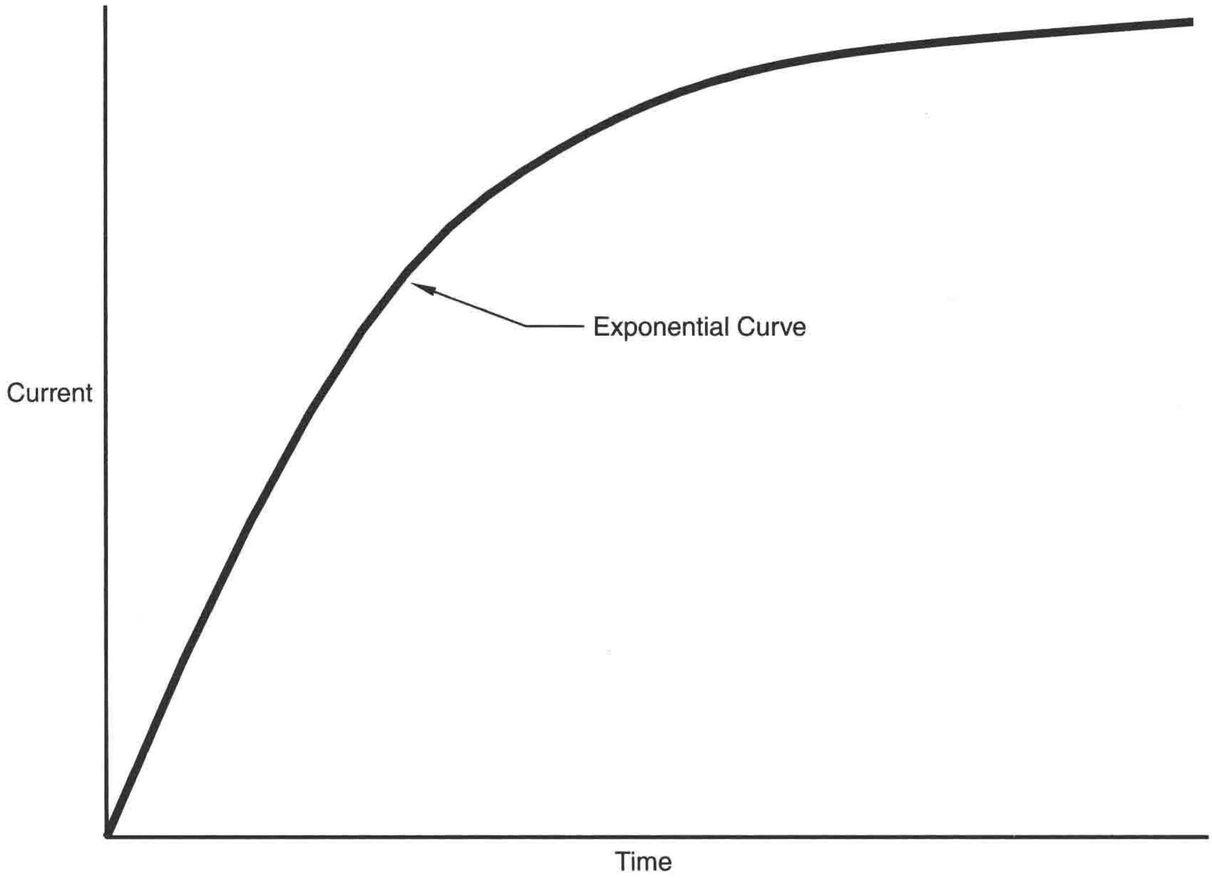

Figure 19-3 The current through an inductor rises at an exponential rate.

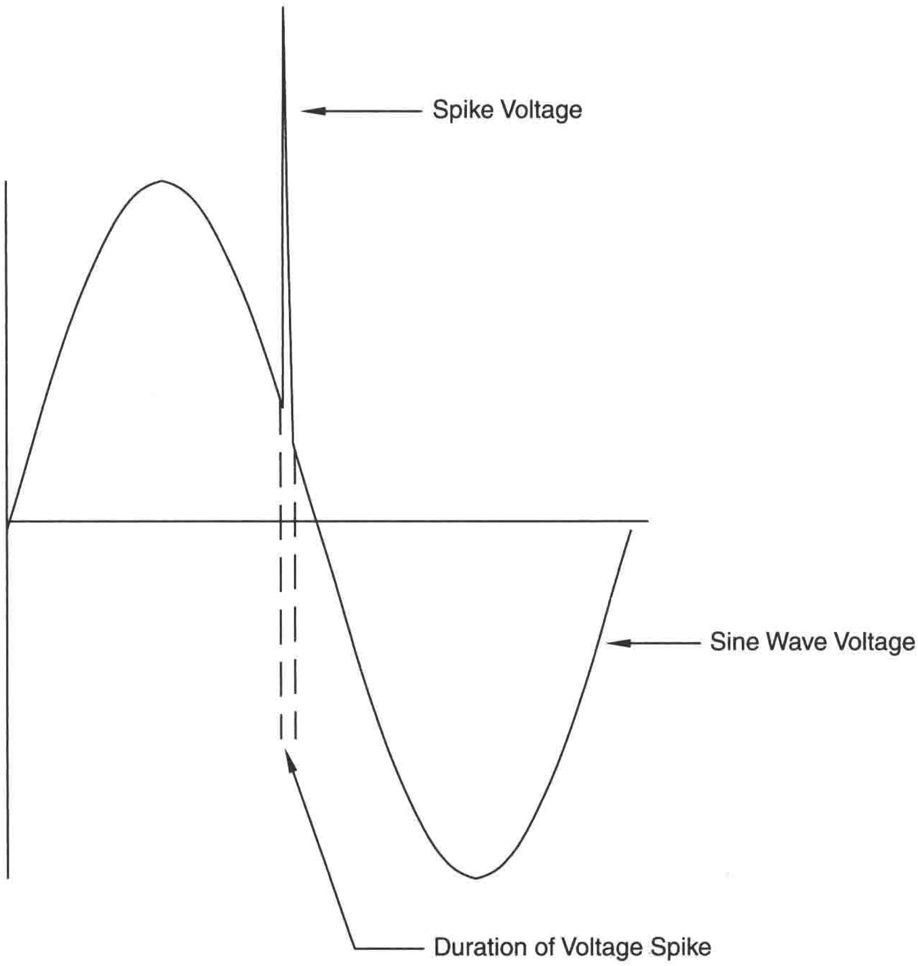

Figure 19-4 Voltage spikes are generally of very short duration.

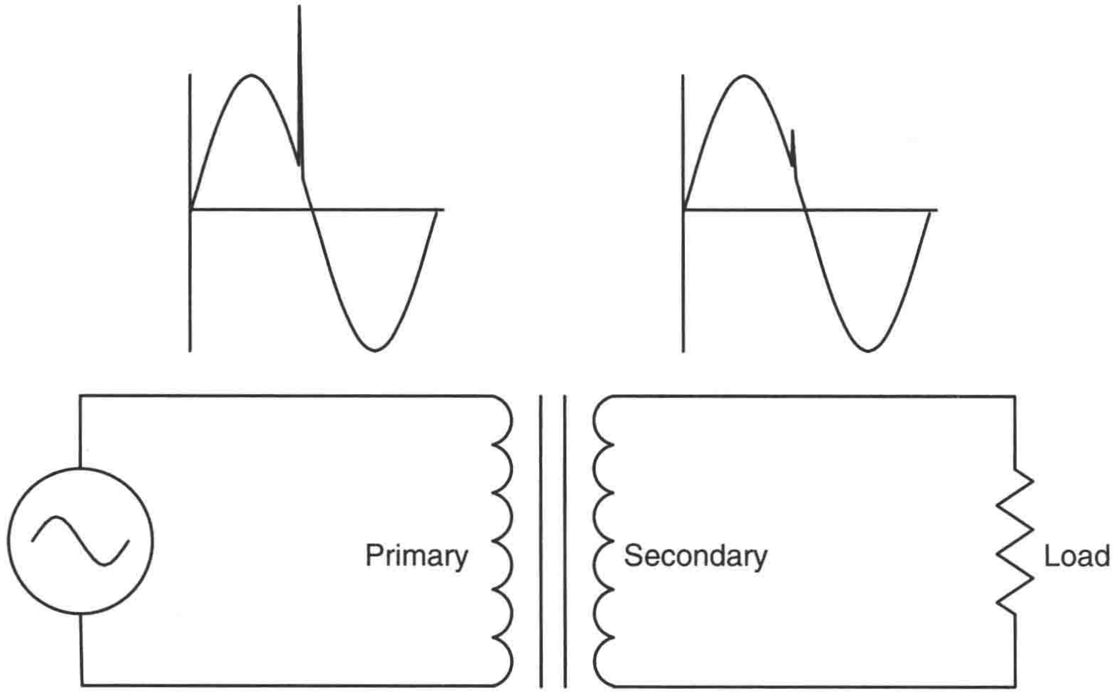

Figure 19-5 The isolation transformer greatly reduces the voltage spike.

precaution to eliminate the hazard of an accidental contact between a person at ground potential and the ungrounded conductor. If the case of the equipment should come in contact with the ungrounded conductor, the isolation transformer would prevent a circuit being completed to ground through a person touching the case of the equipment. Many alternating current circuits have one side connected to ground. A familiar example of this is the common 120 volt circuit with a grounded neutral conductor, as seen in Figure 19-6. An isolation transformer can be used to remove or isolate a piece of equipment from circuit ground.

