Electrical Power Technology
Using Data Acquisition

Power Circuits and Transformers

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Lab-Volt®

Unit 6

Three-Phase Circuits

UNIT OBJECTIVE

After completing this Unit, you will be able to solve balanced three-phase ac circuits connected in wye and delta configurations, and demonstrate the difference between line and phase voltage. You will also be able to determine active, reactive and apparent power, and establish the phase sequence of a three-phase ac supply. You will use voltage and current measurements to verify the theory and calculations presented in the exercises.

DISCUSSION OF FUNDAMENTALS

Three-phase circuits are no more complicated to solve than single-phase circuits. In the majority of cases they are symmetrical and have identical impedances in each of the three branches. Each branch can be treated exactly like 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 rules and methods developed for single-phase circuits. Non-symmetrical, or unbalanced, three-phase circuits represent a special condition and their analysis can become complicated. Unbalanced three-phase circuits are not covered in this manual.

A three-phase ac circuit is energized by three sine waves of the same frequency and magnitude that are displaced from each other by 120°. The phase angle between the voltages of a three-phase power supply is therefore 120° as seen in Unit 2. The voltages of a three-phase power supply can be produced as illustrated by the simplified three-phase generator (alternator) in Figure 6-1. A rotating magnetic field (produced by a rotating magnet) turns inside three identical coils of wire (windings) placed physically at 120° to each other, to produce three separate ac voltages (one per winding). The rotating magnet turns at a fixed speed, thus the frequency is constant, and the three separate voltages attain maximum one after the other at intervals of 120°.

Three-Phase Circuits

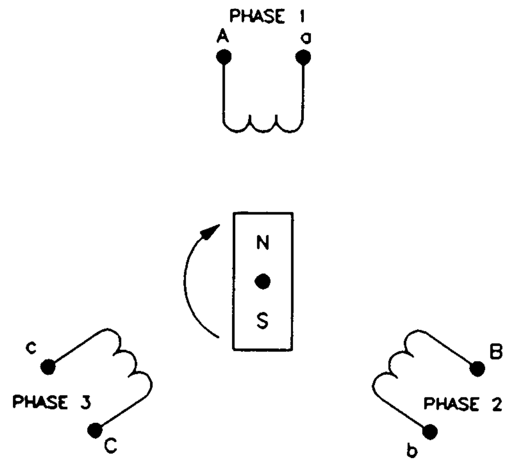


Figure 6-1. A Simplified Three-Phase Generator.

The **phase sequence** of the voltages of a three-phase power supply is the order in which they follow each other and become maximum. Figure 6-2 is an example of the voltage waveforms produced by a three-phase power supply. These voltages are shown with the phase sequence E_A, E_B, E_C, which in shorthand form is the sequence A-B-C. Phase sequence is important because it determines the direction in which three-phase motors turn. If the phases are connected out of sequence, the motor will turn in the opposite direction, and the consequences could be quite serious. For example, if clockwise rotation of a motor is the normal direction to make an elevator go up, connecting the phase wires incorrectly would result in the elevator going down instead of up, and vice-versa, and a serious accident could occur.

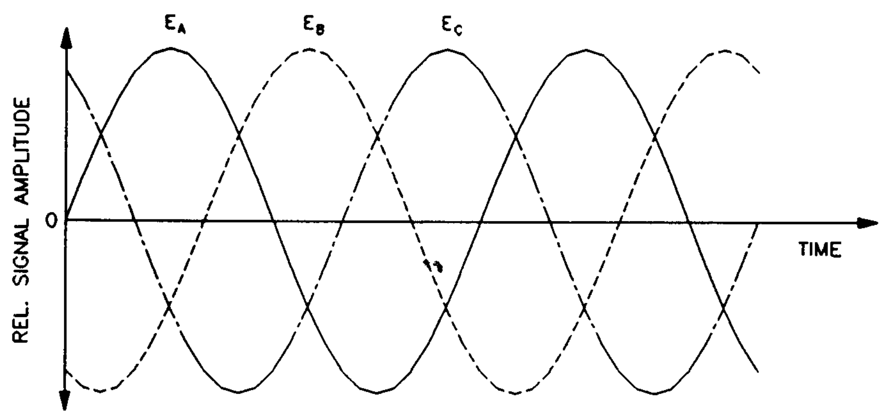


Figure 6-2. A-B-C Phase Sequence of a Three-Phase Supply.

Balanced Three-Phase Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to distinguish between line and phase voltages in wye- and delta-connected ac circuits. Measured parameters in balanced resistive loads will be used to verify the circuit calculations.

DISCUSSION

The windings of a three-phase ac power supply (the generator in Figure 6-1) can be connected in either a wye configuration, or a delta configuration. These names come from the appearance of the circuit drawings which resemble the letter Y and the Greek letter delta. The connections for each configuration are shown in Figure 6-3, and each has definite electrical characteristics. The voltage produced by a single winding is called the **phase voltage**, E_{PHASE} (E_{AN}, E_{BN}, E_{CN}), while the voltage between any two windings is the line-to-line, or **line voltage**, E_{LINE} (E_{AB}, E_{BC}, E_{CA}). In a wye-connected system the line voltage is $\sqrt{3}$ (approximately 1.73) times greater than the phase voltage, as indicated in the following equation:

$$E_{LINE} = \sqrt{3}\,E_{PHASE}$$

Note: *In the EMS System the numbers 1,2,3 (fixed-voltage output) and 4,5,6 (variable-voltage output) are used instead of the letters A,B,C for the corresponding line and phase voltages. The neutral line is designated by N.*

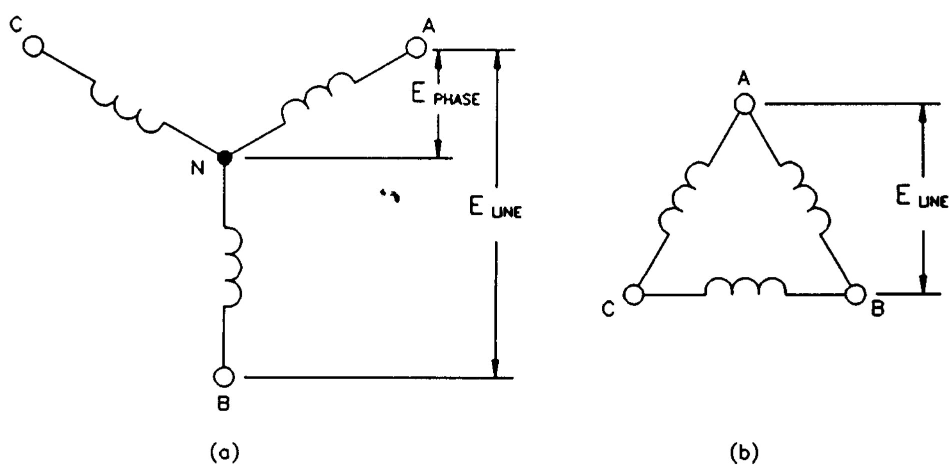


Figure 6-3. (a) Three-Phase Wye Configuration (b) Three-Phase Delta Configuration.

Balanced Three-Phase Circuits

Usually, the three line wires (wires connected to points A, B, and C) and the neutral wire of a three-phase power system are available for connection to the load, which can be set up as either a **wye connection** or a **delta connection**. The two types of circuit connections are illustrated in Figure 6-4. Circuit analysis demonstrates that the voltage between any two line wires, or lines, in a wye-connected load is 1.73 times greater than the voltage across each load resistor (phase voltage). Also, the **line current** in a delta-connected load is 1.73 times greater than the current in each load resistor (phase current). The **phase current** in a delta-connected load is therefore 1.73 times smaller than the line current.

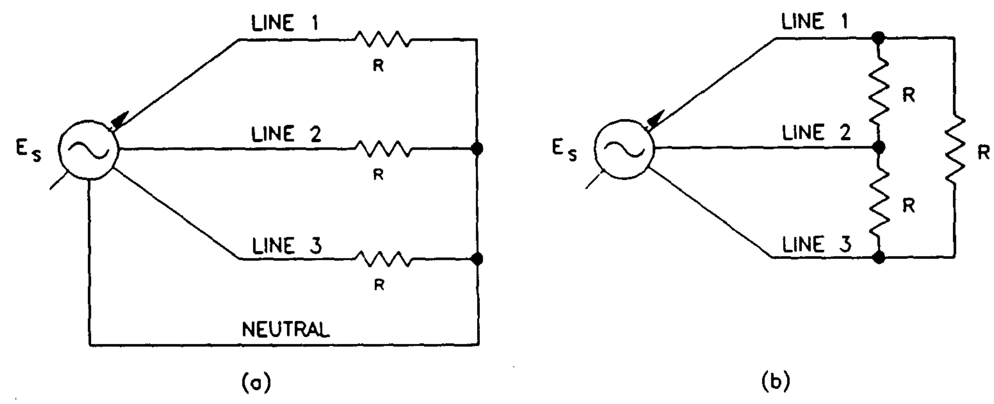


Figure 6-4. (a) Wye-Connected Load (b) Delta-Connected Load.

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

for WYE circuits: $E_{LINE} = \sqrt{3}\, E_{PHASE}$ and $I_{LINE} = I_{PHASE}$

for DELTA circuits: $E_{LINE} = E_{PHASE}$ and $I_{LINE} = \sqrt{3}\, I_{PHASE}$.

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 power in a single-phase circuit, we can state that the active power dissipated in each phase of either a wye- or delta-connected load is:

$$P_{PHASE} = E_{PHASE} \times I_{PHASE} \times \cos \phi$$

where ϕ is the angle between the phase voltage and current.

The total active power P_T supplied to the load is therefore:

$$P_T = 3 \times P_{PHASE} = 3\, E_{PHASE} \times I_{PHASE} \times \cos \phi$$

For a resistive load, $\cos \phi$ equals 1, therefore:

$$P_T = 3\, E_{PHASE} \times I_{PHASE}$$

Balanced Three-Phase Circuits

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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 Interface, and Resistive 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 ccw. Ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, and the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES16-1.cfg*.

☐ 5. Connect E1, E2, and E3 to measure the line-to-neutral and then the line-to-line fixed voltages of the Power Supply shown in Figure 6-5.

Note: *In this manual E_{PHASE} is used to designate the line-to-neutral voltage, and E_{LINE} the line-to-line voltage.*

☐ 6. Turn on the main Power Supply and set the 24 V - AC power switch to the I (ON) position.

☐ 7. Record your measurements and then turn off the power. Determine the average value of the phase and line voltages.

E_{1-N} = _______ V E_{2-N} = _______ V E_{3-N} = _______ V

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

E_{1-2} = _______ V E_{2-3} = _______ V E_{3-1} = _______ V

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

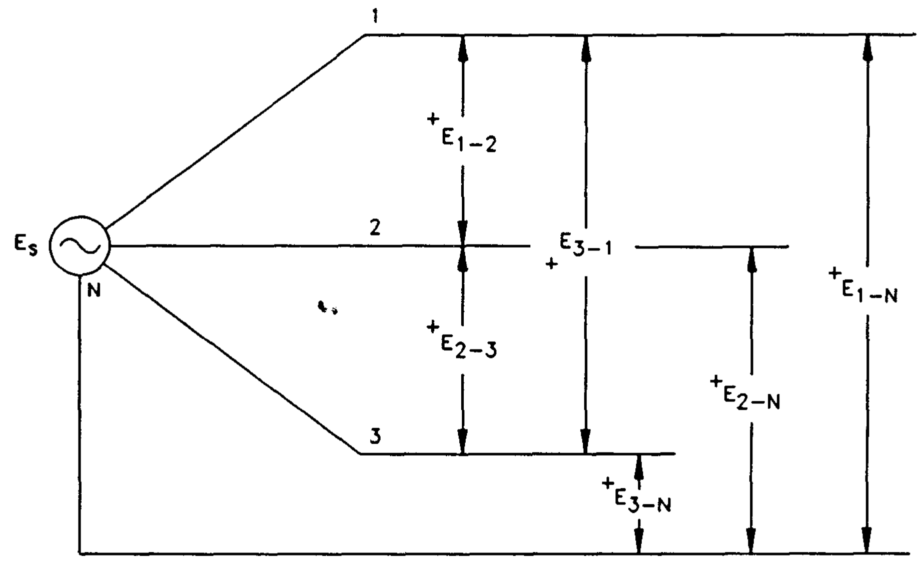


Figure 6-5. Measurement of Line and Phase Voltages.

☐ 8. Calculate the ratio of the average line to phase voltage.

$$\frac{E_{LINE}}{E_{PHASE}} = \_\_\_\_\_\_\_\_$$

☐ 9. Is the ratio approximately equal to 1.73 ($\sqrt{3}$)?

☐ Yes ☐ No

☐ 10. Connect E1, E2, and E3 to measure the line-to-neutral and line-to-line variable voltages of the Power Supply, $E_{4\text{-}N}$, $E_{5\text{-}N}$, $E_{6\text{-}N}$, and $E_{4\text{-}5}$, $E_{5\text{-}6}$, $E_{6\text{-}4}$.

☐ 11. Turn on the power and adjust the voltage control to 100 %. Record your measurements and then turn off the power. Determine the average value of the phase and line voltages.

$E_{4\text{-}N}$ = ________ V $E_{5\text{-}N}$ = ________ V $E_{6\text{-}N}$ = ________ V

$$\text{Average } E_{PHASE} = \frac{E_{4\text{-}N} + E_{5\text{-}N} + E_{6\text{-}N}}{3} = \_\_\_\_\_\_\_\_ \text{ V}$$

$E_{4\text{-}5}$ = ________ V $E_{5\text{-}6}$ = ________ V $E_{6\text{-}4}$ = ________ V

$$\text{Average } E_{LINE} = \frac{E_{4\text{-}5} + E_{5\text{-}6} + E_{6\text{-}4}}{3} = \_\_\_\_\_\_\_\_ \text{ V}$$

☐ 12. Calculate the ratio of the average line to phase voltage.

$$\frac{E_{LINE}}{E_{PHASE}} = \_\_\_\_\_\_\_$$

☐ 13. Is the ratio approximately equal to 1.73 ($\sqrt{3}$)?

☐ Yes ☐ No

☐ 14. Set up the three-phase, wye-connected, resistive circuit shown in Figure 6-6. *Do not connect the neutral of the resistive load to the neutral of the Power Supply.* Connect I1, I2, I3, E1, E2, and E3 as shown to measure the currents and voltages.

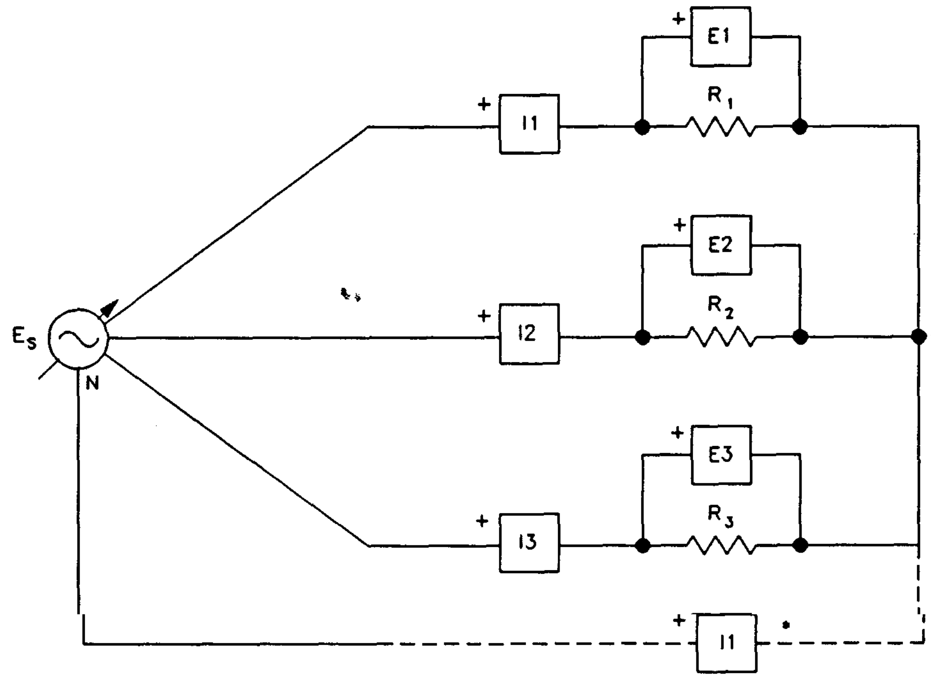
☐ 15. Set the voltmeter select switch to the 4-5 position. Turn on the power and adjust voltage control for the line-to-line voltage E_S (E_{4-5}, E_{5-6}, or E_{4-6}) given in Figure 6-6. Select setup configuration file *ES16-2.cfg*. Measure the circuit voltages and currents and then turn off the power.

E_{R1} = _______ V E_{R2} = _______ V E_{R3} = _______ V

I_{R1} = _______ A I_{R2} = _______ A I_{R3} = _______ A

☐ 16. Compare the individual load voltages and load currents. Are they approximately equal, showing that the load is balanced?

☐ Yes ☐ No



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	208	300	300	300
220	380	1100	1100	1100
240	415	1200	1200	1200

Figure 6-6. Three-Phase Wye-Connected Resistive Load.

☐ 17. Calculate the average phase voltage from the measurements in step 15.

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

☐ 18. Is the ratio of E_{LINE} to E_{PHASE} approximately equal to $\sqrt{3}$?

☐ Yes ☐ No

☐ 19. Connect I1 as shown by the dashed line in Figure 6-6 to measure the neutral line current with the Power Supply neutral connected to the neutral of the wye-connected load. Select setup configuration file *ES16-3.cfg*. Turn on the power and record the value of I_N with E_S adjusted to the same value of E_S as in step 15.

I_N = ________ A

☐ 20. Is the neutral current equal to zero?

☐ Yes ☐ No

☐ 21. Using the results of step 15, calculate the active power consumed in each phase of the circuit, and the total power consumed by the load.

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

☐ 22. Determine the phase current using the values measured in step 15.

$I_{PHASE} =$ _______ A

Calculate P_T using the phase voltage and current, and compare it with step 21. Are both values approximately the same?

$P_T = 3\ (E_{PHASE} \times I_{PHASE}) =$ _______ W

☐ Yes ☐ No

☐ 23. Turn off the power and set up the three-phase, delta-connected, resistive circuit shown in Figure 6-7. Connect I1, I2, I3, E1, E2, and E3 as shown to measure the currents and voltages.

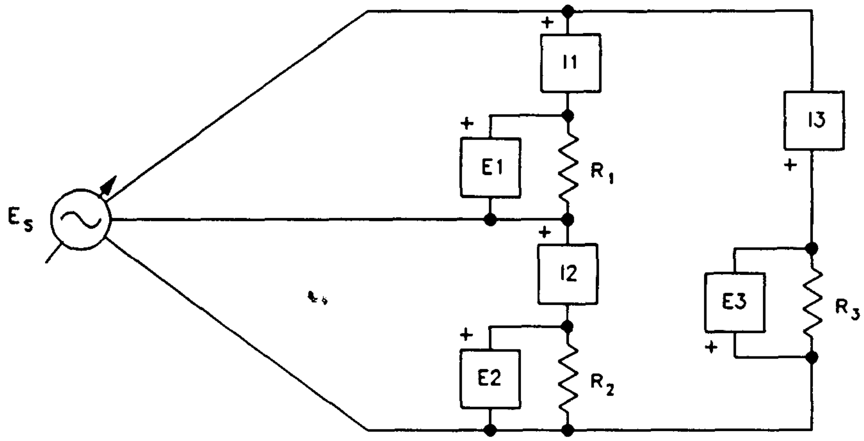
☐ 24. Turn on the power and adjust the voltage control for the line-to-line voltage E_S (E_{4-5}, E_{5-6}, or E_{4-6}) given in Figure 6-7. Select setup configuration file *ES16-4.cfg*. Measure the circuit voltages and currents and then turn off the power.

