neutral line, then turn the three-phase ac power source on.

Does disconnecting the neutral line affect the measured voltages and currents indicated in the Metering window?

❑ Yes ❑ No

Is the neutral line required in a balanced, wye-connected, three-phase circuit?

❑ Yes ❑ No

32. Turn the three-phase ac power source off.

33. Calculate the active power dissipated in each phase of the circuit and the total active power P_T dissipated in the circuit using the voltages and currents recorded in step 25.

$P_{R1} = E_{R1} \times I_{R1} =$ _______ W

$P_{R2} = E_{R2} \times I_{R2} =$ _______ W

$P_{R3} = E_{R3} \times I_{R3} =$ _______ W

$P_T = P_{R1} + P_{R2} + P_{R3} =$ _______ W

34. Calculate the average phase current I_{Phase} using the phase currents recorded in step 25.

$$\text{Average } I_{Phase} = \frac{I_{R1} + I_{R2} + I_{R3}}{3} = \_\_\_\_\_\_\_ \text{ A}$$

35. Calculate the total active power P_T dissipated in the circuit, using the average phase voltage E_{Phase} obtained in step 28 and the average phase current I_{Phase} obtained in the previous step. Then, compare the result with the total active power P_T calculated in step 33. Are both values approximately equal?

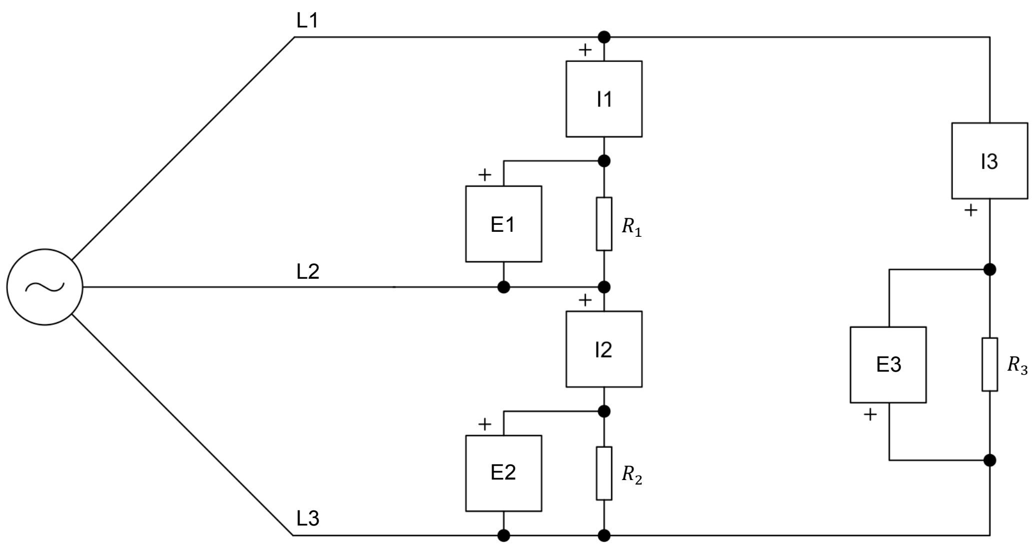
$P_T = 3 \times E_{Phase} \times I_{Phase} =$ _______ W

❑ Yes ❑ No

Voltage, current, and power measurements in a delta-connected circuit

In this section, you will set up a delta-connected, three-phase circuit using three load resistors. You will measure the phase voltages and currents in the circuit. You will then modify the circuit to measure the line currents in the circuit. You will confirm that the load is balanced and that the ratio between the average line current and the average phase current in the circuit is equal to √3. You will then calculate the active power dissipated in each phase of the circuit and the total active power dissipated in the circuit using the measured phase voltages and currents. Finally, you will calculate the total active power dissipated in the circuit using the measured average phase voltage and current, and compare the two calculated total active power values.

36. Set up the delta-connected, resistive, three-phase circuit shown in Figure 7.



Local ac power network		R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
Voltage (V)	Frequency (Hz)			
120	60	300	300	300
220	50	1100	1100	1100
240	50	1200	1200	1200
220	60	1100	1100	1100

Figure 7. Delta-connected, three-phase circuit supplying power to a three-phase resistive load.

37. Make the necessary switch settings on the Resistive Load module to obtain the resistance values required.

38. Turn the three-phase ac power source on, record below the circuit voltages and currents, then immediately turn the three-phase ac power source off.

CAUTION

Do not leave the three-phase ac power source on for a long time as the power the resistors dissipate exceeds their nominal power rating.

$E_{R1} =$ _______ V $E_{R2} =$ _______ V

$E_{R3} =$ _______ V

$I_{R1} =$ _______ A $I_{R2} =$ _______ A

$I_{R3} =$ _______ A

39. Compare the individual load voltages E_{R1}, E_{R2}, and E_{R3} measured in the previous step. Are they approximately equal?

❑ Yes ❑ No

Compare the individual load currents I_{R1}, I_{R2}, and I_{R3} measured in the previous step. Are they approximately equal?

❑ Yes ❑ No

Does this mean that the load is balanced?

❑ Yes ❑ No

40. Calculate the average phase current I_{Phase} using the phase current values recorded in step 38.

$$\text{Average } I_{Phase} = \frac{I_{R1} + I_{R2} + I_{R3}}{3} = \_\_\_\_\_\_\_ \text{ A}$$

41. Reconnect current inputs *I1*, *I2*, and *I3* of the DACI as shown in Figure 8 to measure the line currents in the delta-connected, three-phase circuit.

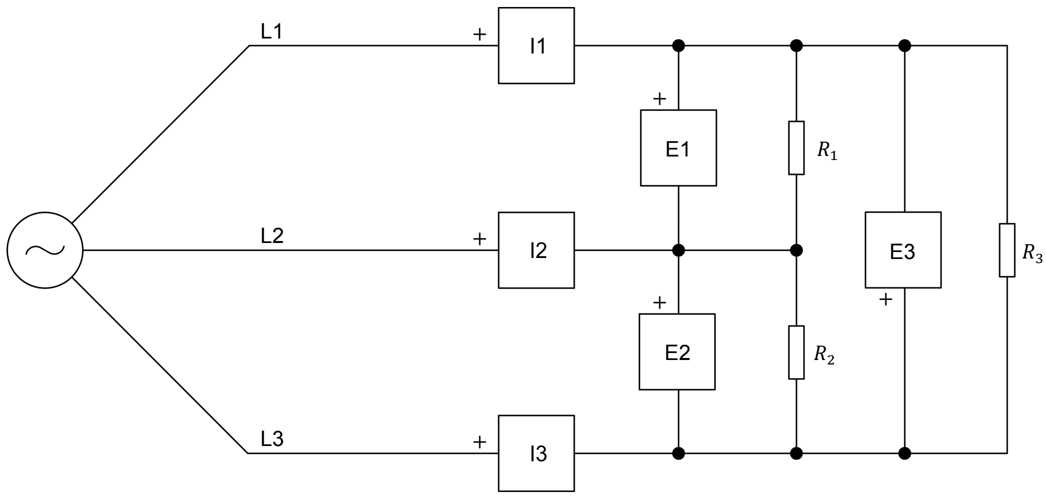


Figure 8. Line current measurements in the delta-connected, three-phase circuit.

42. Turn the three-phase ac power source on, record below the line currents in the circuit, then immediately turn the three-phase ac power source off.

CAUTION

Do not leave the three-phase ac power source on for a long time as the power the resistors dissipate exceeds their nominal power rating.

$I_{Line\ 1} =$ ________ A

$I_{Line\ 2} =$ ________ A

$I_{Line\ 3} =$ ________ A

43. Determine the average value of the line currents measured in the previous step.

$$\text{Average } I_{Line} = \frac{I_{Line\ 1} + I_{Line\ 2} + I_{Line\ 3}}{3} = \_\_\_\_\_\_\_\_ \text{ A}$$

44. Calculate the ratio of the average line current I_{Line} obtained in the previous step to the average phase current I_{Phase} obtained in step 40.

$$\frac{\text{Average } I_{Line}}{\text{Average } I_{Phase}} = \_\_\_\_\_\_\_\_$$

Is the ratio approximately equal to $\sqrt{3}$?

❑ Yes ❑ No

45. Calculate the active power dissipated in each phase of the circuit and the total active power P_T dissipated in the circuit, using the circuits voltages and currents recorded in step 38.

$P_{R1} = E_{R1} \times I_{R1} =$ _______ W

$P_{R2} = E_{R2} \times I_{R2} =$ _______ W

$P_{R3} = E_{R3} \times I_{R3} =$ _______ W

$P_T = P_{R1} + P_{R2} + P_{R3} =$ _______ W

46. Calculate the average phase voltage E_{Phase} using the phase voltages recorded in step 38.

$$\text{Average } E_{Phase} = \frac{E_{R1} + E_{R2} + E_{R3}}{3} = \_\_\_\_\_\_\_ \text{ V}$$

47. Calculate the total active power P_T dissipated in the circuit, using the average phase voltage E_{Phase} recorded in the previous step and the average phase current I_{Phase} obtained in step 40. Compare the result with the total active power P_T calculated in step 45. Are both values approximately equal?

$P_T = 3 \times E_{Phase} \times I_{Phase} =$ _______ W

❑ Yes ❑ No

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

CONCLUSION

In this exercise, you learned what three-phase circuits are. You saw the difference between line and phase voltages, and line and phase currents, as well as the relationship between line and phase parameter values in wye- and delta-connected three-phase circuits. You learned what the phase sequence of a three-phase circuit is. You also learned how to calculate the active power dissipated in each phase of a three-phase circuit, and how to calculate the total active power dissipated in a three-phase circuit. Finally, you used voltage and current measurements to confirm the theory and calculations presented in the exercise.

REVIEW QUESTIONS

1. Explain the difference between the phase voltage and the line voltage in a three-phase circuit.

____

____

____

____

2. What is the ratio between the line and phase voltages and the ratio between the line and phase currents in a wye-connected, three-phase circuit?

3. What is the ratio between the line and phase voltages and the ratio between the line and phase currents in a delta-connected, three-phase circuit?

4. The phase voltage E_{Phase} measured across a balanced, wye-connected, three-phase resistive load is 60 V. Calculate the line voltage E_{Line}, as well as the current I_N flowing in the neutral line.

5. In a balanced, delta-connected, resistive, three-phase circuit, the phase voltage E_{Phase} is 120 V and the line current I_{Line} is 3.46 A. Calculate the total active power P_T dissipated in the circuit.

Three-Phase Power Measurement

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to calculate active, reactive, and apparent power in balanced, wye- or delta-connected, three-phase circuits. You will know how to use a power meter to measure power in single-phase circuits. You will also know how to measure power in three- and four-wire, three-phase circuits.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Calculating power in balanced three-phase circuits
- Power measurements in single-phase circuits
- Measuring the total power in four-wire, three-phase circuits using three power meters
- Measuring the total power in three-wire, three-phase circuits (two-wattmeter method)
- Measuring the total power in four-wire, three-phase circuits (two-wattmeter method)

DISCUSSION

Calculating power in balanced three-phase circuits

As seen in Exercise 1, the total active power P_T supplied to a balanced three-phase load (i.e., the total active power dissipated in a circuit) can be calculated using the following equation:

$$P_T = 3 \times P_{Phase} = 3\,(E_{Phase} \times I_{Phase} \times \cos\varphi)$$

In a wye-connected circuit, $E_{Phase} = E_{Line}/\sqrt{3}$ and the phase current I_{Phase} is equal to the line current I_{Line}. The above equation therefore becomes:

$$P_T = \frac{3}{\sqrt{3}}\,(E_{Line} \times I_{Line} \times \cos\varphi)$$

The $3/\sqrt{3}$ factor can be simplified to √3, so that the final equation for calculating the total active power dissipated in the wye-connected circuit is:

$$P_T = \sqrt{3}\,(E_{Line} \times I_{Line} \times \cos\varphi) \qquad (3)$$

where P_T is the total active power dissipated in the three-phase circuit, expressed in watts (W).

In a delta-connected circuit, the same equation is obtained because the phase voltage E_{Phase} is equal to the line voltage E_{Line}, and because $I_{Phase} = I_{Line}/\sqrt{3}$. Therefore, in either a balanced wye-connected circuit or a balanced delta-connected circuit, the total active power P_T dissipated in a three-phase circuit can be calculated using Equation (3).

Since $(E_{Phase} \times I_{Phase} \times \cos\varphi)$ is the expression representing the active power P_{Phase} dissipated in a single phase of a three-phase circuit, it follows that the expression $E_{Phase} \times I_{Phase}$ represents the apparent power in a single phase. The total apparent power S_T in a balanced, wye- or delta-connected, three-phase circuit can thus be calculated using the following equation:

$$S_T = 3\,(E_{Phase} \times I_{Phase}) \tag{4}$$

where S_T is the total apparent power in the three-phase circuit, expressed in volt-amperes (VA).

