## Electricity and New Energy

# Three-Phase AC Power Circuits

## Course Sample

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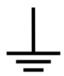
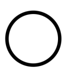
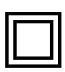
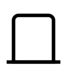
# Safety and Common Symbols

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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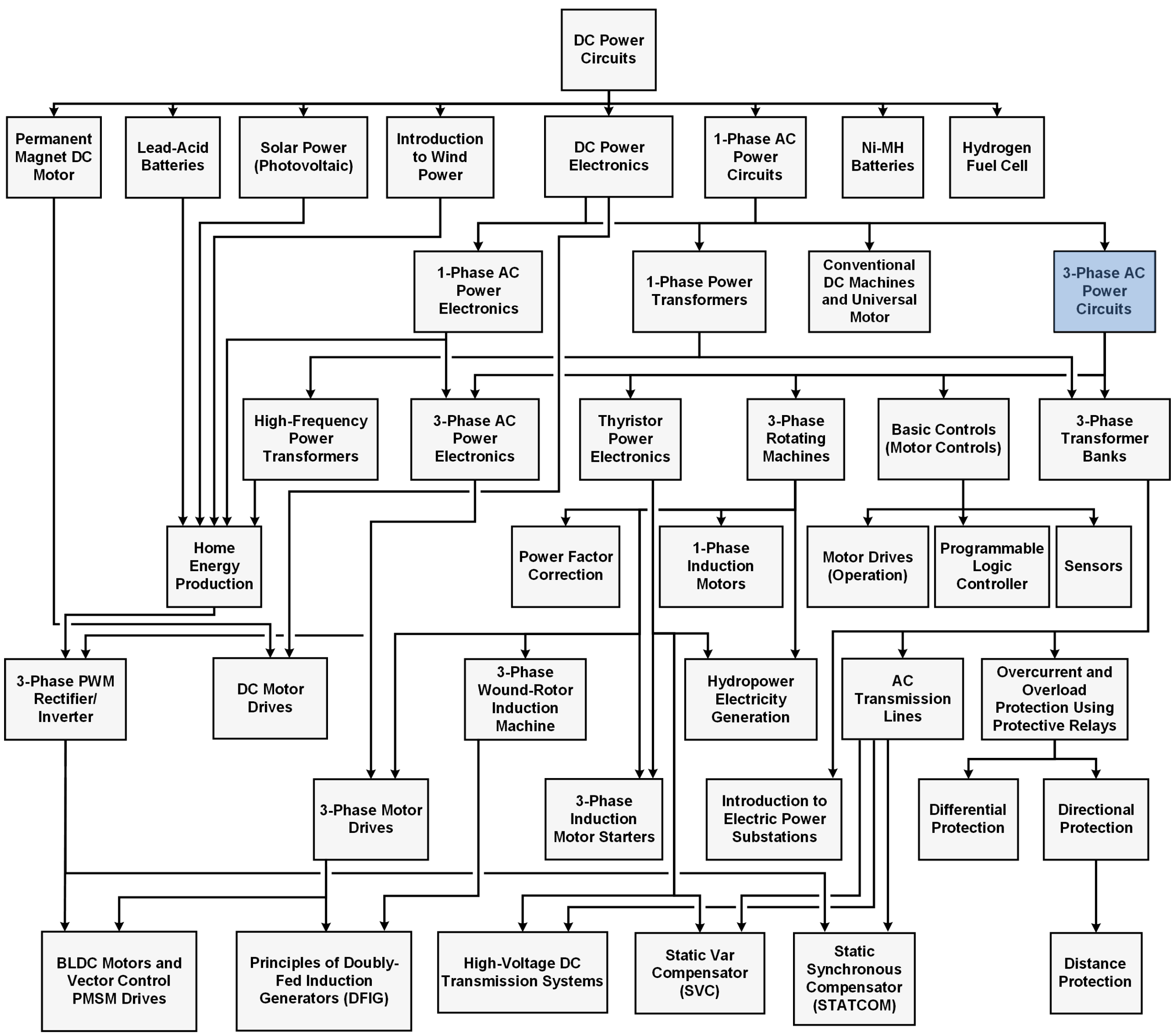
# Preface

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.