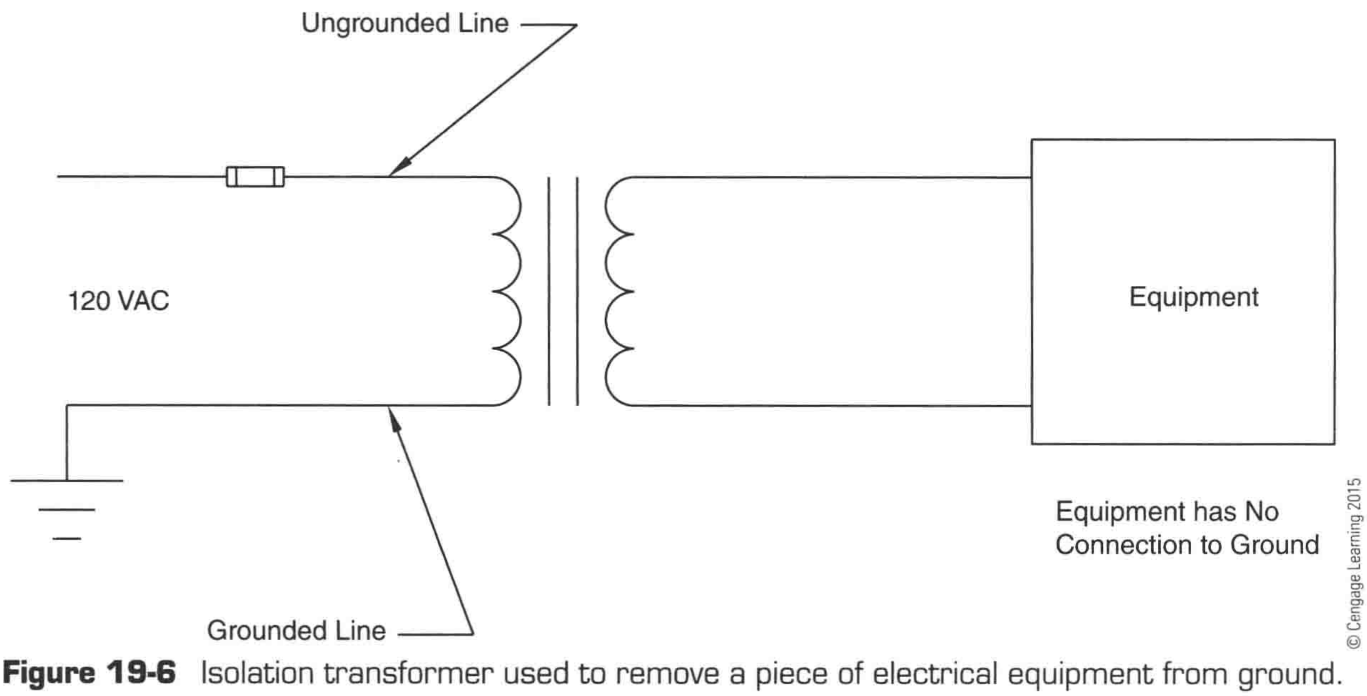

Figure 19-6 Isolation transformer used to remove a piece of electrical equipment from ground.

Excitation Current

There will always be some amount of current flow in the primary of a transformer even if there is no load connected to the secondary. This is called the *excitation current* of the transformer. The excitation current is the amount of current required to magnetize the core of the transformer. The excitation current remains constant from no load to full load. As a general rule, the excitation current is such a small part of the full load current it is often omitted when making calculations.

Transformer Calculations

In the following examples, values of voltage, current, and turns for different transformers will be computed.

Example #1: Assume the isolation transformer shown in Figure 19-2 has 240 turns of wire on the primary and 60 turns of wire on the secondary. This is a ratio of 4:1 (240/60 = 4). Now assume that 120 volts is connected to the primary winding. What is the voltage of the secondary winding?

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{240}{60}$$

$$E_S = 30 \text{ volts}$$

The transformer in this example is known as a step-down transformer because it has a lower secondary voltage than primary voltage.

Now assume that the load connected to the secondary winding has an impedance of 5 Ω. The next problem is to calculate the current flow in the secondary and primary windings. The current flow of the secondary can be computed using Ohm's law since the voltage and impedance are known.

$$I = \frac{E}{Z}$$

$$I = \frac{30}{5}$$

$$I = 6 \text{ amps}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the following formula:

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{30} = \frac{6}{I_P}$$

$$120 I_P = 180$$

$$I_P = 1.5 \text{ amps}$$

Notice that the primary voltage is higher than the secondary voltage, but the primary current is much less than the secondary current. A good rule for transformers is that power in must equal power out. If the primary voltage and current are multiplied together, the result should equal the product of the voltage and current of the secondary.

Primary	Secondary
$120 \times 1.5 = 180$ volt-amps	$30 \times 6 = 180$ volt-amps

Helpful Hint

A good rule for transformers is that power in must equal power out.

Example #2: In the next example, assume that the primary winding contains 240 turns of wire and the secondary contains 1,200 turns of wire. This is a turns-ratio of 1:5 (1,200/240 = 5). Now assume that 120 volts is connected to the primary winding. Compute the voltage output of the secondary winding.

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{240}{1{,}200}$$

$$240E_S = 144{,}000$$

$$E_S = 600 \text{ volts}$$

Notice that the secondary voltage of this transformer is higher than the primary voltage. This type of transformer is known as a *step-up* transformer.

Now assume that the load connected to the secondary has an impedance of 2,400 Ω. Find the amount of current flow in the primary and secondary windings. The current flow in the secondary winding can be computed using Ohm's law.

$$I = \frac{E}{Z}$$

$$I = \frac{600}{2{,}400}$$

$$I = 0.25 \text{ amp}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula:

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{600} = \frac{0.25}{I_P}$$

$$120I_P = 150$$

$$I_P = 1.25 \text{ amps}$$

Notice that the amount of power input equals the amount of power output.

Primary	Secondary
$120 \times 1.25 = 150$ volt-amps	$600 \times 0.25 = 150$ volt-amps

Calculating Transformer Values Using the Turns-Ratio

As illustrated in the previous examples, transformer values of voltage, current, and turns can be computed using formulas. It is also possible to compute these same values using the turns-ratio. There are several ways in which turns-ratios can be expressed. One method is to use a whole number value such as 13:5 or 6:21. The first ratio indicates that one winding has 13 turns of wire for every 5 turns of wire in the other winding. The second ratio indicates that there are 6 turns of wire in one winding for every 21 turns in the other.

A second method is to use the number 1 as a base. When using this method, the number 1 is always assigned to the winding with the lowest voltage rating. The ratio is found by dividing the higher voltage by the lower voltage. The number on the left side of the ratio represents the primary winding and the number on the right of the ratio represents the secondary winding. For example, assume a transformer has a primary rated at 240 volts and a secondary rated at 96 volts, as shown in Figure 19-7. The turns-ratio can be computed by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{240}{96}$$

$$\text{Ratio} = 2.5{:}1$$

Notice in this example that the primary winding has the higher voltage rating and the secondary has the lower. Therefore, the 2.5 is placed on the left and the base unit, 1, is placed on the right. This ratio indicates that there are 2.5 turns of wire in the primary winding for every 1 turn of wire in the secondary.

Now assume that there is a resistance of 24 Ω connected to the secondary winding. The amount of secondary current can be found using Ohm's law.

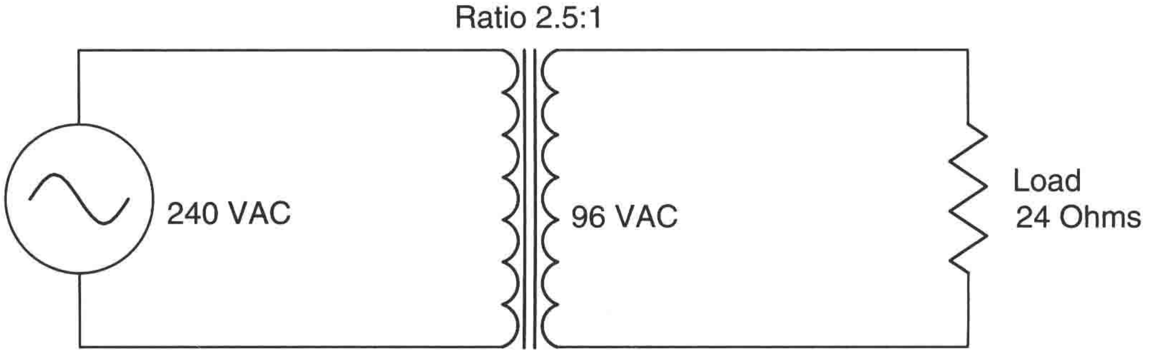

Figure 19-7 Computing transformer values using the turns-ratio.

$$I_s = \frac{96}{24}$$

$$I_s = 4 \text{ amps}$$

The primary current can be found using the turns-ratio. Recall that the volt-amps of the primary must equal the volt-amps of the secondary. Since the primary voltage is greater, the primary current will have to be less than the secondary current. Therefore, the secondary current will be divided by the turns-ratio.

$$I_P = \frac{I_S}{\text{Turns-ratio}}$$

$$I_P = \frac{4}{2.5}$$

$$I_P = 1.6 \text{ amps}$$

To check the answer, find the volt-amps of the primary and secondary.

Primary	Secondary
$240 \times 1.6 = 384$	$96 \times 4 = 384$

Now assume that the secondary winding contains 150 turns of wire. The primary turns can be found by using the turns-ratio, also. Since the primary voltage is higher than the secondary voltage, the primary must have more turns of wire. Since the primary must contain more turns of wire, the secondary turns will be multiplied by the turns-ratio.

$$N_P = N_S \times \text{Turns-ratio}$$

$$N_P = 150 \times 2.5$$

$$N_P = 375 \text{ turns}$$

In the next example, assume a transformer has a primary voltage of 120 volts and a secondary voltage of 500 volts. The secondary has a load impedance of 1,200 Ω. The secondary contains 800 turns of wire (Figure 19-8). The turns-ratio can be found by dividing the higher voltage by the lower voltage.

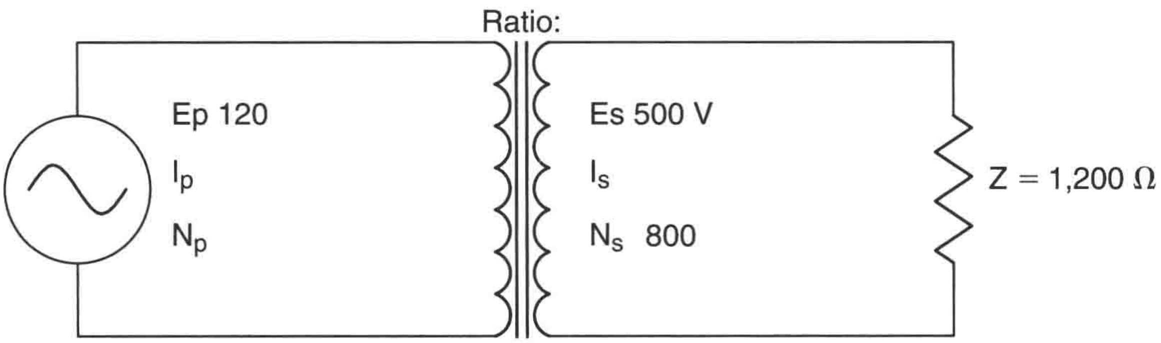

Figure 19-8 Calculating transformer values.

$$\text{Ratio} = \frac{500}{120}$$

$$\text{Ratio} = 1{:}4.17$$

The secondary current can be found using Ohm's law.

$$I_S = \frac{500}{1,200}$$

$$I_S = 0.417 \text{ amps}$$

In this example the primary voltage is lower than the secondary voltage. Therefore, the primary current must be higher. To find the primary current, multiply the secondary current by the turns-ratio.

$$I_P = I_S \times \text{Turns-ratio}$$

$$I_P = 0.417 \times 4.17$$

$$I_P = 1.74 \text{ amps}$$

To check this answer, compute the volt-amps of both windings.