By using the same steps used to obtain the equation for calculating the total active power P_T in three-phase circuits from the line voltage E_{Line} and the line current I_{Line}, the equation for calculating the total apparent power S_T in a three-phase circuit can be rewritten as follows:

$$S_T = \sqrt{3}\;(E_{Line} \times I_{Line}) \tag{5}$$

The power factor of a balanced three-phase circuit is the ratio of the total active power to the total apparent power (i.e., P_T/S_T), and the relationship between P_T, Q_T, and S_T is the same as for single-phase ac circuits (i.e., ${S_T}^2 = {P_T}^2 + {Q_T}^2$). Thus, the total reactive power Q_T in a three-phase circuit can be calculated using the following equation:

$$Q_T = \sqrt{{S_T}^2 - {P_T}^2} \tag{6}$$

where Q_T is the total reactive power in the three-phase circuit, expressed in reactive volt-amperes (var).

Power measurements in single-phase circuits

Commercial instruments are available to measure active, reactive, and apparent power directly. These instruments are referred to as power meters. A selector on the power meter usually allows the unit to measure active, reactive, or apparent power. A power meter determines power by measuring the circuit voltage and current. All power meters thus generally have at least a voltage input and a current input to measure the circuit voltage and current. Figure 9a shows the typical connections of a power meter in a single-phase circuit. Figure 9b shows the equivalent connections required to measure power using the Data Acquisition and Control Interface (DACI) module.

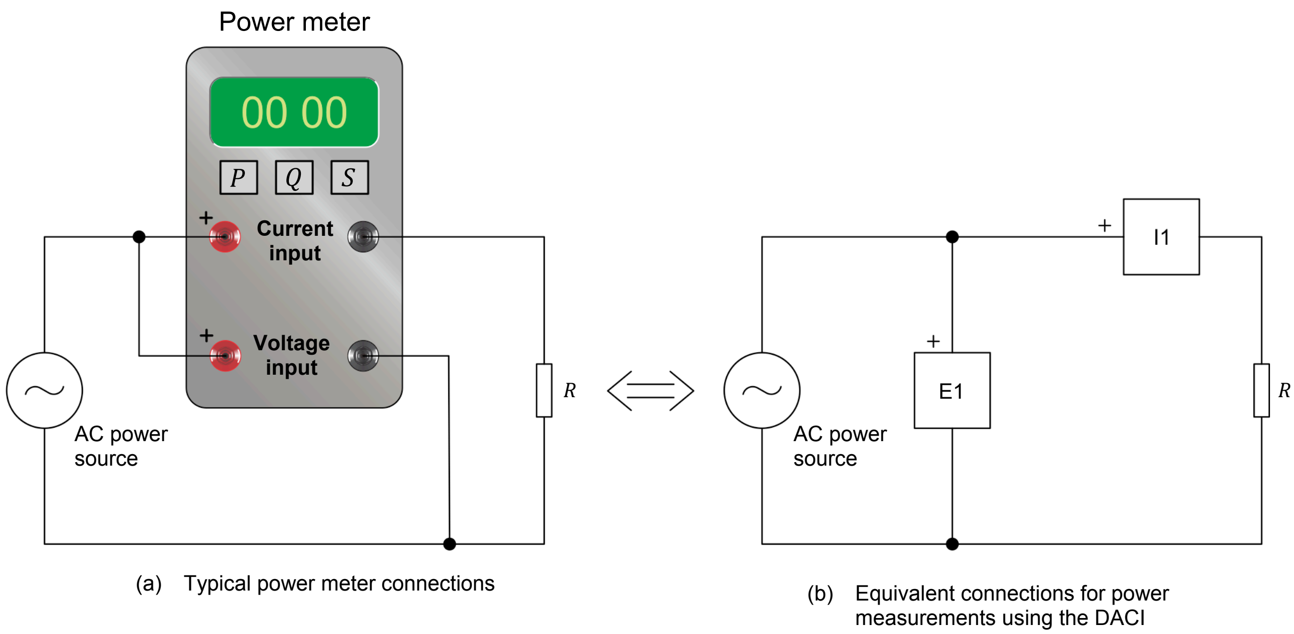


Figure 9. Three-phase circuit diagrams showing the connections required for power measurements.

Measuring the total power in four-wire, three-phase circuits using three power meters

Measuring the total power in a four-wire, three-phase circuit is done by first measuring the voltage and current in each phase of the circuit (i.e., the voltage across each load element and the current flowing in each load element), then calculating the active power and reactive power in each phase of the circuit from the voltage and current measured in each phase. The total active power P_T in the four-wire, three-phase circuit is simply the algebraic sum of the active power values obtained for the three phases of the circuit. Similarly, the total reactive power Q_T is simply the algebraic sum of the reactive power values obtained for the three phases of the circuit.

In other words, it is like measuring the active power and reactive power in each phase independently using three power meters and calculating the algebraic sum of the three measured power (either active or reactive) values. The total apparent power S_T can then be obtained by calculating the vectorial sum of the total active power P_T and the total reactive power Q_T. Figure 10 shows the connections required to measure the total power in a four-wire, three-phase circuit using the DACI. Note that in the circuit diagram, inputs E1 and I1, inputs E2 and I2, and inputs E3 and I3 each represent a power meter.

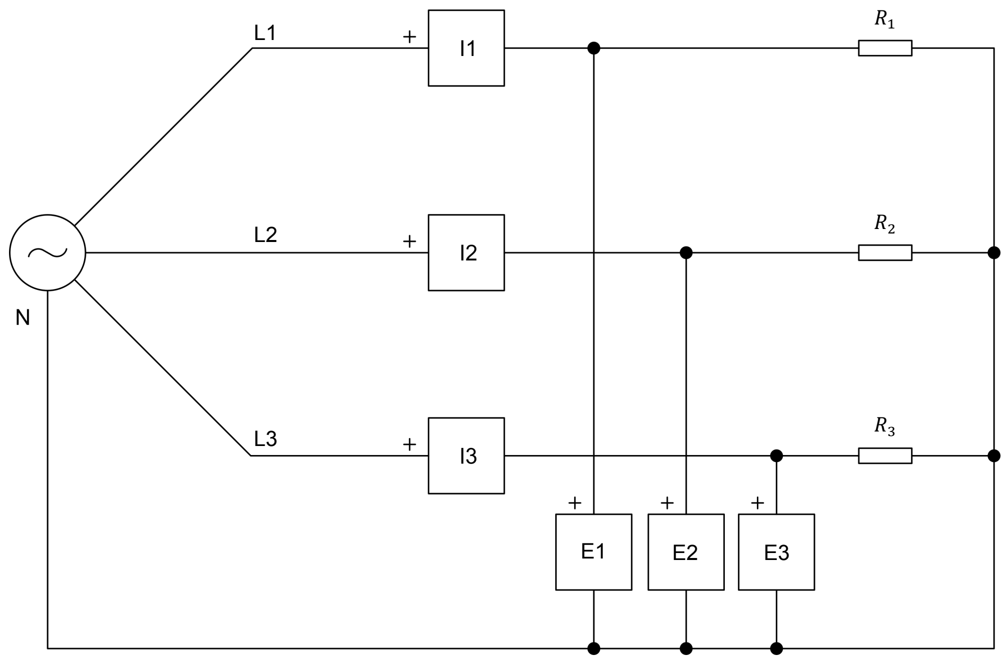


Figure 10. Three-phase power measurement using three power meters.

The method of power measurement shown in Figure 10 works whether the three-phase circuit is balanced or not.

Measuring the total power in three-wire, three-phase circuits (two-wattmeter method)

A three-wire, three-phase circuit is simply a three-phase circuit with three line conductors but no neutral conductor. Three-wire, three-phase circuits are commonly used because they allow three-phase power to be conveyed using three conductors instead of four conductors. This makes three-wire, three-phase circuits more economical than four-wire, three-phase circuits.

The method for measuring the total power in four-wire, three-phase circuits discussed in the previous section cannot be used to measure the total power in three-wire, three-phase circuits. For instance, when the load is connected in a wye configuration, the phase currents can be measured but the phase voltages (voltage across each load element) cannot be measured because the neutral point is generally not available to connect the voltage inputs of the power meters, as Figure 11 shows.

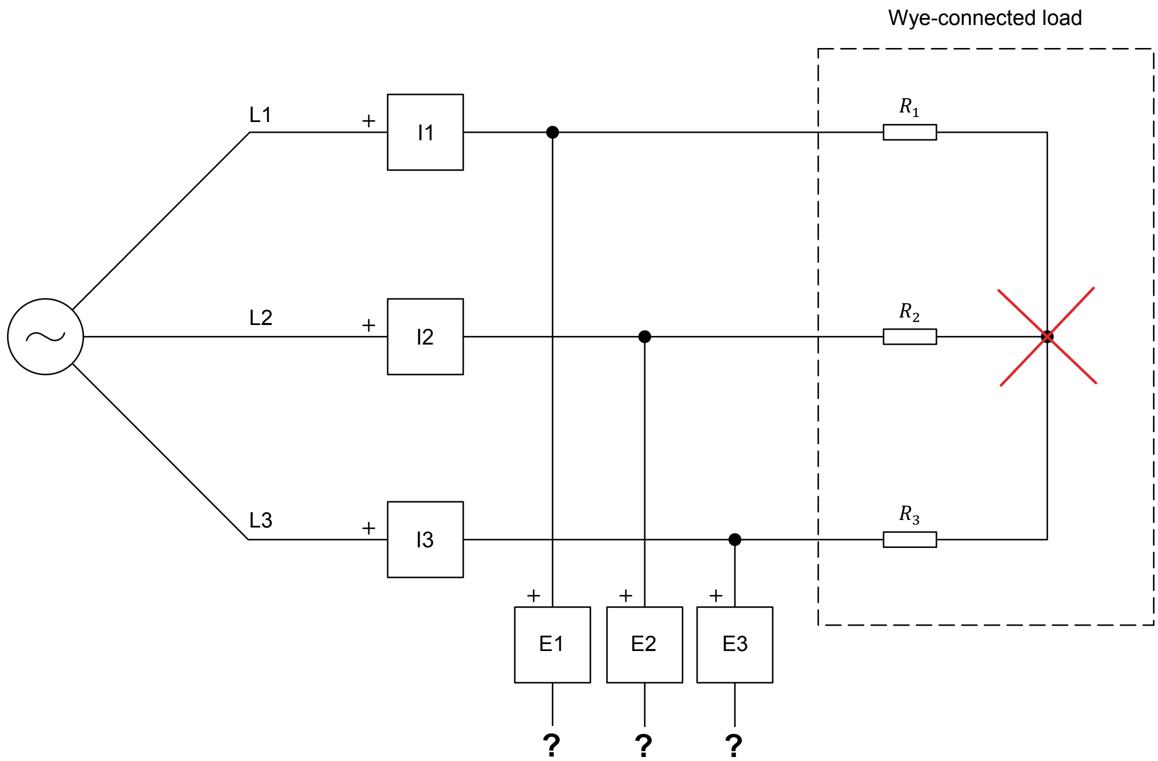


Figure 11. Diagram of a three-wire, wye-connected, three-phase circuit showing that the voltage inputs of the power meters generally cannot be connected to the neutral point of the circuit.

Similarly, when the load is connected in a delta configuration, the phase voltages can be measured but the phase currents (currents flowing through the load elements) cannot be measured because individual access to each load element is generally not possible (i.e., it is impossible to connect the current inputs of the power meters to measure the phase currents), as Figure 12 shows.

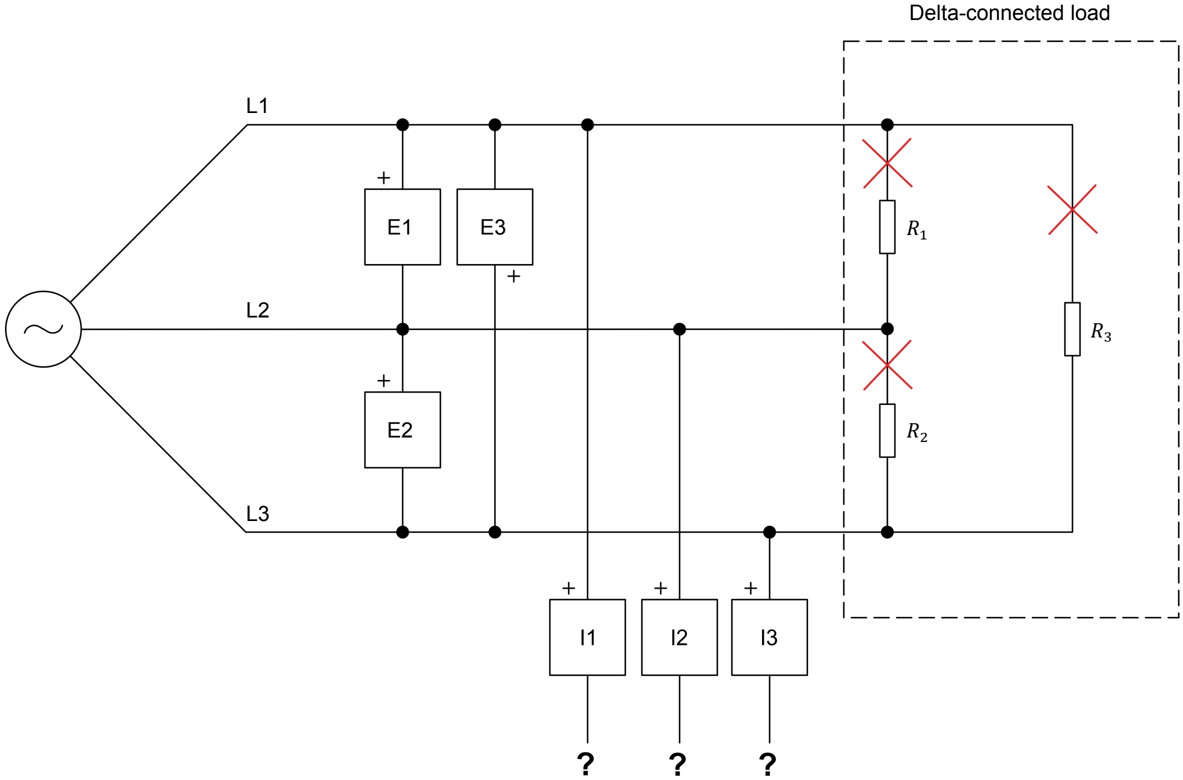


Figure 12. Diagram of a three-wire, delta-connected, three-phase circuit showing that the current inputs of the power meters cannot be connected to measure the phase currents.