# To the Instructor

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

### Accuracy of measurements

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

### Equipment installation

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

Sample

Extracted from

Instructor Guide

# Exercise 1

# 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°.

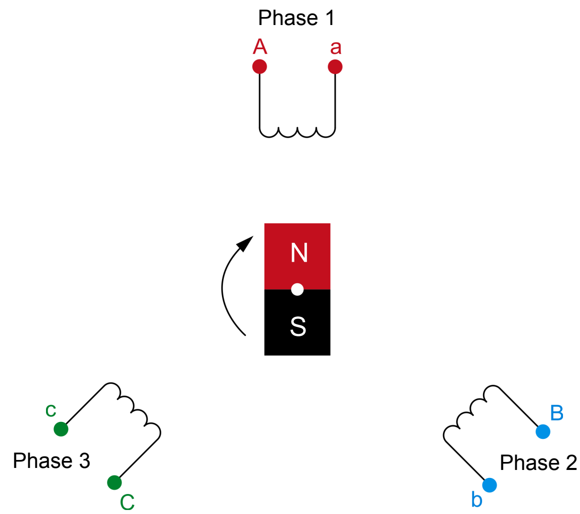
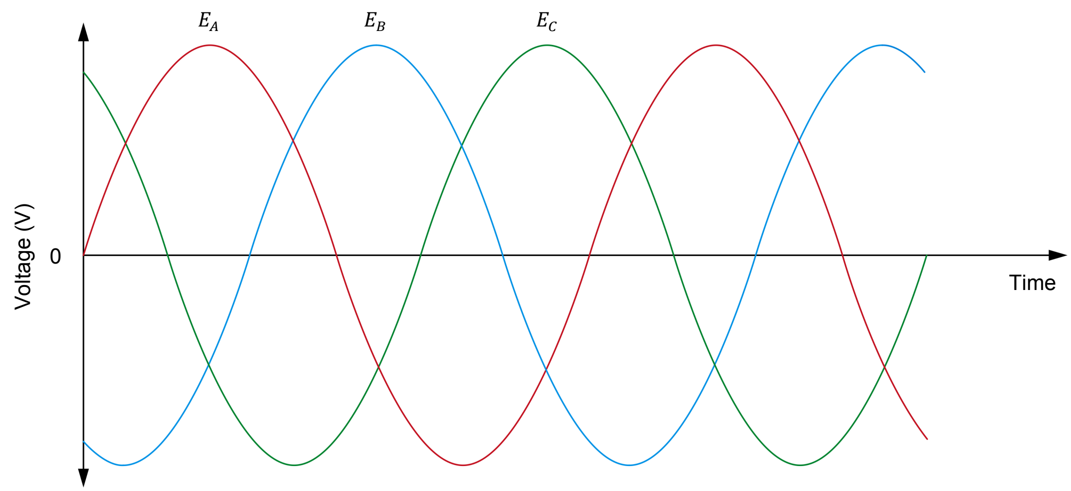


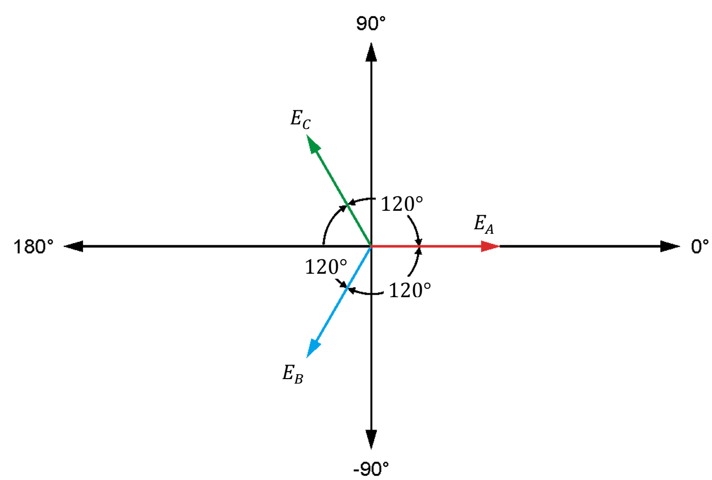

**Figure 1. A simplified three-phase generator.**

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.