Primary	Secondary
$120 \times 1.74 = 208.8$	$500 \times 0.417 = 208.5$

The slight difference in answers is caused by rounding off of values.

Since the primary voltage is less than the secondary voltage, the turns of wire in the primary will also be less. The primary turns will be found by dividing the turns of wire in the secondary by the turns-ratio.

$$N_P = \frac{N_S}{\text{Turns-ratio}}$$

$$N_P = \frac{800}{4.17}$$

$$N_P = 192 \text{ turns}$$

LABORATORY EXERCISE

Name ____ Date __________

Materials Required

480-240/120-volt, 0.5-kVA control transformer

Ohmmeter

AC voltmeter, in-line or clamp-on. (If a clamp-on type is used, a 10:1 scale divider is recommended.)

These experiments are intended to provide the electrician with hands-on experience dealing with transformers. The transformers used in these experiments are standard control transformers with two high-voltage windings rated at 240 volts each generally used to provide primary voltages of 480/240, and one low-voltage winding rated at 120 volts. The transformers have a rating of 0.5 kVA. The loads are standard 100 watt lamps that may be connected in parallel or series. It is assumed that the power supply is 208/120 volt three-phase four wire. It is also possible used with a 240/120 volt three-phase high leg system, provided adjustments are made in the calculations.

As in industry, these transformers will be operated with full voltage applied to the windings. The utmost caution must be exercised when dealing with these transformers. These transformers can provide enough voltage and current to seriously injure or kill anyone. The power should be disconnected before attempting to make or change any connections.

Caution

These transformers can provide enough voltage and current to seriously injure or kill anyone.

The transformer used in this experiment contains two high-voltage windings and one low-voltage winding. The high-voltage windings are labeled H_1 - H_2 and H_3 - H_4. The low-voltage winding is labeled X_1 - X_2.

1. Set the ohmmeter to the Rx1 range and measure the resistance between the following terminals:

   H_1 - H_2 ____________ Ω
   H_1 - H_3 ____________ Ω
   H_1 - H_4 ____________ Ω
   H_1 - X_1 ____________ Ω
   H_1 - X_2 ____________ Ω
   H_2 - H_3 ____________ Ω
   H_2 - H_4 ____________ Ω
   H_2 - X_1 ____________ Ω
   H_2 - X_2 ____________ Ω
   H_3 - H_4 ____________ Ω
   H_3 - X_1 ____________ Ω
   H_3 - X_2 ____________ Ω
   H_4 - X_1 ____________ Ω
   H_4 - X_2 ____________ Ω
   X_1 - X_2 ____________ Ω

2. Using the information provided by the measurements from step 1, which sets or terminals form complete circuits within the transformer?

   ____

   ____

   ____

   These circuits represent the connections to the three separate windings within the transformer.

3. Which of the windings exhibits the lowest resistance and why?

___

___

___

4. The H_1 - H_2 terminals are connected to one of the high-voltage windings and the H_3 - H_4 terminals are connected to the second high-voltage winding. Each of these windings is rated at 240 volts. When this transformer will be connected for 240 volt operation, the two high-voltage windings are connected in parallel to form one winding by connecting H_1 to H_3 and H_2 to H_4, as shown in Figure 19-9. This will provide a 2:1 turns-ratio with the low-voltage winding.

   When this transformer is operated with 480 volts connected to the primary, the high-voltage windings are connected in series by connecting H_2 to H_3 and connecting power to H_1 and H_4, as shown in Figure 19-10. This effectively doubles the primary turns, providing a 4:1 turns-ratio with the low-voltage winding.

5. Connect the two high-voltage windings for parallel operation as shown in Figure 19-9. Assume a voltage of 208 volts is applied to the high-voltage windings. Compute the voltage that should be seen on the low-voltage winding between terminals X_1 and X_2.

   ___ volts.

6. Make certain that the incoming power leads are connected to terminals H_1 and H_4 as shown in Figure 19-9. Apply a voltage of 208 volts to the transformer and measure the voltage across terminals X_1 and X_2.

   ___ volts.

7. The measured voltage may be slightly higher than the computered voltage. The rated voltage of a transformer is based on full load. It is normal for the secondary voltage to be slightly higher when no load is connected to the transformer. Transformers are generally wound with a few extra turns of wire in the winding that is intended to be used as the load side. This helps overcome the voltage drop when load is added. The slight change in turns-ratio does not affect the operation of the transformer to a great extent.

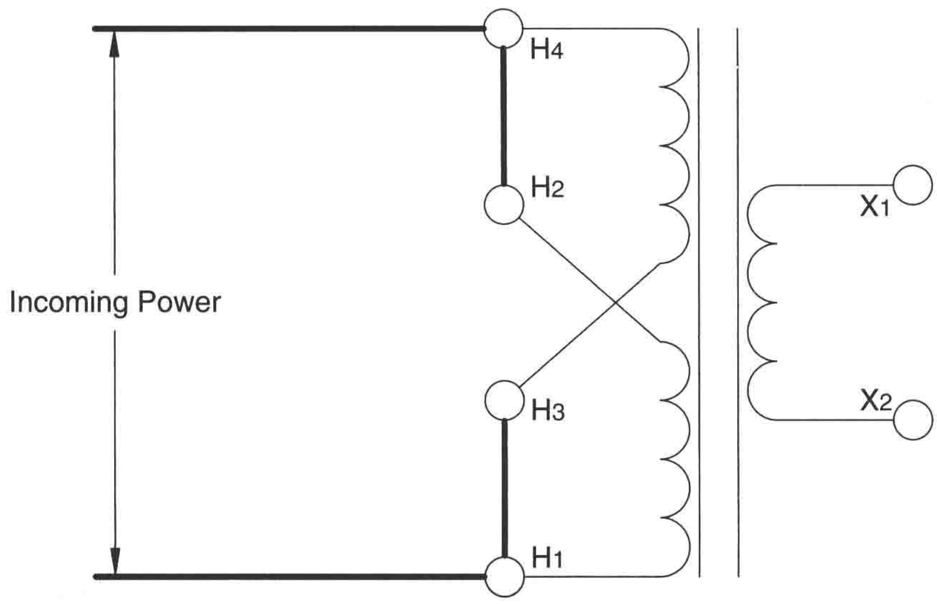

Figure 19-9 High-voltage windings connected in parallel.

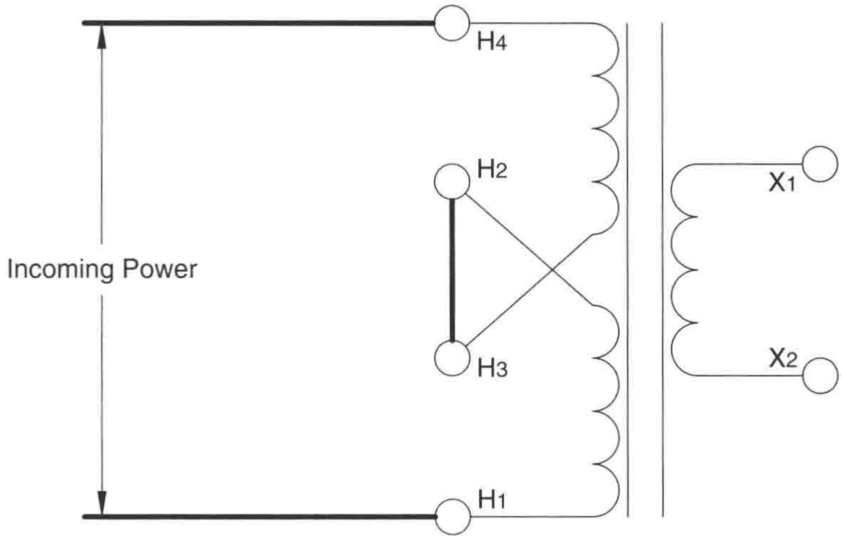

Figure 19-10 High-voltage windings connected in series.

8. **Turn off the power to the transformer.**
9. Disconnect the wires connected to the transformer and reconnect the transformer as shown in Figure 19-10. The two high-voltage windings are connected in series by connecting H_2 and H_3 together. This connection changes the turns-ratio of the transformer from 2:1 to 4:1. Make certain that the incoming power is connected to terminals H_1 and H_4.
10. Assume that a voltage of 208 volts is applied to the high-voltage windings. Compute the voltage across the low-voltage winding.

    _________ volts
11. Turn on the power and apply a voltage of 208 volts to the transformer. Measure the voltage across terminals X_1 and X_2.

    _________ volts
12. **Turn off the power.** Disconnect the power lines that are connected to terminals H_1 and H_4. Do not disconnect the wire between terminals H_2 and H_3.
13. In the next part of the exercise, the low-voltage winding will be used as the primary and the high-voltage windings will be used as the secondary. If the high-voltage windings are connected in series, the turns-ratio will be 1:4, which means that the secondary voltage will be four times greater than the primary voltage. The transformer has now become a step-up transformer instead of a step-down transformer. Assume that a voltage of 120 volts is connected to terminals X_1 and X_2. If the high-voltage windings are connected in series, compute the voltage across terminals H_1 and H_4.

    _________ volts
14. Connect the transformer as shown in Figure 19-11. Make certain that the voltage applied to terminals X_1 and X_2 is 120 volts and not 208 volts. Also make certain that the AC voltmeter is set for a higher range than the computed value of voltage in step 13.

Caution

The secondary voltage in this step will be 480 volts or higher. Use extreme caution when making this measurement. Be sure to wear safety glasses at all times.