To measure the total power (either the total active power P_T, the total reactive power Q_T, or the total apparent power S_T) in three-wire, three-phase circuits, a method using only two power meters can be used. This method is usually referred to as the **two-wattmeter method** because historically, it was first implemented with two wattmeters instead of two power meters. Figure 13 shows the connections of the voltage and current inputs of the two power meters required for the two-wattmeter method of measuring three-phase power. Note that the voltage and current inputs of the power meters must be connected with the polarity indicated in the figure in order to obtain correct power measurements.

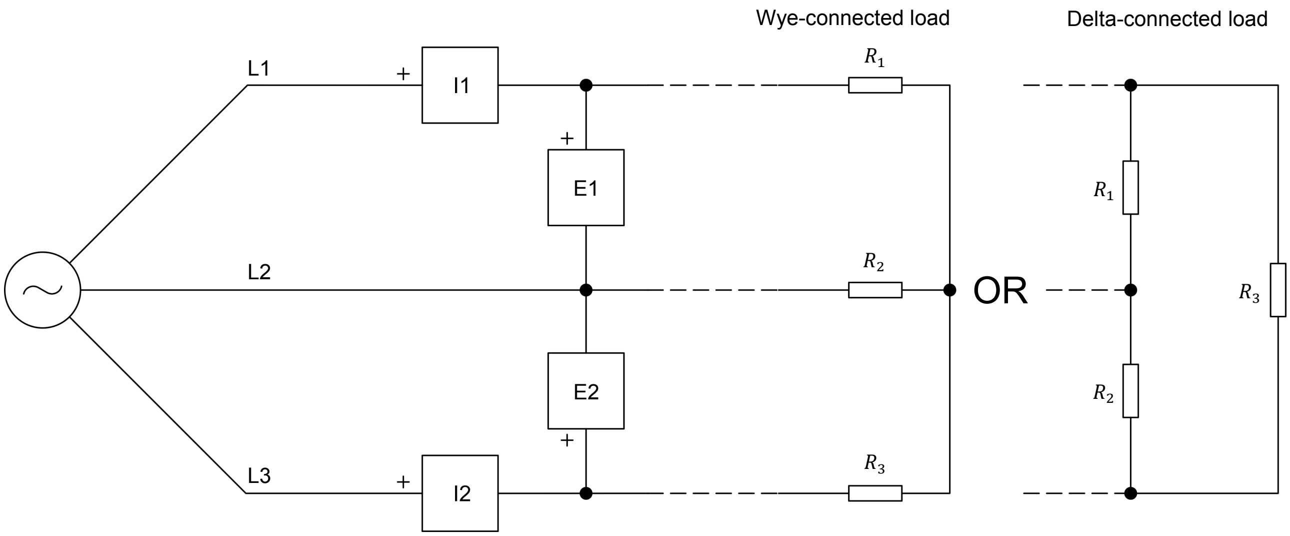


Figure 13. Connections of the voltage and current inputs of the power meters to a three-wire, three-phase circuit when measuring the total power using the two-wattmeter method.

The total active power P_T in the three-wire, three-phase circuit of Figure 13 is simply the algebraic sum of the active power values indicated by the two power meters. Similarly, the total reactive power Q_T is simply the algebraic sum of the reactive power values indicated by the two power meters. The total apparent power S_T can then be obtained by calculating the vectorial sum of the total active power P_T and the total reactive power Q_T. This method of power measurement works whether the three-phase circuit is balanced or not.

Measuring the total power in four-wire, three-phase circuits (two-wattmeter method)

The two-wattmeter method of power measurement can also be used to measure the total power (either active, reactive, or apparent) in four-wire, three-phase circuits. The two-wattmeter method can be useful because it requires only two power meters (i.e., two voltage inputs and two current inputs) instead of three power meters (i.e., three voltage inputs and three current inputs), as with the method seen earlier in this discussion. However, care must be exercised when using the two-wattmeter method to measure the total power in four-wire, three-phase circuits because the method works only with balanced circuits.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Measuring the total power in four-wire, three-phase circuits (wye configuration) using three power meters
- Measuring the total power in three-wire, three-phase circuits (wye configuration) using the two-wattmeter method
- Measuring the total power in three-wire, three-phase circuits (delta configuration) using the two-wattmeter method
- Measuring the total power in four-wire, three-phase circuits (wye configuration) using the two-wattmeter method

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.

Setup and connections

In this section, you will set up the equipment to measure power in a four-wire, three-phase circuit using three power meters.

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

2. Install the required equipment in the Workstation.

3. 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.

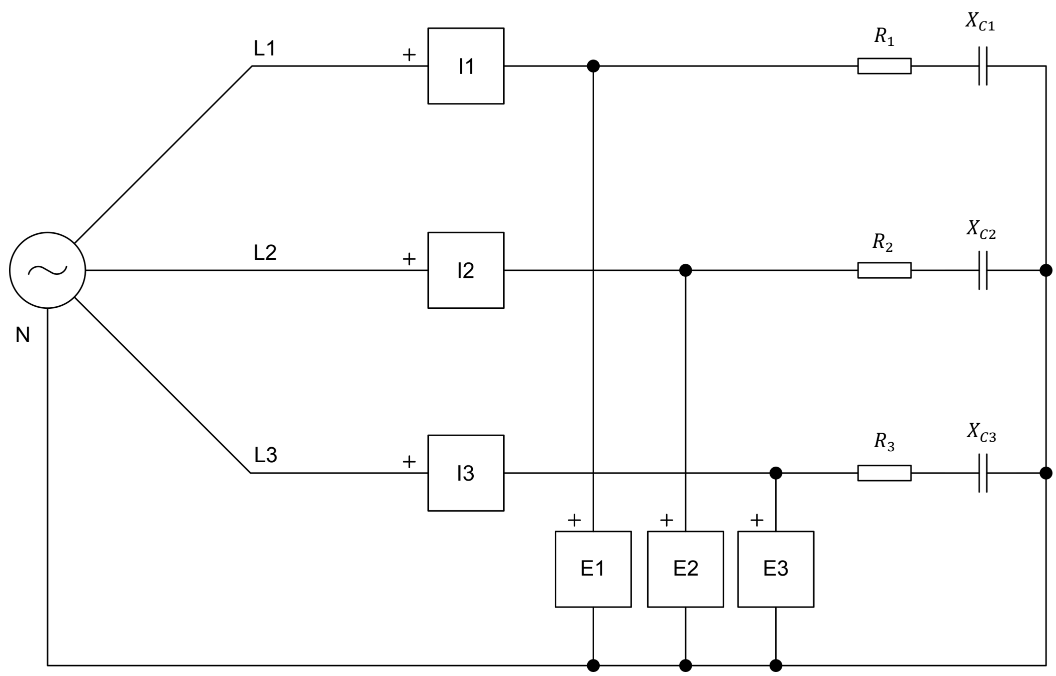
4. Connect the *Power Input* of the Data Acquisition and Control Interface to the *Power Output* of the 24 V AC Power Supply module. Turn the 24 V AC Power Supply module on.

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

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

7. 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 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.

8. Set up the circuit shown in Figure 14.



Local ac power network		R_1, R_2, R_3 (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)		
120	60	171	240
220	50	629	880
240	50	686	960
220	60	629	880

Figure 14. Balanced, four-wire, wye-connected, three-phase circuit set up to measure power using three power meters.

9. Make the necessary switch settings on the Resistive Load and Capacitive Load modules to obtain the resistance and capacitive reactance values required.

Appendix C lists the switch settings required on the Resistive Load and Capacitive Load modules to obtain various resistance and capacitive reactance values.

10. In LVDAC-EMS, open the Metering window. Make the required settings to measure the rms (ac) values of the phase voltages E_{1-N}, E_{2-N}, and E_{3-N} (inputs *E1*, *E2*, and *E3*, respectively), and phase currents $I_{Phase\ 1}$, $I_{Phase\ 2}$, and $I_{Phase\ 3}$ (inputs *I1*, *I2*, and *I3*, respectively). Set three other meters to measure power from inputs *E1* and *I1* (meter *PQS1*), inputs *E2* and *I2* (meter *PQS2*), and inputs *E3* and *I3* (meter *PQS3*). These three power meters will be used to successively measure the active power (P_1, P_2, and P_3), the reactive power (Q_1, Q_2, and Q_3), and the apparent power (S_1, S_2, and S_3) in each phase of the circuit. Set the meters to continuous refresh mode.

Measuring the total power in four-wire, three-phase circuits (wye configuration) using three power meters

In this section, you will solve the circuit set up in the previous section by calculating the active, reactive, and apparent power values in each phase of the circuit, as well as the total active, reactive, and apparent power values in the circuit. You will measure the circuit voltage, current, and power values, and confirm that the measured circuit parameters are approximately equal to the calculated circuit parameters. You will then unbalance the three-phase circuit by modifying the impedance in one phase of the circuit, and solve the resulting unbalanced, three-phase circuit. Finally, you will measure the total active, reactive, and apparent power values in the circuit, and verify that the measured circuit parameters are approximately equal to the calculated circuit parameters, thus confirming that the total power in both balanced and unbalanced, four-wire, three-phase circuits can be measured using three power meters.

11. Solve the circuit set up in the previous section (Figure 14) to determine the values of the following parameters: the active power P, reactive power Q, and apparent power S in each phase of the circuit, as well as the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit.

12. Turn the three-phase ac power source on.

Record below the voltages and currents measured in the circuit of Figure 14, as well as the active power, reactive power, and apparent power in each phase of the circuit, then turn the three-phase ac power source off.

You can change the type of power (i.e., active, reactive, or apparent) measured by a power meter in the Metering window by clicking on the meter Mode button. With this method, you can rapidly perform all active power measurements, then all reactive power measurements, and finally all apparent power measurements using the same three power meters.

Measured voltages and currents:

E_{1-N} = _______ V $I_{Phase\ 1}$ = _______ A

E_{2-N} = _______ V $I_{Phase\ 2}$ = _______ A

E_{3-N} = _______ V $I_{Phase\ 3}$ = _______ A

Measured active, reactive, and apparent power:

P_1 = _______ W P_2 = _______ W

P_3 = _______ W

Q_1 = _______ var Q_2 = _______ var

Q_3 = _______ var

S_1 = _______ VA S_2 = _______ VA

S_3 = _______ VA

13. Compare the voltage, current, and power (active, reactive, and apparent) values measured in the previous step with the parameter values calculated in step 11. Are all values approximately equal?

❑ Yes ❑ No

14. In the Metering window, set an additional meter to measure the total power (either active, reactive, or apparent) from the values provided by the three meters used for measuring power in each phase of the circuit.

The PQS1 + PQS2 + PQS3 *function (accessible through the Meter Settings window of the* Metering *application) provides the sum (either algebraic or vectorial) of the power values measured by meters* PQS1*,* PQS2*, and* PQS3*. The total power meter can be set to indicate either the active, reactive, or apparent power value.*

15. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit, using the power meter set to indicate the total power, then turn the three-phase ac power source off.

P_T = _______ W Q_T = _______ var

S_T = _______ VA

Compare the total power values just measured with the total active power P_T, total reactive power Q_T, and total apparent power S_T calculated in step 11. Are all values approximately equal?

❑ Yes ❑ No

16. Modify the switch settings on the Resistive Load and Capacitive Load modules in order to set the resistance and capacitive reactance values in the circuit of Figure 14 to the values indicated in Table 1. Due to these modifications, the three-phase load is now unbalanced (i.e., the first phase of the circuit has an impedance different from that of the second and third phases).

Table 1. Resistance and capacitive reactance values used for unbalancing the four-wire, wye-connected, three-phase circuit of Figure 14.

Local ac power network		R_1 (Ω)	R_2, R_3 (Ω)	X_{C1} (Ω)	X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)				
120	60	300	171	600	240
220	50	1100	629	2200	880
240	50	1200	686	2400	960
220	60	1100	629	2200	880

17. Solve the circuit in Figure 14 using the resistance and capacitive reactance values indicated in Table 1 to determine the following parameters: the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit.

18. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit using the power meter set to indicate the total power, then turn the three-phase ac power source off.