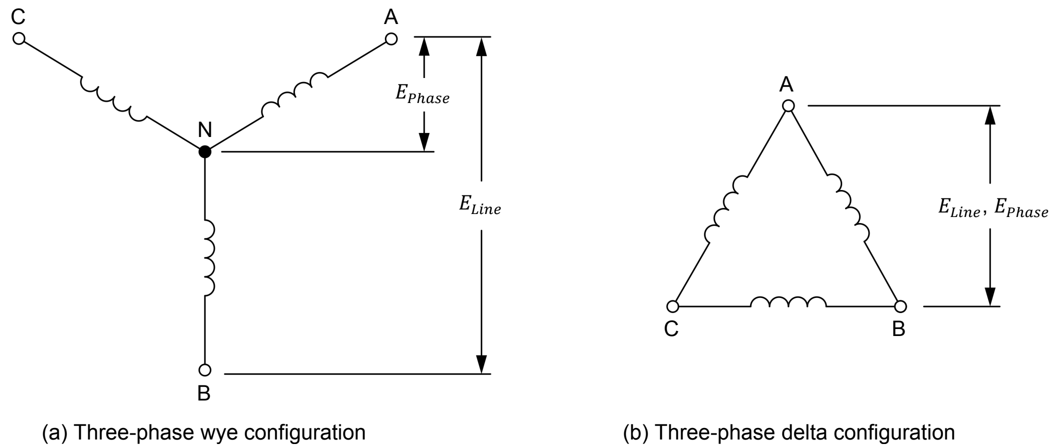



**Figure 3. Types of three-phase system configurations.**

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.

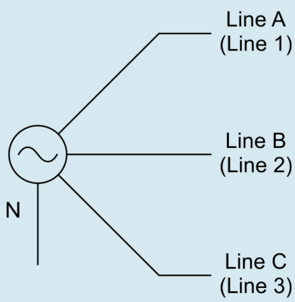
Figure 3b shows that, in a delta-connected circuit, the three windings of the three-phase ac power source are connected one to another, forming a triangle. The three line wires are connected to the three junction points of the circuit (points A, B, and C in Figure 3b). There is no point to which a neutral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

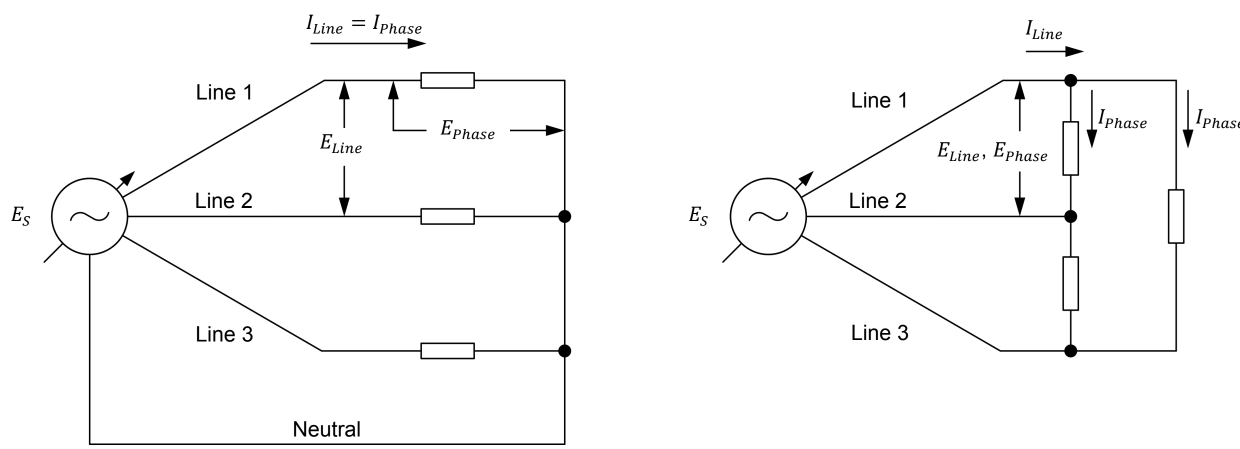
The voltage produced by a single winding of a three-phase circuit is called the line-to-neutral voltage, or simply the **phase voltage**, $E_{Phase}$. In a wye-connected three-phase ac power source, the phase voltage is measured between the neutral line and any one of points A, B, and C, as shown in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