E_{R1} _______ V $E_{R2} =$ _______ V $E_{R3} =$ _______ V

$I_{R1} =$ _______ A $I_{R2} =$ _______ A $I_{R3} =$ _______ A

☐ 25. Compare the individual load voltages and load currents. Are they approximately equal, showing that the load is balanced?

☐ Yes ☐ No



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	120	300	300	300
220	220	1100	1100	1100
240	240	1200	1200	1200

Figure 6-7. Three-Phase Delta-Connected Resistive Load.

☐ 26. Calculate the average phase current from the measurements in step 24.

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

☐ 27. Reconnect I1, I2, and I3 as shown in Figure 6-8 to measure the line currents for the delta-connected load. Ensure that E_S is set at the same value used in step 24. Select setup configuration file *ES16-5.cfg*. Measure and record the line currents and then turn off the power. Determine the average line current.

I_1 = ________ A I_2 = ________ A I_3 = ________ A

$$\text{Average } I_{LINE} = \frac{I_1 + I_2 + I_3}{3} = \_\_\_\_\_\_\_\_ \text{ A}$$

☐ 28. Calculate the ratio of the average line current to the average phase current.

$$\frac{I_{LINE}}{I_{PHASE}} = \_\_\_\_\_\_\_\_$$

Is it approximately equal to $\sqrt{3}$?

☐ Yes ☐ No

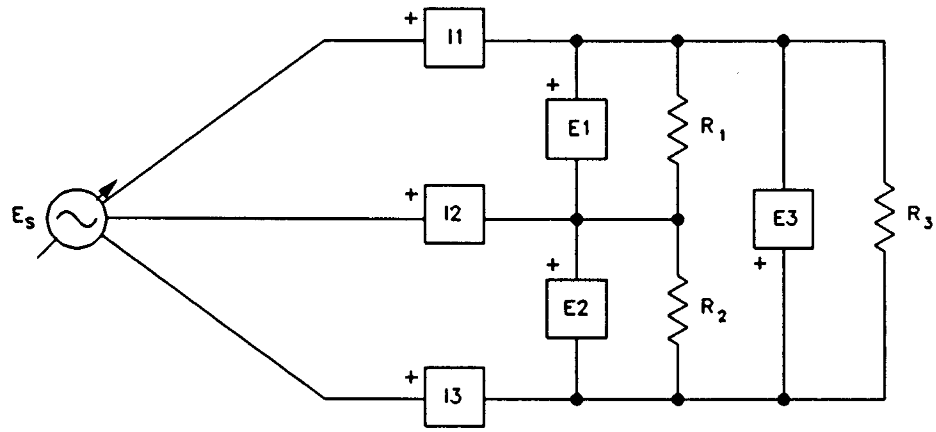


Figure 6-8. Measuring The Line Currents in The Delta-Connected Resistive Load.

☐ 29. Using the results of step 24, calculate the active power consumed in each phase of the circuit, and the total power consumed by the load.

$P_{R1} = E_{R1} \times I_{R1} =$ ________ 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

☐ 30. Determine the phase voltage using the values measured in step 24.

$E_{PHASE} =$ ________ V

Calculate P_T using the phase voltage and current, and compare it with step 29. Are both values approximately the same?

$P_T = 3\ (E_{PHASE} \times I_{PHASE}) =$ ________ W

☐ Yes ☐ No

☐ 31. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You measured the line and phase voltages and currents for balanced wye- and delta-connected resistive loads, and saw that the line and phase values were related by the factor $\sqrt{3}$. You saw that no current flows in the neutral wire of a balanced wye-connected load, and demonstrated that individual line voltages and currents are equal with balanced three-phase loads. Finally, you demonstrated that total power for a three-phase resistive load is three times the power supplied to one of the circuit branches.

REVIEW QUESTIONS

1. In a balanced wye-connected circuit the

   a. line voltages and currents equal the load values.
   b. line voltage is $\sqrt{3}$ times greater than the phase voltage.
   c. line voltage is $\sqrt{3}$ times smaller than the phase voltage.
   d. line current is $\sqrt{3}$ times greater than the phase current.

2. In a balanced delta-connected circuit the

   a. line voltages and currents equal the load values.
   b. line current is $\sqrt{3}$ times smaller than the phase current.
   c. line current is $\sqrt{3}$ times greater than the phase current.
   d. line voltage is $\sqrt{3}$ times greater than the phase voltage.

3. What is the line-to-neutral (phase) voltage in a balanced wye-connected circuit when the line-to-line voltage is 346 V?

   a. 346 V.
   b. 600 V.
   c. 200 V.
   d. 245 V.

4. What is the line current in a balanced delta-connected resistive load when the load current through each branch is 10 A?

   a. 27.3 A.
   b. 17.3 A.
   c. 11.6 A.
   d. 5.8 A.

5. The line current in a balanced three-phase, wye-connected, resistive load is 25 A. What will happen if the neutral wire is disconnected?

   a. The power protection circuits will operate because of the imbalance.
   b. Nothing, because there is no current in the neutral line.
   c. The line voltage will become unbalanced.
   d. The phase current will increase to dangerous levels.

Exercise 6-2

Three-Phase Power Measurement

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine active power in balanced three-phase circuits using the two-wattmeter method of power measurement. Reactive and apparent power will also be determined using measurements of circuit voltages and currents.

DISCUSSION

As seen in the previous exercise, the total active power P_T supplied to a balanced three-phase load is given by the expression,

$$P_T = 3 \times P_{PHASE} = 3\ (E_{PHASE} \times I_{PHASE} \times \cos \phi)$$

However, in a wye-connected circuit, $E_{PHASE} = E_{LINE} / \sqrt{3}$ and the phase current equals the line current. The above formula then becomes

$$P_T = \frac{3}{\sqrt{3}} \times E_{LINE} \times I_{LINE} \times \cos \phi$$

The factor $3/\sqrt{3}$ can be simplified to become $\sqrt{3}$, so that finally for a wye-connected circuit,

$$P_T = \sqrt{3}\ (E_{LINE} \times I_{LINE} \times \cos \phi) = 1.73\ (E_{LINE} \times I_{LINE} \times \cos \phi)$$

In a delta-connected circuit, the same result is obtained because the phase voltage equals the line voltage and $I_{PHASE} = I_{LINE} / \sqrt{3}$. Therefore, for either a balanced wye-connected load or a balanced delta-connected load, the total three-phase active power is given by the expression,

$$P_{ACTIVE}\ (P) = 1.73\ (E_{LINE} \times I_{LINE} \times \cos \phi)$$

Since $(E_{PHASE} \times I_{PHASE} \times \cos \phi)$ is the expression for the active power per phase, it follows that the product $E_{PHASE} \times I_{PHASE}$ represents the apparent power per phase, and the total three-phase apparent power in a balanced wye- or delta-connected load can be found using the formula,

$$P_{APPARENT}\ (S) = 3\ (E_{PHASE} \times I_{PHASE})$$

Following the steps used to obtain the equation for calculating active power (P_{ACTIVE}) in three-phase circuits, the apparent power equation can be rewritten as follows:

$$P_{APPARENT}\ (S) - 1.73\ (E_{LINE} \times I_{LINE})$$

The power factor for a balanced three-phase load is the ratio of active power to apparent power, P/S, and the relationship between P, Q, and S is the same as seen previously, $S^2 - P^2 + Q^2$. Thus, reactive power Q can be calculated using the following equation:

$$P_{REACTIVE}\ (Q) - \sqrt{S^2 - P^2}$$

Active power is measured with a wattmeter, which is an electrodynamometer type instrument that has two coils. One coil is fixed (current coil) and the second (voltage coil) is capable of turning in the magnetic field produced by the first. The fixed coil is connected in series with the load so as to carry the load current. The movable coil, which has a high resistance, is connected across the load like a voltmeter and the small current in this coil is proportional to the load voltage. The voltage coil turns against a helical spring and its torque is proportional to the product of the currents in both coils. The torque is therefore proportional to the product of the current and voltage being measured, and the measurement scale of the instrument is calibrated to indicate watts of active power. Figure 6-9 shows a wattmeter connected to measure the power delivered to a load, and the equivalent circuit connections of the DAI to obtain the same result with the *Metering* system.

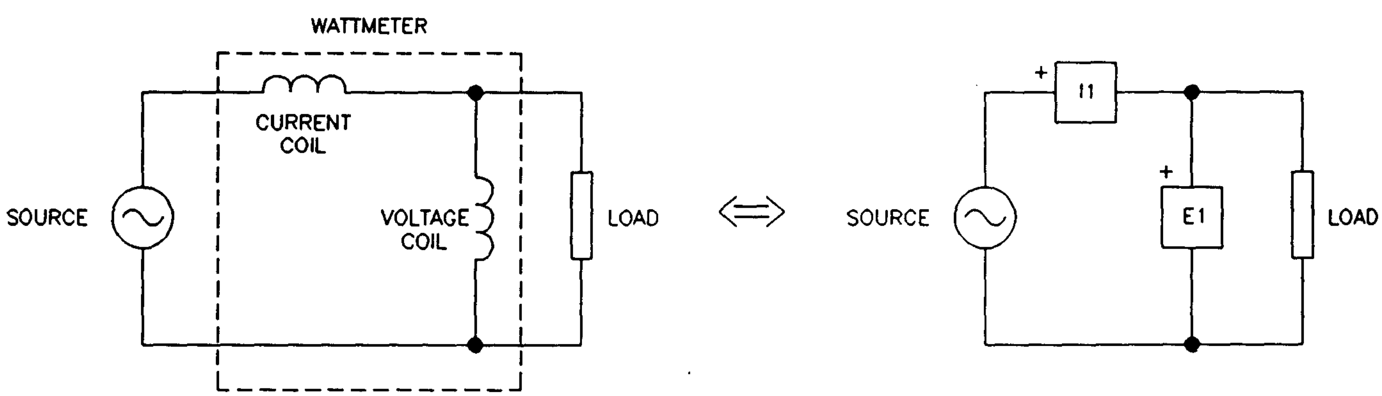


Figure 6-9. Measuring Power With a Wattmeter.

To measure the power delivered by a three-phase, 4-wire system, three single-phase wattmeters could be connected to measure the power in each of the phases and the readings added to obtain the total power, as seen in the previous exercise. This, however, is not necessary because two single-phase wattmeters connected as shown in Figure 6-10 will give the same result. Mathematical analysis shows that connecting the current coils to measure the current in two of the three lines, while connecting the two voltage coils between these lines and the remaining line, allows the total power delivered by a three-phase system to be measured. The total power is the algebraic sum of the two wattmeter readings, and this method of power measurement is known as the **two-wattmeter method**.

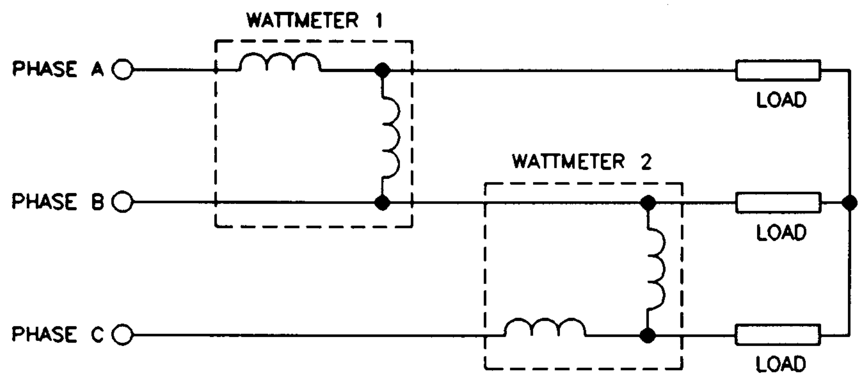


Figure 6-10. The Two-Wattmeter Method of Measuring Three-Phase Power.

For balanced loads at unity power factor, the wattmeter readings are identical. When the load power factor equals 0.5, one meter indicates zero and the other indicates the total power. When the power factor is between 0.5 and 1, one meter reads higher than the other. At power factors below 0.5, the indication of one meter is negative, and the total power is reduced by this negative value. At zero power factor, the two meters give identical readings, but of opposite sign, and the result is naturally zero watts. In all cases, the total power is the algebraic sum of the two wattmeter readings. Figure 6-11 shows how E1, E2, I1, and I2 on the DAI can be connected to a three-phase circuit to measure the total power using the two-wattmeter method. Note the manner in which E2 is connected to give a positive reading.

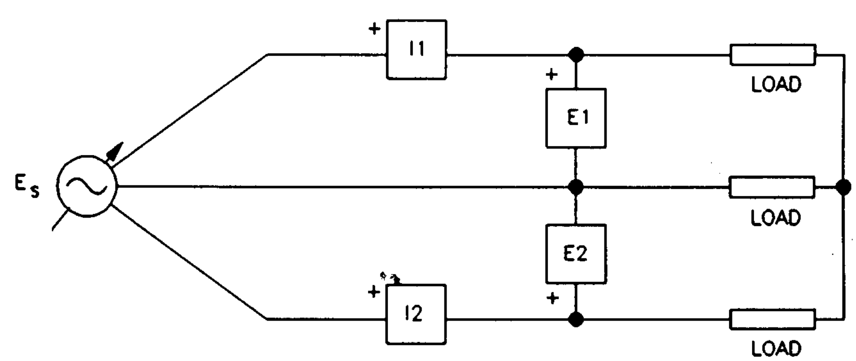


Figure 6-11. DAI Connection for The Two-Wattmeter Method of Power Measurement.

EQUIPMENT REQUIRED

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

PROCEDURE

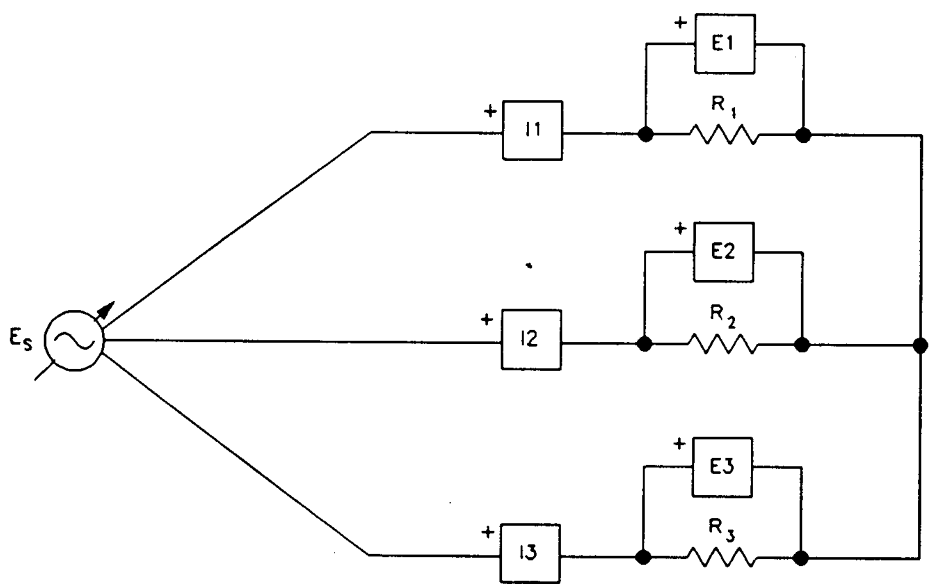
CAUTION!

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 Interface, 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 ccw. Set the voltmeter select switch to the 4-5 position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Set up the three-phase, wye-connected, resistive circuit shown in Figure 6-12. *Do not connect the neutral of the resistive load to the neutral of the Power Supply.* Connect I1, I2, I3, E1, E2, and E3 as shown to measure the currents and voltages.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	208	300	300	300
220	380	1100	1100	1100
240	415	1200	1200	1200

Figure 6-12. Three-Phase Wye-Connected Resistive Load.

☐ 4. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, and the flat cable from the computer is connected to the DAI.

☐ 5. Display the *Metering* window and select setup configuration file *ES16-6.cfg*.

☐ 6. Turn on the main Power Supply and set the 24 V - AC power switch to the I (ON) position. Adjust the voltage control to obtain the line-to-line voltage E_S given in Figure 6-12.

☐ 7. Measure the circuit voltages and currents and turn off the power.

E_{R1} = ________ V E_{R2} = ________ V E_{R3} = ________ V

I_{R1} = ________ A I_{R2} = ________ A I_{R3} = ________ A

☐ 8. Calculate the active power consumed in each phase of the circuit, and the total power consumed by the load.

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

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

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

$P_{TOTAL} = P_{R1} + P_{R2} + P_{R3} =$ ________ W

☐ 9. Determine the average load voltage and current.

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

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

☐ 10. Is the average load voltage approximately $\sqrt{3}$ times smaller than the line voltage set in step 6?

☐ Yes ☐ No

☐ 11. Calculate the total power using the line voltage and current. Note that $I_{LOAD} = I_{LINE}$ in this circuit, and E_{LINE} is the value set in step 6.

$P_{TOTAL} = 1.73\,(E_{LINE} \times I_{LINE}) =$ ________ W

Compare the total power found in step 8 with the power calculated using the line voltage and current. Are they approximately equal?

☐ Yes ☐ No

☐ 12. Reconnect the circuit as shown in Figure 6-13 to measure the total load power using the two-wattmeter method.

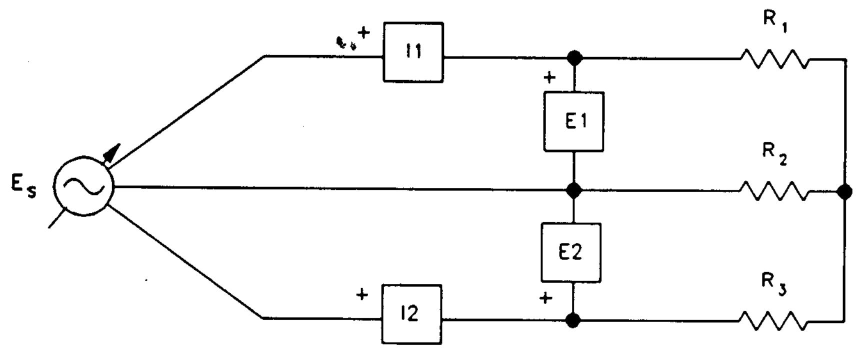


Figure 6-13. Total Power Measurement using Two-Wattmeter Method.

☐ 13. Turn on the power and readjust E_S if necessary to obtain the value used previously. Select setup configuration file *ES16-7.cfg*. Record the active power measurements given by meters PQS1, PQS2, and the total apparent power on programmable meter A. Turn off the power and determine P_{TOTAL}.