$P_T =$ _______ W $Q_T =$ _______ var

$S_T =$ _______ VA

19. Compare the total active power P_T, total reactive power Q_T, and total apparent power S_T measured in the previous step with the total power values calculated in step 17. Are all values approximately equal?

❑ Yes ❑ No

Do the circuit measurements performed in this section confirm that the total power in both balanced and unbalanced, four-wire, three-phase circuits can be measured using three power meters?

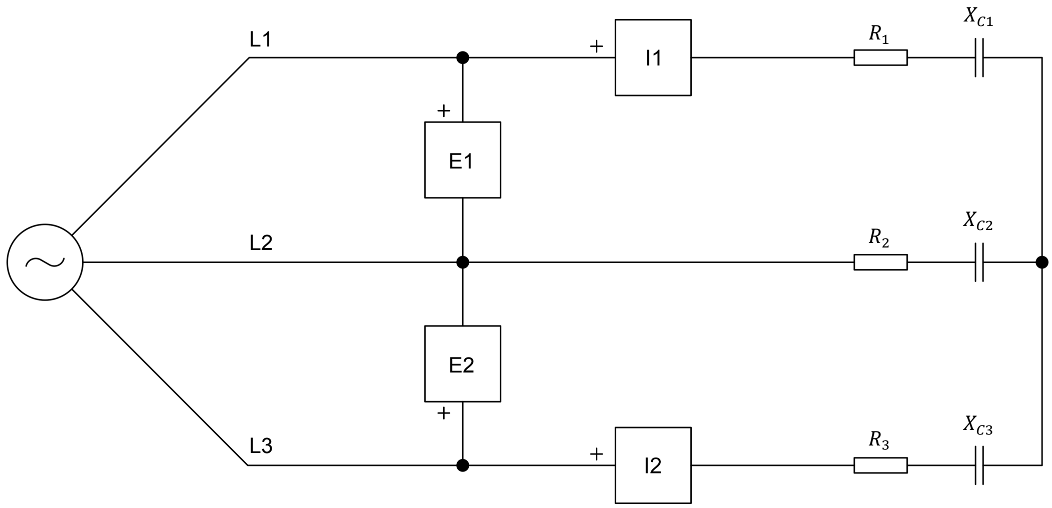
❑ Yes ❑ No

Measuring the total power in three-wire, three-phase circuits (wye configuration) using the two-wattmeter method

In this section, you will set up a balanced, three-wire, wye-connected, three-phase circuit. You will measure the total active, reactive, and apparent power values in the circuit using the two-wattmeter method, and verify that the measured power values are equal to the calculated power values, thus confirming that the two-wattmeter method of power measurement works for measuring the total power in balanced, three-wire, three-phase circuits.

20. Set up the circuit shown in Figure 15.

The balanced, three-phase load in the circuit of Figure 15 is identical to the balanced, three-phase load in the circuit (Figure 14) used in the previous section of this exercise. The values of the total active power P_T, total reactive power Q_T, and total apparent power S_T are therefore equal to the values calculated in the previous section (see step 11) of the exercise.



Local ac power network		R_1, R_2, R_3 (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)		
120	60	171	240
220	50	629	880
240	50	686	960
220	60	629	880

Figure 15. Balanced, three-wire, wye-connected, three-phase circuit set up for power measurements using the two-wattmeter method.

21. Make the necessary switch settings on the Resistive Load and Capacitive Load modules to obtain the resistance and capacitive reactance values required.

22. In the Metering window of LVDAC-EMS, make the required settings to measure the rms (ac) values of the line voltages E_{1-2} and E_{3-2} (inputs *E1* and *E2*, respectively) and the line currents $I_{Line\ 1}$ and $I_{Line\ 3}$ (inputs *I1* and *I2*). Set two other meters to measure power from inputs *E1* and *I1* (meter *PQS1*) and inputs *E2* and *I2* (meter *PQS2*). Finally, set another meter to measure the total power from the values provided by meters *PQS1* and *PQS2*.

The PQS1 + PQS2 *function (accessible through the Meter Settings window of the* Metering *application) performs the sum (either algebraic or vectorial) of the power values measured by meters* PQS1 *and* PQS2*. The total power meter can be set to indicate either the active, reactive, or apparent power value.*

23. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit, using the meter set to measure the total power, then turn the three-phase ac power source off.

$P_T =$ _______ W $\qquad$ $Q_T =$ _______ var

$S_T =$ _______ VA

24. Compare the total active power P_T, total reactive power Q_T, and total apparent power S_T measured in the previous step with the total power values calculated in step 11. Are all values approximately equal?

❑ Yes ❑ No

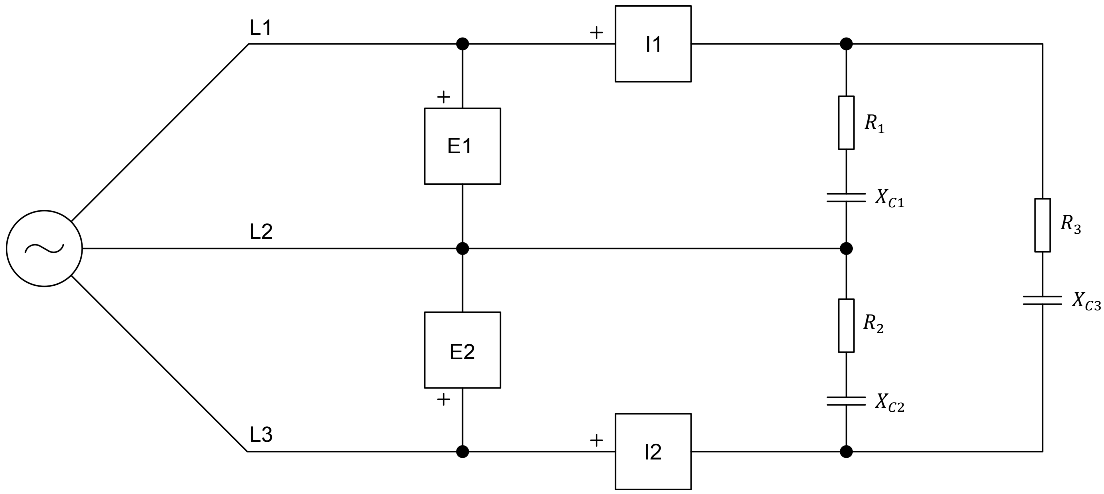
Do the circuit measurements performed in this section confirm that the two-wattmeter method of power measurement can be used to measure the total power in balanced, three-wire, wye-connected, three-phase circuits?

❑ Yes ❑ No

Measuring the total power in three-wire, three-phase circuits (delta configuration) using the two-wattmeter method

In this section, you will set up a balanced, three-wire, delta-connected, three-phase circuit. You will solve the circuit by calculating the active, reactive, and apparent power values in each phase of the circuit, as well as the total active, reactive, and apparent power values in the circuit. You will measure the total active, reactive, and apparent power values in the circuit using the two-wattmeter method, and confirm that the measured values are equal to the calculated values. You will then unbalance the three-phase circuit by modifying the impedance in one phase of the circuit, and solve the resulting unbalanced three-phase circuit. Finally, you will measure the total active, reactive, and apparent power values in the circuit using the two-wattmeter method, and verify that the measured values are equal to the calculated values, thus confirming that the two-wattmeter method of power measurement can be used to measure the total power in both balanced and unbalanced, three-wire, three-phase circuits.

25. Set up the circuit shown in Figure 16.



Local ac power network		R_1, R_2, R_3 (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)		
120	60	171	240
220	50	629	880
240	50	686	960
220	60	629	880

Figure 16. Balanced, three-wire, delta-connected, three-phase circuit set up for power measurements using the two-wattmeter method.

26. Make the necessary switch settings on the Resistive Load and Capacitive Load modules to obtain the resistance and capacitive reactance values required.

27. Solve the circuit in Figure 16 to determine the following parameters: the active power P, reactive power Q, and apparent power S in each phase of the circuit, as well as the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit.

28. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit using the meter set to measure the total power, then turn the three-phase ac power source off.

$P_T =$ _______ W $Q_T =$ _______ var

$S_T =$ _______ VA

29. Compare the total active power P_T, total reactive power Q_T, and total apparent power S_T measured in the previous step with the total power values calculated in step 27. Are all values approximately equal?

❑ Yes ❑ No

30. Modify the switch settings on the Resistive Load and Capacitive Load modules in order to set the resistance and capacitive reactance values in the circuit of Figure 16 to the values indicated in Table 2. Due to these modifications, the three-phase load is now unbalanced (i.e., the first phase of the circuit has an impedance different from that of the second and third phases).

Table 2. Resistance and capacitive reactance values used for unbalancing the three-wire, delta-connected, three-phase circuit in Figure 16.

Local ac power network		R_1 (Ω)	R_2, R_3 (Ω)	X_{C1} (Ω)	X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)				
120	60	300	171	600	240
220	50	1100	629	2200	880
240	50	1200	686	2400	960
220	60	1100	629	2200	880

31. Solve the circuit in Figure 16 using the resistance and capacitive reactance values indicated in Table 2 to determine the following parameters: the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit.

32. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit using the meter set to measure the total power, then turn the three-phase ac power source off.

$P_T =$ _______ W $\qquad$ $Q_T =$ _______ var

$S_T =$ _______ VA

33. Compare the total active power P_T, total reactive power Q_T, and total apparent power S_T measured in the previous step with the total power values calculated in step 31. Are all values approximately equal?

❑ Yes ❑ No

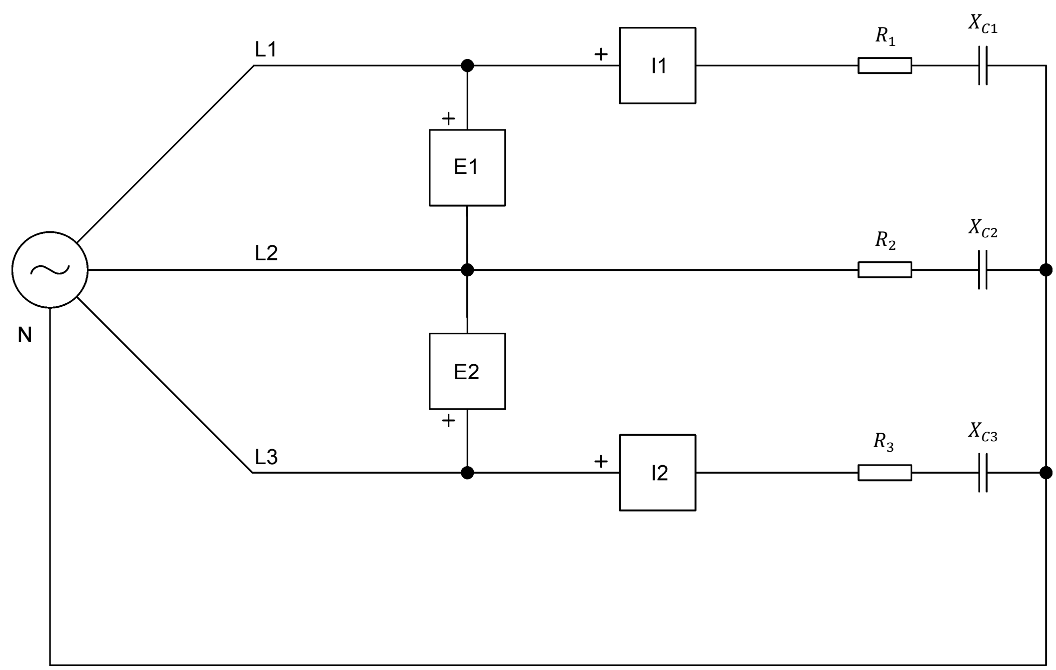
Do the circuit measurements performed in this section confirm that the two-wattmeter method of power measurement can be used to measure the total power in both balanced and unbalanced, three-wire, delta-connected, three-phase circuits?

❑ Yes ❑ No

Measuring the total power in four-wire, three-phase circuits (wye configuration) using the two-wattmeter method

In this section, you will set up a balanced, four-wire, wye-connected, three-phase circuit similar to the one set up in the first section of this exercise for measuring the total power using three power meters, but you will use only two wattmeters (i.e., two voltage inputs and two current inputs) for measuring the total power. You will measure the total active, reactive, and apparent power values in the balanced, three-phase circuit using the two-wattmeter method, and confirm that the measured values are the same as those calculated for this circuit when it is set up for measuring power using three power meters. You will then unbalance the three-phase circuit by modifying the impedance in one phase of the circuit. You will measure the total active, reactive, and apparent power values in the circuit using the two-wattmeter method, and verify that the measured values differ from those calculated for this circuit when it is set up for measuring power using three power meters. You will confirm that the two-wattmeter method can only be used for measuring the total power in four-wire, three-phase circuits that are balanced.

34. Set up the circuit shown in Figure 17.



Local ac power network		R_1, R_2, R_3 (Ω)	X_{C1}, X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)		
120	60	171	240
220	50	629	880
240	50	686	960
220	60	629	880

Figure 17. Four-wire, wye-connected, three-phase circuit set up for power measurements using the two-wattmeter method.

35. Make the necessary switch settings on the Resistive Load and Capacitive Load modules to obtain the resistance and capacitive reactance values required.