(a) Wye-connected load (b) Delta-connected load

**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:

$$P_{Phase} = E_{Phase} \times I_{Phase} \times \cos\varphi \qquad (1)$$

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).
$\varphi$ 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:

$$P_T = 3 \times P_{Phase} = 3 \times E_{Phase} \times I_{Phase} \times \cos\varphi \qquad (2)$$

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.*

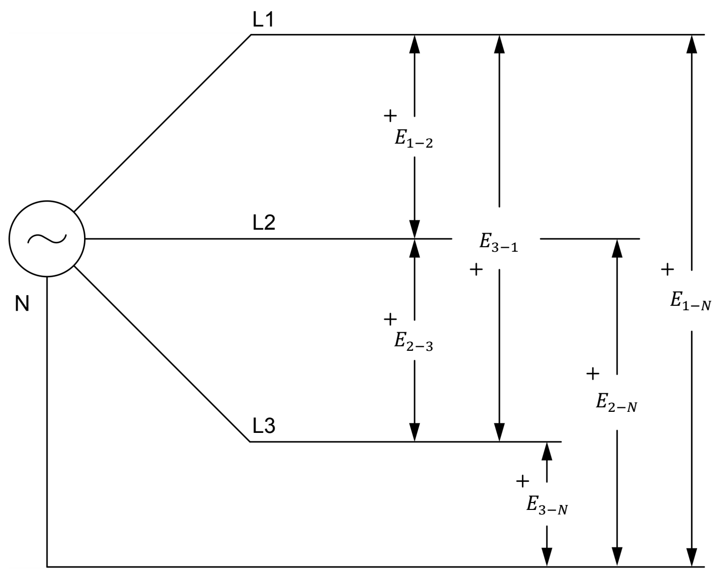



**Figure 5. Phase and line voltage measurements.**

## 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

$E_{1-N} = 120\ \text{V}$

$E_{2-N} = 120\ \text{V}$

$E_{3-N} = 120\ \text{V}$

Determine the average value of the phase voltages.

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

$$\text{Average } E_{Phase} = \frac{E_{1-N} + E_{2-N} + E_{3-N}}{3} = \frac{120\text{ V} + 120\text{ V} + 120\text{ V}}{3} = 120\text{ V}$$

**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.

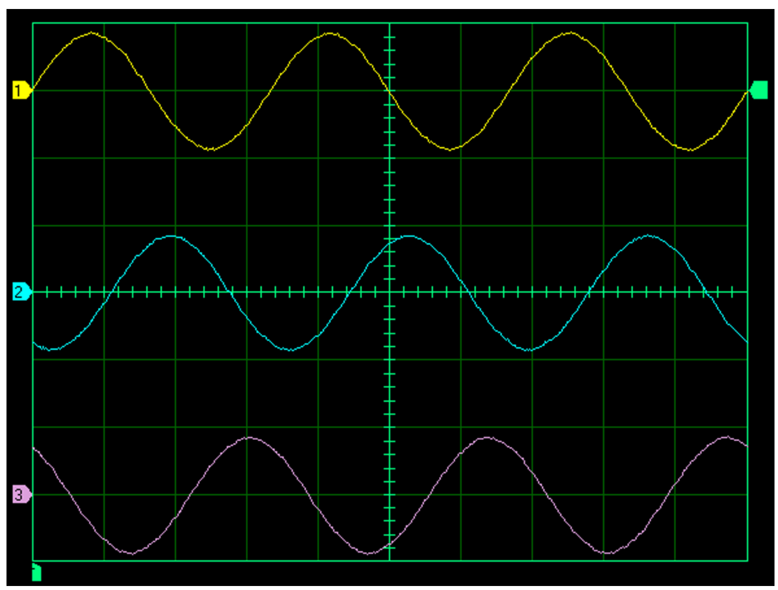
Is the phase shift between each voltage sine wave of the three-phase ac power source equal to 120°?