PQS1 = ________ W PQS2 = ________ W

$P_{APPARENT}$ = ________ VA P_{TOTAL} = PQS1+ PQS2 = ________W

☐ 14. Compare the measurement results in step 13 with the results obtained in steps 8 and 11. Is P_{TOTAL} approximately the same in all cases?

☐ Yes ☐ No

☐ 15. Do the results for $P_{APPARENT}$ and P_{TOTAL} show that apparent power and active power are approximately the same?

☐ Yes ☐ No

☐ 16. Add capacitance in parallel with the wye-connected load as shown in Figure 6-14, and set X_{C1}, X_{C2}, and X_{C3} to the same values as R_1, R_2, and R_3. Select setup configuration file *ES16-8.cfg*. Turn on the power and readjust E_S if necessary to obtain the value used previously.

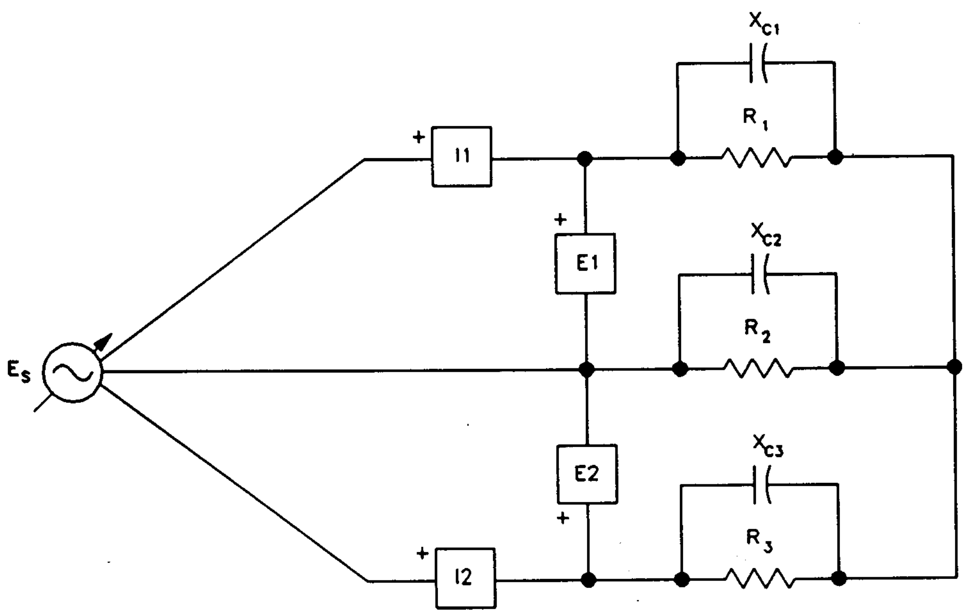


Figure 6-14. Adding Capacitance to The Wye-Connected Load.

☐ 17. Measure the line voltage and current, and record the readings for total apparent, active, and reactive power given by programmable meters A, B, C, and then turn off the power.

E_{LINE} = ________ V $\qquad$ I_{LINE} = ________ A

$P_{APPARENT}$ = ________ VA

P_{ACTIVE} = ________ W $\qquad$ $P_{REACTIVE}$ = ________ vars

☐ 18. Calculate the total apparent power consumed by the load, and cos φ.

$P_{APPARENT} = 1.73\,(E_{LINE} \times I_{LINE})$ = ________ VA

$$\cos\phi = \frac{P_{ACTIVE}}{P_{APPARENT}}$$

☐ 19. Use cos φ to calculate P_{ACTIVE}, and compare the result with the active power measured in step 17. Are the results approximately the same?

$P_{ACTIVE} = 1.73\,(E_{LINE} \times I_{LINE} \times \cos\phi)$ = ________ W

☐ Yes ☐ No

☐ 20. Determine $P_{REACTIVE}$ using the values of $P_{APPARENT}$ and P_{ACTIVE}.

$$P_{REACTIVE} = \sqrt{S^2 - P^2} = \_\_\_\_\_\_\_\_ \text{ vars}$$

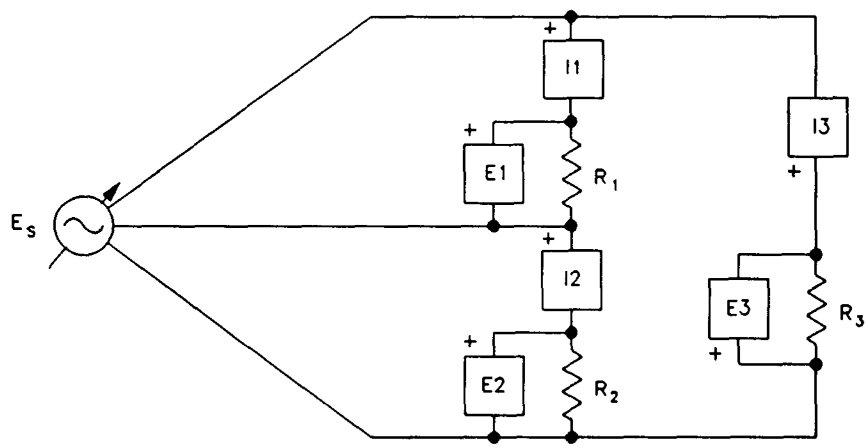
☐ 21. Is the calculated value for reactive power approximately the same as the measured value in step 17?

☐ Yes ☐ No

☐ 22. Is the apparent power calculated in step 18 approximately equal to the measured value recorded in step 17?

☐ Yes ☐ No

☐ 23. Set up the three-phase, delta-connected, resistive circuit shown in Figure 6-15. Connect I1, I2, I3, E1, E2, and E3 as shown to measure the currents and voltages.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	120	300	300	300
220	220	1100	1100	1100
240	240	1200	1200	1200

Figure 6-15. Three-Phase Delta-Connected Resistive Load.

☐ 24. Turn on the Power Supply and adjust the voltage control to obtain the line-to-line voltage E_S given in Figure 6-15. Select setup configuration file *ES16-9.cfg*. Measure the circuit voltages and currents and turn off the power.

E_{R1} = _______ V E_{R2} = _______ V E_{R3} = _______ V

I_{R1} = _______ A I_{R2} = _______ A I_{R3} = _______

☐ 25. Calculate the active power consumed in each circuit branch, and the total active power consumed by the load.

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

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

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

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

☐ 26. Calculate the total active power using the line voltage and line current.

$$I_{LINE} = \sqrt{3}\ \frac{I_{R1} + I_{R2} + I_{R3}}{3} = \_\_\_\_\_\_\_ \text{ A}$$

$P_{ACTIVE} = 1.73\ (E_{LINE} \times I_{LINE})$ = _______ W

Compare the total active power found in step 25 with the active power calculated using the line voltage and current. Are they approximately equal?

☐ Yes ☐ No

☐ 27. Reconnect the circuit as shown in Figure 6-16 to measure the total load power using the two-wattmeter method.

☐ 28. Turn on the power and readjust E_S if necessary to obtain the value used previously. Select setup configuration file *ES16-10.cfg*. Record the measurements of meters PQS1, PQS2, and programmable meter B, and then turn off the power.

PQS1 = _______ W PQS2 = _______ W

P_{ACTIVE} = _______ W

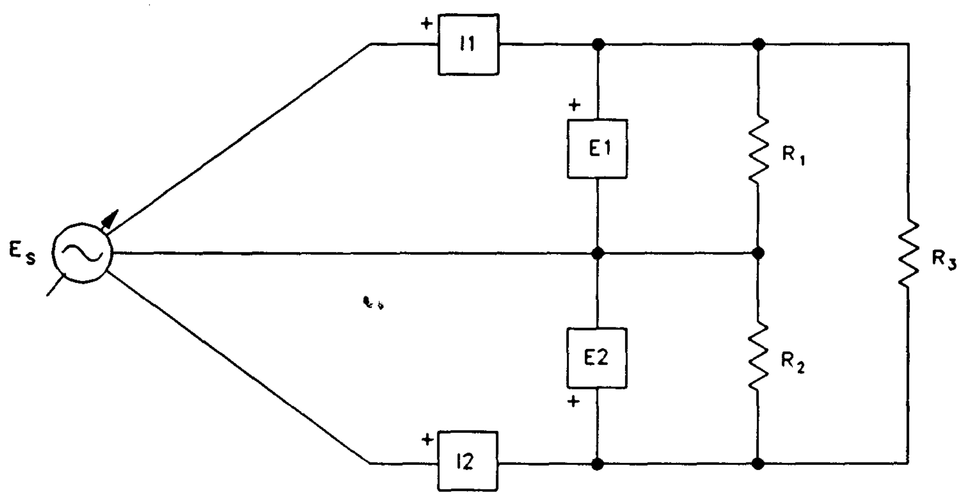


Figure 6-16. Total Power Measurement using Two-Wattmeter Method.

☐ 29. Is the measured value for P_{ACTIVE} approximately the same as those found in steps 25 and 26, thus confirming the calculations?

☐ Yes ☐ No

☐ 30. Is P_{ACTIVE} equal to the sum of the wattmeter readings PQS1 and PQS2?

☐ Yes ☐ No

☐ 31. Add capacitance in parallel with the delta-connected load as shown in Figure 6-17, and set X_{C1}, X_{C2}, and X_{C3} to the same values as R_1, R_2, and R_3. Turn on the power and readjust E_S if necessary to obtain the value used previously.

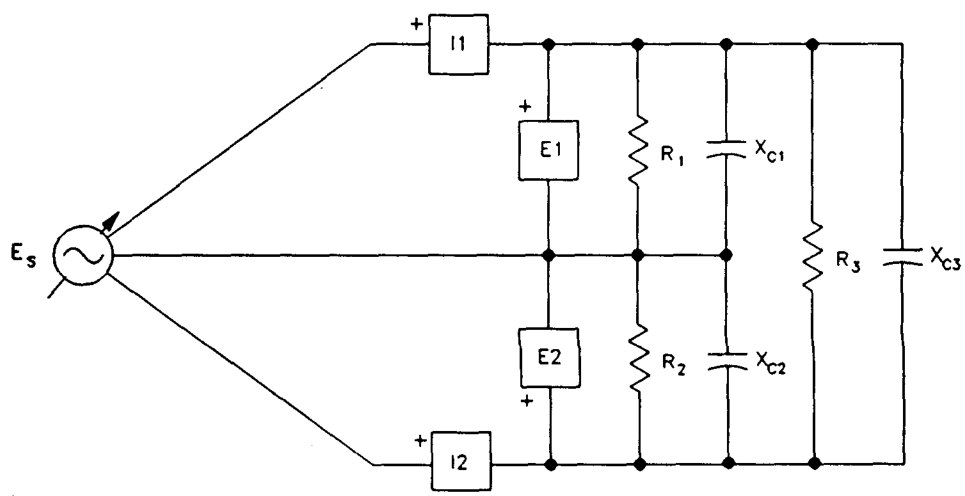


Figure 6-17. Adding Capacitance to The Delta-Connected Load.

☐ 32. Measure the line voltage and current, and record the readings for total apparent, active, and reactive power given by programmable meters A, B, C, and then turn off the power.

E_{LINE} = _______ V I_{LINE} = _______ A

$P_{APPARENT}$ = _______ VA

P_{ACTIVE} = _______ W $P_{REACTIVE}$ = _______ vars

☐ 33. Calculate the total apparent power consumed by the load, and cos ϕ.

$P_{APPARENT} = 1.73\ (E_{LINE} \times I_{LINE})$ = _______ VA

$\cos \phi = \frac{P_{ACTIVE}}{P_{APPARENT}}$ = _______

☐ 34. Use cos ϕ to calculate P_{ACTIVE}, and compare the result with the active power measured in step 32. Are the results approximately the same?

$P_{ACTIVE} = 1.73\ (E_{LINE} \times I_{LINE} \times \cos \phi)$ = _______ W

☐ Yes   ☐ No

☐ 35. Determine $P_{REACTIVE}$ using the values of $P_{APPARENT}$ and P_{ACTIVE}.

$P_{REACTIVE} = \sqrt{S^2 - P^2}$ = _______ vars

☐ 36. Is the calculated value for reactive power approximately the same as the measured value in step 32?

☐ Yes   ☐ No

☐ 37. Is the apparent power calculated in step 33 approximately equal to the measured value recorded in step 32?

☐ Yes   ☐ No

☐ 38. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You demonstrated that apparent, active and reactive power for three-phase loads can be determined using the two-wattmeter method, thus reducing the amount of equipment needed to measure power. You also saw that balanced three-phase circuits could be solved as if they were three separate single-phase circuits. You confirmed your calculations with actual measurements of the circuit parameters.

REVIEW QUESTIONS

1. In a three-phase balanced circuit, the active power can be determined using two wattmeters connected according to the

   a. single-phase wattmeter method.
   b. three-phase wattmeter method.
   c. two-wattmeter method.
   d. apparent power method.

2. The formula for total active power in a three-phase balanced circuit is

   a. $P_{ACTIVE} = 1.73\ (E_{PHASE} \times I_{PHASE} \times \cos \phi)$.
   b. $P_{ACTIVE} = 1.73\ (E_{LINE} \times I_{PHASE} \times \cos \phi)$.
   c. $P_{ACTIVE} = 1.73\ (E_{LINE} \times I_{LINE})$.
   d. $P_{ACTIVE} = 1.73\ (E_{LINE} \times I_{LINE} \times \cos \phi)$.

3. The total apparent power in a delta-connected resistive load equals

   a. $\sqrt{3}$ times the active power.
   b. the product of the line voltage with the line current.
   c. 1.73 times the product of the line voltage with the line current.
   d. $\sqrt{3}$ times the reactive power.

4. The two wattmeter readings for a three-phase balanced load are 175 W and -35 W. Knowing that the power measurements have been made using the two-wattmeter method, what is the total power consumed by the load?

   a. 220 W.
   b. 140 W.
   c. 175 W.
   d. -35 W.

5. Is the power factor in Question 4 greater than, equal to, or less than 0.5?

   a. The power factor cannot be determined with the information given.
   b. The power factor is less than 0.5.
   c. The power factor is equal to 0.5.
   d. The power factor is greater than 0.5.

Exercise 6-3

Phase Sequence

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the phase sequence of a three-phase voltage source, and explain the importance of connecting certain types of three-phase loads according to the proper phase sequence.

DISCUSSION

As mentioned earlier, a three-phase electric power system is one in which three voltages E_A, E_B, E_C, have equal magnitudes and are displaced 120° from each other. However, simply stating that the voltages are 120° out of phase with each other is not sufficient. The order in which the voltages succeed each other, their phase sequence, is important. This sequence is determined at the power generating station by the direction of rotation of the generators.

When connecting three-phase motors to the power line, it is extremely important to know the phase sequence because the direction in which the motors turn depends on the phasing. Consider for example the connection of a 4000-kW motor, which could take several hours of work for an electrician to connect the three large leads of the motor to the power supply. If the phase sequence is not determined in advance, the motor has one chance in two of turning in the wrong direction, resulting in work having to be redone and possible damage if the motor is connected to a load. Another situation where phase sequence is of critical importance is when additional power is needed, and one or more alternators must be added to share the load. The alternators are placed in parallel and if the phase sequencing is incorrect, serious damage will occur when the switch connecting them to the power network is turned on.

Phase sequence can be found quickly using two incandescent lamps and a capacitor connected in a wye configuration as shown in Figure 6-18.

One of the lamps will be brighter than the other and the phase sequence will be, *bright - dim - capacitor*, meaning that the phase sequence is A-B-C if the circuit has been connected to lines A,B,C as shown. The bright lamp will be the most leading phase of the three voltages, the dim lamp will correspond to the middle phase, and the capacitor will therefore correspond to the most lagging of the three voltages. If an inductor were used in place of a capacitor, the phase sequence for this example would be *bright-inductor-dim*.

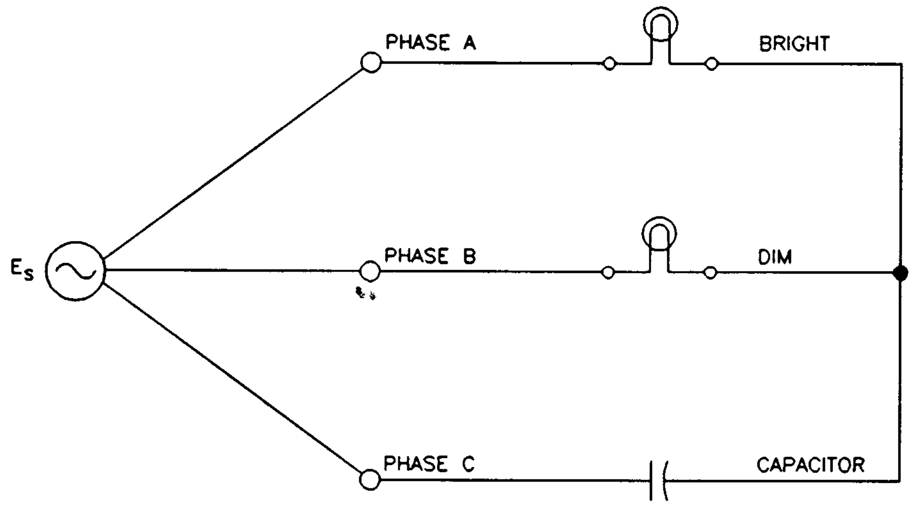


Figure 6-18. Determining the Phase Sequence of a Three-Phase Power Supply.

If phase sequence A-B-C is written in the form, A-B-C-A-B-C-A-B-C..., we see that B-C-A and C-A-B represent the same sequence as A-B-C. Its just a question of which voltage is being used as reference to describe the sequence. The opposite sequence to A-B-C is A-C-B, which can be seen to be the same as C-B-A and B-A-C when the sequence is written as A-C-B-A-C-B-A-C-B-A.... Phase sequence, and therefore the direction of rotation of three-phase motors, can be changed by simply interchanging the connections of any two of the ac power supply leads.

EQUIPMENT REQUIRED

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

PROCEDURE

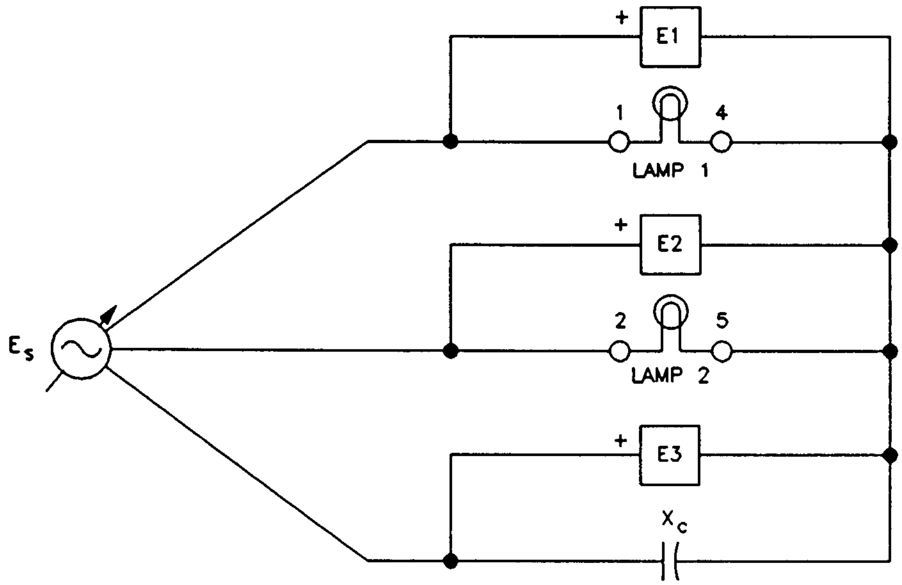
CAUTION!