The balanced, three-phase circuit just set up corresponds to the balanced, four-wire three-phase circuit set up in the first section of this exercise for measuring the total power using three power meters. The calculations required for solving the circuit are identical to those made in step 11 and do not need to be repeated.

36. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit, using the meter set to measure the total power, then turn the three-phase ac power source off.

$P_T =$ _______ W $Q_T =$ _______ var

$S_T =$ _______ VA

37. Compare the total active power P_T, total reactive power Q_T, and total apparent power S_T measured in the previous step with the total power values calculated in step 11. Are all values approximately equal?

❑ Yes ❑ No

38. Modify the switch settings on the Resistive Load and Capacitive Load modules in order to set the resistance and capacitive reactance values in the circuit of Figure 17 to the values indicated in Table 3. Due to these modifications, the three-phase load is now unbalanced (i.e., the first phase of the circuit has an impedance different from that of the second and third phases).

Table 3. Resistance and capacitive reactance values used for unbalancing the four-wire, wye-connected, three-phase circuit.

Local ac power network		R_1 (Ω)	R_2, R_3 (Ω)	X_{C1} (Ω)	X_{C2}, X_{C3} (Ω)
Voltage (V)	Frequency (Hz)				
120	60	300	171	600	240
220	50	1100	629	2200	880
240	50	1200	686	2400	960
220	60	1100	629	2200	880

The unbalanced, three-phase circuit just set up corresponds to the unbalanced, four-wire, three-phase circuit set up to measure power using three power meters in the second section of this exercise. The calculations required for solving the circuit are identical to those made in step 17 and do not need to be repeated.

39. Turn the three-phase ac power source on.

Successively measure and record the total active power P_T, total reactive power Q_T, and total apparent power S_T in the circuit using the meter set to measure the total power, then turn the three-phase ac power source off.

$P_T =$ _______ W $Q_T =$ _______ var

$S_T =$ _______ VA

40. Compare the total active power P_T, total reactive power Q_T, and total apparent power S_T values measured in the previous step with the total power values calculated in step 17. Are all values equal?

❑ Yes ❑ No

What conclusions can you draw concerning the two-wattmeter method of power measurement when measuring power in four-wire, three-phase circuits?

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

Conclusion

In this exercise, you learned how to calculate active, reactive, and apparent power in balanced, wye- and delta-connected, three-phase circuits. You also learned how to use power meters to measure power in three-phase circuits. You learned how to measure power in three- and four-wire, three-phase circuits, as well as when it is possible to use the two-wattmeter method of power measurement to measure power in a three-phase circuit.

Review Questions

1. A balanced, delta-connected, purely resistive, three-phase circuit has a line voltage E_{Line} of 100 V and a line current I_{Line} of 1.5 A. Calculate the total active power P_T dissipated in the resistive load of the circuit.

2. Explain how to connect the two power meters to the lines of a three-wire, three-phase circuit when using the two-wattmeter method of power measurement.

3. A balanced, wye-connected, resistive and capacitive, three-phase circuit has a phase voltage E_{Phase} of 80 V and a phase current I_{Phase} of 2.5 A. Calculate the total apparent power S_T in the circuit.

4. A balanced, three-wire, resistive and capacitive, three-phase circuit is connected to two power meters set to measure power using the two-wattmeter method of power measurement. The two power meters indicate active power readings of 175 W and -35 W. Calculate the total active power P_T dissipated in the circuit.

____

____

5. In which type of three-phase circuits does the two-wattmeter method of power measurement not work to measure the total power in the circuit?

____

____

Phase Sequence

EXERCISE OBJECTIVE

When you have completed this exercise, you will know what a phase sequence is and why it is important to know the phase sequence of a three-phase power system. You will be able to determine the phase sequence of a three-phase power system using an oscilloscope.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

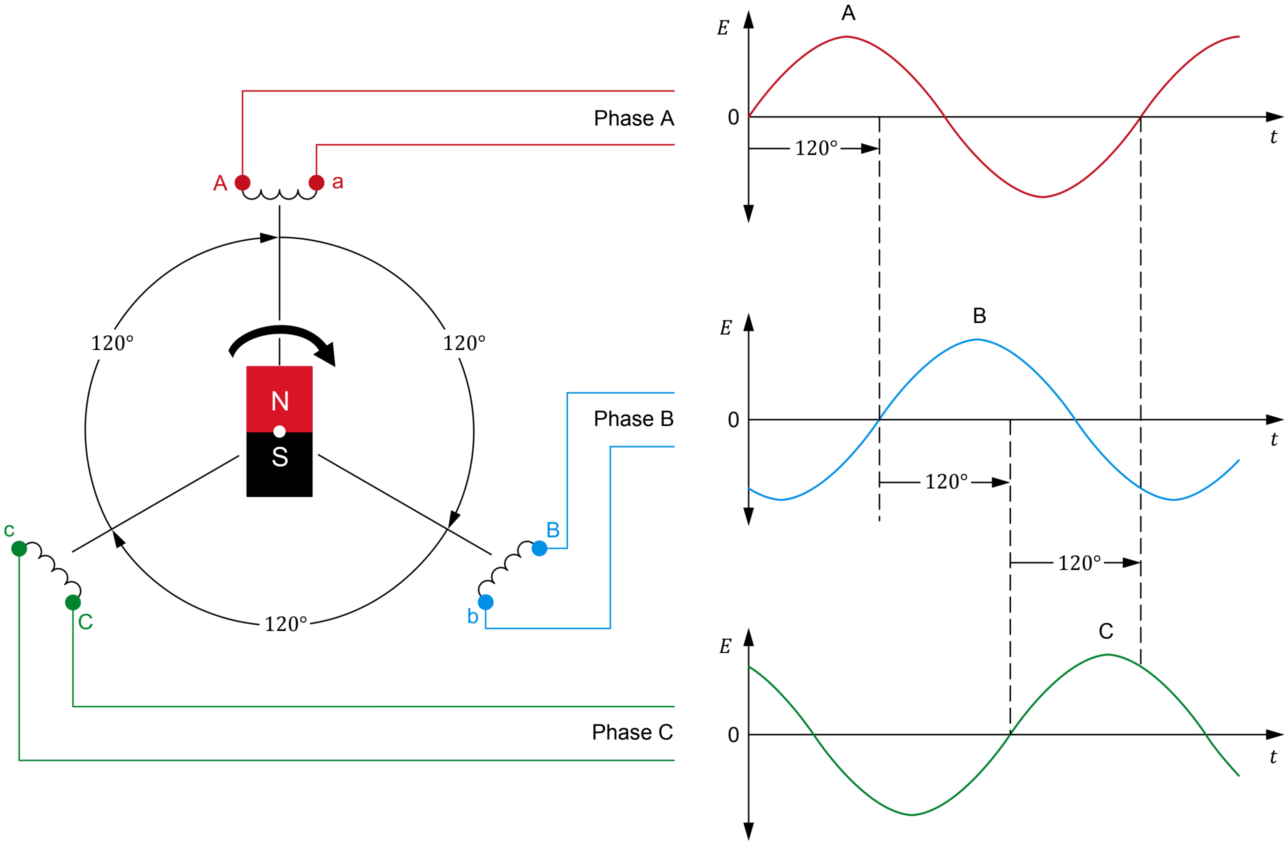
- Phase sequence fundamentals
- Determining the phase sequence of a three-phase power system using an oscilloscope
- Connecting an oscilloscope to a three-phase power system

DISCUSSION

Phase sequence fundamentals

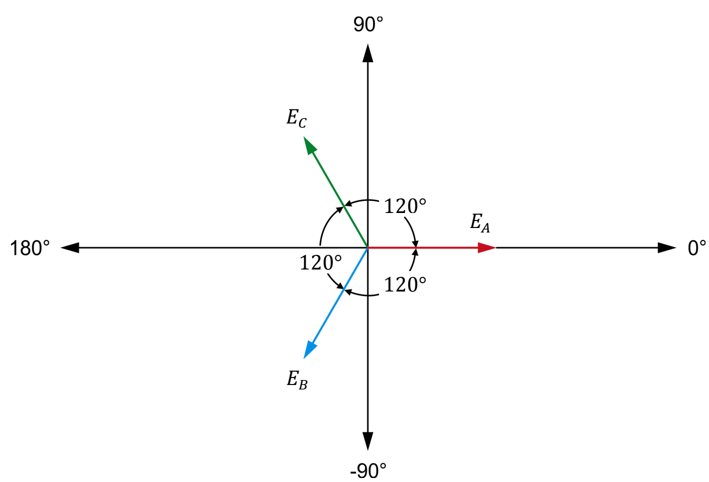
As mentioned earlier in this manual, a three-phase power system is a polyphase system in which three voltages, E_A, E_B, and E_C, have an equal magnitude and are displaced 120° from each other. However, simply stating that the voltages are 120° out of phase with each other is not sufficient to fully describe the system. The order in which the voltages succeed each other, i.e., the phase sequence of the power system, is also important.

The phase sequence of a power system is determined directly at the power generating station by the direction of rotation of the ac generators. Figure 18a shows a three-phase power system rotating in the clockwise (cw) direction. The phase sequence is thus A-B-C-A-B-C… Figure 18b and Figure 18c show the resulting phase voltage waveforms and phase voltage phasor diagram, respectively.



(a) Three-phase power system rotating in the clockwise (cw) direction

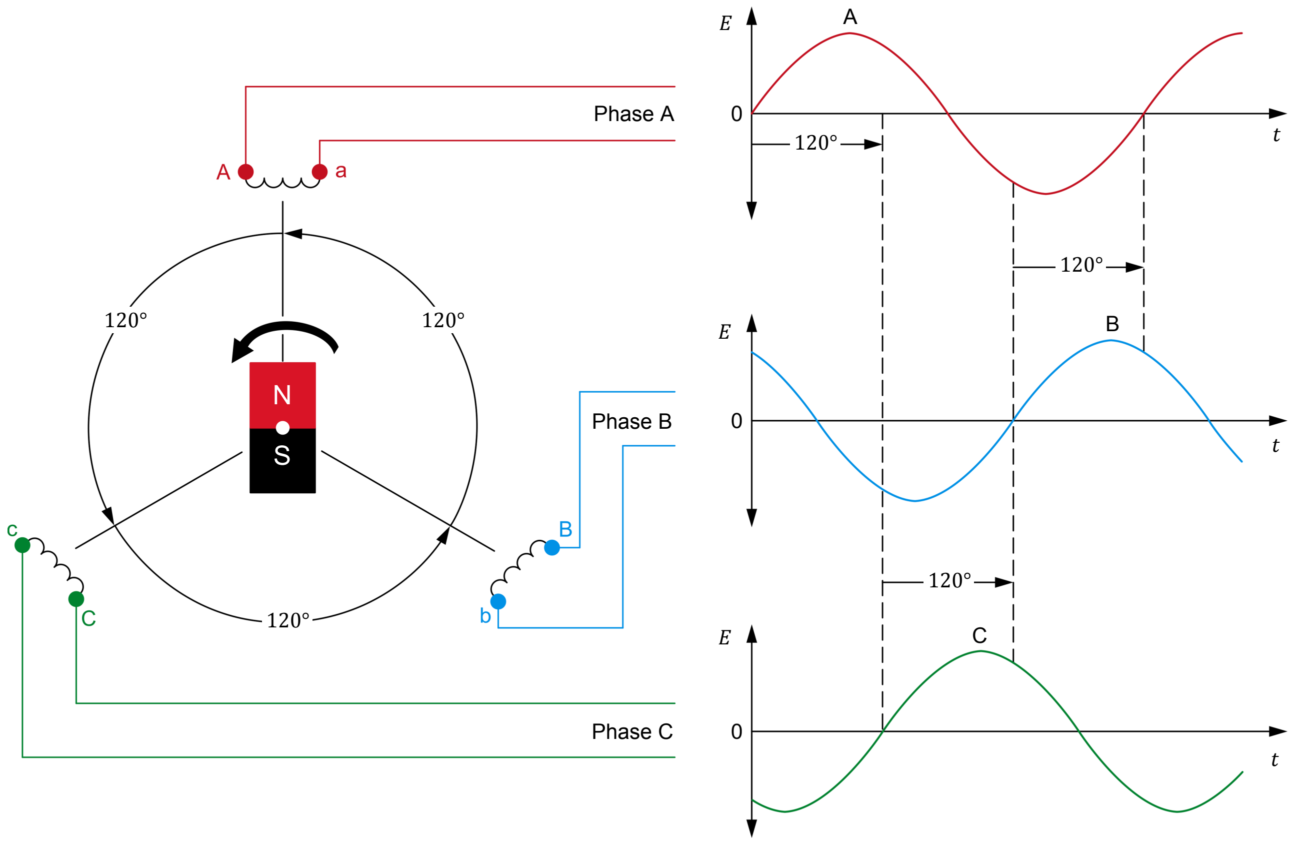
(b) Corresponding phase voltage waveforms



(c) Corresponding phase voltage phasor diagram

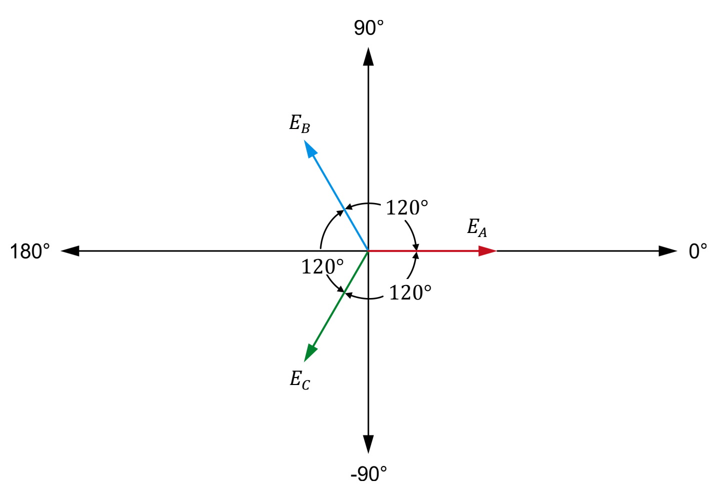
Figure 18. A-B-C-A-B-C… phase sequence.