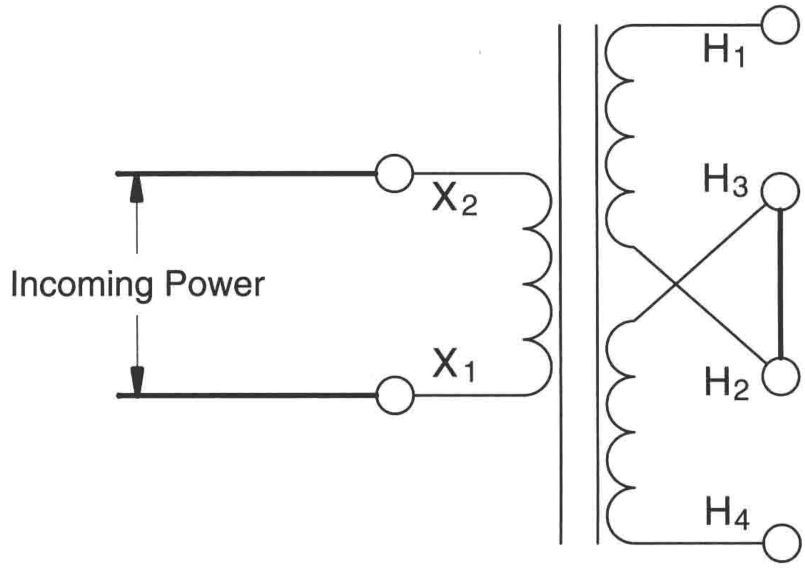

Figure 19-11 The incoming power is connected to terminals X_1 and X_2.

15. Turn on the power and measure the voltage across terminals H_1 and H_4.

    __________ volts

16. **Turn off the power supply.**
17. Disconnect the lead between terminals H_2 and H_3. Reconnect the transformer so that the high-voltage windings are connected in parallel by connecting H_1 and H_3 together and H_2 and H_4 together as shown in Figure 19-12. Do not disconnect the power leads to terminals X_1 and X_2. The transformer now has a turns-ratio of 1:2.
18. Assume that a voltage of 120 volts is connected to the low-voltage winding. Compute the voltage across the high-voltage winding.

    __________ volts

19. Make certain the power leads are still connected to terminals X_1 and X_2. Turn on the power and apply 120 volts to terminals X_1 and X_2. Measure the voltage across terminals H_1 and H_4.

    __________ volts

20. **Turn off the power supply** and disconnect all leads to the transformer. Return the components to their proper places.

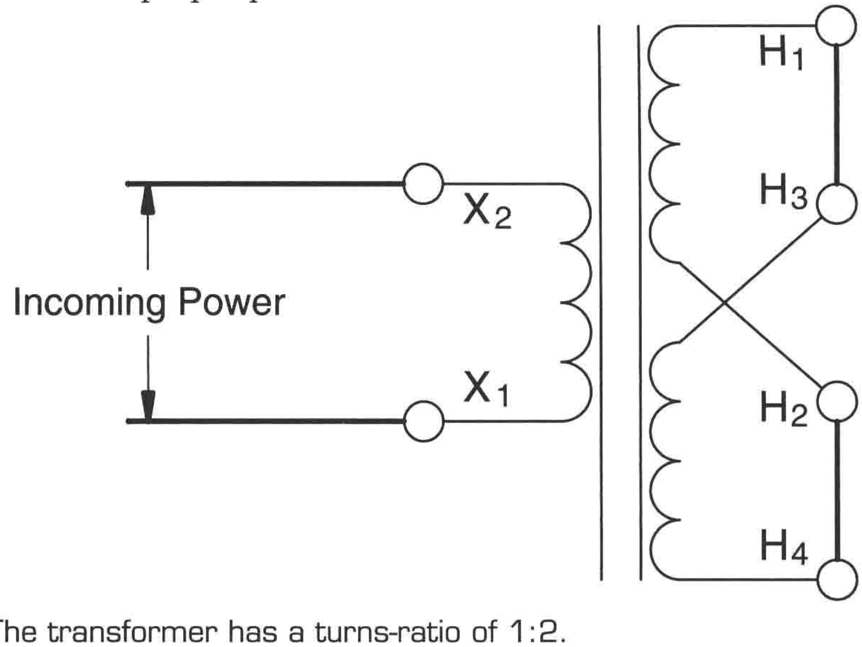

Figure 19-12 The transformer has a turns-ratio of 1:2.

Review Questions

1. What is a transformer?

2. What are common efficiencies for transformers?

3. What is an isolation transformer?

4. All values of a transformer are proportional to its:

5. A transformer has a primary voltage of 480 volts and a secondary voltage of 20 volts. What is the turns-ratio of the transformer?

6. If the secondary of the transformer in question 5 supplies a current of 9.6 amperes to a load, what is the primary current (disregard excitation current)?

7. Explain the difference between a step-up and a step-down transformer.

8. A transformer has a primary voltage of 240 volts and a secondary voltage of 48 volts. What is the turns-ratio of this transformer?

9. A transformer has an output of 750 volt-amps. The primary voltage is 120 volts. What is the primary current?

10. A transformer has a turns-ratio of 1:6. The primary current is 18 amperes. What is the secondary current?

Unit 20 Single-Phase Transformer Calculations

Objectives

After studying this unit, you should be able to:

- Discuss transformer excitation current.
- Compute values of primary current using the secondary current and the turns-ratio.
- Compute the turns-ratio of a transformer using measured values.
- Connect a step-down or step-up isolation transformer.

LABORATORY EXERCISE

Name ____ Date __________

Materials Required

480-240/120-volt, 0.5-kVA control transformer

4 150-ohm resistors

AC voltmeter

AC ammeter, in-line or clamp-on. (If a clamp-on type is used, the use of a 10:1 scale divider is recommended.)

In this experiment the excitation current of an isolation transformer will be measured. The transformer will then be connected as both a step-down and a step-up transformer. The turns-ratio will be determined from measured values and the primary current will be computed and then measured.

1. Connect the high-voltage windings of the transformer in parallel for 240 volt operation.
2. Connect the high-voltage winding to a 208 volt AC source with an AC ammeter connected in series with one of the lines, as shown in Figure 20-1.
3. Turn on the power source and measure the current. This is the *excitation* current of the transformer. The excitation current is the amount of current necessary to magnetize the iron in the transformer and will remain constant regardless of the load on the transformer.

   ___________ amp(s)
4. Measure the voltage across the low-voltage winding at terminals X_1 - X_2.

   ___________ volts

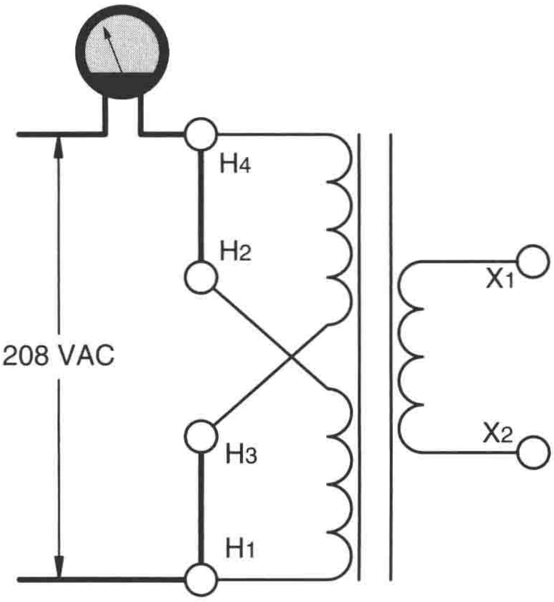

Figure 20-1 Connecting the high-voltage winding for parallel operation.

5. Compute the turns-ratio by dividing the primary voltage by the secondary voltage. Since the primary has the higher voltage, the larger number will be placed on the left side of the ratio, such as 3:1 or 4:1.

   ____________ ratio

6. **Turn off the power supply.**
7. Connect two 150-ohm resistors in parallel with the low-voltage winding of the transformer. Connect an AC ammeter in series with one of the lines, as shown in Figure 20-2.
8. Turn on the power and measure the current flow in the secondary circuit of the transformer.

   ____________ amp(s)

9. **Turn off the power supply.**
10. Compute the amount of primary current using the turns-ratio. Since the primary voltage is higher, the amount of primary current will be less. Divide the secondary current by the turns-ratio. Then add the excitation current to this value.

    ____________ $I_{(PRIMARY)}$

$$I_{(PRIMARY)} = \frac{I_{(SECONDARY)}}{\text{Turns-ratio}} + \text{Excitation current}$$

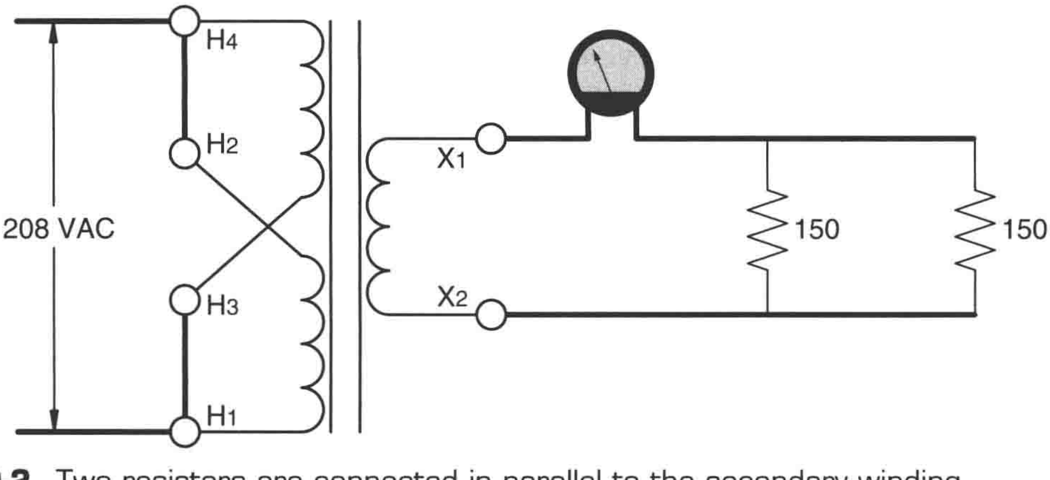

Figure 20-2 Two resistors are connected in parallel to the secondary winding.

