

Electricity and New Energy

Power Circuits and Transformers

Courseware Sample

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By the staff of Festo Didactic

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




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Safety and Common Symbols

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

Symbol	Description
	DANGER indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	WARNING indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	CAUTION indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	CAUTION used without the <i>Caution, risk of danger</i> sign  , indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols









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

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Preface

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

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

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

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

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

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

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

Preface

Do you have suggestions or criticism regarding this manual?

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

The authors and Festo Didactic look forward to your comments.

About This Manual

The 29 exercises in this manual, *Power Circuits and Transformers*, provide a foundation for the study of electrical power technology. Completion of these exercises allows students to continue with the second manual, *AC/DC Motors and Generators* using data acquisition.

This manual is divided into nine units:

- Units 1 to 4 provide a basic review of electrical concepts and theory, as well as highlighting specific details relating to capacitors, inductors and single-phase circuits.
- Unit 5 introduces and explores the concepts of vectors, phasors, and impedance, and how they are used in analyzing ac circuit operation.
- Units 6 to 9 deal with three-phase circuits, single- and three-phase transformers, as well as special transformer connections.

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

The hands-on exercises guide students through circuit setup and operation, and explore many of the measurement and observation capabilities of the virtual instrumentation system. Much detailed information about circuit parameters (voltage and current levels, waveforms, phase angles, etc.) can be visualized with the virtual instruments, and students are encouraged to fully explore system capabilities.

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

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

Appendix B provides a table giving the usual impedance values that can be obtained with each of the 120-V, 220-V, and 240-V versions of the EMS load modules. Finally, Appendix C provides a chart outlining the exact equipment required for each exercise.

About This Manual

Safety considerations

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

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

To the Instructor

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

Accuracy of measurements

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

Samples Exercises
Extracted from
the Student Manual
and the Instructor Guide

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

Calculating power in balanced three-phase circuits

As seen in the previous exercise, 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:

$$P_T = 3 \times P_{\text{phase}} = 3 (E_{\text{phase}} \times I_{\text{phase}} \times \cos \varphi)$$

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

$$P_T = \frac{3}{\sqrt{3}} \times E_{\text{Line}} \times I_{\text{Line}} \times \cos \varphi$$

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

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

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

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

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:

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

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

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

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

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:

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

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 6-9a shows the typical connections of a power meter in a single-phase circuit and Figure 6-9b shows the equivalent connections required to measure power using the data acquisition module.

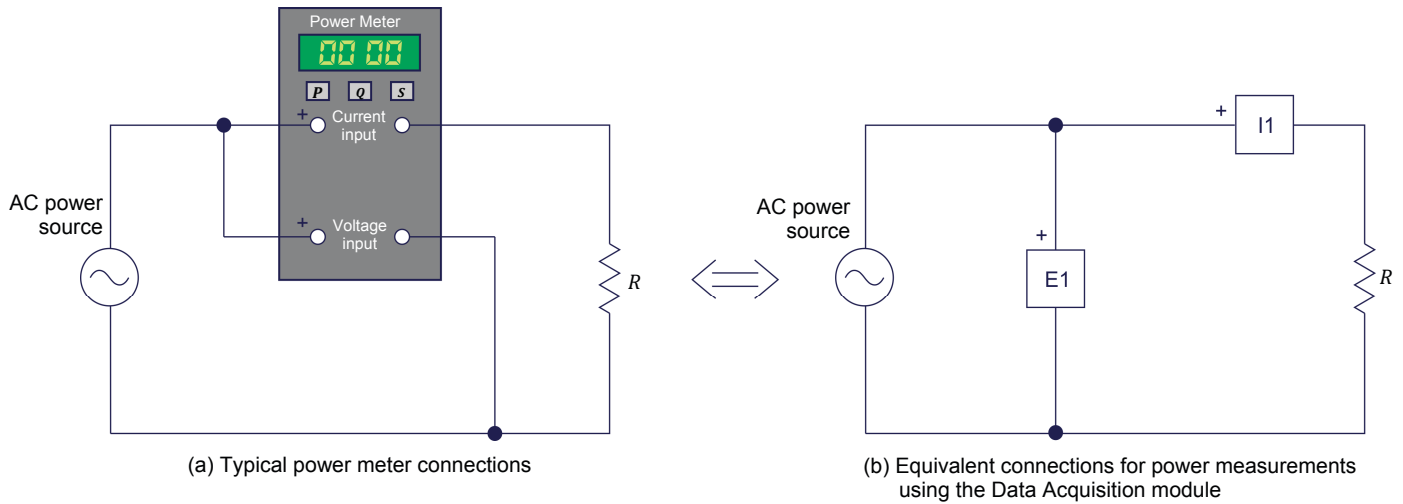


Figure 6-9. Three-phase circuit diagrams showing the connections required for power measurements.

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

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) and calculating the active power and reactive power in each phase from the voltage and current measured in each phase of the circuit. 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 algebraically adding the three measured power (either active or reactive) values. The total apparent power (S_T) can then be obtained by computing the vectorial sum of the total active power P_T and the total reactive power Q_T . Figure 6-10 shows the connections required to measure the total power in a four-wire, three-phase circuit using the data acquisition module. Note that, in the circuit diagram, inputs E1 and I1, inputs E2 and I2, and inputs E3 and I3 each represent a power meter.

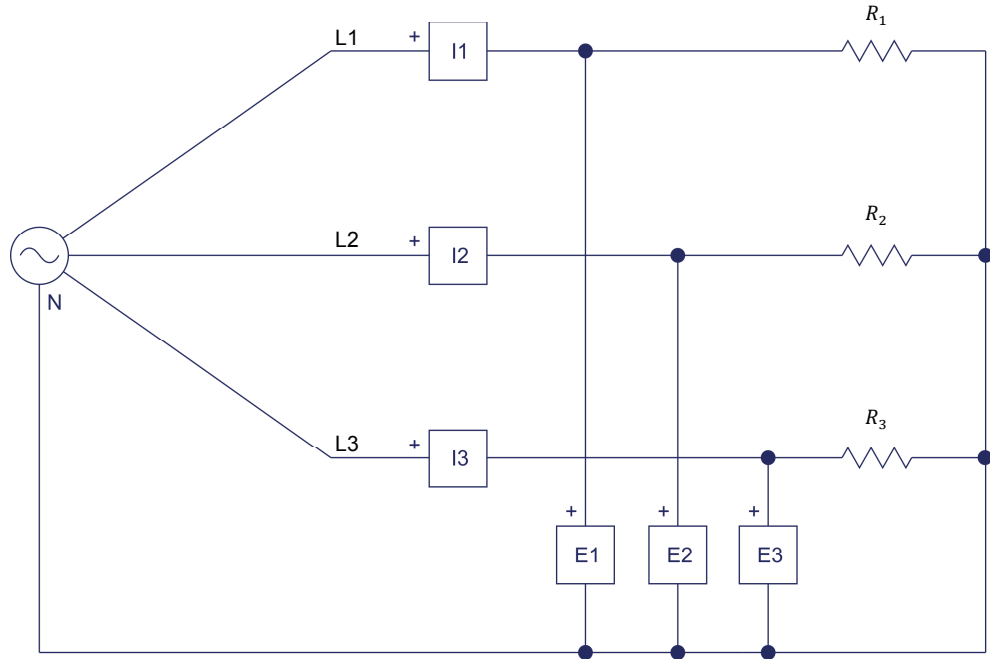


Figure 6-10. Three-phase power measurement using three power meters.

The method of power measurement shown in Figure 6-10 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 used commonly 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 because the neutral point generally is not available to connect the voltage inputs of the power meters, as Figure 6-11 shows.