Figure 19a, on the other hand, shows the same three-phase power system rotating in the counterclockwise (ccw) direction. The corresponding phase sequence is A-C-B-A-C-B… Figure 19b and Figure 19c show the resulting phase voltage waveforms and phase voltage phasor diagram, respectively.



(a) Three-phase power system rotating in the counterclockwise (ccw) direction

(b) Corresponding phase voltage waveforms



(c) Corresponding phase voltage phasor diagram

Figure 19. A-C-B-A-C-B… phase sequence.

When phase sequence A-B-C is written in the form A-B-C-A-B-C..., it becomes clear that B-C-A and C-A-B represent the same sequence as A-B-C and that only the phase used as reference for describing the sequence has changed. The sequence opposite to A-B-C is A-C-B, which is the same as C-B-A and B-A-C (as demonstrated when the sequence is written in the form A-C-B-A-C-B...). Thus, the phase sequence of a three-phase system can be inverted simply by interchanging any two phases of the system.

When connecting a three-phase motor to power lines, it is extremely important to know the phase sequence of the power distribution system because the direction in which the motor turns depends on this sequence. For example, consider the connection of a 4000-kW three-phase motor. It takes several hours of work for an electrician to connect the three large leads of the motor to the local three-phase power system. If the phase sequence is not determined before doing so, the motor has a fifty percent chance of turning in the wrong direction, which would result in the work having to be redone and possibly in damage to the equipment if the motor is connected to a load. Another situation where phase sequence is of critical importance is when additional power is needed in a three-phase ac power network, and one or more alternators (three-phase ac generators) must be added to share the load. The alternators are connected in parallel, so that if the phase sequencing is incorrect, serious damage will occur when the switch connecting the alternators to the power network is turned on.

Determining the phase sequence of a three-phase power system using an oscilloscope

The phase sequence of a three-phase power system can be determined quickly by observing the phase voltage waveforms related to the power system using an oscilloscope. Figure 20 shows an oscilloscope display obtained when channels 1, 2, and 3 of the oscilloscope are connected to phases A, B, and C, respectively, of a three-phase ac power source. In this case, the voltage waveforms of phases A, B, and C appear in sequence from top to bottom on the oscilloscope display, and they indicate that the phase sequence for the present connections to channels 1, 2, and 3 is A-B-C.

Oscilloscope Settings
Channel-1 Scale ....200 V/div
Channel-2 Scale ....200 V/div
Channel-3 Scale ....200 V/div
Time Base............................ 5 ms/div

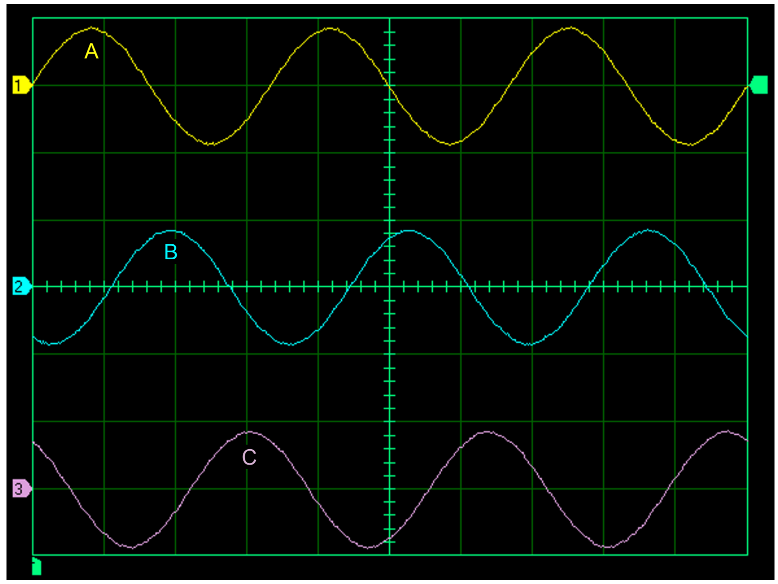


Figure 20. Oscilloscope display when channels 1, 2, and 3 of the oscilloscope are connected to phases A, B, and C, respectively, of a three-phase ac power source.

Figure 21 shows the oscilloscope display when the connections to phases B and C of the three-phase ac power source are inverted, so that channels 1, 2, and 3 of the oscilloscope are now connected to phases A, C, and B, respectively. In this case, the voltage waveforms of phases A, C, and B appear in sequence from top to bottom on the oscilloscope display, and they indicate that the phase sequence with the present connections to channels 1, 2, and 3 is A-C-B. Thus, the oscilloscope display clearly shows that the phase sequence has been inverted.

Oscilloscope Settings
Channel-1 Scale ....200 V/div
Channel-2 Scale ....200 V/div
Channel-3 Scale ....200 V/div
Time Base............................ 5 ms/div

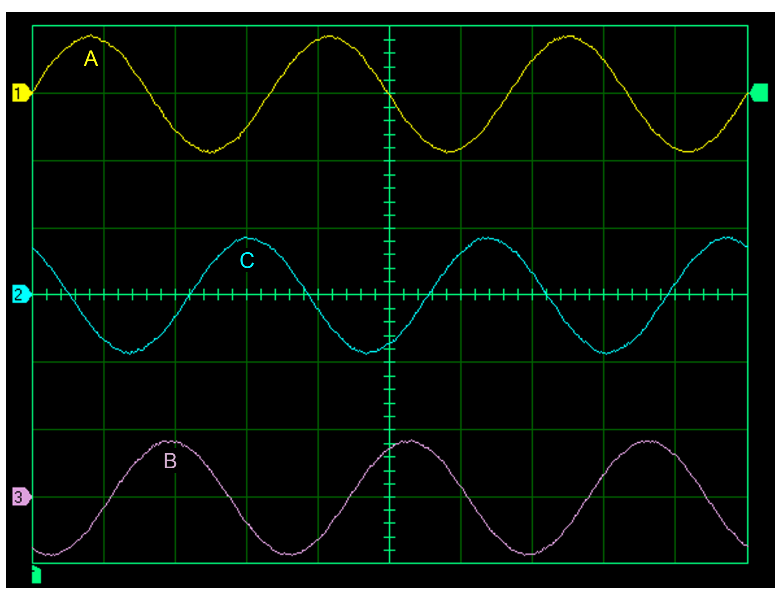


Figure 21. Oscilloscope display when channels 1, 2, and 3 of the oscilloscope are connected to phases A, C, and B, respectively, of a three-phase ac power source.

Connecting an oscilloscope to a three-phase power system

When the neutral wire of a three-phase power system is available, each channel of the oscilloscope can be connected directly to a line wire and the neutral wire to measure a phase voltage, as shown in Figure 22.

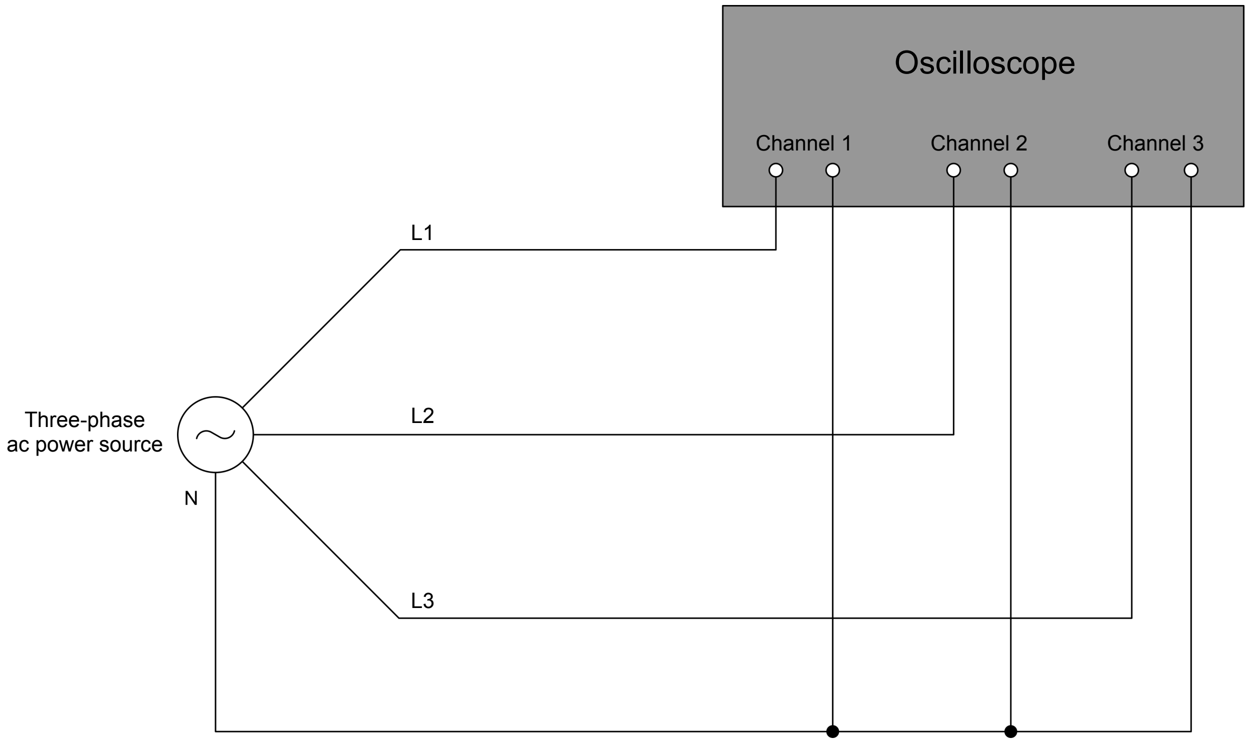


Figure 22. Oscilloscope connections to a four-wire, three-phase power system.

In most cases, direct connection of the oscilloscope to a three-wire, three-phase power system to measure the phase voltages is not possible because the neutral point is generally not available. In this case, a balanced, wye-connected resistive load is temporarily connected to the line wires of the three-phase power system, and each oscilloscope channel is connected to measure the phase voltage across one of the load resistors. Figure 23 shows the circuit connections required to connect an oscilloscope to a three-wire, three-phase power system (system with no neutral wire).

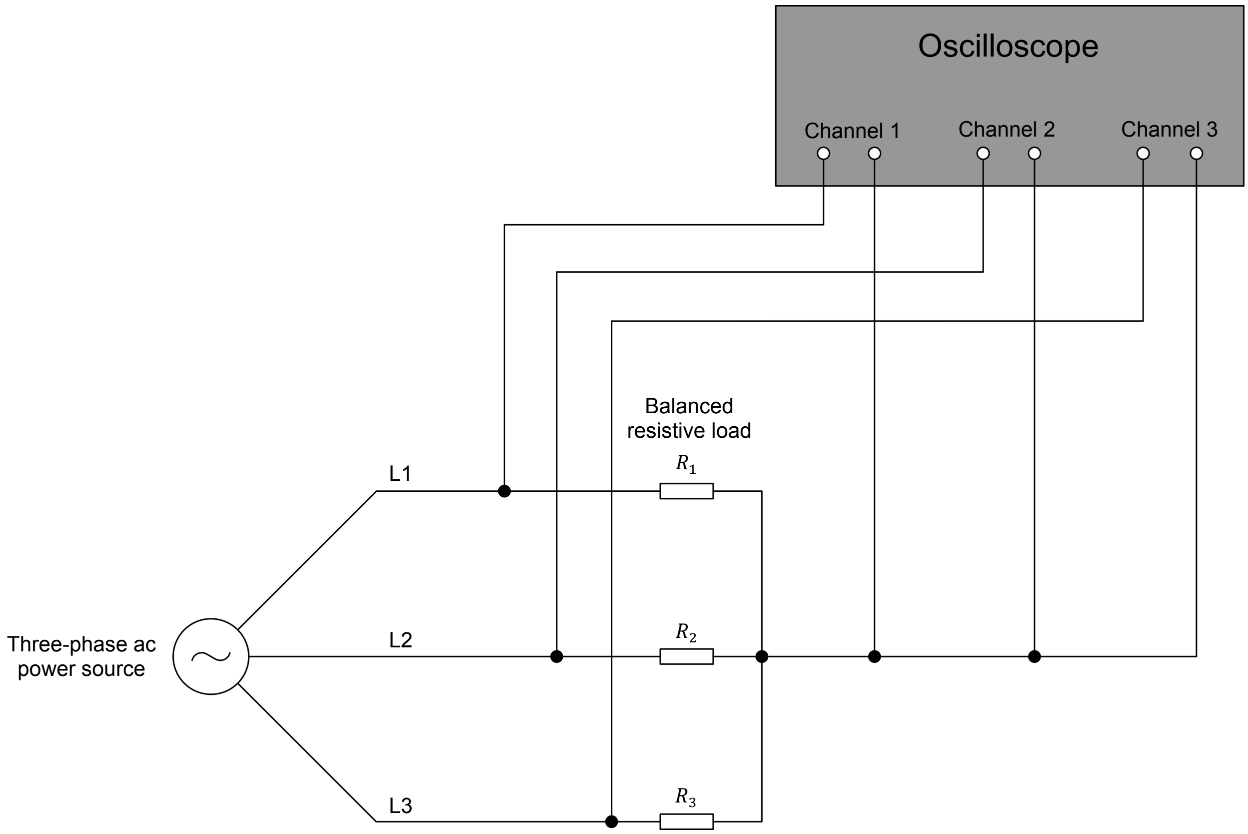


Figure 23. Oscilloscope connections to a three-wire, three-phase power system (system with no neutral wire).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Determining the phase sequence of the three-phase ac power source

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.