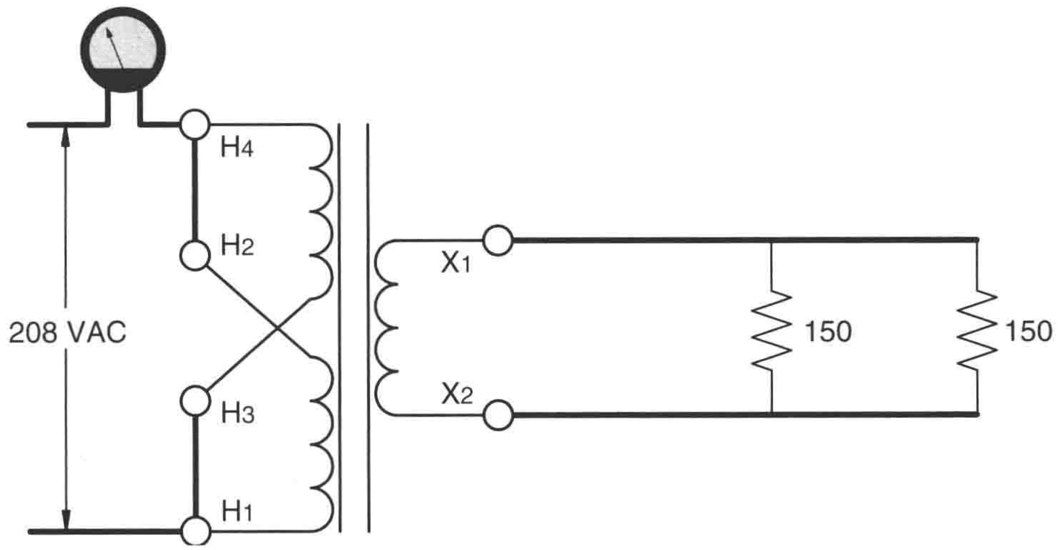

Figure 20-3 Measuring primary current.

11. Reconnect the AC ammeter in one of the primary lines, as shown in Figure 20-3.
12. Turn on the power supply and measure the primary current. Compare this value with the computed value.

    ___________ $I_{(PRIMARY)}$
13. **Turn off the power supply** and reconnect the AC ammeter in the secondary circuit and add two more 150-ohm resistors in parallel with the transformer secondary (Figure 20-4).
14. Turn on the power and measure the secondary current.

    ___________ amp(s)
15. **Turn off the power supply.**
16. Compute the amount of current flow that should be in the primary circuit using the turns-ratio. Be sure to add the excitation current.

    ___________ $I_{(PRIMARY)}$
17. Reconnect the AC ammeter in series with one of the lines of the primary winding of the transformer.

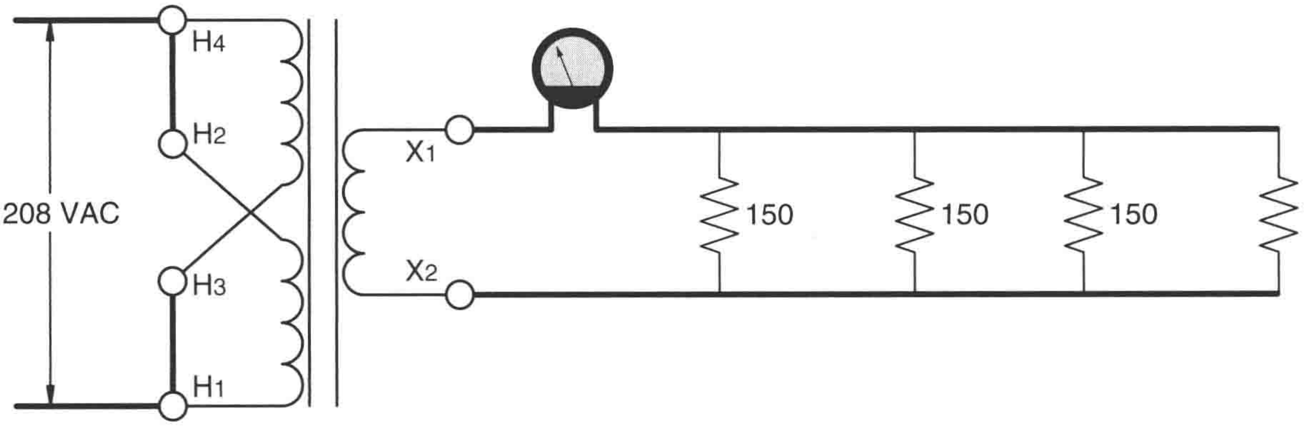

Figure 20-4 Adding load to the transformer secondary.

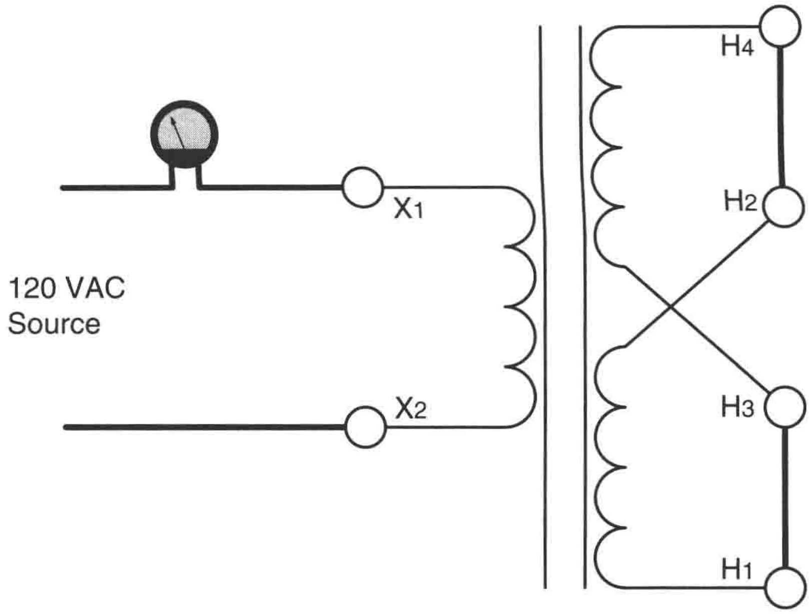

Figure 20-5 Using the low-voltage winding as the primary.

18. Turn on the power and measure the current flow. Compare the measured value with the computed value.

    ____________ $I_{(PRIMARY)}$

19. **Turn off the power supply.**
20. Reconnect the transformer by connecting the low-voltage terminals, X_1 - X_2, to a 120 volt AC source. Connect an AC ammeter in series with one of the power lines, as shown in Figure 20-5.
21. Turn on the power and measure the excitation current of the transformer.

    ____________ amp(s)

22. Measure the secondary voltage with an AC voltmeter.

    ____________ volts

23. Determine the turns-ratio by dividing the secondary voltage by the primary voltage. Since the primary voltage is lower, the higher number will be placed on the right-hand side of the ratio: 1:3 or 1:4.

    ____________ ratio

24. **Turn off the power supply.**
25. Connect two 150-ohm resistors in series. Connect these two resistors in parallel with the high-voltage winding. Connect an AC ammeter in series with one of the secondary leads, as shown in Figure 20-6.
26. Turn on the power supply and measure the secondary current.

    ____________ amp(s)

27. Compute the primary current using the turns-ratio. Since the primary voltage is less than the secondary voltage, the primary current will be more than the secondary current. To determine the primary current, multiply the secondary current by the turns-ratio and add the excitation current.

$$I_{(PRIMARY)} = I_{(SECONDARY)} \times \text{Turns-ratio} + \text{Excitation current}$$

    ____________ $I_{(PRIMARY)}$

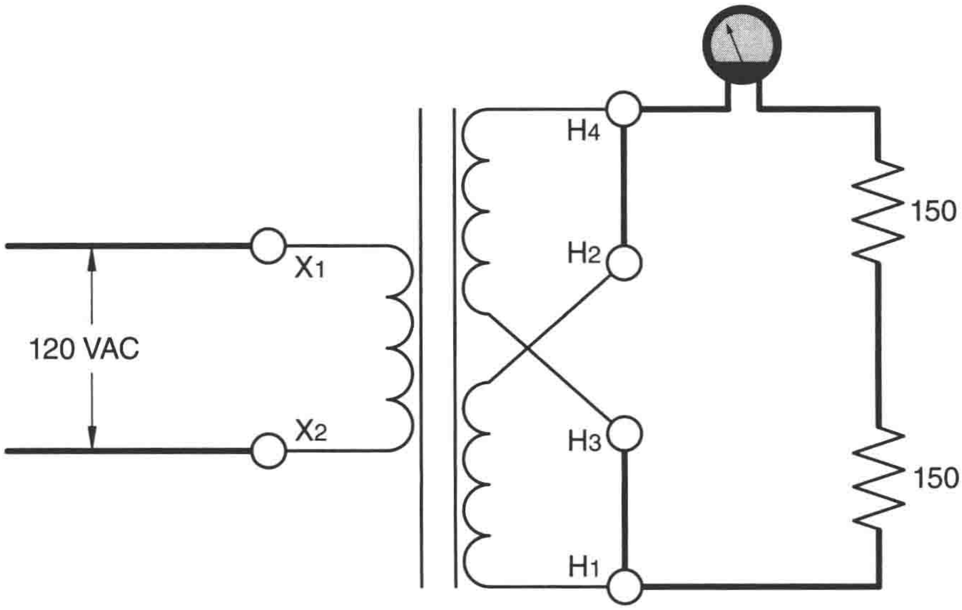

Figure 20-6 Connecting the load to the secondary.

28. **Turn off the power supply.**
29. Reconnect the AC ammeter in series with the primary side of the transformer.
30. Turn on the power supply and measure the primary current. Compare this value with the computed value.

    ___________ $I_{(PRIMARY)}$
31. **Turn off the power supply.**
32. Reconnect the AC ammeter in series with the secondary winding. Add two more 150-ohm resistors that have been connected in series to the secondary circuit. These two resistors should be connected in parallel with the first two resistors, seen in Figure 20-7.
33. Turn on the power supply and measure the secondary current.