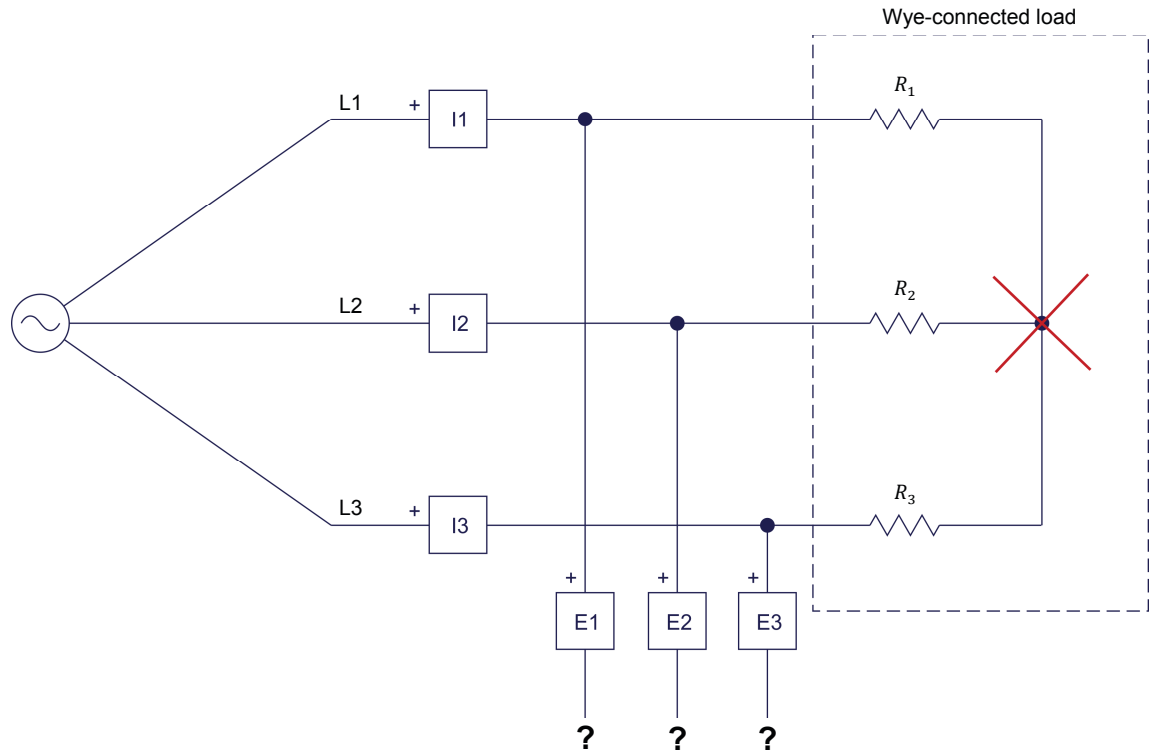


Figure 6-11. Diagram of a three-wire, wye-connected, three-phase circuit showing that the voltage inputs of the power meters generally cannot be connected to the neutral point of the circuit.

Similarly, when the load is connected in a delta configuration, the phase voltages can be measured but the phase currents (current flowing through each load element) cannot be measured because individual access to each load element generally is not possible (i.e., it is impossible to connect the current inputs of the power meters to measure the phase currents), as Figure 6-12 shows.

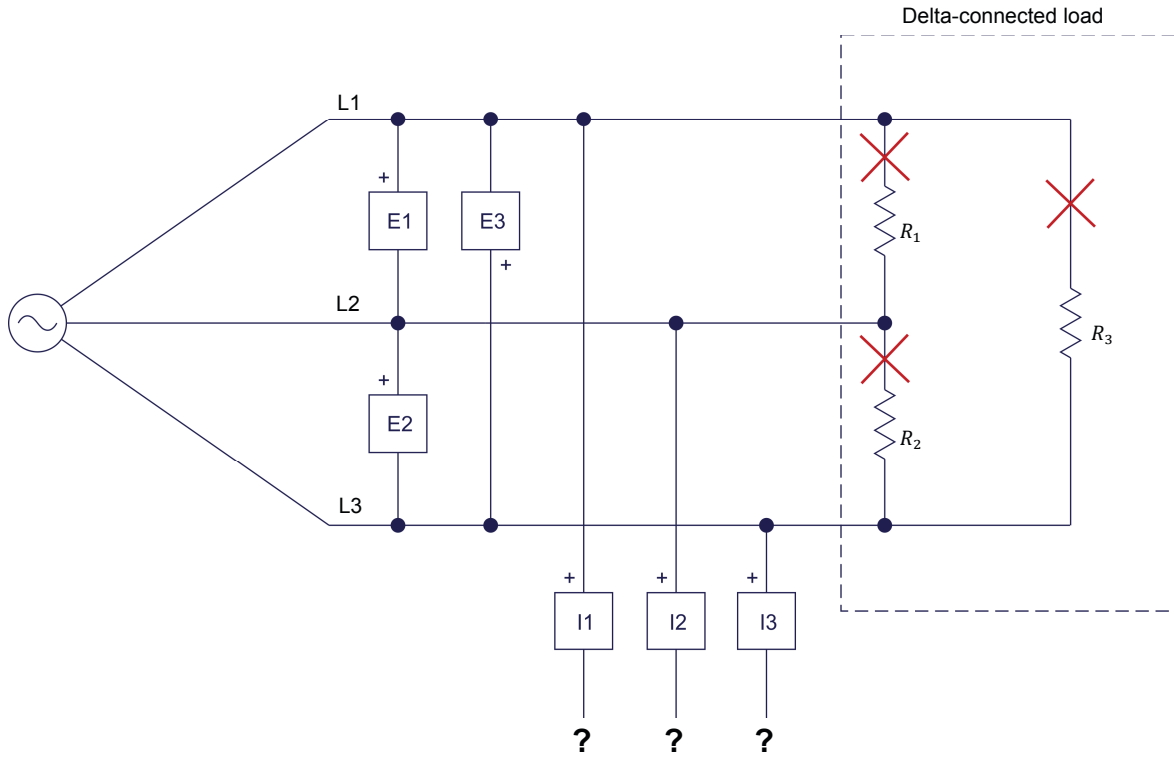


Figure 6-12. Diagram of a three-wire, delta-connected, three-phase circuit showing that the current inputs of the power meters cannot be connected to measure the phase currents.

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 6-13 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.

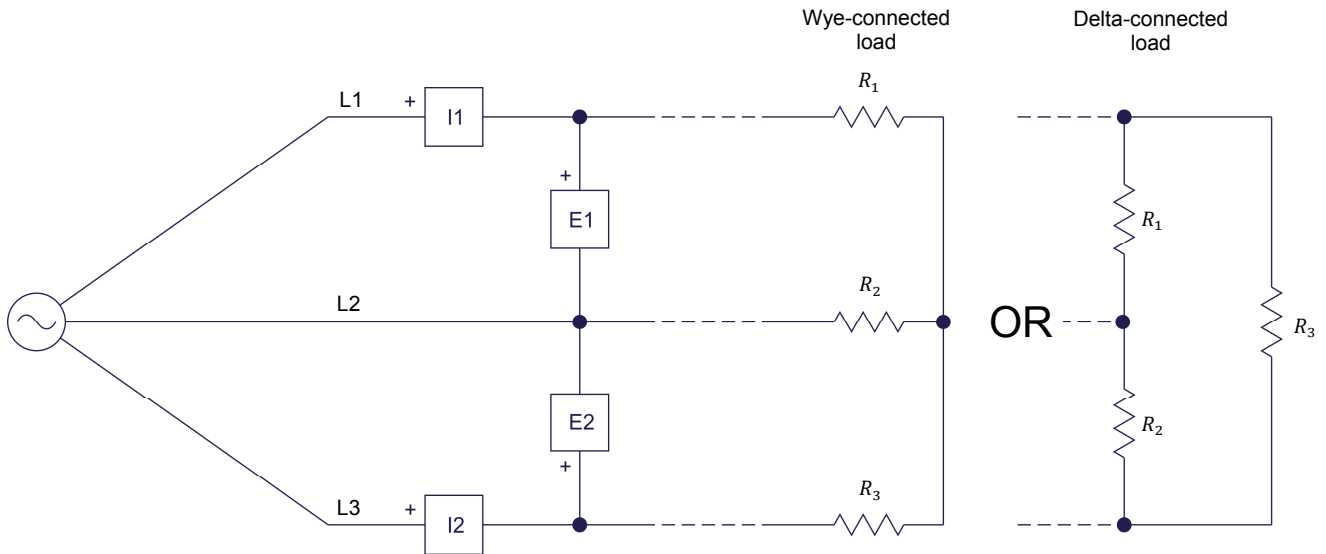


Figure 6-13. Connections of the voltage and current inputs of the power meters to a three-wire, three-phase circuit when measuring the total power using the two-wattmeter method.