❑ Yes ❑ No

Yes

The resulting voltage waveforms of the three-phase ac power source are shown in the following picture.

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




**Phase voltage waveforms of the three-phase ac power source observed using the Oscilloscope.**

**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.

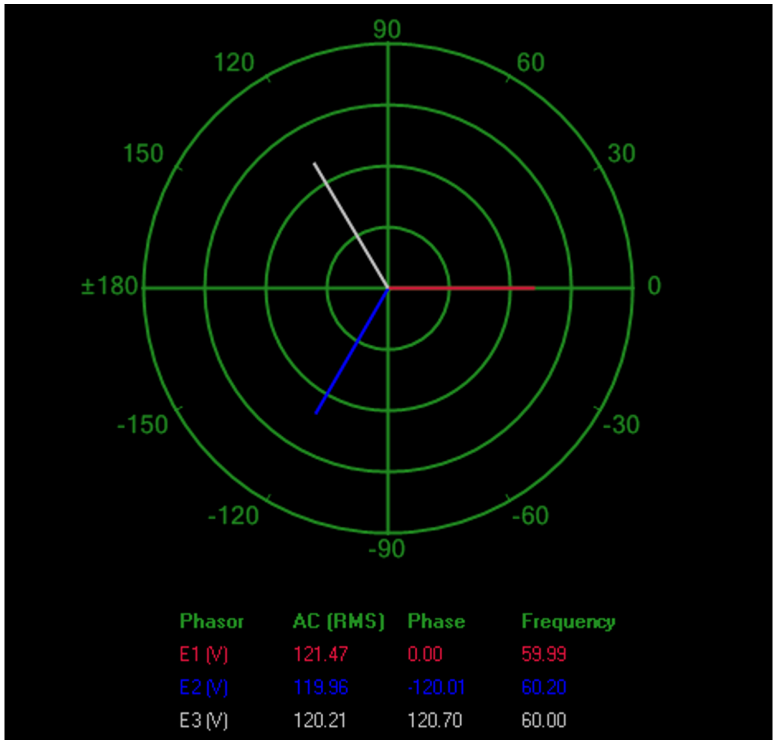
Is the phase shift between each voltage phasor of the three-phase ac power source equal to 120°?

❑ Yes ❑ No

Yes

The resulting voltage phasors of the three-phase ac power source are shown in the following picture.

Phasor Analyzer Settings
Reference Phasor.......................... E1
Voltage Scale..........................50 V/div




**Phase voltage phasors of the three-phase ac power source observed using the Phasor Analyzer.**

**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

$E_{1-2} = 208\ \text{V}$

$E_{2-3} = 207\ \text{V}$

$E_{3-1} = 209\ \text{V}$

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

**18.** Determine the average value of the line voltages.

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

$$\text{Average } E_{Line} = \frac{E_{1-2} + E_{2-3} + E_{3-1}}{3} = \frac{208\ \text{V} + 207\ \text{V} + 209\ \text{V}}{3} = 208\ \text{V}$$

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

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

The ratio of the average line voltage $E_{Line}$ to the average phase voltage $E_{Phase}$ is equal to:

$$\frac{\text{Average } E_{Line}}{\text{Average } E_{Phase}} = \frac{208\ \text{V}}{120\ \text{V}} = 1.73 = \sqrt{3}$$