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 Interface, Resistive Load, Capacitive Load, Inductive Load, and Synchronizing Switch 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 ccw. Ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Set up the circuit in Figure 6-19. Set X_C to the given value, and connect E1, E2, E3 as shown in the figure. **Ensure that the switch on the Synchronizing Module is in the open position or you will cause a short circuit across the ac supply lines.**



LINE VOLTAGE (V)	X_C (Ω)
120	1200
220	4400
240	4800

Figure 6-19. Determining Phase Sequence of an AC Supply.

☐ 4. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, and the flat cable from the computer is connected to the DAI.

☐ 5. Display the *Metering* window and select setup configuration file *ES16-11.cfg*.

☐ 6. Turn on the main Power Supply and set the 24 V - AC power switch to the I (ON) position. Adjust the main voltage control to about 50%. Note that the exact value of the ac supply voltage is not critical for this exercise.

☐ 7. Determine the phase sequence from the *bright-dim-capacitor* sequence.

Note: *For the EMS Power Supply module, phase sequence 4-5-6 corresponds to the sequence A-B-C. If the Power Supply wall receptacle is wired accordingly, sequence 4-5-6 will correspond to bright-dim-capacitor. The corresponding voltage phasor sequence will be E1-E2-E3.*

☐ 8. Use the *Phasor Analyzer* to observe the relative positions of the voltage phasors corresponding to the ac supply lines. With E1 as the reference phasor, is the phase sequence the same as that determined with the lamps/capacitor circuit?

☐ Yes ☐ No

☐ 9. Turn off the power and interchange any two circuit connections of the ac supply leads, 4 and 5, 5 and 6, or 4 and 6. Turn on the power and note the new phase sequence.

____

☐ 10. Is the new sequence opposite to the previous one?

☐ Yes ☐ No

☐ 11. Turn off the power and replace X_C in Figure 6-19 with an inductive reactance X_L having the same value. Reconnect the ac supply leads as they were in the original circuit.

☐ 12. Determine the phase sequence using the lamps/inductor circuit.

____

☐ 13. Does the *bright-inductor-dim* sequence give the same phase sequence as found in step 7?

☐ Yes ☐ No

☐ 14. Does the *Phasor Analyzer* show the same phase sequence as in step 7?

☐ Yes ☐ No

☐ 15. Turn off the power and interchange any two circuit connections of the ac supply leads. Turn on the power and note the new phase sequence.

____

☐ 16. Is this new phase sequence opposite to the previous one?

☐ Yes ☐ No

☐ 17. Does the *Phasor Analyzer* display confirm that the phase sequence has been reversed?

☐ Yes ☐ No

☐ 18. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You saw that the phase sequence of a three-phase power supply can be determined using a simple indicator circuit made with two lamps and a capacitor connected in a wye configuration. The phase sequence will always be in the order *bright-dim-capacitor*. This simple circuit can be used to confirm a known phase sequence, or determine the sequence of unmarked power leads.

REVIEW QUESTIONS

1. An unknown phase sequence can be determined using two lamps and a capacitor

   a. connected in series.
   b. connected in a delta configuration.
   c. connected in a wye configuration.
   d. connected in parallel.

2. The opposite phase sequence to B-A-C is

   a. A-B-C.
   b. A-C-B.
   c. B-A-C.
   d. both a and b.

3. A three-phase motor rotates clockwise when ac supply lines A,B,C are connected to motor leads 1,2,3 respectively. If the connections are changed so that lines A,B,C are now connected to leads 3,1,2 respectively, the motor

   a. will rotate counterclockwise.
   b. rotates clockwise because line connections are reversed twice.
   c. rotates clockwise because the sequence is reversed.
   d. will stop because the sequence is incorrect.

4. In a three-phase system, the phase sequence B-A-C is the order in which

   a. the phase shifts between voltage and current occur.
   b. the current lags the voltage.
   c. power surges are counted.
   d. the supply voltages succeed each other.

5. The phase sequence of a three-phase power network depends on

   a. the direction of rotation of the power station alternators.
   b. the amount of phase shift that is acceptable on the power network.
   c. the time of day, because power demand is lower during the night.
   d. the amount of loading on the power network.

Unit Test

1. The line current is $\sqrt{3}$ times greater than the phase current

   a. with a balanced wye-connected load.
   b. with a balanced delta-connected load.
   c. when the line voltage is $\sqrt{3}$ times smaller than the phase voltage.
   d. when the line voltage is $\sqrt{3}$ times greater than the phase voltage.

2. The line voltage is $\sqrt{3}$ times greater than the phase voltage

   a. with a balanced wye-connected load.
   b. with a balanced delta-connected load.
   c. when the line current is $\sqrt{3}$ times greater than the phase current.
   d. when the line current is $\sqrt{3}$ times smaller than the phase current.

3. What is the neutral line current in a balanced wye-connected circuit when the line-to-line voltage is 346 V, and the load resistors are 100 Ω?

   a. 3.46 amperes.
   b. 10.38 amperes.
   c. 0 amperes.
   d. 2 amperes.

4. What is the current in each phase of a balanced delta-connected resistive load when the line current is 34.6 A?

   a. 60 A.
   b. 11.5 A.
   c. 20 A.
   d. 104 A.

5. The apparent power in a three-phase balanced circuit is 150 VA, and the active power is 100 W. What is the load power factor?

   a. 0.67.
   b. 1.5.
   c. 0.33.
   d. 0.25.

6. The two-wattmeter method of power measurement

   a. allows reactive power in a single-phase circuit to be determined.
   b. allows active power in a single-phase circuit to be determined.
   c. allows active power in a balanced three-phase circuit to be determined.
   d. allows apparent power in a single-phase circuit to be determined.

Unit Test (cont'd)

7. The formula for total apparent power in a three-phase balanced circuit is

   a. $P_{APPARENT} = 1.73\ (E_{PHASE} \times I_{PHASE} \times \cos\phi)$.
   b. $P_{APPARENT} = 1.73\ (E_{LINE} \times I_{PHASE} \times \cos\phi)$.
   c. $P_{APPARENT} = 1.73\ (E_{LINE} \times I_{LINE} \times \cos\phi)$.
   d. $P_{APPARENT} = 1.73\ (E_{LINE} \times I_{LINE})$.

8. The two wattmeter readings for a three-phase balanced load are 200 W and 50 W. Knowing that the power measurements have been made using the two-wattmeter method, what is the total power consumed by the load?

   a. 250 W.
   b. 150 W.
   c. 500 W.
   d. 750 W.

9. The phase sequence A-C-B is the same as

   a. A-B-C.
   b. C-B-A.
   c. B-C-A.
   d. both a and c.

10. What changes in supply-line connections must be made for a three-phase motor to reverse direction?

    a. All leads must be reversed.
    b. The leads must be connected through a transformer.
    c. Two leads must be interchanged.
    d. Motor direction cannot be changed in this way.

Unit 7

Single-Phase Transformers

UNIT OBJECTIVE

After completing this Unit, you will be able to explain and demonstrate important operating characteristics of single-phase transformers. You will be able to connect transformer windings in **series-aiding** and **series-opposing** configurations, and demonstrate the effect that loading has on secondary voltage. Voltage and current measurements along with transformer load curves will be used to study transformer operation and working characteristics.

DISCUSSION OF FUNDAMENTALS

Transformers are magnetically-operated devices that can change voltage, current, and impedance values in ac circuits. In its simplest form, a transformer consists of two coils of wire wound on a common core of ferromagnetic material, such as iron. One coil is called the primary winding while the other is called the secondary winding. Transformers are probably the most universal pieces of equipment in the electrical industry, and range in size from tiny units in transistor radios to extremely large units weighing several tons in power distribution stations. However, all transformers have basically the same operating principles and characteristics, and every transformer has a **primary winding** for the input power and a **secondary winding** for the load. Some transformers are also designed to have more than one secondary winding. The ratio of the number of turns of wire in the primary winding (N_1 or N_P) to the number of turns of wire in the secondary winding (N_2 or N_S) is called the **turns ratio**. This ratio sets the relationship between the input and output values of a transformer. Figure 7-1 shows a single-phase transformer with a turns ratio N_1 / N_2 of 1:1, connected to a resistive load. The first exercise in this Unit will show how E_{PRI}, I_{PRI}, E_{SEC}, and I_{SEC} are related through the turns ratio.

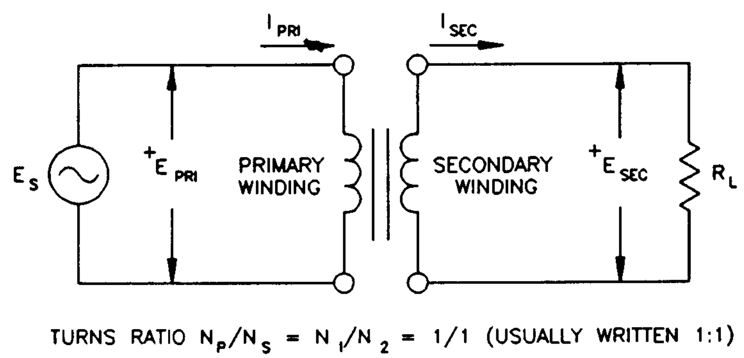


Figure 7-1. Single-Phase Transformer Connected to a Resistive Load.

Single-Phase Transformers

When **mutual inductance** exists between two coils or windings, a change in current in one coil induces a voltage in the other. Also, when the primary winding of a transformer is connected to an ac power source, it receives electrical energy from the source and couples the energy to the secondary winding by means of a changing **magnetic flux**. This energy appears as an electromotive force (a voltage) across the secondary winding, and when a load is connected to the secondary, the energy is transferred to the load. This process of **magnetic coupling** allows electrical energy to be transferred from one circuit to another without any physical connection between the two, therefore providing electrical isolation between them. Because transformers allow power at one voltage and current level to be converted into equivalent power at some other voltage and current level, they are indispensable in ac power distribution systems.

Because alternating current flows in the windings of a transformer, an alternating magnetic field is created in the iron core. Active power is dissipated in the transformer because of **copper loss** and **iron loss**, and the transformer heats up. The resistance of the wire used in the winding causes the copper loss, and the iron loss results from **eddy currents** and hysteresis, the property of magnetic materials causing resistance to changes in magnetization.

Despite the copper and iron losses, transformers are among the most efficient electrical devices that exist, and the apparent power at the primary is frequently considered equal to the apparent power at the secondary. The voltage at the secondary, however, usually varies with changes in the load, from a given value at no load to a lesser value when the secondary is fully loaded. The amount of variation in secondary voltage as the load applied to the secondary changes is called **transformer regulation** and depends on the type of load (resistive, inductive, or capacitive) connected to the secondary. As will be seen in this Unit, the secondary voltage can even rise above its rated value instead of decreasing.

Exercise 7-1

Voltage and Current Ratios

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with voltage and current characteristics of a single-phase transformer, and able to use the transformer turns ratio to predict the voltage and current that will flow in the secondary winding.

DISCUSSION

The windings of a standard single-phase transformer are called the primary winding and the secondary winding, as shown in Figure 7-1 of the Unit Discussion. The primary winding is the power input winding and this is the side that is connected to the ac power source. The secondary winding is connected to the load and is physically and electrically isolated from the primary. The voltage and current that flow in the secondary are related to the primary voltage and current by the transformer turns ratio N_1 / N_2 (or N_P / N_S) through a very simple relationship. The ratio of primary voltage to secondary voltage equals N_1 / N_2, while the ratio of primary to secondary current is equal to the inverse of the turns ratio, N_2 / N_1. This results in the following,

$$\frac{E_{PRI}}{E_{SEC}} = \frac{N_1}{N_2}$$

which gives: $$E_{SEC} = \frac{E_{PRI} \times N_2}{N_1}$$

and $$\frac{I_{PRI}}{I_{SEC}} = \frac{N_2}{N_1}$$

which gives: $$I_{SEC} = \frac{I_{PRI} \times N_1}{N_2}$$

Transformers are designed with fixed ratios between primary and secondary voltages, and are widely used to step-up (increase) or step-down (decrease) load voltages and currents. The Single-Phase Transformer module used in these exercises has its nominal ratings silk-screened on the front panel, and most transformers have markings to indicate their nominal characteristics. Also, many transformers have intermediate taps, or connection terminals on the secondary side, so that different voltage ratios can be obtained using a single transformer.

Determining a transformer's voltage ratio is a relatively simple matter. With no load connected to the secondary winding, only the small **exciting current** necessary to create the magnetic flux inside the transformer flows in the primary winding. Transformer losses are minimum and the ratio of primary to secondary voltage equals the turns ratio. The turns ratio can be found by measuring the unloaded secondary voltage with nominal voltage applied to the primary. The current ratio can be evaluated by measuring the short-circuit secondary current with a small ac voltage applied to the primary. The voltage applied to the primary must be low enough to ensure that the nominal current in the primary winding is not exceeded. Otherwise, the windings may overheat and be damaged.

The exciting current, which is directly related to the alternating magnetic flux, increases in direct proportion to the applied voltage until core saturation sets in. This occurs when the applied voltage exceeds the rated value of the primary, and then the linear relationship between the primary voltage and the exciting current breaks down. The curve of primary voltage versus exciting current flattens and smaller increases in primary voltage lead to larger increases in exciting current as shown in Figure 7-2. The exciting current is only a few milliamperes in the EMS Single-Phase Transformer module, and generally its value is a small percentage of the nominal current of a transformer.

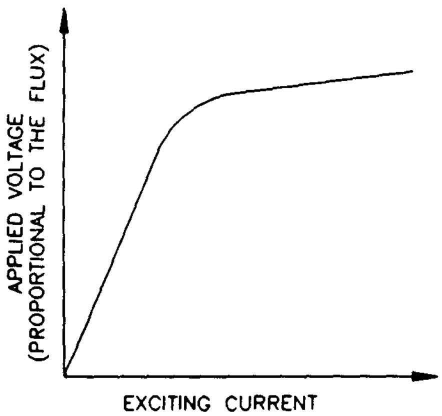


Figure 7-2. Saturation Curve of a Transformer.

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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

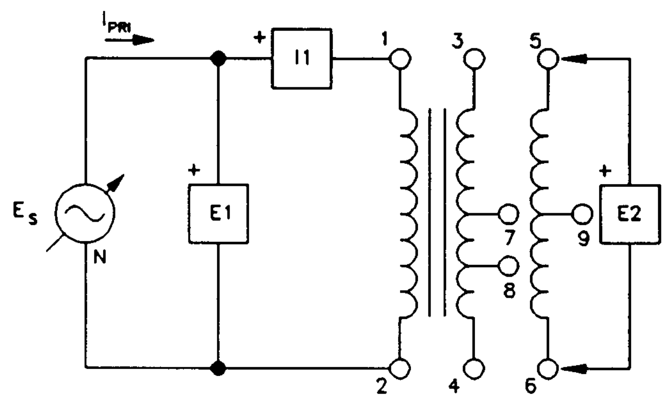
☐ 1. Install the Power Supply, Data Acquisition Interface, and Single-Phase Transformer modules in the EMS Workstation.

☐ 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 ccw. Set the voltmeter select switch to the 4-N position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, set the 24 V - AC power switch to the I (ON) position, and ensure the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES17-1.cfg*.

☐ 5. Set up the transformer circuit shown in Figure 7-3. Connect E1 and I1 as shown and use E2 to measure the different secondary voltages.



LINE VOLTAGE (V)	E_S (V)
120	120
220	220
240	240

Figure 7-3. Single-Phase Transformer Measurements.

☐ 6. Turn on the power and adjust the voltage control for the value of E_S given in Figure 7-3. Measure the transformer primary current and the different terminal voltages. After recording the measurements, rotate the voltage control fully ccw and then turn off the power.

> **Note:** *When measuring the various voltages, turn off the Power Supply before modifying the connections of the DAI to the circuit.*

I_{PRI} = ________ A　　E_{1-2} = ________ V　　E_{3-4} = ________ V

E_{5-6} = ________ V　　E_{3-7} = ________ V　　E_{7-8} = ________ V

E_{8-4} = ________ V　　E_{5-9} = ________ V　　E_{9-6} = ________ V

☐ 7. Do the secondary voltages compare well with the rated values written on the front panel?

☐ Yes ☐ No

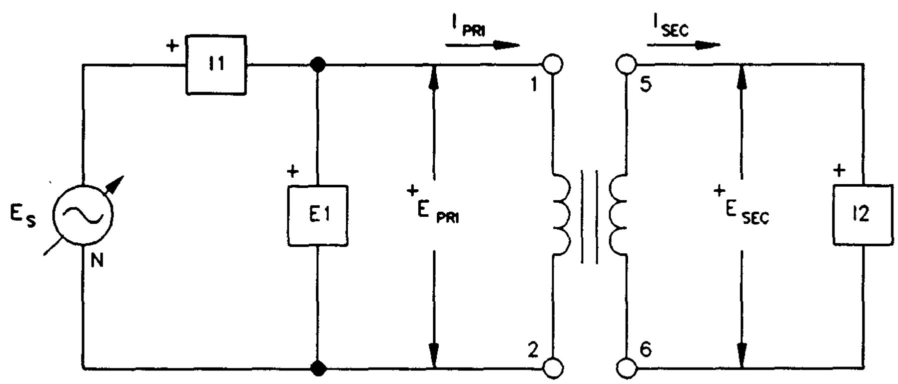
☐ 8. The transformer windings between terminals 1 and 2, and between terminals 5 and 6, each have 500 turns of wire. The number of turns in the winding between terminals 3 and 4 is 865. Calculate the turns ratios between the primary and secondary windings for each case.

$\frac{N_{1-2}}{N_{5-6}}$ = ________ $\frac{N_{1-2}}{N_{3-4}}$ = ________

☐ 9. Using the measured values in step 6, compare these transformer turns ratios with the corresponding voltage ratios. Are they approximately the same?

☐ Yes ☐ No

☐ 10. Connect I2 as shown in Figure 7-4 and note that it short-circuits secondary winding 5-6. Select setup configuration file *ES17-2.cfg*. Turn on the power and slowly adjust the voltage control to obtain the value of current I_S given in Figure 7-4.



LINE VOLTAGE (V)	I_S (A)
120	0.40
220	0.20
240	0.20

Figure 7-4. Determining The Ratio of Primary Current to Secondary Current.

☐ 11. Record the values of primary voltage and current, and the value of the short-circuit secondary current in winding 5-6.

E_{PRI} - ________ V I_{PRI} - ________ A I_{SEC} - ________ A

☐ 12. Return the voltage control to zero and turn off the power. Calculate the ratio of primary current to secondary current.

$\frac{I_{PR1}}{I_{SEC}}$ - ________

☐ 13. Is the ratio approximately equal to N_2 / N_1?

☐ Yes ☐ No

☐ 14. Connect I2 so that it now short-circuits secondary terminals 3-4. Turn on the Power Supply and slowly adjust the voltage control knob for the same value of current used in step 10. Once again, record the values of primary voltage and current, and the secondary winding current.