Setup and connections

In this section, you will set up the equipment to determine the phase sequence of the three-phase ac power source in the Power Supply.

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

2. Install the required equipment in the Workstation.

3. 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.

4. Connect the *Power Input* of the Data Acquisition and Control Interface to the *Power Output* of the 24 V AC Power Supply module. Turn the 24 V AC Power Supply module on.

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

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

7. 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 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.

8. Set up the circuit shown in Figure 24.

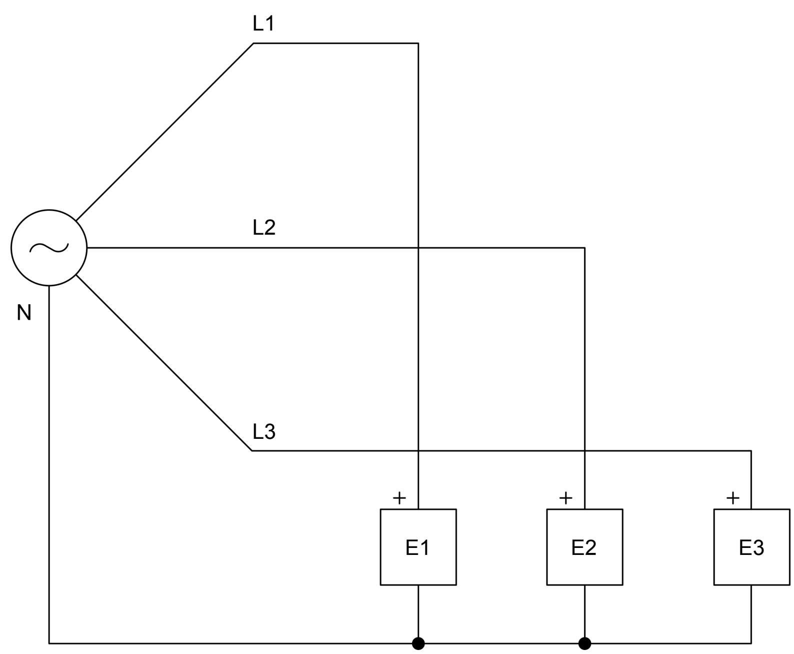


Figure 24. Circuit set up for determining the phase sequence of the three-phase ac power source in the Power Supply.

Determining the phase sequence of the three-phase ac power source

In this section, you will determine the phase sequence of the three-phase ac power source in the Power Supply by observing the phase voltage waveforms using the Oscilloscope, and confirm the phase sequence by observing the phase voltage phasors using the Phasor Analyzer. You will then interchange the connections at two terminals of the three-phase ac power source and determine the new phase sequence using the Oscilloscope. Finally, you will confirm the new phase sequence using the Phasor Analyzer.

9. Turn the three-phase ac power source on.

10. In LVDAC-EMS, open the Oscilloscope, then make the appropriate settings in order to observe the phase voltage waveforms related to inputs *E1*, *E2*, and *E3* of the Data Acquisition and Control Interface (DACI).

    Determine the phase sequence of the three-phase ac power source from the phase voltage waveforms observed on the Oscilloscope.

    The phase sequence related to terminals L1, L2, and L3 of the Power Supply is A-B-C. When the three-phase ac power outlet to which the Power Supply is connected is wired accordingly, the sequence of the phase voltages at terminals L1, L2, and L3 is A-B-C.

    Phase sequence: ________

11. In LVDAC-EMS, open the Phasor Analyzer, then make the appropriate settings in order to observe the phasors of the phase voltages measured using inputs *E1*, *E2*, and *E3* of the DACI.

12. On the Phasor Analyzer, observe the relative positions of the phase voltage phasors at terminals *L1*, *L2*, and *L3* of the Power Supply (i.e., the phasors of the phase voltages measured using inputs *E1*, *E2*, and *E3* of the DACI, respectively). Determine the phase sequence from the observed phase voltage phasors.

    Phase sequence: ________

    Is the phase sequence the same as the phase sequence determined in step 10?

    ❑ Yes ❑ No

13. Turn the three-phase ac power source off.

    Interchange the connections at terminals *L2* and *L3* of the Power Supply. This does not change the phase sequence of the three-phase ac power source in the Power Supply. However, this reverses the phase sequence of the source voltages that is perceived at voltage inputs *E1*, *E2,* and *E3* of the DACI.

    Turn the three-phase ac power source on.

14. Using the Oscilloscope, determine the phase sequence of the source voltages perceived at voltage inputs *E1*, *E2*, and *E3* of the DACI. Record this sequence below.

Phase sequence: ________

Is the phase voltage sequence opposite to the one recorded in step 10?

❑ Yes ❑ No

15. Using the Phasor Analyzer, observe the relative positions of the phase voltage phasors measured using inputs *E1*, *E2*, and *E3* of the DACI. Determine the phase sequence of the source voltages perceived at voltage inputs *E1*, *E2*, and *E3* of the DACI. Record this sequence below.

Phase sequence: ________

Is the phase sequence the same as the phase sequence determined in the previous step?

❑ Yes ❑ No

16. What is the effect on the perceived phase sequence of the three-phase ac power source in the Power Supply of interchanging the connections at two terminals of the Power Supply?

____

____

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

Conclusion

In this exercise, you learned what a phase sequence is and why it is important to know the phase sequence of a three-phase ac power system. You learned how to determine the phase sequence of a three-phase ac power source using an oscilloscope.

Review Questions

1. Why is it important to know the phase sequence of a three-phase power distribution system when connecting a three-phase motor to the system?

____

____

____

2. What is the phase sequence opposite to B-A-C?

____

3. Determine the phase sequence of the voltage waveforms shown in the following figure.

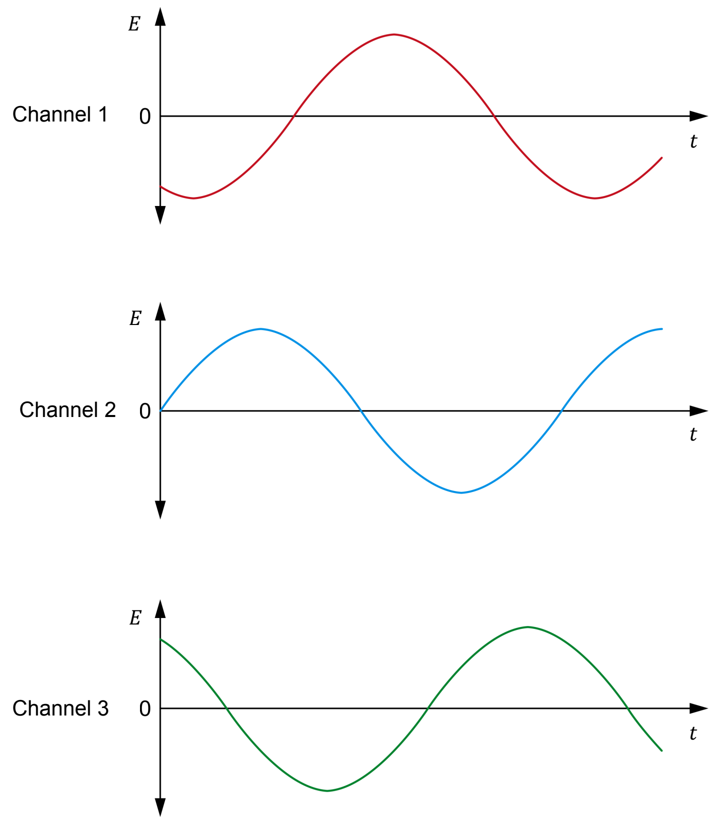


Figure 25. Voltage waveforms.

Phase sequence: _________

4. How can an oscilloscope be used to determine the phase sequence of a three-wire, three-phase ac power system?

____

____

____

____

____

5. A three-phase motor rotates clockwise when lines A, B, and C of a three-phase ac power source are connected to motor leads 1, 2, and 3, respectively. If the connections are interchanged so that lines A, B, and C are now connected to leads 3, 1, and 2, respectively, what will be the motor direction of rotation? Explain.

Equipment Utilization Chart

The following equipment is required to perform the exercises in this course.

Equipment		Exercise		
Model	**Description**	**1**	**2**	**3**
8131(1)	Three-Module Workstation	1	1	1
8311-0(2)	Resistive Load	1	1	1
8331	Capacitive Load		1	
8823	Power Supply	1	1	1
8951-L	Connection Leads	1	1	1
9063-B(3)	Data Acquisition and Control Interface	1	1	1

(1) The Mobile Workstation, Model 8110, and the Workstation, Model 8134, can also be used.
(2) Resistive Load unit with voltage rating corresponding to your local ac power network voltage (Model variant 8311-0).
(3) Model 9063-B consists of the Data Acquisition and Control Interface, Model 9063, with the Computer-Based Instrumentation function set, Model 9069-1.

Glossary of New Terms

balanced three-phase circuit A balanced, three-phase circuit is a three-phase ac circuit with equal impedances in each of the three load branches. The three phase voltages that power the circuit are equal in amplitude, but are shifted 120° from each other. A balanced, three-phase circuit is thus simply a combination of three single-phase circuits. Therefore, the rules for calculating voltage, current, and power in single-phase circuits also apply to balanced three-phase circuits.

delta configuration A delta configuration is a type of three-phase circuit connection in which the three branches of the source or load are connected end-to-end to form a continuous (closed) circuit loop. The three line wires are connected to the three junction points of the circuit. There is no point to which a neutral wire can be connected in a delta-connected, three-phase circuit.

line current The line current in a three-phase circuit is the current measured in any line wire of the circuit. In balanced, delta-connected, three-phase circuits, the line current is $\sqrt{3}$ times higher than the phase current.

line voltage The line voltage in a three-phase circuit is the voltage measured between any two line wires of the circuit. In balanced, wye-connected, three-phase circuits, the line voltage is $\sqrt{3}$ times higher than the phase voltage.

phase current The phase current in a three-phase circuit is the current measured in any phase of the circuit (i.e., the current flowing in each element of a three-phase load). In balanced, delta-connected, three-phase circuits, the phase current is $\sqrt{3}$ times lower than the line current.

phase sequence The phase sequence of a three-phase ac power system is the sequence in which the phase voltages reach the maximum (peak) value. The usual shorthand form of indicating phase sequence is A-B-C, which is the same as the sequences B-C-A and C-A-B. The opposite phase sequence to A-B-C is A-C-B (C-B-A, B-A-C).

phase voltage The phase voltage in a three-phase circuit is the voltage measured between any line wire and the neutral wire of the circuit. In balanced, wye-connected, three-phase circuits, the phase voltage is $\sqrt{3}$ times lower than the line voltage.

two-wattmeter method The two-wattmeter method is a method of measuring power in three-phase circuits in which two single-phase power meters are connected across the line wires so that the total power is the algebraic sum of the two power meter readings. When using this method, the two current inputs of the power meters are connected to measure the line current in two of the line wires while the two voltage inputs of the power meters are connected to measure the line voltages between the two line wires connected to the current inputs and the remaining line wire. The two-wattmeter method allows power in three-wire, three-phase power systems to be measured as it uses line voltage and current measurements only.

wye configuration A wye configuration is a type of three-phase circuit connection in which one end of each of the three branches of the source or load are connected together at a common junction point called the neutral. The three line wires are each connected to an individual circuit branch, and a neutral wire can be connected to the neutral point of the circuit. In a balanced three-phase circuit, no current flows in the neutral wire.

Impedance Table for the Load Modules

The following table gives impedance values which can be obtained using either the Resistive Load, Model 8311, the Inductive Load, Model 8321, or the Capacitive Load, Model 8331. Figure 26 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

Table 4. Impedance table for the load modules.