**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)?

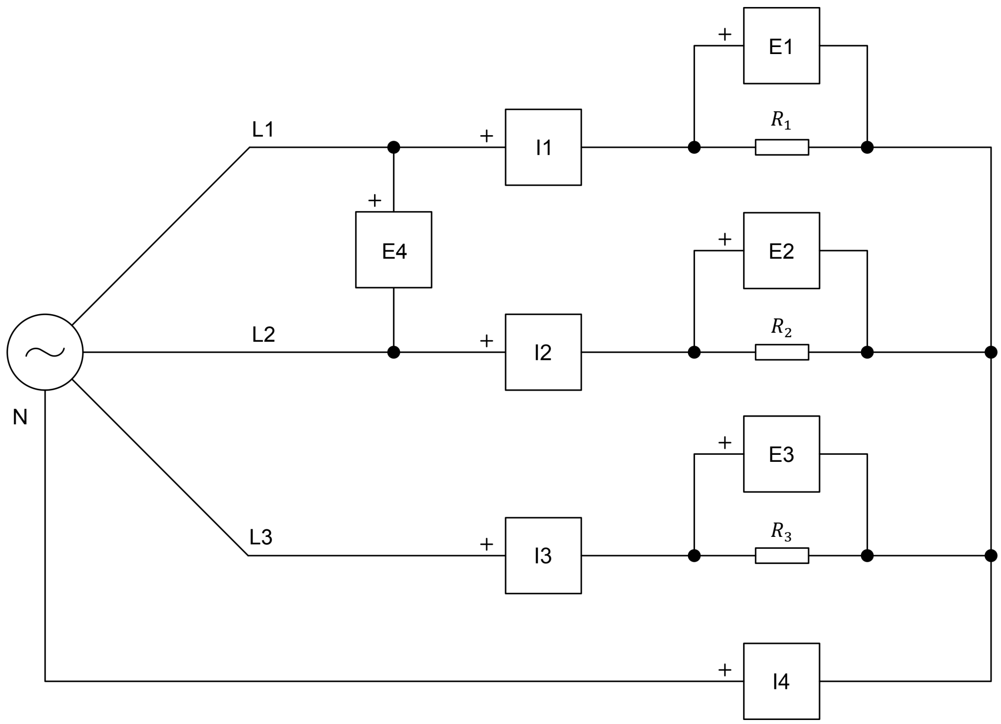
❑ Yes ❑ No

Yes

## 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

$E_{R1} = 119\ \text{V}$    $E_{R2} = 118\ \text{V}$

$E_{R3} = 118\ \text{V}$    $E_{Line} = 205\ \text{V}$

$I_{R1} = 0.40\ \text{A}$    $I_{R2} = 0.40\ \text{A}$

$I_{R3} = 0.41\ \text{A}$    $I_N = 0.01\ \text{A}$

**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

Yes

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

❑ Yes ❑ No

Yes

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

❑ Yes ❑ No

Yes

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

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

The average phase voltage $E_{Phase}$ is equal to:

$$\text{Average } E_{Phase} = \frac{E_{R1} + E_{R2} + E_{R3}}{3} = \frac{119 \text{ V} + 118 \text{ V} + 118 \text{ V}}{3} = 118 \text{ V}$$

**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

Yes

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

❑ Yes ❑ No

Yes

**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

No

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

❑ Yes ❑ No

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

$P_{R1} = E_{R1} \times I_{R1} = 119\ \text{V} \times 0.40\ \text{A} = 47.6\ \text{W}$

$P_{R2} = E_{R2} \times I_{R2} = 118\ \text{V} \times 0.40\ \text{A} = 47.2\ \text{W}$

$P_{R3} = E_{R3} \times I_{R3} = 118\ \text{V} \times 0.41\ \text{A} = 48.4\ \text{W}$

$P_T = P_{R1} + P_{R2} + P_{R3} = 47.6\ \text{W} + 47.2\ \text{W} + 48.4\ \text{W} = 143.2\ \text{W}$

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

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

The average phase current $I_{Phase}$ is equal to:

$$\text{Average } I_{Phase} = \frac{I_{R1} + I_{R2} + I_{R3}}{3} = \frac{0.40\ \text{A} + 0.40\ \text{A} + 0.41\ \text{A}}{3} = 0.40\ \text{A}$$

**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

The total active power $P_T$ dissipated in the circuit is equal to:

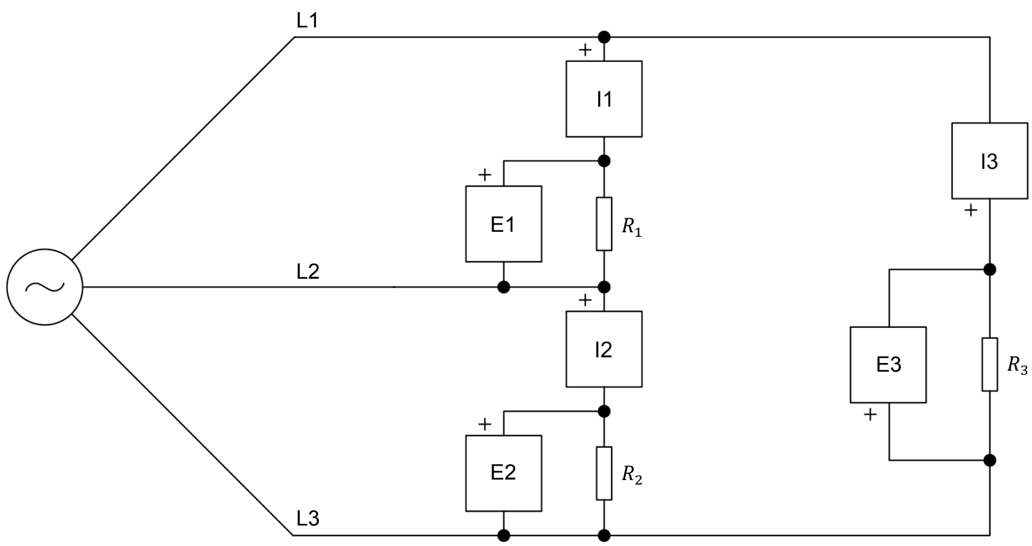
$P_T = 3 \times E_{Phase} \times I_{Phase} = 3 \times 118\ \text{V} \times 0.40\ \text{A} = 141.6\ \text{W}$

Yes

### 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

$E_{R1} = 205\ \text{V}$ $E_{R2} = 204\ \text{V}$

$E_{R3} = 206\ \text{V}$

$I_{R1} = 0.69\ \text{A}$ $I_{R2} = 0.69\ \text{A}$

$I_{R3} = 0.70\ \text{A}$

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

❑ Yes ❑ No

Yes

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

❑ Yes ❑ No

Yes

Does this mean that the load is balanced?

❑ Yes ❑ No

Yes

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

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

The average phase current $I_{Phase}$ is equal to:

$$\text{Average } I_{Phase} = \frac{I_{R1} + I_{R2} + I_{R3}}{3} = \frac{0.69 \text{ A} + 0.69 \text{ A} + 0.70 \text{ A}}{3} = 0.69 \text{ A}$$