The total active power (P_T) in the three-wire, three-phase circuit 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 computing 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 using the 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. This can be useful because the two-wattmeter method 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.

EQUIPMENT REQUIRED

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

PROCEDURE



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.

1. Install the Power Supply, data acquisition module, Resistive Load, and Capacitive Load modules in the EMS Workstation.
2. Make sure that the main switch of the Power Supply is set to the O (OFF) position, and the voltage control knob is turned fully counterclockwise. Set the voltmeter select switch to the 4-5 position, then make sure that the Power Supply is connected to a three-phase wall receptacle.
3. Make sure that the data acquisition module is connected to a USB port of the computer.

Connect the POWER INPUT of the data acquisition module to the 24 V - AC output of the Power Supply. Set the 24 V - AC power switch to the I (ON) position.

4. Start the Data Acquisition software (LVDAC or LVDAM). Open setup configuration file *ES16-6a.dai*.

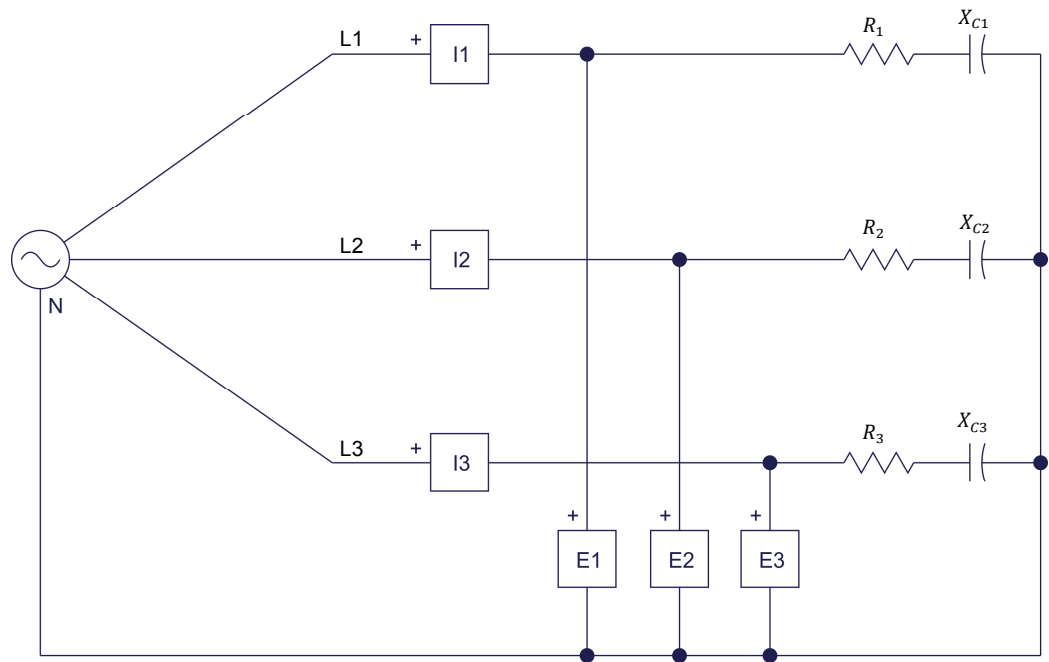


If you are using LVSIM-EMS in LVVL, you must use the IMPORT option in the File menu to open the configuration file.



Make sure that the continuous refresh mode is selected.

5. Set up the circuit shown in Figure 6-14.



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
220	60	629	880
240	50	686	960

Figure 6-14. Balanced, four-wire, wye-connected, three-phase circuit set up for power measurements.

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

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

In this section, you will solve the circuit you set up in the previous section by calculating the active, reactive, and apparent power values in each phase of the circuit, and the total active, reactive, and apparent power values in the circuit. You will measure the circuit's voltage, current, and power values, and confirm that the measured circuit parameters are 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 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.

7. Solve the circuit in Figure 6-14 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.

The following steps are necessary in order to solve the circuit:

$$Z_{PHASE} = \sqrt{R^2 + X_C^2} = \sqrt{(171 \Omega)^2 + (-240 \Omega)^2} = 295 \Omega$$

$$I_{PHASE} = \frac{E_{PHASE}}{Z_{PHASE}} = \frac{120 \text{ V}}{295 \Omega} = 0.41 \text{ A}$$

$$P_{PHASE} = P_R = R \times I_{PHASE}^2 = 171 \Omega \times (0.41 \text{ A})^2 = 28.7 \text{ W}$$

$$Q_{PHASE} = Q_{X_C} = X_C \times I_{PHASE}^2 = -240 \Omega \times (0.41 \text{ A})^2 = -40.3 \text{ var}$$

$$S_{PHASE} = \sqrt{P_{PHASE}^2 + Q_{PHASE}^2} = \sqrt{(28.7 \text{ W})^2 + (-40.3 \text{ var})^2} = 49.5 \text{ VA}$$

$$P_T = 3 \times P_{PHASE} = 3 \times 28.7 \text{ W} = 86.1 \text{ W}$$

$$Q_T = 3 \times Q_{PHASE} = 3 \times (-40.3 \text{ var}) = -121 \text{ var}$$

$$S_T = \sqrt{P_T^2 + Q_T^2} = \sqrt{(86.1 \text{ W})^2 + (-121 \text{ var})^2} = 149 \text{ VA}$$

8. Turn on the main Power Supply and set the voltage control knob so that the ac power source voltage (indicated by meter E_{1-N}) is equal to the nominal voltage of the ac power network. Do not change the setting of the voltage control knob until the end of the exercise.

Measure and record below the voltages and currents in the circuit of Figure 6-14, as well as the active power, reactive power, and apparent power in each phase of the circuit, then turn off the Power Supply.



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 meters.

Voltage and current measurements:

$$E_{1-N} = \underline{\hspace{2cm}} \text{ V}$$

$$E_{2-N} = \underline{\hspace{2cm}} \text{ V}$$

$$E_{3-N} = \underline{\hspace{2cm}} \text{ V}$$

$$I_{PHASE 1} = \underline{\hspace{2cm}} \text{ A}$$

$$I_{PHASE 2} = \underline{\hspace{2cm}} \text{ A}$$

$$I_{PHASE 3} = \underline{\hspace{2cm}} \text{ A}$$

$$E_{1-N} = 121 \text{ V}$$

$$E_{2-N} = 119 \text{ V}$$

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

$$I_{PHASE 1} = 0.41 \text{ A}$$

$$I_{PHASE 2} = 0.41 \text{ A}$$

$$I_{PHASE 3} = 0.41 \text{ A}$$

Active, reactive, and apparent power measurements:

$$P_1 = \underline{\hspace{2cm}} \text{ W}$$

$$P_2 = \underline{\hspace{2cm}} \text{ W}$$

$$P_3 = \underline{\hspace{2cm}} \text{ W}$$

$$Q_1 = \underline{\hspace{2cm}} \text{ var}$$

$$Q_2 = \underline{\hspace{2cm}} \text{ var}$$

$$Q_3 = \underline{\hspace{2cm}} \text{ var}$$

$$S_1 = \underline{\hspace{2cm}} \text{ VA}$$

$$S_2 = \underline{\hspace{2cm}} \text{ VA}$$

$$S_3 = \underline{\hspace{2cm}} \text{ VA}$$

$$P_1 = 29.3 \text{ W}$$

$$P_2 = 28.1 \text{ W}$$

$$P_3 = 28.6 \text{ W}$$

$$Q_1 = -40.2 \text{ var}$$

$$Q_2 = -39.2 \text{ var}$$

$$Q_3 = -39.1 \text{ var}$$

$$S_1 = 49.8 \text{ VA}$$

$$S_2 = 48.3 \text{ VA}$$

$$S_3 = 48.6 \text{ VA}$$

9. Compare the voltage, current, and power (active, reactive, and apparent) values measured in the previous step with the parameter values calculated in step 7. Are all values approximately equal?

Yes No

Yes

10. Open setup configuration file *ES16-7a.dai*. This file adds a meter in the Metering window that indicates the total power in the three-phase circuit.