E_{PRI} - ________ V I_{PRI} - ________ A I_{SEC} - ________ A

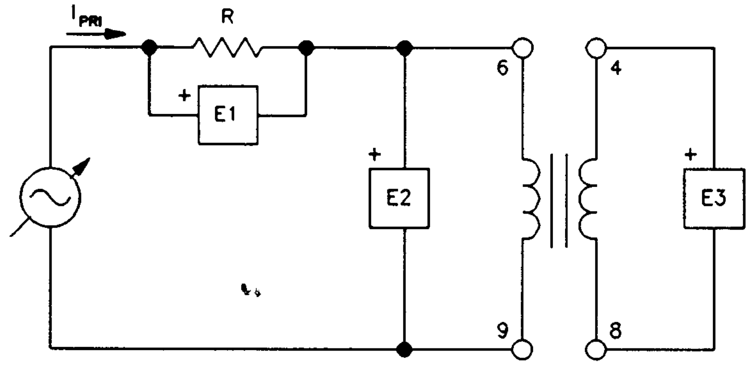
☐ 15. Return the voltage control to zero and turn off the power. Again, calculate the ratio of primary current to secondary current. Is it equal to N_2 / N_1?

☐ Yes ☐ No

☐ 16. Set up the transformer circuit shown in Figure 7-5. It will be used to show how exciting current is affected when the transformer core becomes saturated. Since the exciting current is so small, the corresponding voltage across a sense resistor R will be used to illustrate its variation. Connect the transformer primary terminals to Power Supply terminals 4 and 5 through sense resistor R. Connect E1, E2, and E3 to measure the transformer voltages.

☐ 17. Select setup configuration file *ES17-3.cfg*. Turn on the power and use the output voltage control to obtain values for E2 equally spaced at about 10% intervals over the complete control knob range. At each voltage adjustment, click the *Record Data* button to enter the measurements in the *Data Table*.

☐ 18. When all data values have been recorded, rotate the voltage control fully ccw, and turn off the Power Supply.



LINE VOLTAGE (V)	R (Ω)
120	100
220	367
240	400

Figure 7-5. Effect of Core Saturation on Exciting Current.

☐ 19. Display the *Graph* screen, select E1 as the X-axis parameter, and E2 as the Y-axis parameter. Click the *Line Graph* button to observe the curve of primary voltage versus exciting current, represented by E1. Does the exciting current increase more rapidly after the rated voltage is exceeded?

☐ Yes ☐ No

☐ 20. Does the curve illustrate that the transformer core becomes saturated?

☐ Yes ☐ No

☐ 21. Review the measured data to determine how the primary-to-secondary voltage ratio was affected when the transformer core became saturated.

____

____

____

☐ 22. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You measured the primary and secondary voltages in a single-phase transformer and confirmed that the ratio of primary-to-secondary voltage equals the transformer turns ratio N_1 / N_2. Measurements of primary and secondary currents showed that the ratio of currents was equal to the inverse of the turns ratio. You also observed the phenomenon of core saturation, and saw that transformer saturation did not affect the voltage ratio.

REVIEW QUESTIONS

1. The turns ratio for a transformer with 225 turns of wire in its primary winding and 675 turns in the secondary is

   a. 1 : 3.
   b. 3 : 1.
   c. N_1 / N_2.
   d. N_2 / N_1.

2. The short-circuit secondary current in a transformer is 5 A. What is the primary current if the transformer turns ratio is 1 : 4?

   a. 20 A.
   b. 1.25 A.
   c. 2.0 A.
   d. 0.8 A.

3. Transformer saturation occurs when the

   a. primary current is greater than the rated value.
   b. secondary winding is short-circuited.
   c. secondary voltage is greater than the rated value.
   d. primary voltage is greater than the rated value.

4. When 200 V is applied to the primary winding of a step-up transformer that doubles the primary voltage, how much current will flow in a 100-Ω load resistor connected across the secondary winding?

   a. 1 A.
   b. 2 A.
   c. 3 A.
   d. 4 A.

5. Why is it necessary to apply a low voltage to the primary winding instead of the rated voltage when evaluating the current ratio of a transformer?

   a. To ensure that rated current will flow in the secondary.
   b. To ensure that the current rating of the primary is not exceeded.
   c. To ensure that the voltage rating of the secondary is respected.
   d. To ensure that exciting current is maximum.

Exercise 7-2

Transformer Polarity

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine and use transformer polarities to properly connect separate windings so that the voltages add (series-aiding) or subtract (series-opposing).

DISCUSSION

When the primary winding of a transformer is energized by an ac source, an alternating magnetic flux is established in the iron core. This alternating flux links, or couples, the turns of each winding on the transformer and induces ac voltages in the windings. Polarity might seem to be of minor importance for transformers since they are ac devices. However, when two or more windings are connected together, their relative instantaneous polarities have a significant effect on the resulting net voltage. If the voltage in one winding is at its maximum positive peak when the voltage in another winding is at its maximum negative peak, i.e. they are 180° out of phase, they will oppose each other and the resulting voltage will be the difference between the two. For this reason, standards have been adopted for marking the polarity of transformer leads. In North American standards, the high-voltage leads are identified H1 and H2, and low voltage leads are marked X1 and X2. When H1 is instantaneously positive, X1 is also instantaneously positive. This system of marking allows transformers to be properly connected so that winding voltages will add or subtract as desired. Other types of markings are also used to identify the polarity of transformers, and transformer terminals could be marked with dots, crosses, numerals, or other convenient symbols. In Figure 7-6 dots have been used in the schematic drawing of a transformer and its windings.

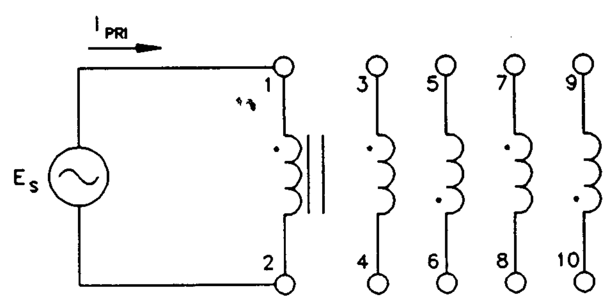


Figure 7-6. Transformer Polarity Markings.

When we speak of the polarity of transformer windings, we are identifying all terminals that have the same polarity, either negative or positive, at any instant in time. The dots used in Figure 7-6 indicate that at a given instant in time, when terminal 1 is positive with respect to terminal 2, then

terminal 3 is positive with respect to terminal 4,
terminal 6 is positive with respect to terminal 5,
terminal 7 is positive with respect to terminal 8,
terminal 10 is positive with respect to terminal 9.

Note that a terminal cannot be positive by itself, it can only be positive with respect to another terminal. Therefore, terminals 1, 3, 6, 7 and 10 are all positive with respect to terminals 2, 4, 5, 8 and 9 at any given instant in time.

When two dc cells or batteries are connected in series to obtain a higher output voltage, the positive terminal of one battery must be connected to the negative terminal of the other. In the same manner, if two transformer windings are to be connected in series so that their voltages add, the marked terminal of one of the windings must be connected to the unmarked terminal of the other winding. Conversely, if two transformer windings are to be connected in series so that their voltages subtract, the marked terminal of one of the windings must be connected to the marked terminal of the other winding.

It is also very important to respect polarities when connecting transformer windings having the same nominal voltage in parallel to share the current supplied to a load. Connecting transformer windings in parallel with opposite polarities will cause a large current to flow in the windings. An exercise in the next unit of this manual deals with parallel connections of transformers.

There are two methods for determining the polarity of a transformer, one using a dc source, the other an ac source. In the dc method, a dc voltmeter is connected across the secondary winding and a small dc voltage is applied to the primary. The direction in which the voltmeter pointer deflects when power is turned on will indicate the polarity of the secondary winding. The pointer will deflect to the right if the secondary winding terminal to which the voltmeter positive probe is connected has the same polarity as the primary winding terminal to which the positive side of the source is connected. If it deflects to the left, the primary and secondary terminals have opposite polarities. With the ac source method, an ac voltage is connected to the primary winding which is temporarily connected in series with the secondary. The voltage across the series combination will be less than the applied voltage if the two terminals that are interconnected have the same polarity. If the voltage is greater, the interconnected terminals have opposite polarities. Figure 7-7 illustrates both methods of determining transformer polarity.

Transformer Polarity

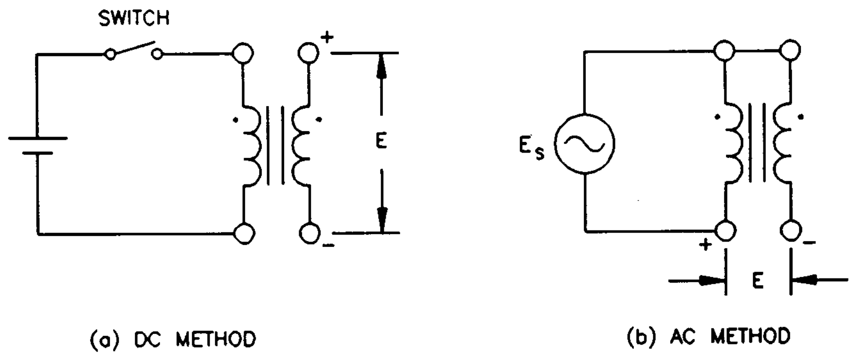


Figure 7-7. Methods for Determining Transformer Polarity.

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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 Interface, and Single-Phase Transformer 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 ccw. Set the voltmeter select switch to the 4-N position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, set the 24 V - AC power switch to the I (ON) position, and ensure the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES17-4.cfg*.

☐ 5. Set up the transformer circuit in Figure 7-8, and connect terminals 1 and 5 together as shown. Note that the ac input power in this circuit is connected at winding 3-4.

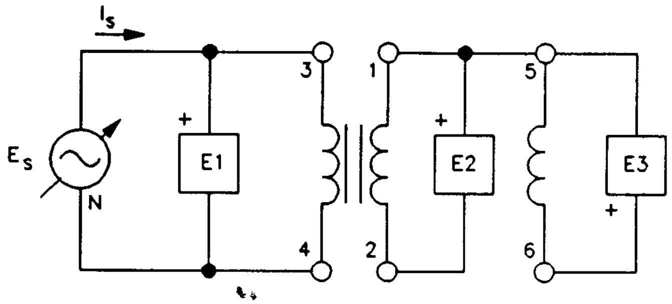


Figure 7-8. Transformer Windings Connected in Series.

☐ 6. Turn on the power and adjust the voltage control to set E_S at exactly 50% of the rated voltage for winding 3-4. *Note that the rated voltage is the sum of the intermediate winding voltages between terminals 3 and 4.* Measure and record the voltages at transformer windings 1-2, 5-6, and 2-6. Note that $E_{2\text{-}6}$ is obtained from programmable meter A using the function E2+ E3.

$E_{1\text{-}2}$ = _______ V $E_{5\text{-}6}$ = _______ V $E_{2\text{-}6}$ = _______ V

☐ 7. Are the windings connected in series-aiding, or series-opposing?

____

Note: *The voltage measured between terminals 2 and 6 is normally around zero volts, meaning that the windings are connected so that the voltages subtract from each other. Transformer polarity can be determined in this manner because the voltage across two interconnected windings will be less than the applied voltage when the interconnected terminals have the same polarity.*

☐ 8. Return the voltage control to zero and turn off the Power Supply. Disconnect terminals 1 and 5, and connect terminals 1 and 6 together. Reverse connections to meter E3. If this new connection is series-aiding, what will be the value of $E_{2\text{-}5}$ when the same voltage of step 6 is applied to winding 3-4?

____

☐ 9. Select setup configuration file *ES17-5.cfg*. Turn on the power and once again set E_S at exactly 50% of the rated voltage for winding 3-4. Measure and record the voltages at transformer windings 1-2, 5-6, and 2-5. Note that $E_{2\text{-}5}$ is obtained from programmable meter A.

$E_{1\text{-}2}$ = _______ V $E_{5\text{-}6}$ = _______ V $E_{2\text{-}5}$ = _______ V

☐ 10. Is the value obtained for $E_{2\text{-}5}$ the same as predicted in step 8?

☐ Yes ☐ No

☐ 11. Return the voltage control to zero, turn off the power supply and remove the connection between terminals 1 and 6. What are the two voltages which can be obtained across the series combination of windings 3-4 and 1-2 when the same voltage as that in step 9 is applied to winding 3-4?

____

☐ 12. Connect terminals 1 and 4 together, turn on the power and set E_S at exactly 50% of the rated voltage for winding 3-4. Select setup configuration file *ES17-6.cfg*. Measure and record the voltages at transformer windings 1-2, and 2-3 using E2 et E3.

$E_{1\text{-}2}$ = _______ V $E_{2\text{-}3}$ = _______ V

☐ 13. Return the voltage control to zero and turn off the power supply. Disconnect terminals 1 and 4, and connect terminals 1 and 3 together.

☐ 14. Turn on the power and set E_S at exactly 50% of the rated voltage for winding 3-4. Select setup configuration file *ES17-7.cfg*. Measure and record the voltage at transformer winding 2-4.

$E_{2\text{-}4}$ = _______ V

☐ 15. How do the results of steps 12 and 14 compare with the predictions in step 11?

____

☐ 16. Which sets of terminals have the same polarity, 1 & 3, 2 & 4, 1 & 4, or 2 & 3?

____

☐ 17. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You determined transformer polarity using the ac voltage method. When connecting transformer windings in series, you observed that the winding voltages subtract when winding terminals of the same polarity are connected together. Conversely, you observed that the winding voltages add when winding terminals of opposite polarities are connected together. This is similar to connecting batteries in series to obtain higher voltages.

REVIEW QUESTIONS

1. Can different transformer windings be connected together for higher voltages if the terminals are not marked?

   a. Yes, but the polarity must be determined experimentally beforehand.
   b. No.
   c. Only if the windings are on the primary side of the transformer.
   d. Only if the current is less than 1 A.

2. Two of four secondary terminals on a transformer are marked with a cross. If these two terminals are connected together, the secondary windings are

   a. connected in series-opposing.
   b. connected in series-aiding.
   c. connected to increase the resulting voltage.
   d. both b and c.

3. Is it possible for a voltmeter connected across the secondary windings of a transformer with three windings having nominal voltages of 50 V, 125 V, and 75 V to measure zero volts, even though rated voltage is applied to the primary winding?

   a. No, there must be something wrong with the voltmeter.
   b. Yes, if the 50-V and 75-V windings are connected to oppose the 125-V winding.
   c. Yes, if the 50-V and 75-V windings are connected to aid the 125-V winding.
   d. No, the transformer must be damaged.

4. Two methods of determining the polarity of transformer windings are

   a. the resistive method and the inductive method.
   b. the series-opposing method and the series-aiding method.
   c. the dc method and the ac method.
   d. the experimental method and the theoretical method.

5. To properly connect transformer windings for higher voltage, it is necessary

   a. to know their ratings.
   b. to know the maximum winding current.
   c. to know the type of core material.
   d. to know the polarity of the windings.

Special Transformer Connections

UNIT OBJECTIVE

After completing this Unit, you will be familiar with specially-connected transformers like autotransformers and distribution transformers. You will also be able to connect transformers in parallel so that they work together to supply power to a load. Voltage and current measurements will be used to study transformer operation and working characteristics.

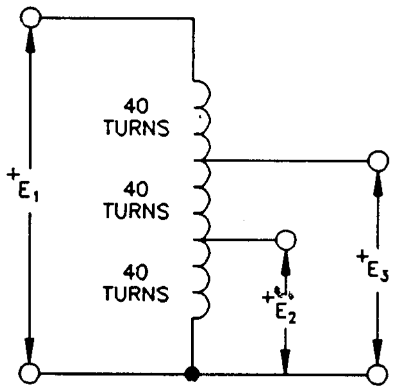
DISCUSSION OF FUNDAMENTALS

As explained in the previous Unit, transformers can change voltage and current levels, and the input-output relationship of a transformer depends on the turns ratio. Some different ways in which single-phase transformers can be connected are as an **autotransformer** to increase or decrease voltage, as a **distribution transformer** to provide different levels of load voltages, or in parallel to provide load sharing.

In general, most transformers provide isolation between an ac source and its load circuit, and this is often an important safety factor. An autotransformer however, does not provide any isolation because the primary and secondary windings share common turns of wire. On the other hand, the autotransformer can operate at an apparent power level that is twice that of a conventional transformer of the same size. Figure 8-1 shows a typical autotransformer with different taps allowing different voltages at the secondary. Since the same rules that were seen previously apply to autotransformers, it is clear from the turns ratios in the figure that

$$E_2 = \frac{E_1}{3}, \text{ and } E_3 = \frac{E_1}{1.5}$$

The figure also shows how the primary and secondary sides of an autotransformer are interconnected through a common point in the single winding, thus illustrating why electrical isolation is lost. This lack of isolation is the major disadvantage of an autotransformer.



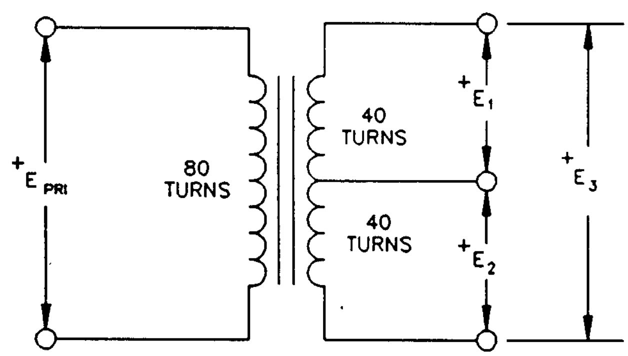
$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \quad \text{AND} \quad \frac{E_1}{E_3} = \frac{N_1}{N_3}$$

$$E_2 = \frac{40}{120} E_1 = \frac{E_1}{3}$$

$$E_3 = \frac{80}{120} E_1 = \frac{E_1}{1.5}$$

Figure 8-1. A Typical Autotransformer.

Distribution transformers have a primary winding and often more than one secondary winding, such as the Single-Phase Transformer module. The secondary windings are usually connected in series so that their voltages add (series-aiding configuration), and the common connection between the secondary windings serves as a neutral in a dual-voltage distribution circuit. Figure 8-2 shows a typical distribution transformer that provides two different load voltages.



$$E_1 = E_2 = 0.5\ E_{PRI}$$

$$E_3 = E_1 + E_2 = E_{PRI}$$

Figure 8-2. A Typical Distribution Transformer.

Exercise 8-1

The Autotransformer

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with voltage and current characteristics of an autotransformer, and you will be able to connect a standard transformer as an autotransformer in step-up and step-down configurations.

DISCUSSION

The autotransformer is a special type of transformer with only one winding which serves as both the primary and secondary. When the autotransformer is used to step-up the voltage, only part of the single winding acts as the primary, while the complete winding serves as the secondary. However, when the autotransformer is used to step-down the voltage, primary and secondary use is reversed. The whole winding is connected for use as the primary and only a part serves as the secondary. Figure 8-3 shows the autotransformer connections necessary for step-up and step-down operation.