Impedance (Ω)			Position of the switches								
120 V 60 Hz	**220/230 V 50 Hz/60 Hz**	**240 V 50 Hz**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1200	4400	4800	I								
600	2200	2400		I							
300	1100	1200			I						
400	1467	1600	I	I							
240	880	960	I		I						
200	733	800		I	I						
171	629	686	I	I	I						
150	550	600	I			I	I	I			
133	489	533		I		I	I	I			
120	440	480			I		I	I			
109	400	436			I	I	I	I			
100	367	400	I		I	I	I	I			
92	338	369		I	I	I	I	I			
86	314	343	I	I	I	I	I	I			
80	293	320	I			I	I	I	I	I	I
75	275	300		I		I	I	I	I	I	I
71	259	282			I		I	I	I	I	I
67	244	267			I	I	I	I	I	I	I
63	232	253	I		I	I	I	I	I	I	I
60	220	240		I	I	I	I	I	I	I	I
57	210	229	I	I	I	I	I	I	I	I	I

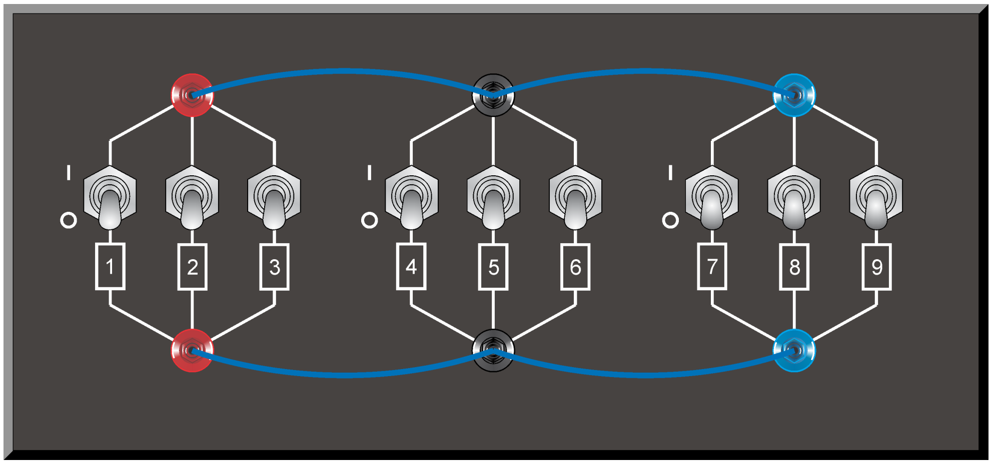


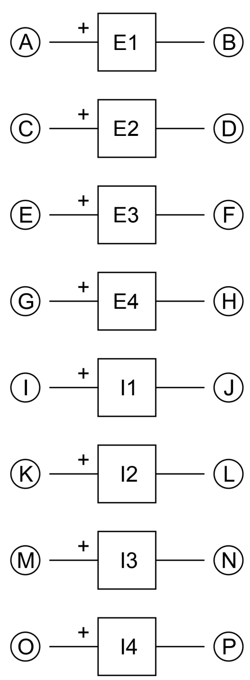
Figure 26. Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

Circuit Diagram Symbols

Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using the equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown in 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.

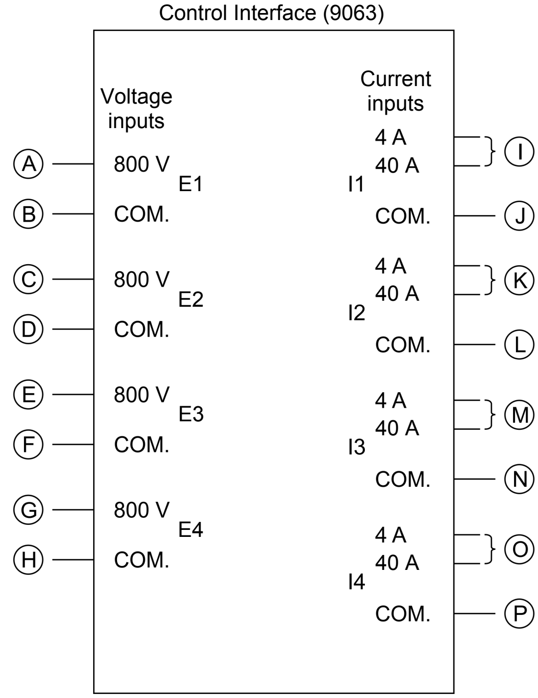
Symbol



Isolated voltage and current measurement inputs

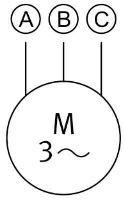
Equipment and Connections

Data Acquisition and Control Interface (9063)



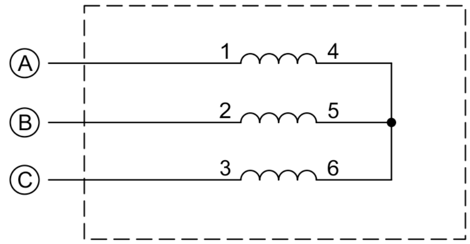
When current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.

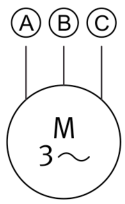
Symbol	**Equipment and Connections**



Three-phase induction machine

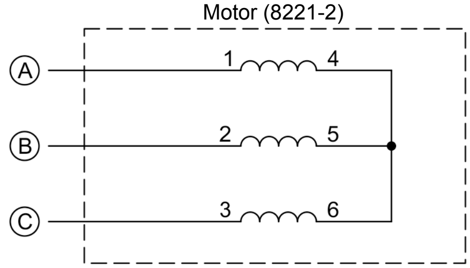
Four-Pole Squirrel-Cage Induction Motor (8221-0)

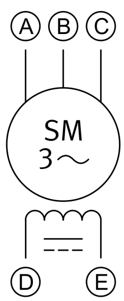




Three-phase induction machine

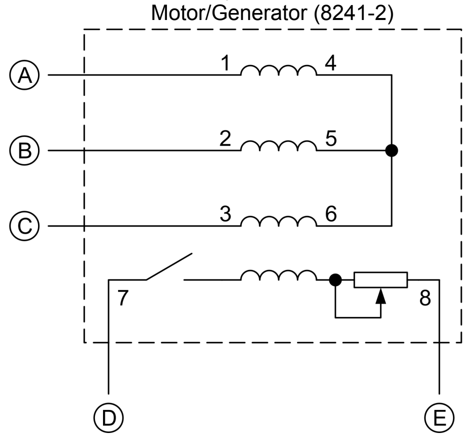
Four-Pole Squirrel-Cage Induction Motor (8221-2)



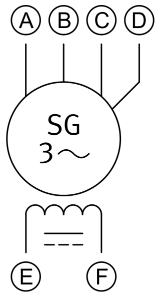


Three-phase synchronous motor

Synchronous Motor/Generator (8241-2)

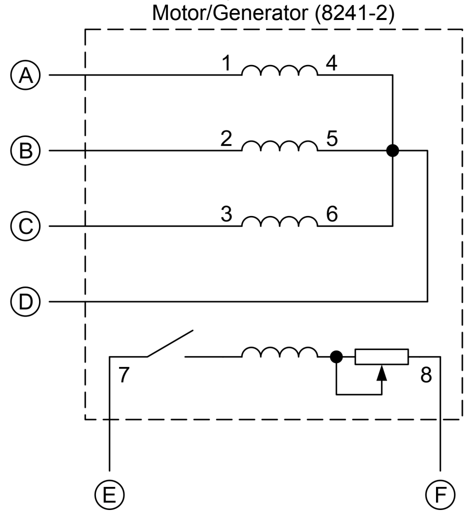


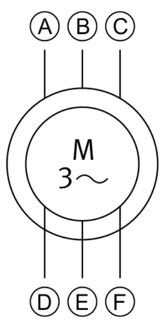
Symbol	**Equipment and Connections**



Three-phase synchronous generator

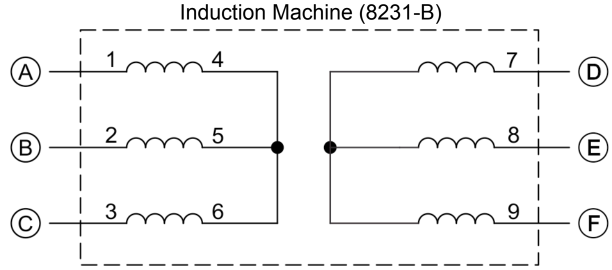
Synchronous Motor/Generator (8241-2)



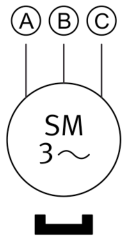


Three-phase wound-rotor induction machine

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

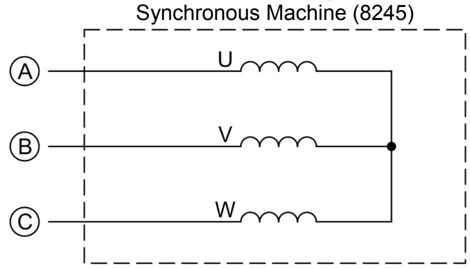


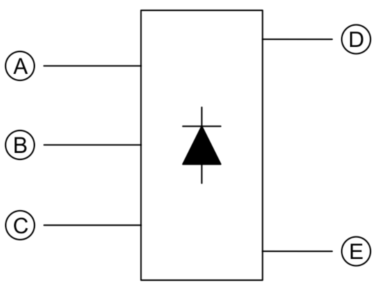
Symbol	**Equipment and Connections**



Permanent Magnet Synchronous Machine

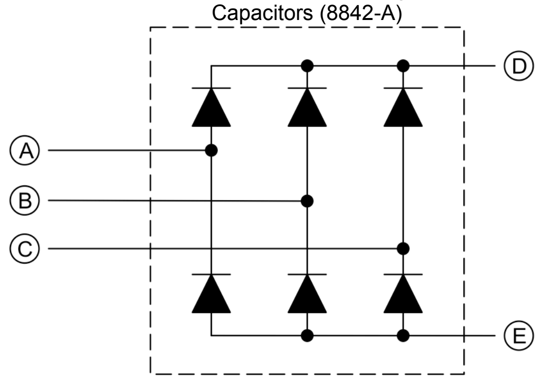
Permanent Magnet Synchronous Machine (8245)

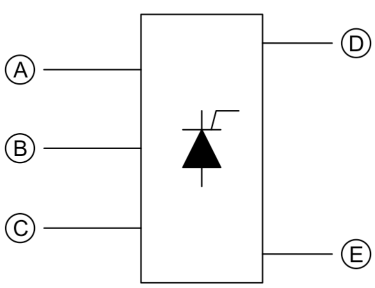




Power diode three-phase full-wave rectifier

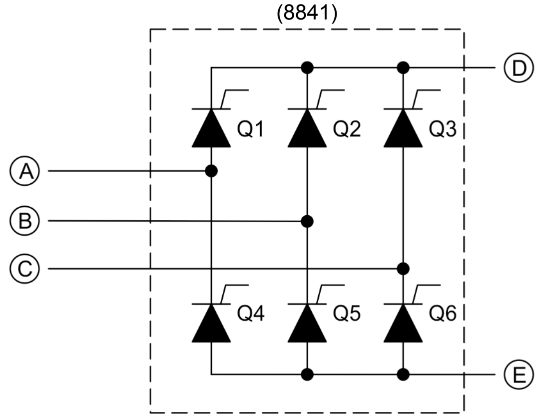
Rectifier and Filtering Capacitors (8842-A)



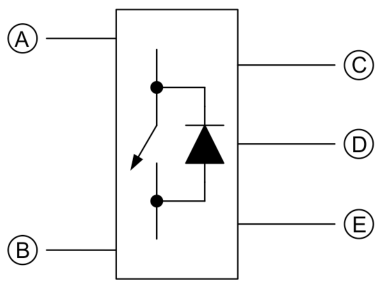


Power thyristor three-phase bridge

Power Thyristors (8841)

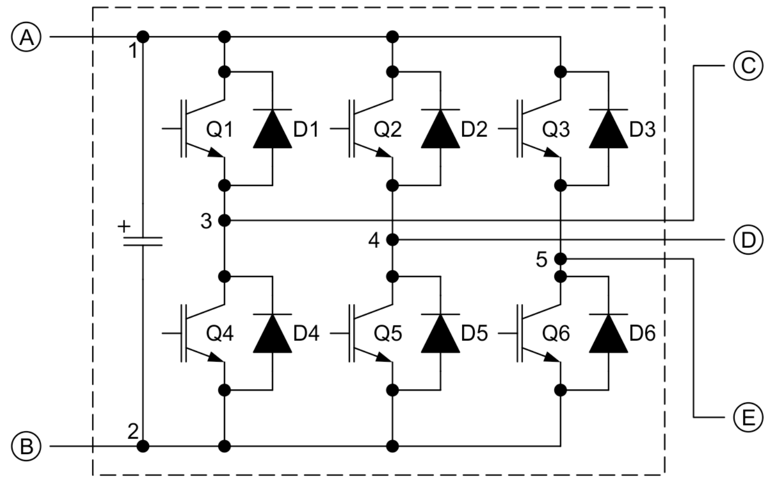


Symbol



Three-phase inverter

Equipment and Connections



The representation of an electronic power switch used in the three-phase inverter symbol above is neither an IEC symbol nor an ANSI symbol.

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.