11. Turn on the Power Supply.

Measure and record successively the total active power P_T , total reactive power Q_T , and total apparent power S_T in the circuit using the total power meter set in the previous step, then turn off the Power Supply.

$$P_T = \text{_____ W}$$

$$Q_T = \text{_____ var}$$

$$S_T = \text{_____ VA}$$

$$P_T = 85.6 \text{ W}$$

$$Q_T = -116 \text{ var}$$

$$S_T = 146 \text{ VA}$$

Compare the total power values you just measured with the total active power P_T , total reactive power Q_T , and total apparent power S_T calculated in step 7. Are all values approximately equal?

Yes No

Yes

12. Modify the switch settings on the Resistive Load and Capacitive Load modules in the circuit of Figure 6-14 in order to obtain the resistance and capacitive reactance values indicated in Table 6-1. Due to these modifications, the three-phase load is now unbalanced (i.e., the first phase of the circuit has a different impedance from that of the second and third phases).

Table 6-1. Resistance and capacitive reactance values used for unbalancing the four-wire, wye-connected, three-phase circuit of Figure 6-14.

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
220	60	1100	629	2200	880
240	50	1200	686	2400	960

13. Solve the circuit in Figure 6-14 using the resistance and capacitive reactance values indicated in Table 6-1, 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.

The following steps are necessary in order to solve the circuit to determine P_T , Q_T , and S_T :

$$Z_{UNB. PHASE} = \sqrt{R_1^2 + X_{C1}^2} = \sqrt{(300 \Omega)^2 + (-600 \Omega)^2} = 671 \Omega$$

$$I_{UNB. PHASE} = \frac{E_{PHASE}}{Z_{UNB. PHASE}} = \frac{120 \text{ V}}{671 \Omega} = 0.18 \text{ A}$$

$$P_{UNB. PHASE} = R_1 \times I_{UNB. PHASE}^2 = 300 \Omega \times (0.18 \text{ A})^2 = 9.72 \text{ W}$$

$$Q_{UNB. PHASE} = X_{C1} \times I_{UNB. PHASE}^2 = -600 \Omega \times (0.18 \text{ A})^2 = -19.4 \text{ var}$$

$$P_T = 2 \times P_{PHASE} + P_{UNB. PHASE} = 2 \times 28.7 \text{ W} + 9.72 \text{ W} = 67.1 \text{ W}$$

$$Q_T = 2 \times Q_{PHASE} + Q_{UNB. PHASE} = 2 \times (-40.3 \text{ var}) + (-19.4 \text{ var}) = -100 \text{ var}$$

$$S_T = \sqrt{P_T^2 + Q_T^2} = \sqrt{(67.1 \text{ W})^2 + (-100 \text{ var})^2} = 120 \text{ VA}$$



The parameters P_{PHASE} and Q_{PHASE} represent power in the two balanced phases. The values of P_{PHASE} and Q_{PHASE} are the same as those calculated in step 7.

14. Turn on the Power Supply.

Successively measure and record the active power P_T , reactive power Q_T , and apparent power S_T in the circuit using the total power meter you set up before, then turn off the Power Supply.

$$P_T = \underline{\hspace{2cm}} \text{ W}$$

$$Q_T = \underline{\hspace{2cm}} \text{ var}$$

$$S_T = \underline{\hspace{2cm}} \text{ VA}$$

$$P_T = 67.5 \text{ W}$$

$$Q_T = -98.2 \text{ var}$$

$$S_T = 119 \text{ VA}$$

15. 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 13. Are all values approximately equal?

Yes No

Yes

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

Yes

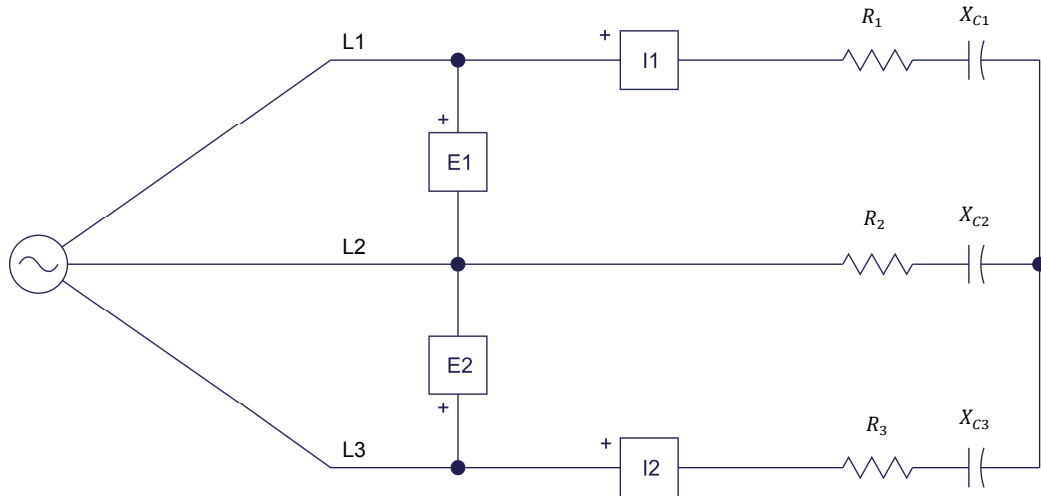
Measuring the total power in three-wire, three-phase circuits (wye configuration)

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.

16. Set up the circuit shown in Figure 6-15.



The balanced, three-phase load in the circuit of Figure 6-15 is identical to the balanced, three-phase load used in the previous section of this exercise. The total active power P_T , total reactive power Q_T , and total apparent power S_T are thus equal to those calculated in the previous section (see step 7) 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
220	60	629	880
240	50	686	960

Figure 6-15. Balanced, three-wire, wye-connected, three-phase circuit set up for power measurements using the two-wattmeter method.

17. Make the necessary switch settings on the Resistive Load and Capacitive Load modules in order to obtain the resistance and capacitive reactance values required.
18. Open setup configuration file *ES16-8a.dai*.
19. Turn on the Power Supply.

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 you set up for total power measurement, then off the Power Supply.

$$P_T = \text{_____ W}$$

$$Q_T = \text{_____ var}$$

$$S_T = \text{_____ VA}$$

$$P_T = 86.6 \text{ W}$$

$$Q_T = -120 \text{ var}$$

$$S_T = 145 \text{ VA}$$

20. 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 7. Are all values approximately equal?

Yes No

Yes

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

Yes

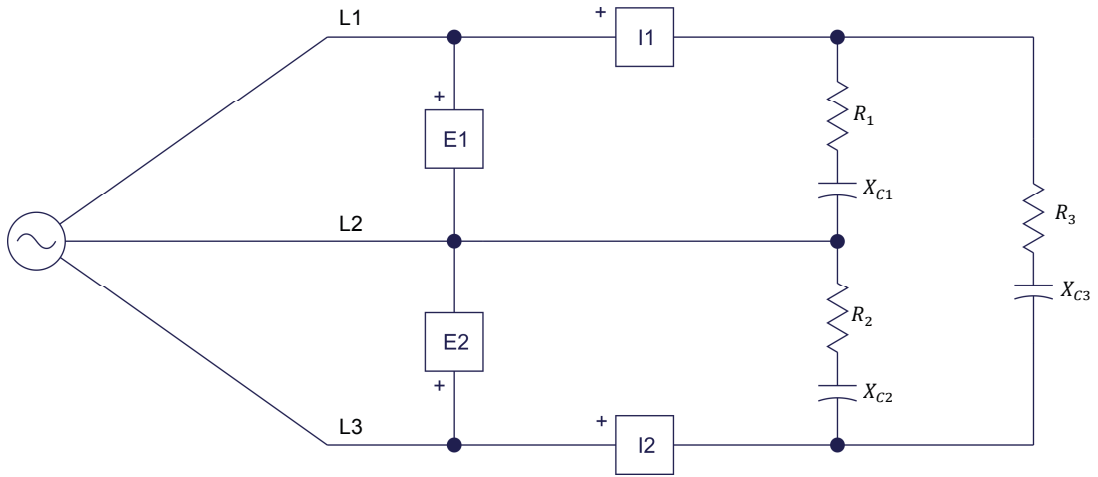


The two-wattmeter method of power measurement can also be used to measure the total power in unbalanced, three-wire, wye-connected, three-phase circuits. This demonstration, however, is not performed in this exercise.