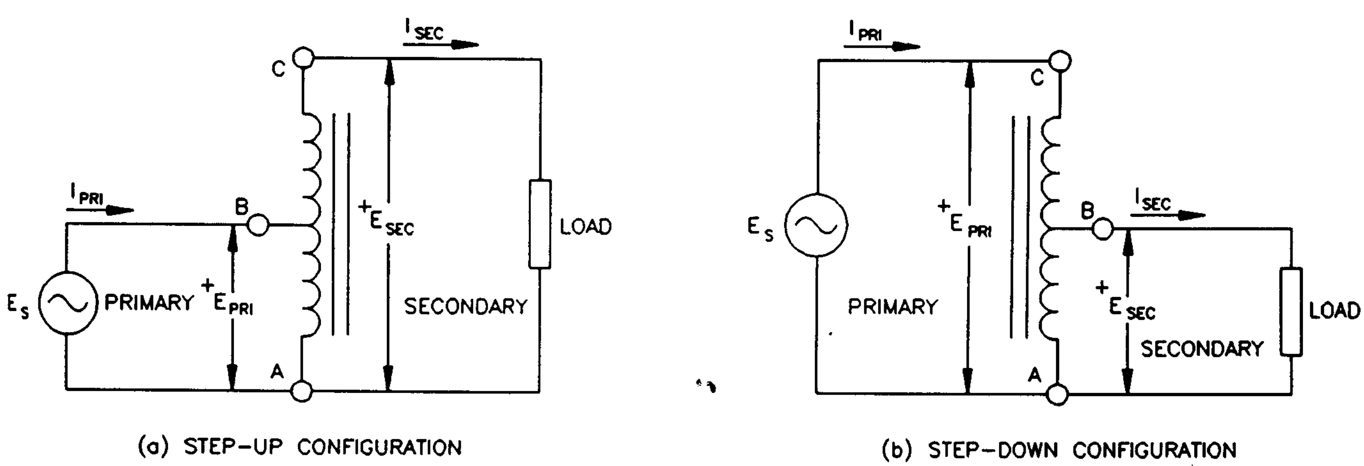


Figure 8-3. Autotransformer Connections (a) Step-Up Configuration. (b) Step-Down Configuration.

Autotransformer operation is basically the same as a standard two-winding transformer. Power is transferred from the primary to the secondary by a changing magnetic flux. The amount of increase or decrease in the voltage depends on the turns ratio between the primary and the secondary. To determine the turns ratio of the autotransformer, each winding is considered as separate even though some turns are common to both the primary and the secondary. Voltages and currents can be found using two simple equations:

$E_{PRI} \times I_{PRI} = E_{SEC} \times I_{SEC}$, and

$$\frac{E_{PRI}}{E_{SEC}} = \frac{N_P}{N_S}$$

The first equation simply states that the apparent power on the primary side ($E_{PRI} \times I_{PRI}$) of the transformer equals the apparent power on the secondary side ($E_{SEC} \times I_{SEC}$). The second equation relates the primary and secondary voltages (E_{PRI} and E_{SEC}) with the turns ratio (N_P/N_S). Thus, from Figure 8-3 we obtain the relationships,

$$\frac{E_{PRI}}{E_{SEC}} = \frac{N_{A\text{-}B}}{N_{A\text{-}C}}$$ for step-up operation, and

$$\frac{E_{PRI}}{E_{SEC}} = \frac{N_{A\text{-}C}}{N_{A\text{-}B}}$$ for step-down operation

These relationships are true when voltages $E_{A\text{-}B}$ and $E_{B\text{-}C}$ are in phase, and thus, add in the same direction.

The autotransformer has a great advantage over a conventional transformer: it can operate at an apparent power level that is twice that of a conventional transformer of the same size. Furthermore, the autotransformer is somewhat more efficient than transformers with separate windings because it has smaller copper and iron losses. It is used mainly when small increases or decreases are required in the secondary voltage. For example, to boost a power line voltage and compensate for losses caused by long transmission lines, or to reduce the starting voltage of a motor, thus holding down its starting current within reasonable values. One major disadvantage of an autotransformer is the lack of electrical isolation between the primary and secondary windings since the windings are not separate. Also, it is generally unadvisable to use an autotransformer as a large-ratio step-down device because the high-voltage primary voltage would be placed across the low-voltage load if the low-voltage section of the winding became defective and opened up.

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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

The Autotransformer

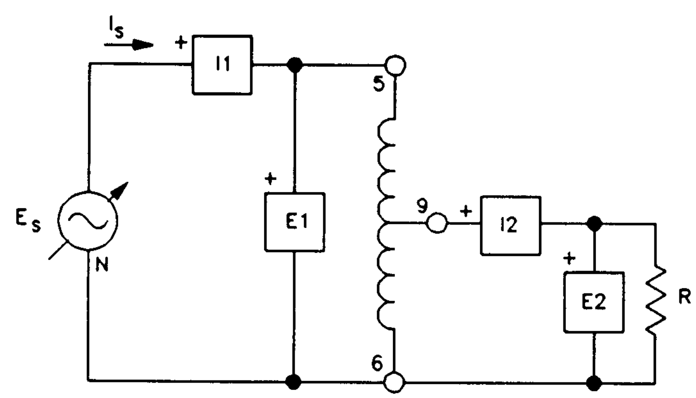
☐ 1. Install the Power Supply, Data Acquisition Interface, Resistive Load, and Single-Phase Transformer modules in the EMS Workstation.

☐ 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 ccw. Set the voltmeter select switch to the 4-N position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, set the 24 V - AC power switch to the I (ON) position, and ensure the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES18-1.cfg*.

☐ 5. Set up the autotransformer circuit shown in Figure 8-4. Connect E1 and I1 as shown, and use E2 and I2 to measure the secondary voltage and current. Note that winding 5-6 is connected as the primary, and that center-tap terminal 9 and terminal 6 act as the secondary winding.



LINE VOLTAGE (V)	E_S (V)	R (Ω)
120	120	∞
220	220	∞
240	240	∞

Figure 8-4. Autotransformer Circuit to Decrease Secondary Voltage.

☐ 6. Turn on the main Power Supply and ensure that all of the Resistive Load module switches are open. Adjust the voltage control to obtain the value of E_S given in Figure 8-4. This is the rated voltage for the primary winding.

☐ 7. Set the Resistive Load module to obtain the value of R given in Table 8-1.

LINE VOLTAGE	R
V	Ω
120	120
220	440
240	480

Table 8-1. Value of Resistor R.

Measure and record I_{PRI}, I_{SEC}, E_{SEC}, S_{PRI}, S_{SEC}. Note that the primary and secondary apparent powers are obtained from electrical power meters PQS1 and PQS2. After recording the measurements, rotate the voltage control fully ccw and turn off the power.

I_{PRI} = ________ A I_{SEC} = ________ A E_{SEC} = ________ V

S_{PRI} = ________ VA S_{SEC} = ________ VA

☐ 8. Compare the values of S_{PRI} and S_{SEC}. Are they approximately the same, except for a small difference caused by copper and core losses?

☐ Yes   ☐ No

☐ 9. Using the measured values in step 7, calculate the apparent power for both the primary and secondary circuits.

$S_{PRI} = E_{PRI} \times I_{PRI}$ = ________ VA

$S_{SEC} = E_{SEC} \times I_{SEC}$ = ________ VA

☐ 10. Are the calculated results approximately the same as the readings obtained with meters PQS1 and PQS2?

☐ Yes   ☐ No

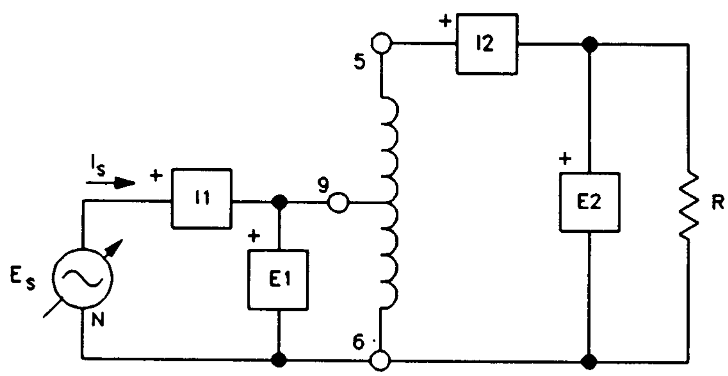
☐ 11. Is the autotransformer connected in a step-up, or a step-down configuration?

____

☐ 12. Compare the ratio of primary to secondary current. Does it agree with the inverse of the turns ratio?

☐ Yes ☐ No

☐ 13. Set up the autotransformer circuit shown in Figure 8-5. Connect E1 and I1 as shown, and use E2 and I2 to measure the secondary voltage and current. Note that winding 9-6 is now connected as the primary, and that terminals 5 and 6 are used for the secondary winding.



LINE VOLTAGE (V)	E_S (V)	R (Ω)
120	60	∞
220	110	∞
240	120	∞

Figure 8-5. Autotransformer Circuit to Increase Secondary Voltage.

☐ 14. Ensure that all of the Resistive Load module switches are open, and turn on the main power. Adjust the voltage control to obtain the value of E_S given in Figure 8-5. This is the rated voltage for winding 9-6.

☐ 15. Set the Resistive Load module to obtain the value of R given in Table 8-2.

LINE VOLTAGE	R
V	Ω
120	600
220	2 200
240	2 400

Table 8-2. Value of Resistor R.

Measure and record I_{PRI}, I_{SEC}, E_{SEC}, S_{PRI}, S_{SEC}. After recording the measurements, rotate the voltage control fully ccw and turn off the power.

I_{PRI} = ________ A I_{SEC} = ________ A E_{SEC} = ________ V

S_{PRI} = ________ VA S_{SEC} = ________ VA

☐ 16. Compare the values of S_{PRI} and S_{SEC}. Are they approximately the same, except for a small difference caused by copper and core losses?

☐ Yes   ☐ No

☐ 17. Using the measured values in step 15, calculate the apparent power for both the primary and secondary circuits.

$S_{PRI} = E_{PRI} \times I_{PRI}$ = ________ VA

$S_{SEC} = E_{SEC} \times I_{SEC}$ = ________ VA

☐ 18. Are the calculated results approximately the same as the readings obtained with meters PQS1 and PQS2?

☐ Yes   ☐ No

☐ 19. Is the autotransformer connected in a step-up, or a step-down configuration?

____

☐ 20. Compare the ratio of primary to secondary current. Does it agree with the inverse of the turns ratio?

☐ Yes   ☐ No

☐ 21. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You connected a standard two-winding transformer to operate as an autotransformer in both step-up and step-down configurations. Measurements of apparent power on the primary and secondary sides of the circuit showed that they are approximately equal except for the small difference caused by transformer losses. You also saw that the voltage and current relationships for an autotransformer are based on the same rules as standard transformers.

The Autotransformer

REVIEW QUESTIONS

1. An autotransformer is a special type of transformer that has

   a. a single winding which serves as both primary and secondary.
   b. a separate primary and secondary winding.
   c. more than one primary winding.
   d. two secondary windings connected in series.

2. The power on the primary side of an autotransformer is

   a. less than the power on the secondary side.
   b. much greater than the power on the secondary side.
   c. exactly equal to the power on the secondary side.
   d. slightly greater than the power on the secondary side.

3. What is the secondary voltage when a source voltage of 150-V is applied across the complete winding of a center-tapped autotransformer?

   a. 300 V.
   b. 150 V.
   c. 75 V.
   d. 225 V.

4. The secondary current in an autotransformer

   a. equals the turns ratio.
   b. cannot exceed the winding current.
   c. must be less than the winding current.
   d. is not limited.

5. The apparent power rating of a 10:1 autotransformer is 450 VA. This means that the apparent power rating of the secondary is

   a. 45 VA.
   b. 4500 VA.
   c. 450 VA.
   d. none of the above.

Exercise 8-3

Distribution Transformers

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the basic concepts of distribution transformers. You will measure line voltages and currents to observe how a distribution transformer behaves under various load conditions.

DISCUSSION

The majority of distribution transformers that supply homes and residential buildings with power in North America have one high-voltage primary winding. The secondary winding provides 120 V for lighting and small appliances, as well as 240 V for heating, electric stoves and other heavy-duty electrical loads. The secondary winding may be a 240-V center-tapped single winding or two 120-V single windings connected in series.

To obtain the advantage of a higher-voltage distribution circuit, while at the same time allowing the operation of lower-voltage equipment, the 120/240-V three-wire power distribution system was developed. For a given amount of power supplied to a load, the line loss in the 120/240-V three-wire power distribution system is less than that in a 120-V two-wire power distribution system. The three-wire system has the further advantage of setting the voltage between any line wire and ground to an acceptable level, thereby, limiting the risks for harmful electric shocks.

Distribution transformers are usually wound with the secondary or low-voltage winding in two sections, each section having a nominal voltage of 120 V. When the sections are connected in series, the transformer can be used to supply a two-wire 240-V load. The series connection can also supply a three-wire 120/240-V circuit by connecting the neutral or common wire of this circuit to the common terminal of the secondary (point of junction of the two winding sections). In this way, 120-V lamps and equipment can be connected between the neutral wire and either one of the two other wires (line wires), while 240-V loads like stoves and electric heaters can be connected across the two line wires.

When the loads on each side of the neutral wire are balanced, no current flows in this wire. However, when a heavy load is added between one line wire and the neutral wire, the neutral wire carries the unbalanced current from the transformer to the load. The neutral current is always the difference between the currents flowing in the two line wires. Therefore, the loads on each side of the neutral wire should be as balanced as possible to minimize the neutral current.

If a load is connected to only one side of a three-wire system, the neutral wire carries all the load current. For this reason the neutral wire is the same size as the two line wires. An accidental opening of the neutral wire when an unbalanced load is being supplied results in large imbalances in the voltages across the other loads, causing incandescent lamps, for example, to brighten or become dim. Therefore, the neutral wire is solidly connected from the transformer to the load, and no fuses or overcurrent devices are installed in series with the neutral wire.

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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

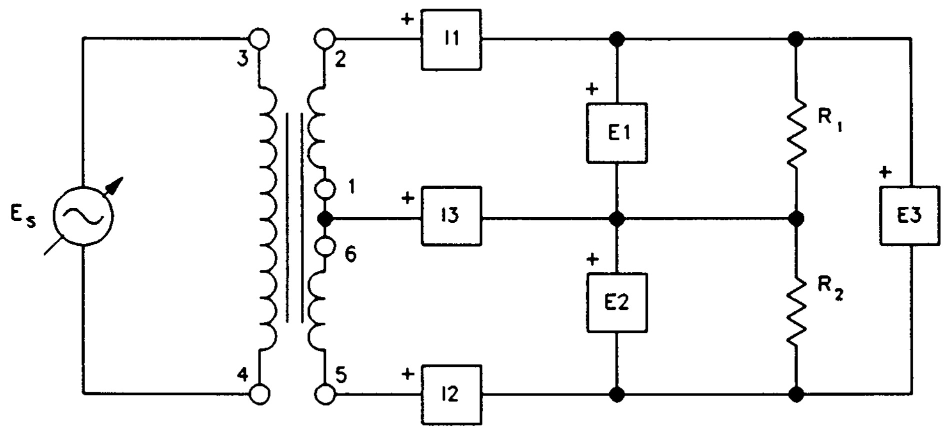
☐ 1. Install the Power Supply, Data Acquisition Interface, Resistive Load, Inductive Load, and Single-Phase Transformer modules in the EMS Workstation.

☐ 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 ccw. Set the voltmeter select switch to the 4-5 position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, set the 24 V - AC power switch to the I (ON) position, and ensure the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES18-5.cfg*.

☐ 5. Set up the distribution transformer circuit shown in Figure 8-8. Note that winding 3-4 is used as the primary and is connected to variable ac output terminals 4-5 on the Power Supply. Transformer windings 1-2 and 5-6 are connected in series to obtain high-voltage across terminals 2 and 5. Ensure that all switches on the Resistive Load and Inductive Load modules are open, and connect the voltmeters and ammeters as shown in the figure.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)
120	208	∞	∞
220	380	∞	∞
240	415	∞	∞

Figure 8-8. Distribution Transformer With a Resistive Load.

☐ 6. Turn on the main Power Supply and adjust the main voltage control to obtain the value of E_S given in Figure 8-8. With no load on the transformer (all switches open on the load modules), click the *Record Data* button to enter the circuit measurements in the *Data Table*.

☐ 7. Set the Resistive Load module to obtain the values of R_1 and R_2 given Table 8-4.

LINE VOLTAGE	R_1	R_2
V	Ω	Ω
120	300	300
220	1 100	1 100
240	1 200	1 200

Table 8-4. Values of Resistors R_1 and R_2.

Record the circuit measurements as in step 6. Note that separate sections of the Resistive Load module are used for R_1 and R_2.

☐ 8. Why is the neutral current indicated by I3 equal to zero?

___

☐ 9. Set R_2 so that it is now double the value of R_1. Once again record the circuit measurements.

☐ 10. Is the neutral line current measured by I3 equal to the difference in the readings between I1 and I2?

☐ Yes ☐ No

☐ 11. Turn off the Power Supply and disconnect the neutral line between the transformer and the load circuit. Turn on the Power Supply and ensure that E_S is at the same value as in step 6. Use the *Record Data* button to enter the measurements as before.

☐ 12. What difference do you observe in the load voltages?

___

☐ 13. If the load resistors were incandescent lamps in a home, what would be noticeable with this imbalance?

___

☐ 14. Turn off the Power Supply. Disconnect resistor R_2 from the circuit of Figure 8-8 and replace it with an inductive reactance X_L. Reconnect the neutral line between the transformer and load circuit (through I3). Set R_1 and X_L to the values given in Table 8-5.

LINE VOLTAGE	R_1	X_L
V	Ω	Ω
120	400	400
220	1 467	1 467
240	1 600	1 600

Table 8-5. Value of Resistor R_1 and Inductive Reactance X_L.

☐ 15. Turn on the Power Supply. Ensure that E_S is at the same value as before and click the *Record Data* button to enter the circuit measurements in the *Data Table.*

☐ 16. What difference do you observe in the load voltages?

____

☐ 17. Is the neutral line current measured by I3 equal to the difference in the readings between I1 and I2?

☐ Yes ☐ No

☐ 18. Explain why your answer in step 17 is different than that in step 10.

____

☐ 19. Click the *Data Table* button and review the measured data. Does it agree with the theoretical information presented in the Discussion?

☐ Yes ☐ No

Note: *It should be clear from the measurements that the neutral line current is the vectorial difference between I1 and I2. When the currents are in phase, such as the case for equal load resistors, this difference is the same as the arithmetical difference.*

☐ 20. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You set up the circuit for a typical distribution transformer, and observed its behaviour under various load conditions. You saw that it was possible to supply both high- and low-voltage loads with a distribution transformer, and that the neutral current was equal to zero with a balanced load.

REVIEW QUESTIONS

1. A 120/240-V distribution transformer can provide power for

   a. loads at different voltage levels.
   b. loads at one voltage level only.
   c. resistive loads only.
   d. loads that are less than 1000 VA.

2. A typical 120/240-V distribution transformer requires

   a. three wires for the primary circuit.
   b. two wires for the secondary circuit.
   c. two wires and a neutral wire for the secondary circuit.
   d. four wires for each 120-V secondary circuit.

3. Neutral current in a distribution transformer

   a. is not important.
   b. equals zero when loads are properly balanced.
   c. equals the difference of the currents in the line wires.
   d. both b and c.