    ___________ amp(s)
34. **Turn off the power supply.**

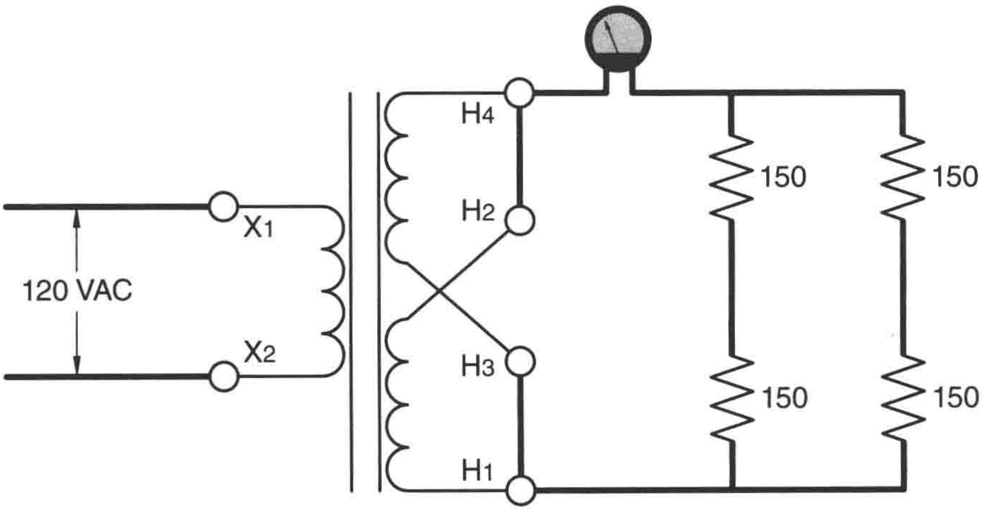

Figure 20-7 Adding load to the secondary.

35. Compute the amount of current that should flow in the primary circuit.

    ___________ $I_{(PRIMARY)}$

36. Reconnect the AC ammeter in series with one of the primary lines.
37. Turn on the power supply and measure the primary current. Compare this value with the computed value.

    ___________ $I_{(PRIMARY)}$

38. **Turn off the power supply** and disconnect the transformer and resistors.
39. Reconnect the transformer as shown in Figure 20-8 by connecting the two high-voltage windings in series. Connect four 150-ohm resistors in series and connect them to terminals H_1 and H_4 for the transformer. Connect an ammeter in series with the secondary winding.

Caution

The transformer now has a turns-ratio of 1:4. The output voltage will be approximately 480 volts when 120 volts are applied to terminals X_1 and X_2. Make sure that the power is turned off before making any adjustments to the circuit.

40. Turn on the power and measure the secondary current.

    __________ amp(s)

41. Make certain the voltmeter is set for a range greater than 480 volts. Measure the voltage across terminals H_1 and H_4. **Use caution when making this measurement.**

    __________ volts

42. **Turn off the power.**

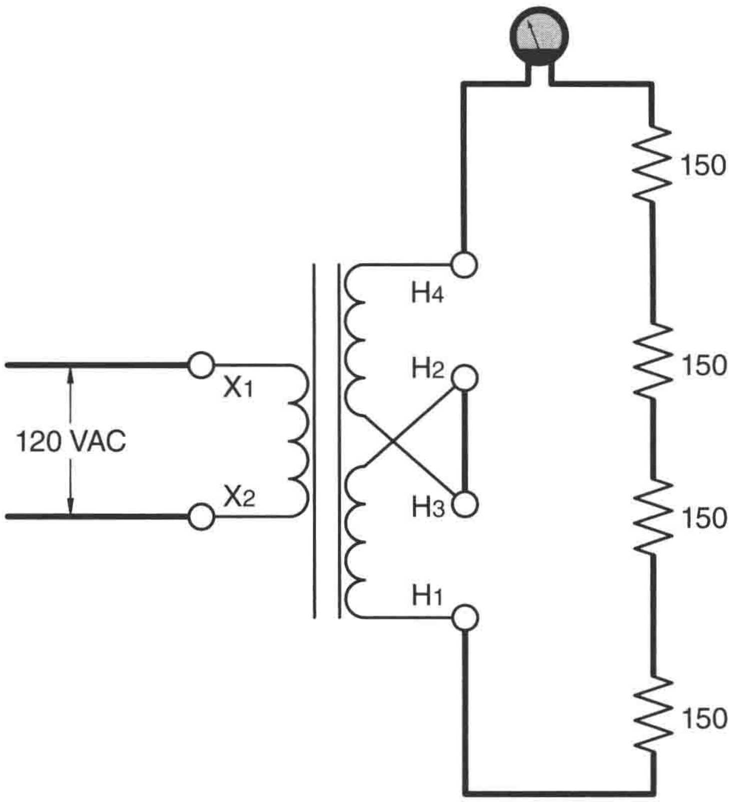

Figure 20-8 Connect the two high voltage windings in series. The transformer now has a turns-ratio of 1:4.

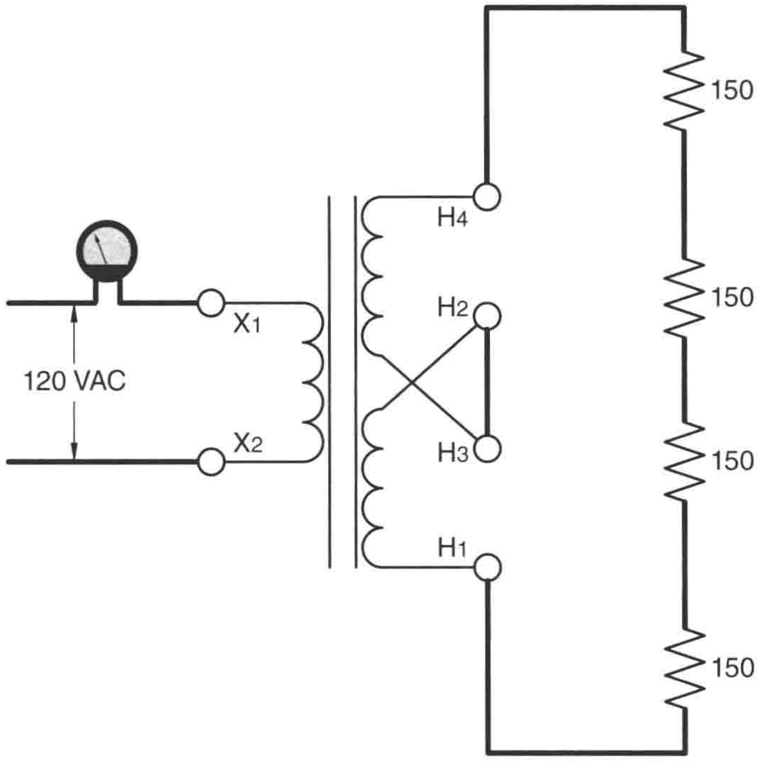

Figure 20-9 The ammeter is reconnected in the primary winding.

43. Use the turns-ratio to compute the primary current. Be sure to add the excitation current to the calculation.

    ________ $I_{(PRIMARY)}$

44. Reconnect the ammeter in series with the primary as shown in Figure 20-9.
45. Turn on the power and measure the amount of primary current. Compare this value with the computed value.

    ________ amp(s)

46. **Turn off the power.** Disconnect the circuit and return the components to their proper place.

Review Questions

1. A transformer has a primary voltage of 277 volts and a secondary voltage of 120 volts. What is the turns-ratio of this transformer?

   ____

2. A transformer has a turns-ratio of 1:6. Is this a step-up or a step-down transformer?

   ____

3. A transformer with a turns-ratio of 3.5:1 has a secondary current of 16 amperes. What is the primary current?

   ____

4. A transformer has a primary current of 18 amperes and a secondary current of 6 amperes. What is the turns-ratio of the transformer?

   ____

5. A transformer has a primary voltage of 240 volts and a secondary voltage of 60 volts. It has a power rating of 7.5 VA. What is the rated current of the secondary?

____

6. A 75 kVA transformer has a secondary voltage of 480 volts and a current of 183 amperes. Is this transformer being operated within its power rating?

____

7. A transformer has a primary voltage of 120 volts and a secondary voltage of 18 volts. The primary excitation current is 0.25 amp. The total primary current is 6.5 amperes. What is the secondary current?

____

8. Would a 1 kVA transformer be large enough to supply the load of the transformer in question 7?

____

9. A transformer has a primary voltage of 12,470 volts and a secondary voltage of 2,400 volts. If the secondary current is 22.6 amperes, what is the primary current (disregard excitation current)?

____

10. Would a 75 kVA transformer supply the power needed by the load in question 7?

____

Unit 21 Transformer Polarities

Objectives

After studying this unit, you should be able to:

- Discuss buck and boost connections for a transformer.
- Connect a transformer for additive polarity.
- Connect a transformer for subtractive polarity.
- Determine the turns-ratio and calculate current values using measured values.

To understand what is meant by transformer polarity, the voltage produced across a winding must be considered during some point in time. In a 60 Hz AC circuit, the voltage changes polarity 120 times per second. When discussing transformer polarity, it is necessary to consider the relationship between the different windings at the same point in time. It will, therefore, be assumed that this point in time is when the peak positive voltage is being produced across the winding.

Polarity Markings on Schematics

When a transformer is shown on a schematic diagram, it is common practice to indicate the polarity of the transformer windings by placing a dot beside one end of each winding, as shown in Figure 21-1. These dots signify that the polarity is the same at that point in time for each winding. For example, assume the voltage applied to the primary winding is at its peak positive value at the terminal indicated by the dot. The voltage at the dotted lead of the secondary will be at its peak positive value at the same time.

This same type of polarity notation is used for transformers that have more than one primary or secondary winding. An example of a transformer with a multisecondary is shown in Figure 21-2.

Additive and Subtractive Polarities

The polarity of transformer windings can be determined by connecting one lead of the primary to one lead of the secondary and testing for an increase or decrease in voltage. This

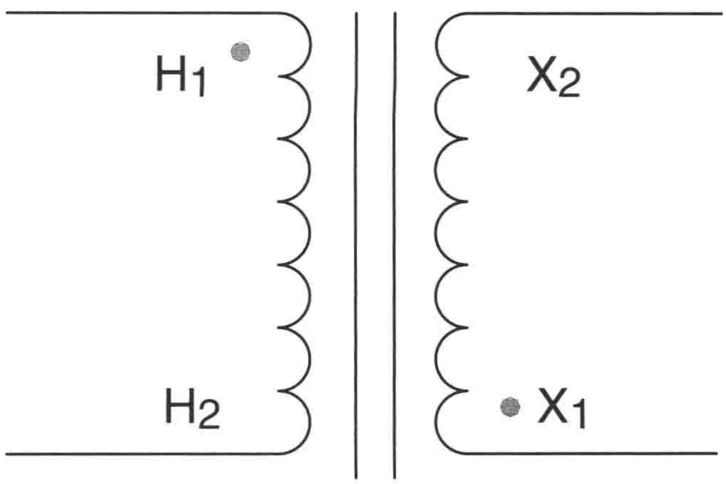

Figure 21-1 Transformer polarity dots.