Measuring the total power in three-wire, three-phase circuits (delta configuration)

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, and 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.

21. Set up the circuit shown in Figure 6-16.



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
220	60	629	880
240	50	686	960

Figure 6-16. Balanced, three-wire, delta-connected, three-phase circuit set up for power measurements using the two-wattmeter method.

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

- 23.** Solve the circuit in Figure 6-16 to determine the following parameters: the active power P and reactive power Q 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.

The following steps are necessary in order to solve the circuit:

$$Z_{PHASE} = \sqrt{R^2 + X_C^2} = \sqrt{(171 \Omega)^2 + (-240 \Omega)^2} = 295 \Omega$$

$$I_{PHASE} = \frac{E_{LINE}}{Z_{PHASE}} = \frac{208 \text{ V}}{295 \Omega} = 0.71 \text{ A}$$

$$P_{PHASE} = P_R = R \times I_{PHASE}^2 = 171 \Omega \times (0.71 \text{ A})^2 = 86.2 \text{ W}$$

$$Q_{PHASE} = Q_{X_C} = X_C \times I_{PHASE}^2 = -240 \Omega \times (0.71 \text{ A})^2 = -121 \text{ var}$$

$$P_T = 3 \times P_{PHASE} = 3 \times 86.2 \text{ W} = 259 \text{ W}$$

$$Q_T = 3 \times Q_{PHASE} = 3 \times (-121 \text{ var}) = -363 \text{ var}$$

$$S_T = \sqrt{P_T^2 + Q_T^2} = \sqrt{(259 \text{ W})^2 + (-363 \text{ var})^2} = 446 \text{ VA}$$

- 24.** Turn on the Power Supply.

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 you set up for total power measurement, then off the power.

$$P_T = \underline{\hspace{2cm}} \text{ W}$$

$$Q_T = \underline{\hspace{2cm}} \text{ var}$$

$$S_T = \underline{\hspace{2cm}} \text{ VA}$$

$$P_T = 254 \text{ W}$$

$$Q_T = -355 \text{ var}$$

$$S_T = 436 \text{ VA}$$

25. 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 23. Are all values approximately equal?

Yes No

Yes

26. Modify the switch settings on the Resistive Load and Capacitive Load modules in the circuit of Figure 6-16 in order to obtain the resistance and capacitive reactance values indicated in Table 6-2. Due to these modifications, the three-phase load is now unbalanced (i.e., the first phase of the circuit has a different impedance from that of the second and third phases).

Table 6-2. Resistance and capacitive reactance values used for unbalancing the three-wire, delta-connected, three-phase circuit in Figure 6-16.

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
220	60	1100	629	2200	880
240	50	1200	686	2400	960

27. Solve the circuit in Figure 6-16 using the resistance and capacitive reactance values indicated in Table 6-2, 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.

The following steps are necessary in order to solve the circuit to determine P_T , Q_T , and S_T :

$$Z_{UNB. PHASE} = \sqrt{R_1^2 + X_{C1}^2} = \sqrt{(300 \Omega)^2 + (-600 \Omega)^2} = 671 \Omega$$

$$I_{UNB. PHASE} = \frac{E_{LINE}}{Z_{UNB. PHASE}} = \frac{208 \text{ V}}{671 \Omega} = 0.31 \text{ A}$$

$$P_{UNB. PHASE} = R_1 \times I_{UNB. PHASE}^2 = 300 \Omega \times (0.31 \text{ A})^2 = 28.8 \text{ W}$$

$$Q_{UNB. PHASE} = X_{C1} \times I_{UNB. PHASE}^2 = -600 \Omega \times (0.31 \text{ A})^2 = -57.7 \text{ var}$$

$$P_T = 2 \times P_{PHASE} + P_{UNB. PHASE} = 2 \times 86.2 \text{ W} + 28.8 \text{ W} = 201 \text{ W}$$

$$Q_T = 2 \times Q_{PHASE} + Q_{UNB. PHASE} = 2 \times (-121 \text{ var}) + (-57.7 \text{ var}) = -300 \text{ var}$$

$$S_T = \sqrt{P_T^2 + Q_T^2} = \sqrt{(201 \text{ W})^2 + (-300 \text{ var})^2} = 361 \text{ VA}$$



Parameters P_{Phase} and Q_{Phase} represent power in the two balanced phases. The values of P_{Phase} and Q_{Phase} are the same as those calculated in step 23.

28. Turn on the Power Supply.

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 you set up for total power measurement, then turn off the Power Supply.

$$P_T = \underline{\hspace{2cm}} \text{ W}$$

$$Q_T = \underline{\hspace{2cm}} \text{ var}$$

$$S_T = \underline{\hspace{2cm}} \text{ VA}$$

$$P_T = 200 \text{ W}$$

$$Q_T = -295 \text{ var}$$

$$S_T = 358 \text{ VA}$$

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

Yes

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?

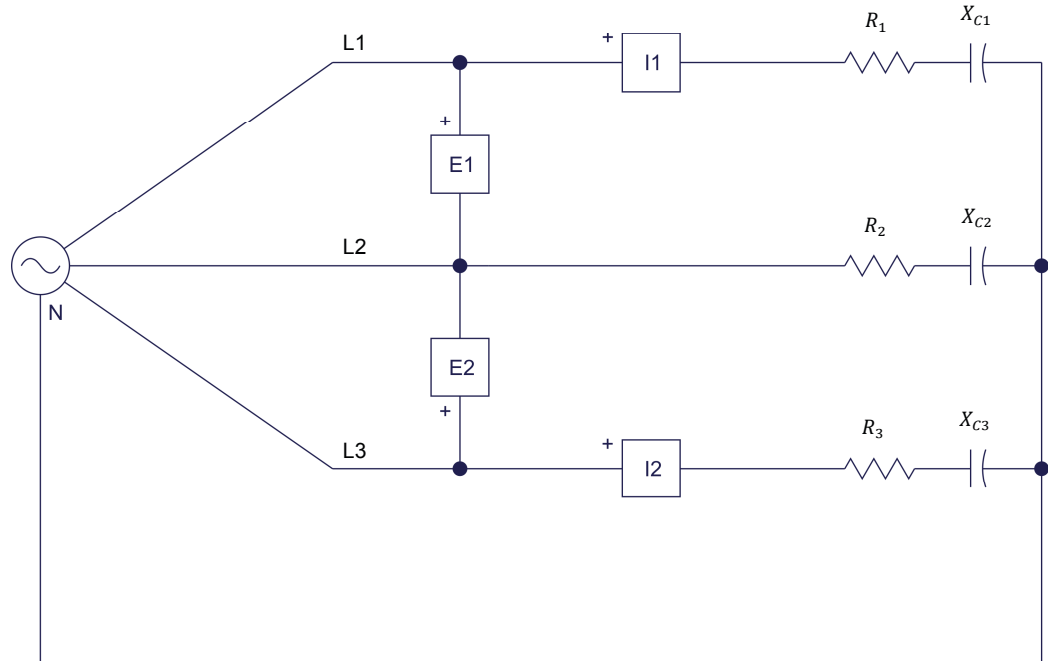
Yes No

Yes

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

In this section, you will set up a balanced, four-wire, wye-connected, three-phase circuit similar (same load but voltage and current inputs connected for total power measurement using the two-wattmeter method) to the one you set up in the “Measuring the total power in four-wire, three-phase circuits” section of this exercise. 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 values calculated for this balanced, three-phase circuit in the “Measuring the total power in four-wire, three-phase circuits” section of this exercise. You will then unbalance the three-phase circuit by modifying the impedance in one phase of the circuit. Finally, you will measure the total active, reactive, and apparent power values in the circuit, and verify that the measured values differ from the values calculated for this unbalanced, three-phase circuit in the section “Measuring the total power in four-wire, three-phase circuits” of this exercise. You will confirm that the two-wattmeter method of power measurement can only be used to measure power in four-wire, three-phase circuits that are balanced.