4. The neutral wire in a three-wire distribution system

   a. is the same size as the line wires.
   b. is smaller in size than the line wires.
   c. is larger in size than the line wires.
   d. must be a larger size than the line wires.

5. Circuit breakers and fuses are

   a. always connected to the neutral wire.
   b. never connected to the neutral wire.
   c. not useful for a three-wire system.
   d. can only protect against lightning.

Unit Test

1. A transformer with a single winding serving as primary and secondary

   a. is called a distribution transformer.
   b. is called an autotransformer.
   c. is called a double-winding transformer.
   d. is called a current transformer.

2. The apparent power rating of an autotransformer fixes

   a. the power on the secondary side.
   b. the minimum current that can flow in the winding.
   c. the maximum power available for a load.
   d. both a and c.

3. What is the primary voltage when the secondary voltage at the center-tap of an autotransformer is 100 V?

   a. 100 V.
   b. 200 V.
   c. 300 V.
   d. 50 V.

4. Parallel-connected transformers can supply more power when

   a. they are connected in series-opposing.
   b. they are connected in series-aiding.
   c. they are connected with the proper polarity.
   d. they are connected to a purely-capacitive load.

5. Two 300-VA parallel-connected transformers can supply a maximum load of

   a. 150 VA.
   b. 300 VA.
   c. 450 VA.
   d. 600 VA.

6. To ensure connections are correct when two transformers are put in parallel

   a. secondary current is measured at half load and reduced primary voltage.
   b. secondary current is measured at full load and reduced primary voltage.
   c. secondary current is measured at no load and reduced primary voltage.
   d. secondary current is measured at no load and full primary voltage.

Unit Test (cont'd)

7. Two transformers of different apparent power ratings connected in parallel can supply

   a. a maximum load equal to twice the larger rating.
   b. a maximum load equal to one-half the sum of both ratings.
   c. a maximum load equal to twice the smaller rating.
   d. a maximum load equal to the smaller rating.

8. A distribution transformer is used to supply

   a. high-voltage loads only.
   b. low-voltage loads only.
   c. both low- and high-voltage loads.
   d. any type of four-wire load.

9. If the current in the neutral wire of a typical 120/240-V distribution system equals zero,

   a. something must be wrong.
   b. the loads connected to the system are balanced.
   c. the currents in the line wires are out of phase.
   d. the neutral wire is short-circuited to ground.

10. The neutral wire in a three-wire distribution system

    a. is never connected to ground.
    b. is never connected through circuit breakers or fuses.
    c. is always connected through a protection device.
    d. never has any current flowing in it.

Unit 9

Three-Phase Transformers

UNIT OBJECTIVE

After completing this Unit, you will be familiar with operating characteristics of three-phase transformers. You will be able to connect transformer windings in wye and delta configurations, and verify that windings are connected with the proper phase relationships. Voltage and current measurements will be used to study transformer operation and working characteristics.

DISCUSSION OF FUNDAMENTALS

Many of the concepts used in this Unit were seen in Unit 6, and it may be useful to review its contents to ensure better understanding of the material presented here. The main features of three-phase circuits that are important to recall are that there are two types of connections, wye and delta. Furthermore, in wye-connected three-phase circuits, the line voltages are greater than the phase voltages by the factor $\sqrt{3}$ and the line and phase currents are equal. On the other hand, in delta-connected three-phase circuits, the line currents are greater than the phase currents by the factor $\sqrt{3}$ and the line and phase voltages are equal.

A **three-phase transformer** can be a single unit or three single-phase units, and the primary and secondary windings can be connected in either wye or delta to give four types of connections, **delta-delta**, **wye-wye**, **delta-wye**, and **wye-delta**. Usually, three-phase power systems has a line voltage of 208 V (380 V or 415 V in some countries), and standard 120-V voltage (220 V or 240 V in some countries) can be obtained between a line wire and the neutral wire as shown in Figure 9-1. The wye-connected secondary provides three-phase 120/208-V power using 4 wires as shown, and the primary side of the transformer may be connected in delta like in the figure, or in wye. One big advantage of using a delta configuration for the primary is that only three wires are needed to distribute the three phases.

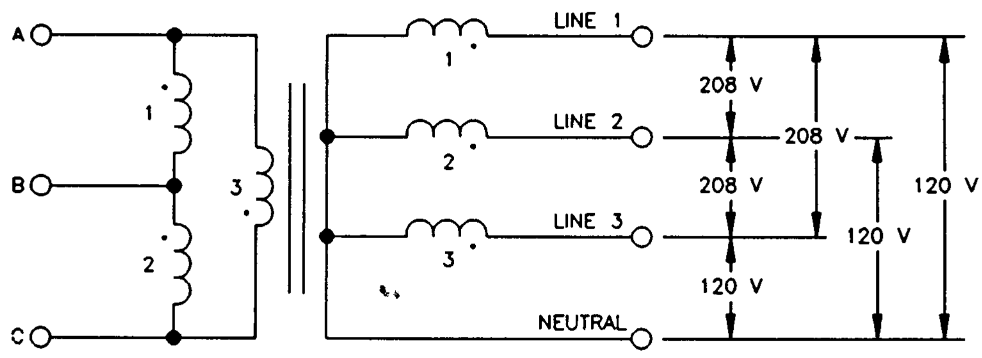


Figure 9-1. Commercial Three-Phase 120/208-V Power System.

An advantage of a delta-delta connection is that two single-phase transformers (instead of three) can be operated in what is known as the **open-delta** or "V" configuration if one of the three transformers becomes damaged or is removed from service. The open-delta transformer bank still delivers phase voltages and currents in the correct relationship, but the capacity of the bank is reduced to 57.7% ($1/\sqrt{3}$) of the total nominal capacity available with three transformers in service.

In the delta-delta and wye-wye configurations, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turns ratio. In the delta-wye configuration, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turn ratio times $\sqrt{3}$. In the wye-delta configuration, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turn ratio times $1/\sqrt{3}$.

Regardless of how the windings in a three-phase transformer are connected, precautions must be taken to ensure that the secondaries are connected with the proper phase relationships. For a wye configuration, this means that the voltage measured across any two secondary windings (line voltage) must be $\sqrt{3}$ times greater than the voltage across either winding (phase voltage). If not, the connections must be reversed before continuing.

With a delta configuration, the voltage measured between the ends of two series-connected secondary windings must equal the voltage across either winding. If not, the connections must be reversed. When one end of the third winding is connected, the voltage measured across all three series-connected windings must equal zero before connecting them together to close the delta. It is extremely important to verify that the voltage within the delta equals zero before the delta is closed. If not, the resulting current will be very high and damage the windings.

Exercise 9-1

Three-Phase Transformer Connections

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to connect three-phase transformers in delta-delta and wye-wye configurations. You will measure winding voltages to verify that the secondary windings are connected with the proper phase relationships, and you will verify that the voltage within a delta equals zero before the delta is closed.

DISCUSSION

As mentioned earlier, four common ways of connecting transformer windings to form a three-phase transformer are: delta-delta, wye-wye, delta-wye, and wye-delta, as shown in Figures 9-2 and 9-3. As seen in Unit 6, in order to set up a wye connection, first connect the three components (windings) together at a common point for interconnection with the neutral wire, then connect the other end of each component in turn to the three line wires. To set up a delta connection, connect the first component in series with the second, the second in series with the third, and the third in series with the first to close the delta loop. The three line wires are then separately connected to each of the junction nodes in the delta loop.

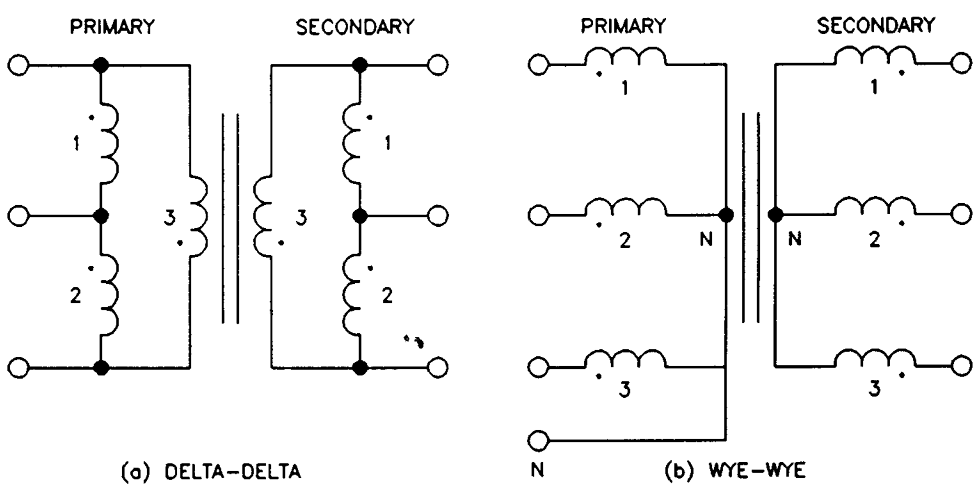


Figure 9-2. Delta-Delta and Wye-Wye Connections.

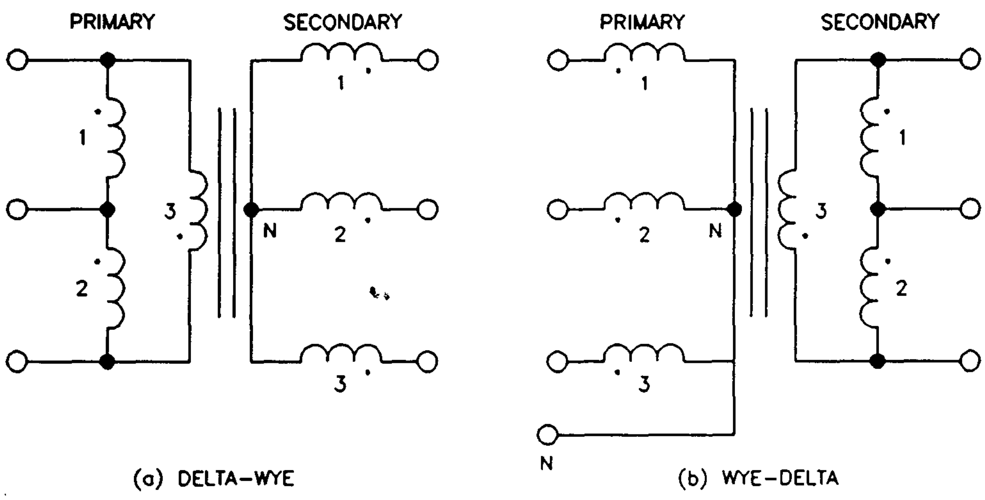


Figure 9-3. Delta-Wye and Wye-Delta Connections.

Before a three-phase transformer is put into service, the phase relationships must be verified. For a wye configuration, the line voltages at the secondary windings must all be $\sqrt{3}$ times greater than the corresponding phase voltages. If not, winding connections must be reversed. To verify that phase relationships are correct for a wye configuration, the voltage between two windings (E_{AB}) is measured as shown in Figure 9-4 (a) to confirm that it is $\sqrt{3}$ times greater than the line-to-neutral voltage across either winding (for example E_{AN}). The voltages between the third winding and the others (E_{BC} and E_{CA}) are then measured to confirm that they are also $\sqrt{3}$ times greater than the phase voltage (E_{AN}), as shown in Figure 9-4 (b).

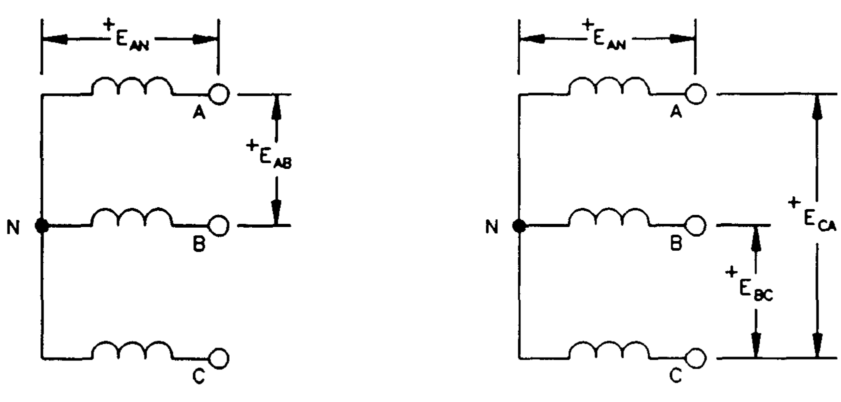


Figure 9-4. Confirming Phase Relationships in a Wye-Connected Secondary.

For a delta configuration, the line voltages at the secondary windings must all be equal. If not, winding connections must be reversed. To verify that phase relationships are correct for a delta configuration, the voltage across two series-connected windings (E_{CA}) is measured as shown in Figure 9-5 (a) to confirm that it equals the voltage across either winding (E_{AB} and E_{BC}). The third winding is then connected in series, and the voltage across the series combination of the three windings is measured to confirm that it is zero before the delta is closed, as shown in Figure 9-5 (b). This is extremely important for a delta configuration, because a very high short-circuit current will flow if the voltage within the delta is not equal to zero when it is closed.

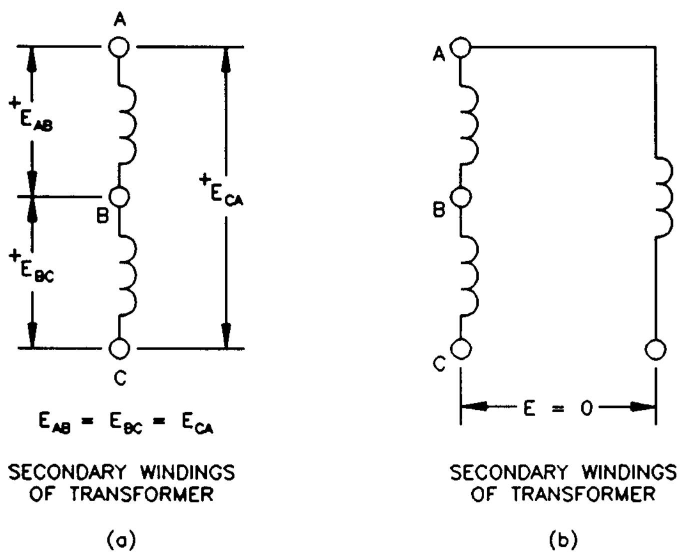


Figure 9-5. Confirming that the Delta Voltage Equals Zero.

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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

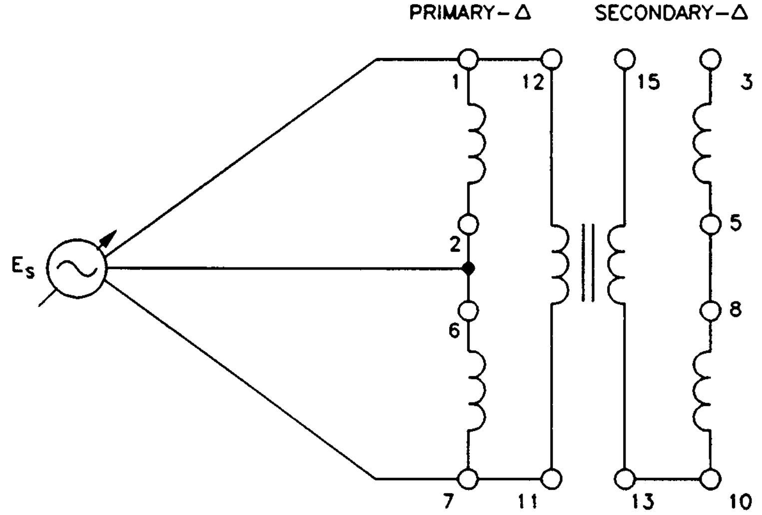
☐ 1. Install the Power Supply, Data Acquisition Interface, and Three-Phase Transformer modules in the EMS Workstation.

☐ 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 ccw. Set the voltmeter select switch to the 4-5 position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, set the 24 V - AC power switch to the I (ON) position, and ensure the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES19-1.cfg*.

☐ 5. Connect the Three-Phase Transformer module in the delta-delta configuration shown in Figure 9-6. *Do not close the delta on the secondary side of the transformer until the voltages are verified.*



LINE VOLTAGE (V)	E_S (V)
120	120
220	220
240	240

Figure 9-6. Three-Phase Transformer Connected in Delta-Delta.

☐ 6. Turn on the power and adjust the voltage control to obtain the line-to-line voltage E_S given in Figure 9-6. Use E1 to measure the winding voltages and record the results. After recording the measurements, rotate the voltage control fully ccw and then turn off the power.

Note: *When measuring the various voltages, turn off the Power Supply before modifying the connections of the DAI to the circuit.*

$E_{1\text{-}2}$ - ________ V $E_{1\text{-}7}$ - ________ V $E_{1\text{-}12}$ - ________ V

$E_{3\text{-}5}$ - ________ V $E_{3\text{-}10}$ - ________ V $E_{3\text{-}15}$ - ________ V

☐ 7. Do the measurements confirm that the secondary windings are connected with the proper phase relationships?

☐ Yes ☐ No

☐ 8. Are the voltages within the secondary delta equal to zero, thus confirming that it is safe to close the delta?

☐ Yes ☐ No

Note: *The value of $E_{3\text{-}15}$ will not be exactly zero volts because of small imbalances in the three-phase line voltages. If it is more than 5 V, the winding connections have to be checked carefully.*

☐ 9. When the winding connections are confirmed to be correct, close the delta on the secondary side of the transformer. Connect E1, E2, and E3 to measure the line voltages at the secondary. Select setup configuration file *ES19-2.cfg*. Turn on the power and adjust the voltage control to obtain the same value of E_S used in step 6. Note that the transformer is connected using the 1:1 ratio, so the primary and secondary voltages should be equal.

☐ 10. Is the value indicated by programmable meter A for the sum of the three line voltages approximately equal to zero?

☐ Yes ☐ No

☐ 11. Observe the voltage phasors on the *Phasor Analyzer*. Does the display confirm they are equal with a 120° phase shift between each of them?

☐ Yes ☐ No

☐ 12. Turn off the power. Connect E2 to measure line voltage $E_{1\text{-}2}$ on the primary side. Turn on the power and adjust the voltage control voltage to obtain the same value of E_S used in step 6. Compare the voltage phasor of $E_{1\text{-}2}$ on the primary side with that of $E_{3\text{-}5}$ on the secondary side. Does the *Phasor Analyzer* display show that the voltages are equal and in phase, except for possibly a small difference due to transformer reactance?

☐ Yes ☐ No

☐ 13. Turn off the power and connect the Three-Phase Transformer module in the wye-wye configuration shown in Figure 9-7.