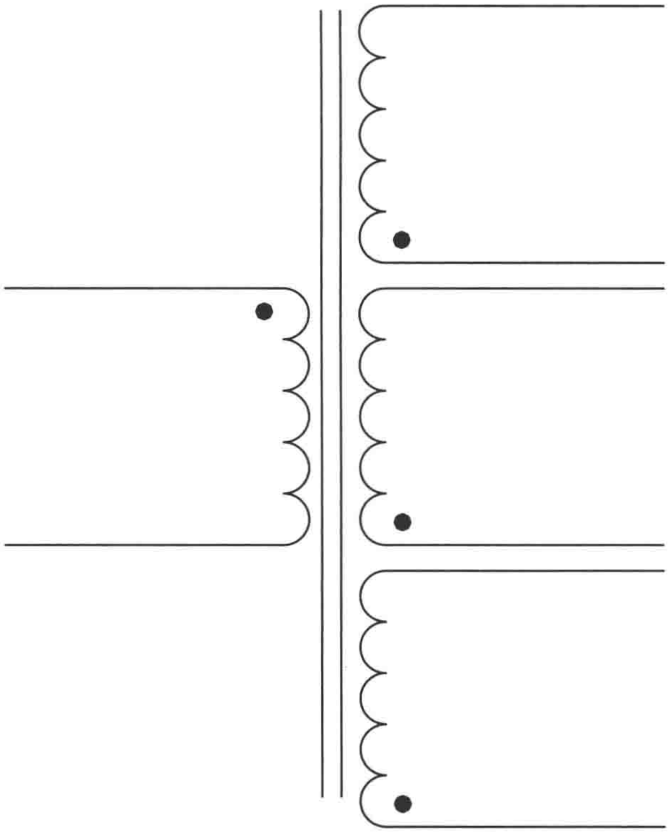

Figure 21-2 Polarity marks for multiple secondaries.

is often referred to as a *buck* or *boost* connection (Figure 21-3). The transformer shown in the example has a primary voltage rating of 120 volts and a secondary voltage rating of 24 volts. This same circuit has been redrawn in Figure 21-4 to show the connection more clearly. Notice that the secondary winding has been connected in series with the primary winding. When 120 volts is applied to the primary winding, the voltmeter connected across the secondary will indicate either the *SUM* of the two voltages or the *DIFFERENCE* between the two voltages. If this voltmeter indicates 144 volts ($120 + 24 = 144$), the windings are connected additive (boost) and polarity dots can be placed as shown in Figure 21-5. Notice in this connection that the secondary voltage is added to the primary voltage.

If the voltmeter connected to the secondary winding should indicate a voltage of 96 volts ($120 - 24 = 96$), the windings are connected subtractive (buck) and polarity dots would be placed as shown in Figure 21-6.

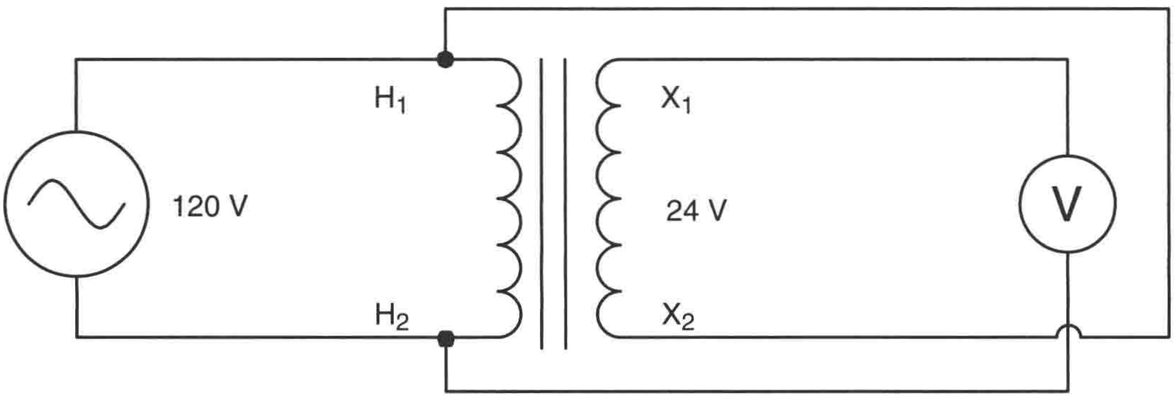

Figure 21-3 Connecting the secondary and primary windings forms an autotransformer.

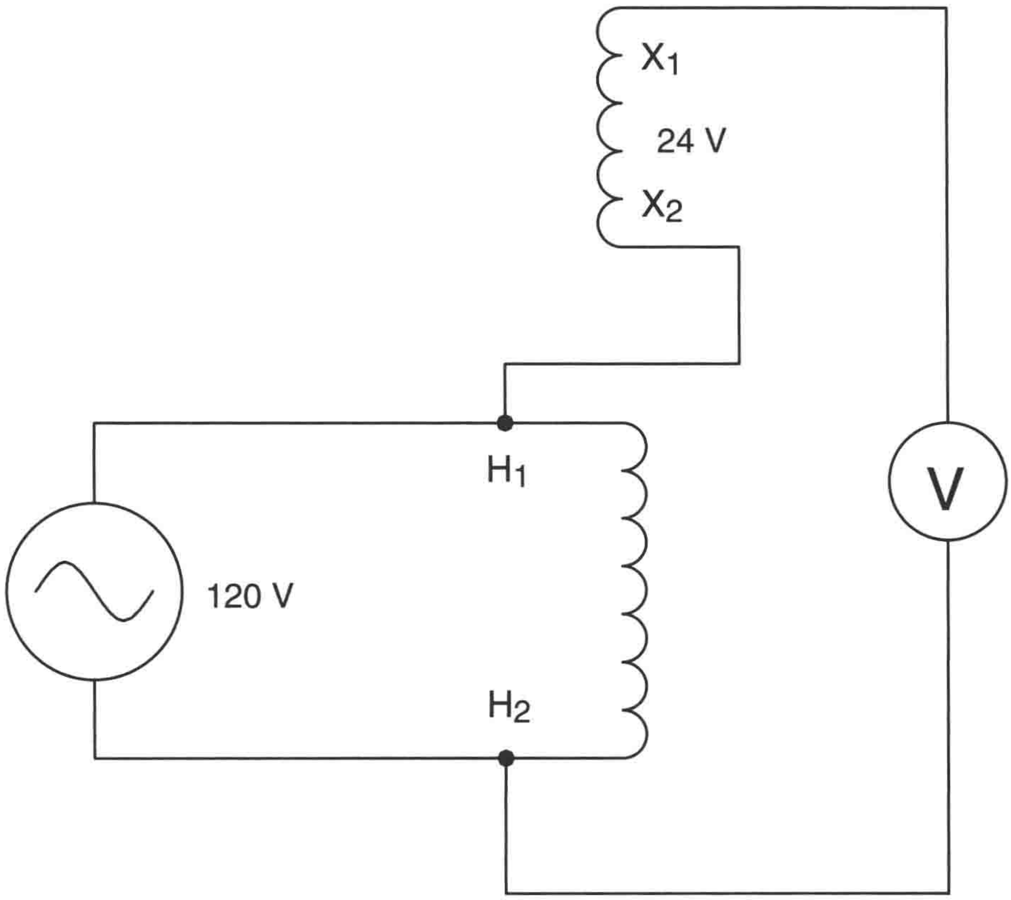

Figure 21-4 Redrawing the connection.

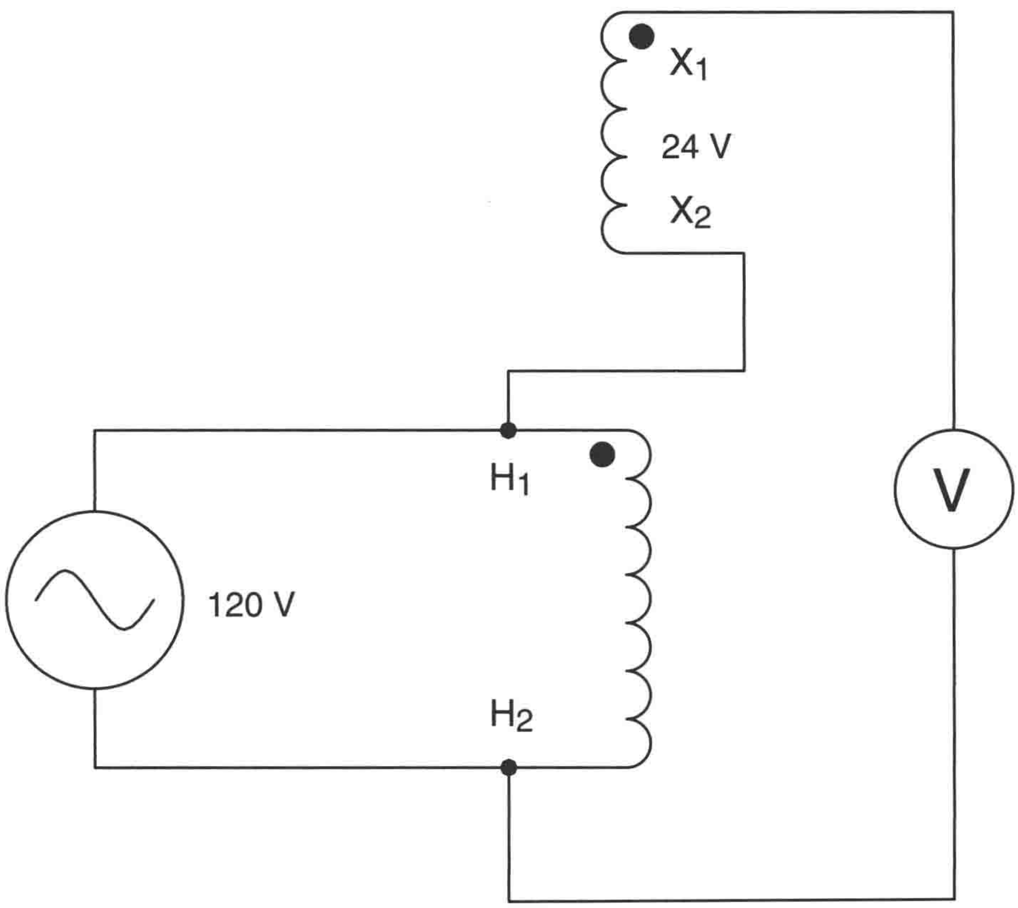

Figure 21-5 Placing polarity dots to indicate additive polarity.