**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.

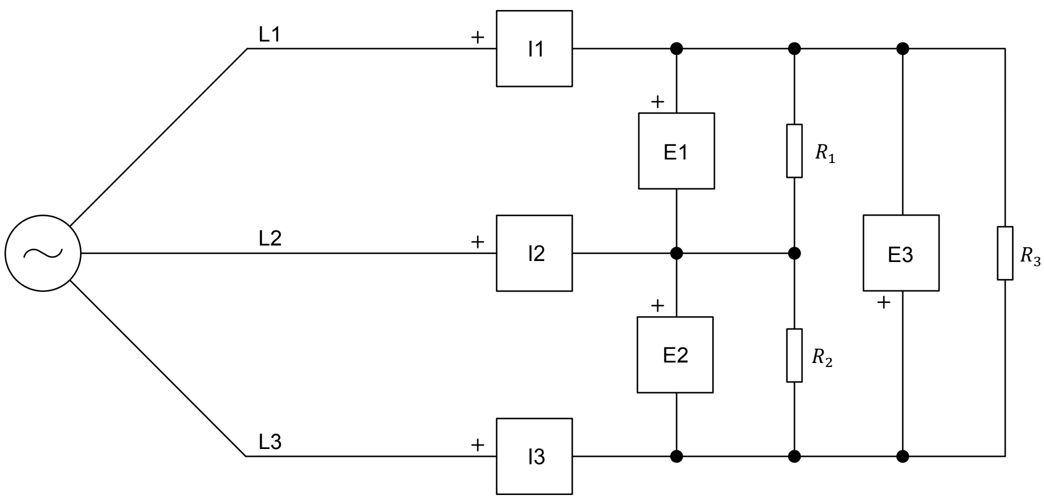



**Figure 8. Line current measurements in the delta-connected, three-phase circuit.**

**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

$I_{Line\ 1} = 1.20$ A

$I_{Line\ 2} = 1.19$ A

$I_{Line\ 3} = 1.20$ A

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

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

$$\text{Average } I_{Line} = \frac{I_{Line\,1} + I_{Line\,2} + I_{Line\,3}}{3} = \frac{1.20 \text{ A} + 1.19 \text{ A} + 1.20 \text{ A}}{3} = 1.20 \text{ A}$$

**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.

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

The ratio of the average line current $I_{Line}$ to the average phase current $I_{Phase}$ is equal to:

$$\frac{\text{Average } I_{Line}}{\text{Average } I_{Phase}} = \frac{1.20 \text{ A}}{0.69 \text{ A}} = 1.74 \cong \sqrt{3}$$

Is the ratio approximately equal to √3?

❑ Yes ❑ No

Yes

**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.

$$P_{R1} = E_{R1} \times I_{R1} = \_\_\_\_\_\_\_ \text{ W}$$

$$P_{R2} = E_{R2} \times I_{R2} = \_\_\_\_\_\_\_ \text{ W}$$

$$P_{R3} = E_{R3} \times I_{R3} = \_\_\_\_\_\_\_ \text{ W}$$

$$P_T = P_{R1} + P_{R2} + P_{R3} = \_\_\_\_\_\_\_ \text{ W}$$

$$P_{R1} = E_{R1} \times I_{R1} = 205 \text{ V} \times 0.69 \text{ A} = 141.5 \text{ W}$$

$$P_{R2} = E_{R2} \times I_{R2} = 204 \text{ V} \times 0.69 \text{ A} = 140.8 \text{ W}$$

$$P_{R3} = E_{R3} \times I_{R3} = 206 \text{ V} \times 0.70 \text{ A} = 144.2 \text{ W}$$

$$P_T = P_{R1} + P_{R2} + P_{R3} = 141.5 \text{ W} + 140.8 \text{ W} + 144.2 \text{ W} = 426.5 \text{ W}$$

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

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

The average phase voltage $E_{Phase}$ is equal to:

$$\text{Average } E_{Phase} = \frac{E_{R1} + E_{R2} + E_{R3}}{3} = \frac{205 \text{ V} + 204 \text{ V} + 206 \text{ V}}{3} = 205 \text{ V}$$

**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?

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

❑ Yes ❑ No

The total active power $P_T$ dissipated in the circuit is equal to:

$$P_T = 3 \times E_{Phase} \times I_{Phase} = 3 \times 205 \text{ V} \times 0.69 \text{ A} = 424.4 \text{ W}$$

Yes

**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.

The phase voltage in a three-phase circuit is the voltage measured across each load element.

The line voltage in a three-phase circuit is the voltage measured between any two phases (or lines) of the 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?

In a wye-connected, three-phase circuit, the line voltage is equal to √3 times the phase voltage. The line and phase currents are equal.

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?

In a delta-connected three-phase circuit, the line current is equal to √3 times the phase current. The line and phase voltages are equal.

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.

$$E_{Line} = \sqrt{3} \times E_{Phase} = \sqrt{3} \times 60 \text{ V} = 104 \text{ V}$$

In a balanced, wye-connected, three-phase circuit, the current $I_N$ flowing in the neutral line is equal to 0 A.

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.

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

$$I_{Phase} = \frac{I_{Line}}{\sqrt{3}} = 2.0 \text{ A}$$

In a purely resistive circuit, $\cos\varphi = 1$. Consequently, the total active power is:

$$P_T = 3 \times 120 \text{ V} \times 2 \text{ A} \times 1 = 720 \text{ W}$$

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