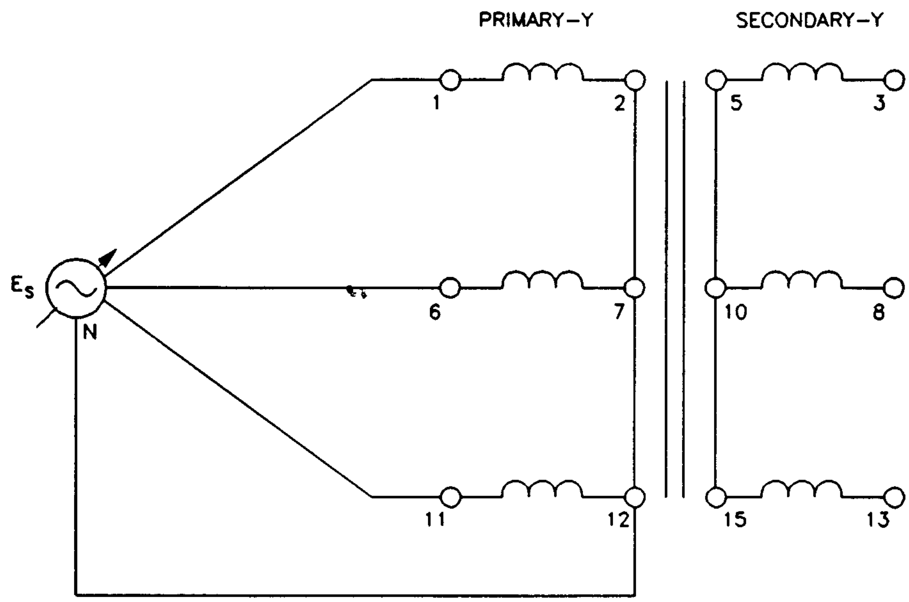


Figure 9-7. Three-Phase Transformer Connected in Wye-Wye.

☐ 14. Turn on the power and adjust the voltage control to obtain the value of E_S used in step 6. Select setup configuration file *ES19-3.cfg*. Use E1 to measure the winding voltages and record the results. After recording the measurements, rotate the voltage control fully ccw and then turn off the power.

> **Note:** *When measuring the various voltages, turn off the Power Supply before modifying the connections of the DAI to the circuit.*

E_{1-6} = ________ V E_{1-11} = ________ V E_{6-11} = ________ V

E_{1-2} = ________ V E_{6-7} = ________ V E_{11-12} = ________ V

E_{3-8} = ________ V E_{3-13} = ________ V E_{8-13} = ________ V

E_{3-5} = ________ V E_{8-10} = ________ V E_{13-15} = ________ V

☐ 15. Do the measurements confirm that the secondary windings are connected with the proper phase relationships?

☐ Yes ☐ No

☐ 16. Are the line-to-line voltages on the primary and secondary sides of the transformer $\sqrt{3}$ times greater than the line-to-neutral values?

☐ Yes ☐ No

☐ 17. Connect E1, E2, and E3 to measure phase voltages $E_{3\text{-}5}$, $E_{8\text{-}10}$, and $E_{13\text{-}15}$ at the secondary. Select setup configuration file *ES19-4.cfg*. Turn on the power and adjust E_S at about the same value as used previously.

☐ 18. Is the value indicated by programmable meter A for the sum of the three phase voltages approximately equal to zero?

☐ Yes ☐ No

☐ 19. Observe the voltage phasors on the *Phasor Analyzer*. Does the display confirm they are equal with a 120° phase shift between each of them?

☐ Yes ☐ No

☐ 20. Turn off the power without modifying the setting of the voltage control. Connect E2 to measure phase voltage $E_{1\text{-}2}$ on the primary side. Turn on the power and compare the voltage phasor of $E_{1\text{-}2}$ on the primary side with that of $E_{3\text{-}5}$ on the secondary side. Does the *Phasor Analyzer* display show that the voltages are equal and in phase, except for possibly a small difference due to transformer reactance?

☐ Yes ☐ No

☐ 21. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You connected transformer windings in three-phase delta-delta and wye-wye configurations, and measured winding voltages to ensure that secondary windings were connected with the proper phase relationships. You confirmed that the voltage within a delta was zero before closing the delta, and that the delta-delta and wye-wye configurations produced no phase shift between the incoming primary voltages and the outgoing secondary voltages.

REVIEW QUESTIONS

1. Why is it extremely important to confirm that the delta voltage equals zero before the delta is closed?

   a. To ensure that the secondary voltage does not become too high.
   b. To avoid possible damage because of high current.
   c. To avoid a short-circuit of the primary winding.
   d. To maintain the secondary voltage at a constant level.

2. In a delta-delta configuration, the line voltage on the secondary side is

   a. equal to the primary voltage times the inverse of the turns ratio.
   b. √3 times the primary voltage.
   c. √3 times the primary voltage times the inverse of the turns ratio.
   d. 1/√3 times the primary voltage.

3. The voltage across two windings in a wye-wye configuration must be

   a. equal to the voltage across each winding.
   b. √3 times the voltage across each winding.
   c. less than the voltage across each winding.
   d. √3 times less than the voltage across each winding.

4. The voltage across two windings in a delta-delta configuration must be

   a. equal to the voltage across each winding.
   b. √3 times the voltage across each winding.
   c. less than the voltage across each winding.
   d. √3 times less than the voltage across each winding.

5. A three-phase transformer can be

   a. a single unit with three separate sets of single-phase windings.
   b. three single-phase transformers connected together.
   c. a single unit with one primary and three secondary windings.
   d. either a or b.

Exercise 9-2

Voltage and Current Relationships

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the voltage and current ratios of three-phase transformers connected in delta-wye and wye-delta configurations. Measurements of primary and secondary voltages will demonstrate that these configurations create a phase shift between the incoming and outgoing voltages.

DISCUSSION

As seen in the previous exercise, primary and secondary voltages in delta-delta and wye-wye connections are in phase and the voltage at the secondary is equal to the voltage at the primary times the inverse of the turns ratio. In delta-wye and wye-delta connections however, there will be a 30° phase difference between the primary and secondary voltages. Also, in the delta-wye configuration, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turn ratio times $\sqrt{3}$. On the other hand, in the wye-delta configuration, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turn ratio times $1/\sqrt{3}$.

The 30° phase shift between the primary and secondary does not create any problems for isolated groups of loads connected to the outgoing lines from the secondary. However, if the outgoing lines from the secondary of a three-phase transformer have to be connected in parallel with another source, the phase shift might make such a parallel connection impossible, even if the line voltages are the same. Recall that in order for three-phase circuits and sources to be connected in parallel, line voltages must be equal, have the same phase sequence, and be in phase when the parallel connection is made.

Figure 9-8 shows a three-phase transformer, with a turns ratio equal to 1:1, connected in the delta-wye configuration and feeding a three-phase load. The voltage across each primary winding E_{PRI} equals the incoming line voltage, but the outgoing line voltage E_{SEC} is $\sqrt{3}$ times that voltage because the voltage across any two secondary windings is $\sqrt{3}$ times greater than the voltage across a single secondary winding. Note that if the three-phase transformer had a turns ratio of 1:10, the line voltage at the secondary would be 10 x $\sqrt{3}$ times greater the line voltage at the primary, because the inverse of the turns ratio is multiplied by the $\sqrt{3}$ factor. The line current in the secondary is the same as the phase current, but the line current in the primary is $\sqrt{3}$ times greater than the corresponding phase current.

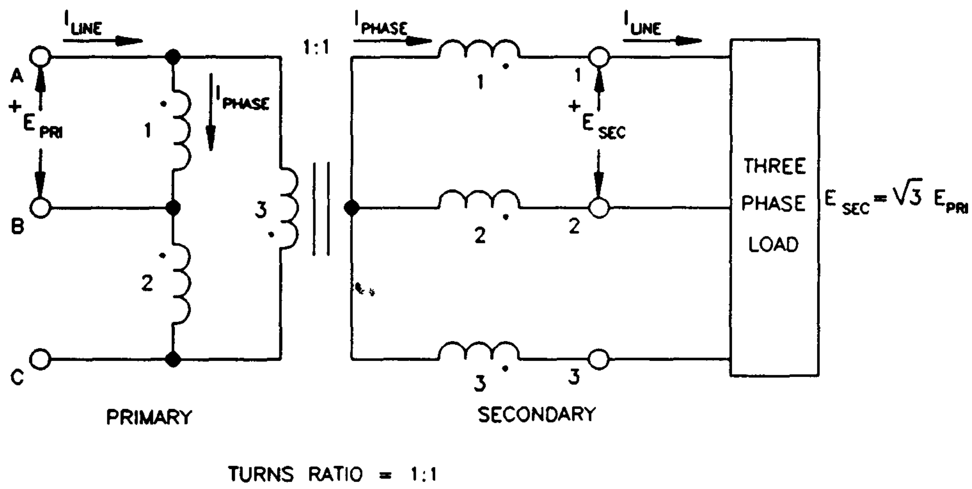


Figure 9-8. Three-Phase Delta-Wye Configuration.

EQUIPMENT REQUIRED

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

PROCEDURE

CAUTION!

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

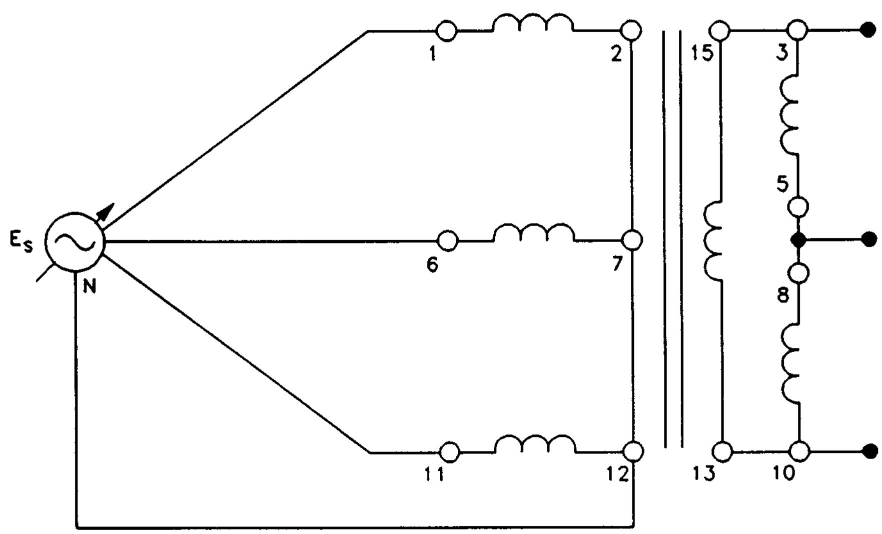
☐ 1. Install the Power Supply, Data Acquisition Interface, Resistive Load, and Three-Phase Transformer modules in the EMS Workstation.

☐ 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 ccw. Set the voltmeter select switch to the 4-5 position, and then ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure that the DAI LOW POWER INPUT is connected to the main Power Supply, set the 24 V - AC power switch to the I (ON) position, and ensure the flat cable from the computer is connected to the DAI.

☐ 4. Display the *Metering* window. Select setup configuration file *ES19-5.cfg*.

☐ 5. Connect the Three-Phase Transformer module in the wye-delta configuration shown in Figure 9-9. *Make sure that the voltage within the delta is zero before closing the delta.*



LINE VOLTAGE (V)	E_S (V)
120	120
220	220
240	240

Figure 9-9. Three-Phase Transformer Connected in Wye-Delta.

☐ 6. Turn on the power and adjust the voltage control to obtain the line-to-line voltage E_S given in Figure 9-9. Connect E1, E2, and E3 to measure the line voltages at the primary and record the results. Record also the average value of the line voltage given by programmable meter B.

E_{1-6} = ________ V E_{11-1} = ________ V E_{6-11} = ________ V

AVG (E1,E2,E3) = ________ V

☐ 7. Does programmable meter A show that the sum of the three line voltages is approximately zero?

☐ Yes ☐ No

☐ 8. Observe the voltage phasors on the *Phasor Analyzer*. Are they approximately equal with a 120° phase shift between each of them?

☐ Yes ☐ No

☐ 9. Turn off the power without modifying the setting of the voltage control. Connect E1, E2, and E3 to now measure the line voltages at the secondary. Select setup configuration file *ES19-6.cfg*. Turn on the power and record the line voltages as well as the average value of the line voltages.

$E_{3\text{-}5}$ = _______ V $E_{8\text{-}10}$ = _______ V $E_{13\text{-}15}$ = _______ V

AVG (E1,E2,E3) = _______ V

☐ 10. Does programmable meter A show that the sum of the three line voltages is approximately zero?

☐ Yes   ☐ No

☐ 11. Observe the voltage phasors on the *Phasor Analyzer*. Does the display confirm they are equal with a 120° phase shift between each of them?

☐ Yes   ☐ No

☐ 12. Turn off the power without modifying the setting of the voltage control. Connect E2 to measure line voltage $E_{1\text{-}6}$ on the primary side. Select setup configuration file *ES19-7.cfg*. Turn on the power and compare the voltage phasor of $E_{1\text{-}6}$ on the primary side with that of $E_{3\text{-}5}$ on the secondary side. Does the *Phasor Analyzer* display confirm a phase shift of around 30° between the two?

☐ Yes   ☐ No

☐ 13. Calculate the ratio AVG E_{SEC} / AVG E_{PRI} using the values recorded in steps 6 and 9. Is it approximately equal to $1/\sqrt{3}$?

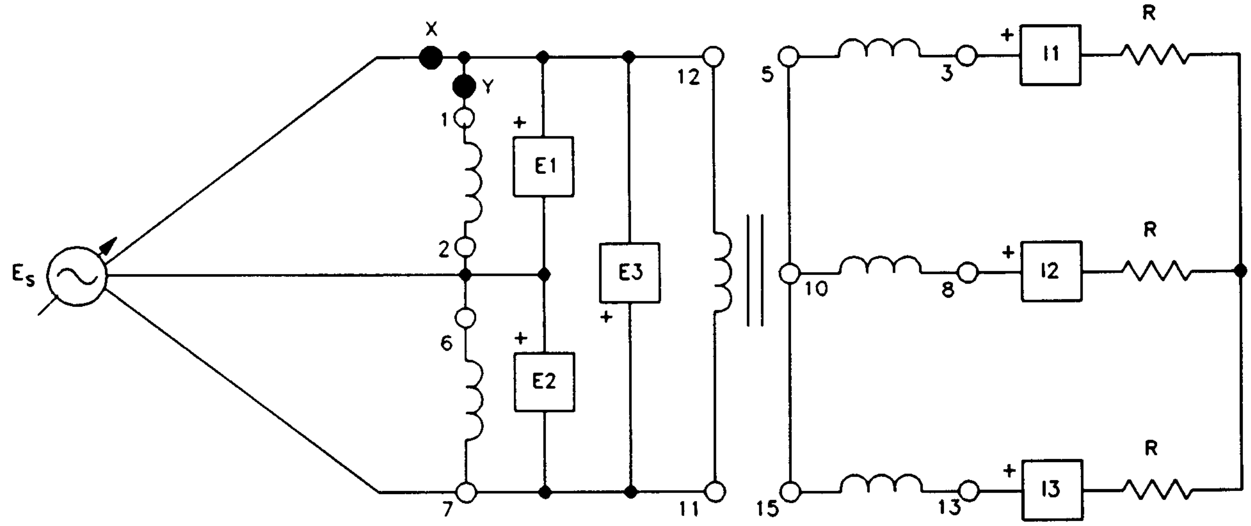
☐ Yes   ☐ No

☐ 14. Turn off the power and connect the Three-Phase Transformer module in the delta-wye configuration shown in Figure 9-10. Set the Resistive Load module for the given values of R, and connect I1, I2, and I3 to measure the three line currents to the load.

☐ 15. Connect E1, E2, and E3 to measure the line voltages at the primary, turn on the power, and adjust the voltage control to obtain the line-to-line voltage of E_S given in Figure 9-10. Select setup configuration file *ES19-8.cfg*. Record the value of the line voltages, as well as the average value.

E_{1-2} = _______ V E_{6-7} = _______ V E_{11-12} = _______ V

AVG (E1,E2,E3) = _______ V



LINE VOLTAGE (V)	E_S (V)	R (Ω)
120	70	300
220	125	1100
240	220	1200

Figure 9-10. Three-Phase Transformer Connected in Delta-Wye.

☐ 16. Observe the voltage and current phasors on the *Phasor Analyzer*. Does the display confirm that the voltage and current phasors are in phase?

☐ Yes   ☐ No

☐ 17. Turn off the power without modifying the setting of the voltage control. Connect E1, E2, and E3 to now measure the line voltages E_{3-8}, E_{8-13}, and E_{13-3} on the secondary side. Select setup configuration file *ES19-9.cfg*. Turn on the power. Does the *Phasor Analyzer* display show that the voltage phasors lead the current phasors by 30°?

☐ Yes   ☐ No

Note: *Since the currents in the secondary are in phase with the voltages in the primary, the Phasor Analyzer display is equivalent to observing all voltage phasors at the same time, except for the difference in scale between the parameters.*

☐ 18. Return to the *Metering* window and record the measured values for the line voltages at the secondary, and also the average value.

$E_{3\text{-}8}$ = _______ V $E_{8\text{-}13}$ = _______ V $E_{13\text{-}3}$ = _______ V

AVG (E1,E2,E3) = _______ V

☐ 19. Calculate the ratio AVG E_{SEC} / AVG E_{PRI} using the values recorded in steps 15 and 18. Is it approximately equal to $\sqrt{3}$?

☐ Yes ☐ No

☐ 20. Turn off the power and connect I1 and I2 to measure the line and phase currents on the primary side of the delta-wye configuration by opening the circuit at points X and Y shown in Figure 9-10. Remember to reconnect the load resistors at the secondary when I1 and I2 are disconnected.

☐ 21. Select setup configuration file *ES19-10.cfg*. Turn on the power and calculate the ratio I_{LINE} / I_{PHASE} for the primary circuit using the measured currents. Is the ratio approximately equal to $\sqrt{3}$?

☐ Yes ☐ No

☐ 22. Is the line current on the primary side approximately equal to the line current on the secondary side, except possibly for a small difference due to exciting current?

☐ Yes ☐ No

☐ 23. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You connected a 1:1 three-phase transformer in wye-delta and delta-wye configurations, and saw that the line voltage between primary and secondary either increased or decreased by a $\sqrt{3}$ factor. You also confirmed that the outgoing line voltages at the secondary were shifted 30° with respect to the incoming line voltages at the primary.

Voltage and Current Relationships

REVIEW QUESTIONS

1. Delta-wye and wye-delta configurations both produce

   a. increases in the secondary voltages and currents.
   b. decreases in the secondary voltages and currents.
   c. phase shifts between the incoming and outgoing line voltages.
   d. additional $\sqrt{3}$ increases in the secondary voltages and currents.

2. The line voltage at the secondary of a 10:1 wye-delta connected transformer will be

   a. equal to the line voltage at the primary times $1/\sqrt{3}$.
   b. equal to the line voltage at the primary times $\sqrt{3}$.
   c. equal to the line voltage at the primary times 0.1 times $1/\sqrt{3}$.
   d. equal to the line voltage at the primary times 0.1 times $\sqrt{3}$.

3. The line voltage at the secondary of a delta-wye connected transformer is

   a. greater than it is with a wye-delta connection.
   b. less than it is with a wye-delta connection.
   c. the same as it is with a wye-delta connection.
   d. only dependant on the turns ratio.

4. The sum of the phase voltages in three-phase transformers

   a. depends on the connection.
   b. equals zero when the transformers are properly connected.
   c. is $\sqrt{3}$ times the turns ratio.
   d. can only be determined when a load is connected to the secondary.

5. Before three-phase transformers are put into service

   a. the phase sequence of the incoming lines must be verified.
   b. the winding connections must be checked to ensure proper phase relationship.
   c. the load must be balanced.
   d. the phase shift must be measured.