30. Set up the circuit shown in Figure 6-17.



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
220	60	629	880
240	50	686	960

Figure 6-17. Four-wire, wye-connected, three-phase circuit set up for power measurements using the two-wattmeter method.

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



The balanced, three-phase circuit you just set up corresponds to the balanced, four-wire three-phase circuit set up in the “Measuring the total power in four-wire, three-phase circuits” section of this exercise. The calculations required for solving the circuit are identical and do not need to be repeated.

32. Turn on the Power Supply.

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 you set up for total power measurement, then turn off the Power Supply.

$$P_T = \text{_____ W}$$

$$Q_T = \text{_____ var}$$

$$S_T = \text{_____ VA}$$

$P_T = 86.0 \text{ W}$
 $Q_T = -119 \text{ var}$
 $S_T = 147 \text{ VA}$

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 7. Are all values approximately equal?

Yes No

Yes

34. Modify the switch settings on the Resistive Load and Capacitive Load modules in the circuit of Figure 6-17 in order to obtain the resistance and capacitive reactance values indicated in Table 6-3. Due to these modifications, the three-phase load is now unbalanced (i.e., the first phase of the circuit has a different impedance from that of the second and third phases).



The unbalanced, three-phase circuit you just set up corresponds to the unbalanced, four-wire, three-phase circuit set up in the section “Measuring the total power in four-wire, three-phase circuits” of this exercise. The calculations required for solving the circuit are identical and do not need to be repeated.

Table 6-3. 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
220	60	1100	629	2200	880
240	50	1200	686	2400	960

35. Turn on the Power Supply.

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 you set up for total power measurement, then turn off the Power Supply.

$$P_T = \text{_____ W}$$

$$Q_T = \text{_____ var}$$

$$S_T = \text{_____ VA}$$

$$P_T = 41.7 \text{ W}$$

$$Q_T = -103 \text{ var}$$

$$S_T = 111 \text{ VA}$$

36. 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 13. Are all values equal?

Yes No

No

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

When measuring power in four-wire, three-phase circuits, the two-wattmeter method of power measurement can only be used when the circuit is balanced. When the four-wire, three-phase circuit is unbalanced, the two-wattmeter method provides false total power values.

37. Ensure that the Power Supply is turned off, and that the voltage control knob is turned fully counterclockwise. Remove all leads and cables.

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 saw 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. What is the total amount of active power P_T dissipated in the resistive load of the circuit?
 - a. 260 W
 - b. 300 W
 - c. 450 W
 - d. 150 W

a

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.
 - a. the current input of one of the power meters is connected to measure the line current flowing in one of the circuit line wires, while the second power meter current input is connected to measure the neutral line current. One voltage input of a power meter is then connected to measure the line voltage between two line wires and the other between a line wire and the neutral line wire.
 - b. the current inputs of the power meters are connected to measure the line current flowing in two of the circuit line wires, while the voltage inputs of the power meters are connected to measure the line voltage between each of the two line wires connected to the current inputs and the neutral wire.
 - c. the current inputs of the power meters are connected to measure the line current flowing in two of the circuit line wires, while the voltage inputs of the power meters are connected to measure the line voltage between each of the two line wires connected to the current inputs and the remaining line wire.
 - d. the current input of one of the power meters is connected to measure the line current flowing in one of the circuit line wires, while the second power meter current input is connected to measure the line current flowing in two of the circuit line wires. One voltage input of a power meter is then connected to measure the line voltage between a line wire and the neutral line wire.

c

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.
- a. 350 VA
 - b. 800 VA
 - c. 600 VA
 - d. 1000 VA

c

4. A balanced, three-wire, resistive and capacitive, three-phase circuit is connected to two power meters set up 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.
- a. 120 W
 - b. 375 W
 - c. 230 W
 - d. 140 W

d

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?
- a. The two-wattmeter method of power measurement does not work to measure power in unbalanced, four-wire, three-phase circuits.
 - b. The two-wattmeter method of power measurement does not work to measure power in balanced, three-wire, three-phase circuits.
 - c. The two-wattmeter method of power measurement does not work to measure power in unbalanced, three-wire, three-phase circuits.
 - d. None of the above

a

Transformer Regulation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the voltage regulation of a transformer with varying loads, and discuss capacitive and inductive loading on transformer regulation. Voltage and current measurements will be used to produce load regulation curves.

DISCUSSION

The load on a large power transformer in a sub-station will vary from a very small value in the early hours of the morning to a very high value during the heavy peaks of maximum industrial and commercial activity. The transformer secondary voltage will vary somewhat with the load, and because motors, incandescent lamps, and heating devices are all quite sensitive to voltage changes, transformer regulation is of considerable importance. The secondary voltage also depends upon whether the power factor of the load is leading, lagging, or unity. Therefore, it should be known how the transformer will behave (its voltage regulation) when connected to a capacitive, an inductive, or a resistive load. Transformer voltage regulation in percent is determined with the following formula:

$$\text{Voltage regulation (\%)} = 100 \times \frac{E_{NL} - E_{FL}}{E_{NL}}$$

where E_{NL} is the no-load secondary voltage.

E_{FL} is the full-load secondary voltage.

The result (a percentage value) obtained gives an indication of transformer behavior under load. The smaller the voltage regulation percentage, the smaller the secondary voltage variation with load, and the better the voltage regulation. Note that E_{NL} is measured with the secondary winding open while E_{FL} is measured when nominal current flows in the secondary winding.

Several factors affect a transformer's operation. The resistance and inductive reactance of its windings cause internal voltage drops that vary with the amount of current flowing in the windings. If the secondary is lightly loaded, current through the winding resistance and reactance is small and the internal voltage drops are not significant. As the load increases, current and internal voltage drops also increase. If a transformer were perfectly ideal, its windings would have neither resistance nor inductive reactance to cause voltage drops. Such a transformer would have perfect regulation under all load conditions and the secondary voltage would remain absolutely constant. But practical transformer coils are made of real wire, and thereby, have resistance and inductive reactance. Therefore, the primary and secondary windings have an overall resistance R , and an overall reactance X . The simplified equivalent circuit of a practical transformer with a 1:1 turns ratio can be approximated by the circuit shown in Figure 7-9. The actual transformer terminals are P_1 , P_2 on the primary side, and S_1 , S_2 on the secondary side.

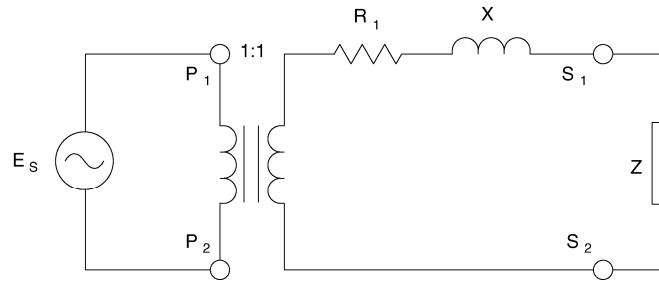


Figure 7-9. Simplified equivalent circuit of a practical transformer.

In this equivalent circuit, the practical transformer is shown to be made up of an ideal transformer in series with an impedance consisting of R and X that represents the imperfections of the transformer. When a load (Z) is connected to the secondary winding terminals (terminals S_1 and S_2), a series ac circuit consisting of the secondary winding of the ideal transformer, R , X , and Z is obtained. Analysis of this series ac circuit shows that when the load is either resistive or inductive, the load voltage decreases continuously as the load increases (as the secondary current increases). Furthermore, when the load is capacitive, the load voltage increases to a maximum as the load increases from zero (no load condition), and then, the load voltage decreases as the load continues to increase.

EQUIPMENT REQUIRED

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

PROCEDURE



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

1. Install the Power Supply, data acquisition module, Single-Phase Transformer, Resistive Load, Capacitive Load, and Inductive Load modules in the EMS Workstation.
2. Make sure that the main switch of the Power Supply is set to the O (OFF) position, and the voltage control knob is turned fully counterclockwise. Set the voltmeter select switch to the 4-N position, then make sure that the Power Supply is connected to a three-phase wall receptacle.
3. Make sure that the data acquisition module is connected to a USB port of the computer.

Connect the POWER INPUT of the data acquisition module to the 24 V - AC output of the Power Supply. Set the 24 V - AC power switch to the I (ON) position.

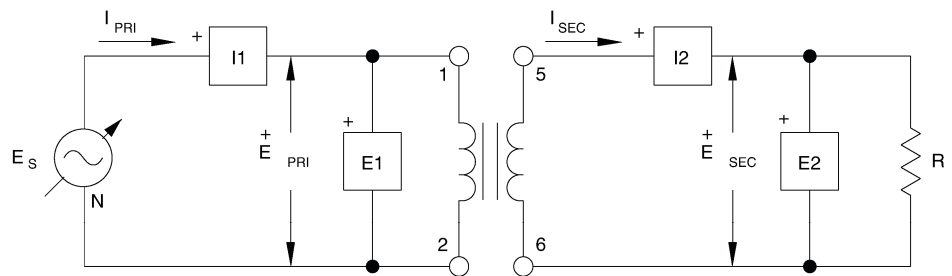
4. Start the Data Acquisition software (LVDAC or LVDAM). Open setup configuration file *ES17-8.dai*.



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

Make sure that the continuous refresh mode is selected.

5. Set up the transformer loading circuit shown in Figure 7-10. Make sure that all switches on the Resistive, Capacitive, and Inductive Load modules are open, and connect meter inputs E1, E2, I1, and I2 as shown in the figure. Different load values will be used to examine how the secondary (load) voltage changes as transformer loading changes.



Local ac power network		E_S (V)	R (Ω)
Voltage (V)	Frequency (Hz)		
120	60	120	∞
220	50	220	∞
220	60	220	∞
240	50	240	∞

Figure 7-10. Transformer with a variable load.

6. Turn on the main Power Supply and adjust the voltage control knob to obtain the value of voltage E_S given in Figure 7-10. With no load on the transformer (all switches open on the load module), record the measured values of E_{PRI} , I_{PRI} , E_{SEC} , and I_{SEC} in the *Data Table*.
7. Adjust the switches on the Resistive Load module to successively obtain the resistance values given in Table 7-1. For each resistance value, record the measured values as in step 6. When all values have been recorded, turn the voltage control knob fully counterclockwise, and turn off the Power Supply.

Table 7-1. Values for R , X_L , and X_C .

Local ac power network		R, X_L, X_C (Ω)	R, X_L, X_C (Ω)	R, X_L, X_C (Ω)	R, X_L, X_C (Ω)	R, X_L, X_C (Ω)
Voltage (V)	Frequency (Hz)					
120	60	1200	600	400	300	240
220	50	4400	2200	1467	1100	880
220	60	4400	2200	1467	1100	880
240	50	4800	2400	1600	1200	9600

The results obtained are presented below.

Transformer with a variable resistive load.

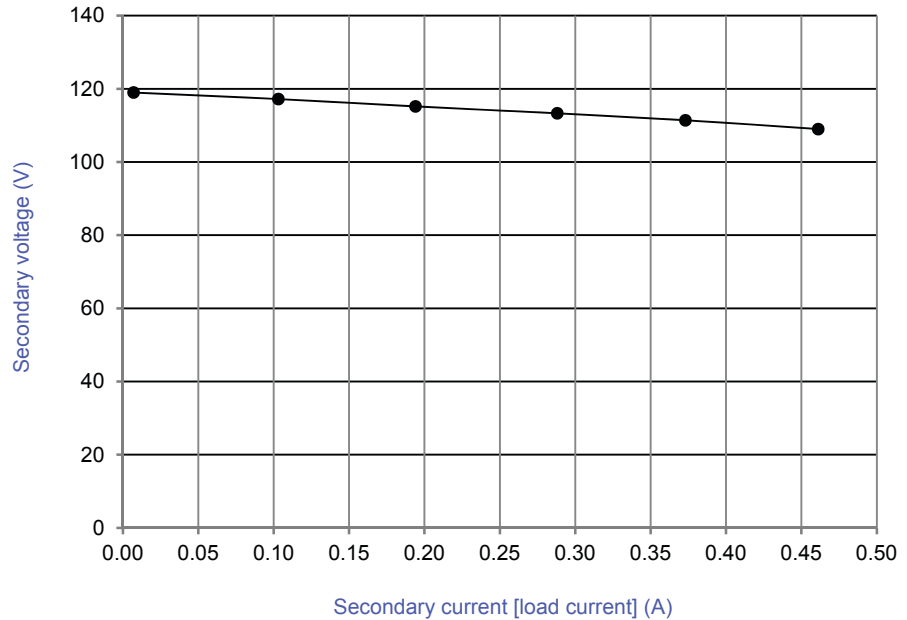
Primary voltage (E_{PRI}) (V)	Secondary voltage (E_{SEC}) (V)	Primary current (I_{PRI}) (A)	Secondary current (I_{SEC}) (A)
119.0	119.0	0.027	0.007
119.3	117.2	0.120	0.103
118.9	115.2	0.212	0.194
118.6	113.3	0.305	0.288
118.5	111.4	0.390	0.373
118.2	109.0	0.477	0.461

8. Display the *Graph* window, select E2 (E_{SEC}) as the Y-axis parameter, and I2 (I_{SEC}) as the X-axis parameter. Make sure the line graph format and the linear scale are selected. Observe the curve of secondary voltage versus current. What happens to the secondary voltage as the resistive load increases, i.e. load resistance decreases?



To make it easier to compare the curves obtained with different loads, hard copies of the graphs in steps 8, 13, and 17 can be printed using the *Print* button on the *Tool Bar*.

The resulting graph is shown below.



Secondary voltage versus current (resistive load).

The secondary voltage decreases.

- Calculate the voltage regulation using the no-load ($R = \infty$) and full-load ($R = \text{minimum value}$) output voltages.

$$100 \frac{(E_{NL} - E_{FL})}{E_{NL}} = \underline{\hspace{2cm}} \%$$

$$100 \frac{(E_{NL} - E_{FL})}{E_{NL}} = 8.4 \%$$

- Clear the *Data Table*, then replace the Resistive Load module in the circuit of Figure 7-10 with the Inductive Load module.
- Turn on the Power Supply and adjust the voltage control knob to obtain the value of voltage E_S given in Figure 7-10. With no load on the transformer (all switches open on the load module), record the measured values of E_{PRI} , I_{PRI} , E_{SEC} , and I_{SEC} in the *Data Table*.

12. Adjust the switches on the Inductive Load module to successively obtain the reactance values given in Table 7-1. For each reactance value, record the measured values as in step 11. When all values have been recorded, turn the voltage control knob fully counterclockwise, and turn off the Power Supply.

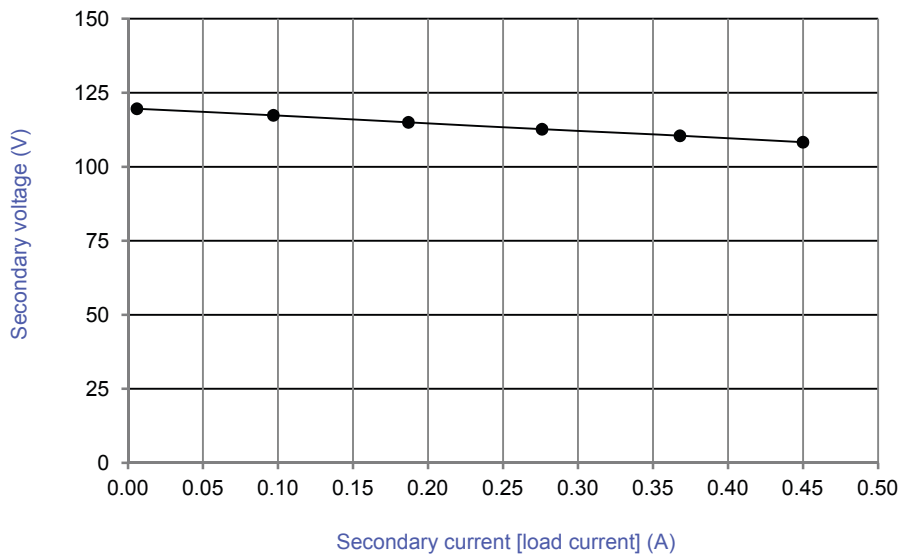
The results obtained are presented below.

Transformer with a variable inductive load.

Primary voltage (E_{PRI}) (V)	Secondary voltage (E_{SEC}) (V)	Primary current (I_{PRI}) (A)	Secondary current (I_{SEC}) (A)
120.0	119.6	0.024	0.006
120.0	117.4	0.115	0.097
120.0	115.0	0.203	0.187
120.0	112.7	0.293	0.276
120.0	110.5	0.385	0.368
120.0	108.3	0.466	0.45

13. Display the *Graph* window, select E2 (E_{SEC}) as the Y-axis parameter, and I2 (I_{SEC}) as the X-axis parameter. Make sure the line graph format and the linear scale are selected. Observe the curve of secondary voltage versus current. How does the secondary voltage vary as the inductive load increases?

The resulting graph is shown below.



Secondary voltage versus current (inductive load).

The secondary voltage decreases.

14. Clear the *Data Table*, then replace the Inductive Load module in the circuit of Figure 7-10 with the Capacitive Load module.
15. Turn on the Power Supply and adjust the voltage control knob to obtain the value of voltage E_S given in Figure 7-10. With no load on the transformer (all switches open on the load module), record the measured values of E_{PRI} , I_{PRI} , E_{SEC} , and I_{SEC} in the *Data Table*.
16. Adjust the switches on the Capacitive Load module to successively obtain the reactance values given in Table 7-1. For each reactance value, record the measured values as in step 15. When all values have been recorded, turn the voltage control knob fully counterclockwise, and turn off the Power Supply.

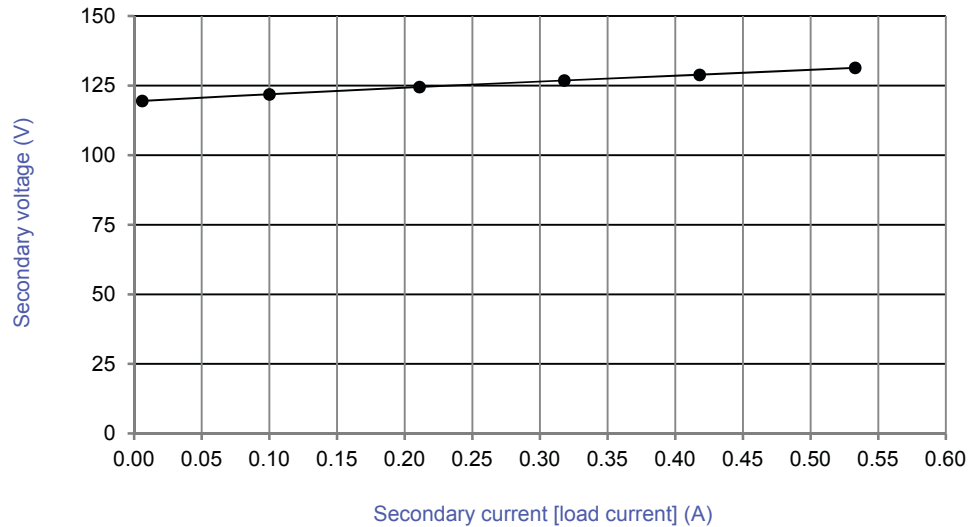
The results obtained are presented below.

Transformer with a variable capacitive load.

Primary voltage (E_{PRI}) (V)	Secondary voltage (E_{SEC}) (V)	Primary current (I_{PRI}) (A)	Secondary current (I_{SEC}) (A)
120.0	119.5	0.024	0.006
120.0	121.9	0.087	0.100
120.0	124.5	0.197	0.211
120.0	126.9	0.304	0.318
120.0	128.9	0.404	0.418
120.0	131.4	0.518	0.533

17. Display the *Graph* window, select $E_2 (E_{SEC})$ as the Y-axis parameter, and $I_2 (I_{SEC})$ as the X-axis parameter. Make sure the line graph format and the linear scale are selected. Observe the curve of secondary voltage versus current. How does the secondary voltage vary as the capacitive load increases?

The resulting graph is shown below.



Secondary voltage versus current (capacitive load).

The secondary voltage increases.

18. What differences do you observe between the three load curves?

When the load is either resistive or inductive, the secondary voltage decreases with the load current. Conversely, when the load is capacitive, the secondary voltage increases with the load current.

19. Ensure that the Power Supply is turned off, and that the voltage control knob is turned fully counterclockwise. Remove all leads and cables.

CONCLUSION

In this exercise, you examined the voltage regulation of a transformer, and saw that the secondary voltage varied as the load placed on the transformer changed. Load variation curves for resistive, inductive, and capacitive loads were plotted. These curves showed that under resistive or inductive loading conditions, the secondary voltage decreases as the load increases, and that under capacitive loading conditions, the secondary voltage can rise above its nominal value. Also, inductive loading caused greater voltage drops than resistive loading, hence poorer regulation.

REVIEW QUESTIONS

1. Transformer regulation can be determined with the formula

- a. $100 (E_{PRI} - E_{SEC})/E_{PRI}$
- b. $100 (E_{NL} - E_{FL})/E_{NL}$
- c. $100 (I_{PRI} - I_{SEC})/I_{PRI}$
- d. $100 (I_{NL} - I_{FL})/I_{NL}$

b

2. What is the transformer regulation if the no-load and full-load voltages are 100 V and 95 V respectively?

- a. 105%
- b. 10.5%
- c. 95%
- d. 5%

d

3. The secondary voltage can rise above its rated value when the load is

- a. resistive.
- b. capacitive.
- c. inductive.
- d. an RL series combination.

b

4. The voltage measured across the secondary winding of a transformer with no load connected is 150 V. This voltage drops to 147 V when the secondary current is equal to the nominal full-load current. What is the transformer regulation?

- a. 90%
- b. 3%
- c. 2%
- d. 6%

c

5. Transformer regulation
- a. depends on the type of load connected at the secondary.
 - b. is independent of the load connected at the secondary.
 - c. can only be determined with no load on the secondary.
 - d. depends on the voltage applied to the primary.

a

Unit Test

1. A transformer primary has 320 turns of wire and the secondary voltage measures 160 V when 40 V is applied to the primary. The voltage ratio is therefore
- a. 1:8
 - b. 2:1
 - c. 1:4
 - d. 1:2

c

2. The short-circuit secondary current in a transformer is 2 A. What is the primary current if the transformer turns ratio is 2: 5?
- a. 2 A
 - b. 5 A
 - c. 2.5 A
 - d. 0.8 A

b

3. When the primary voltage exceeds its rated value
- a. transformer operation is enhanced.
 - b. transformer operation suffers because of core saturation.
 - c. by more than double, transformer operation improves.
 - d. the primary current decreases.

b

4. To evaluate the current ratio of a transformer,
- a. rated voltage must be applied to the primary.
 - b. rated current must flow in the primary.
 - c. a very low primary voltage must be applied.
 - d. the primary must be short-circuited.

c

5. When unmarked transformer terminals are connected together, this usually means that the windings are connected
- in series-aiding.
 - in series-opposing.
 - to increase the resulting voltage.
 - both a and c.

b

6. Voltage regulation of a transformer can be determined with the formula
- $100 (I_{NL} - I_{FL})/I_{NL}$
 - $100 (I_{PRI} - I_{SEC})/I_{PRI}$
 - $100 (E_{NL} - E_{FL})/E_{NL}$
 - $100 (E_{PRI} - E_{SEC})/E_{PRI}$

c

7. What is the no-load voltage when the full-load secondary voltage is 108 V and transformer regulation is 10%?
- 98 V
 - 120 V
 - 12 V
 - 118.8 V

b

8. A capacitive load can cause the secondary voltage of a transformer to
- rise above its rated value.
 - steadily decrease with increasing load.
 - steadily increase with decreasing load.
 - none of the above.

a

9. What is the transformer regulation if the no-load and full-load voltages are 2 kV and 1.95 kV, respectively?
- 5%
 - 2.5%
 - 3.6%
 - 0.25%

b

10. The type of load connected to the secondary of a transformer has
- a. a small effect on transformer regulation.
 - b. a significant effect on transformer regulation.
 - c. no effect on transformer regulation.
 - d. none of the above.

b

Bibliography

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