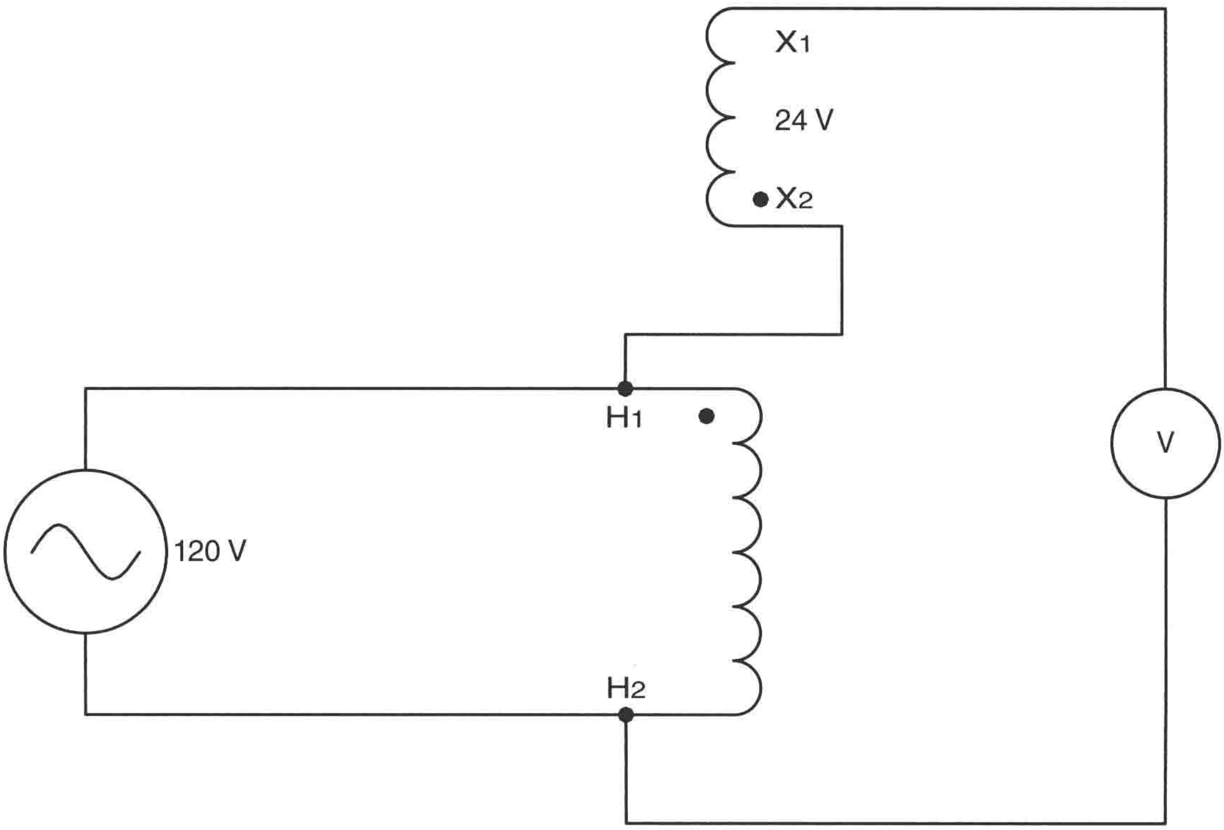

Figure 21-6 Polarity dots indicate subtractive polarity.

Using Arrows to Place Dots

To help in the understanding of additive and subtractive polarity, arrows can be used to indicate a direction of greater-than or less-than values. In Figure 21-7, arrows have been added to indicate the direction in which the dot is to be placed. In this example, the transformer is connected additive, or boost, and both of the arrows point in the same direction. Notice that the arrow points to the dot. In Figure 21-8, it is seen that the values of the two arrows add to produce 144 volts.

In Figure 21-9, arrows have been added to a subtractive, or buck, connection. In this instance, the arrows point in opposite directions and the voltage of one tries to cancel the voltage of the other. The result is that the smaller value is eliminated and the larger value is reduced as shown in Figure 21-10.

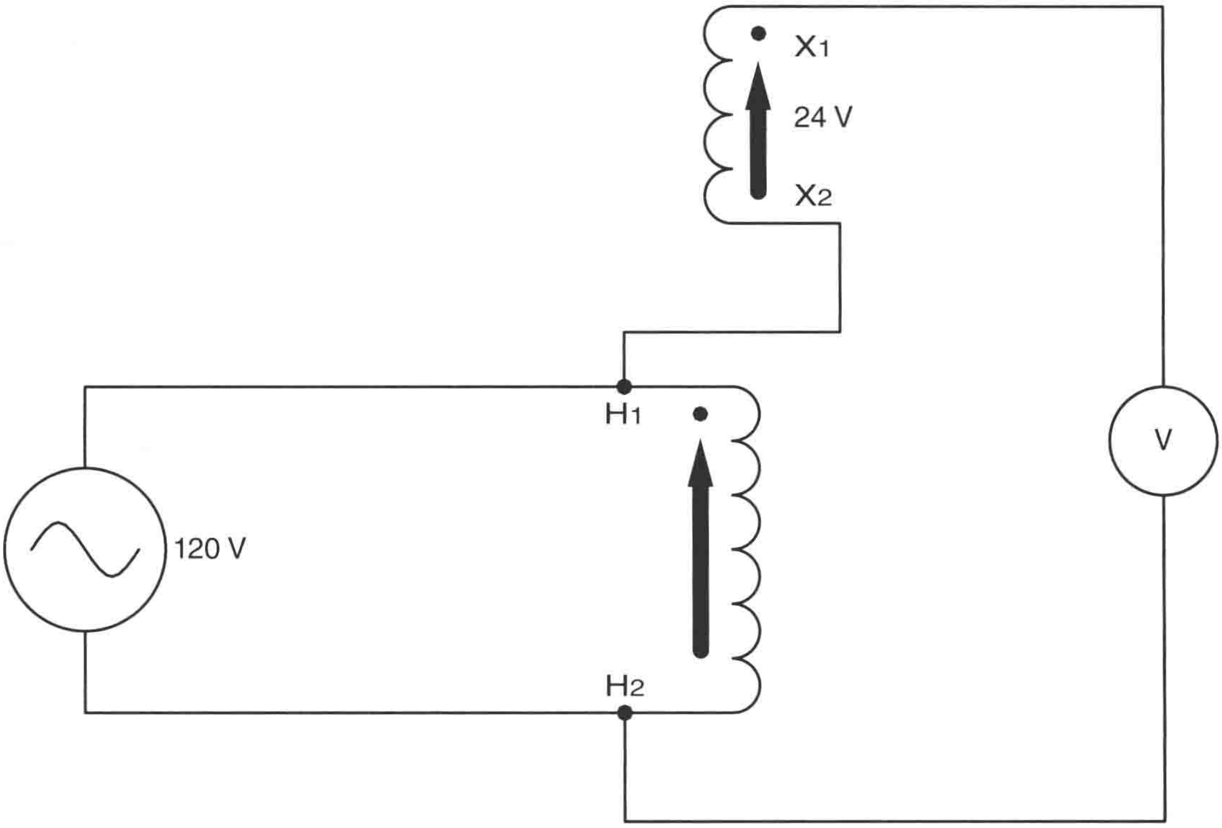

Figure 21-7 Arrows help indicate the placement of the polarity dots.

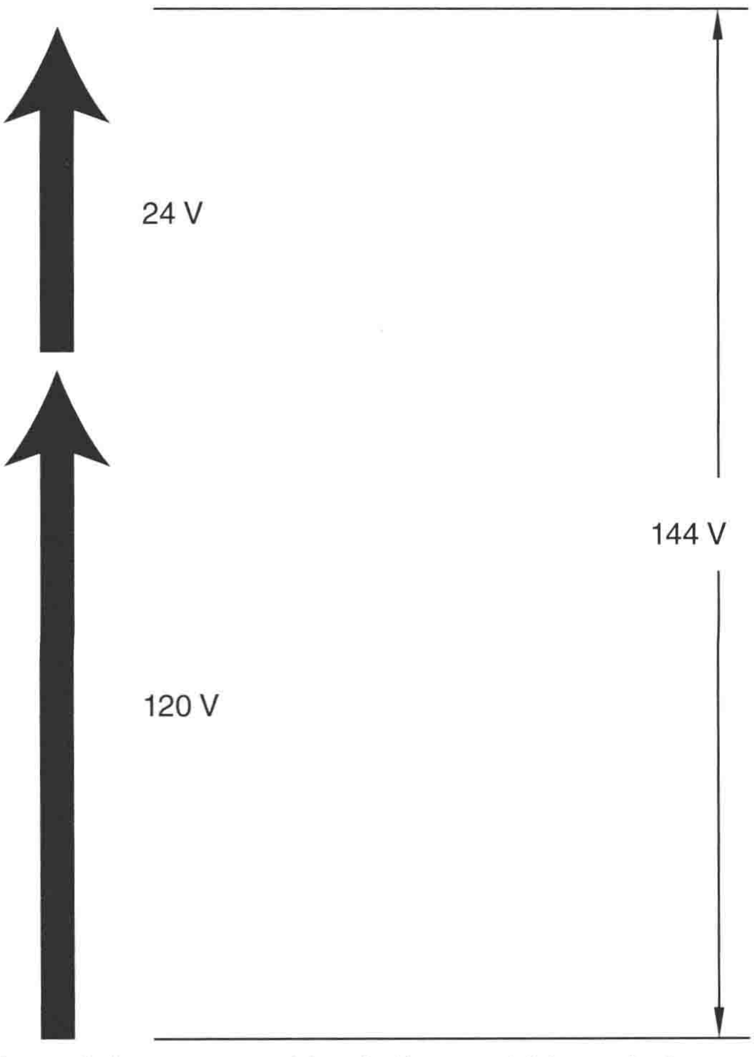

Figure 21-8 The values of the arrows add to indicate additive polarity.

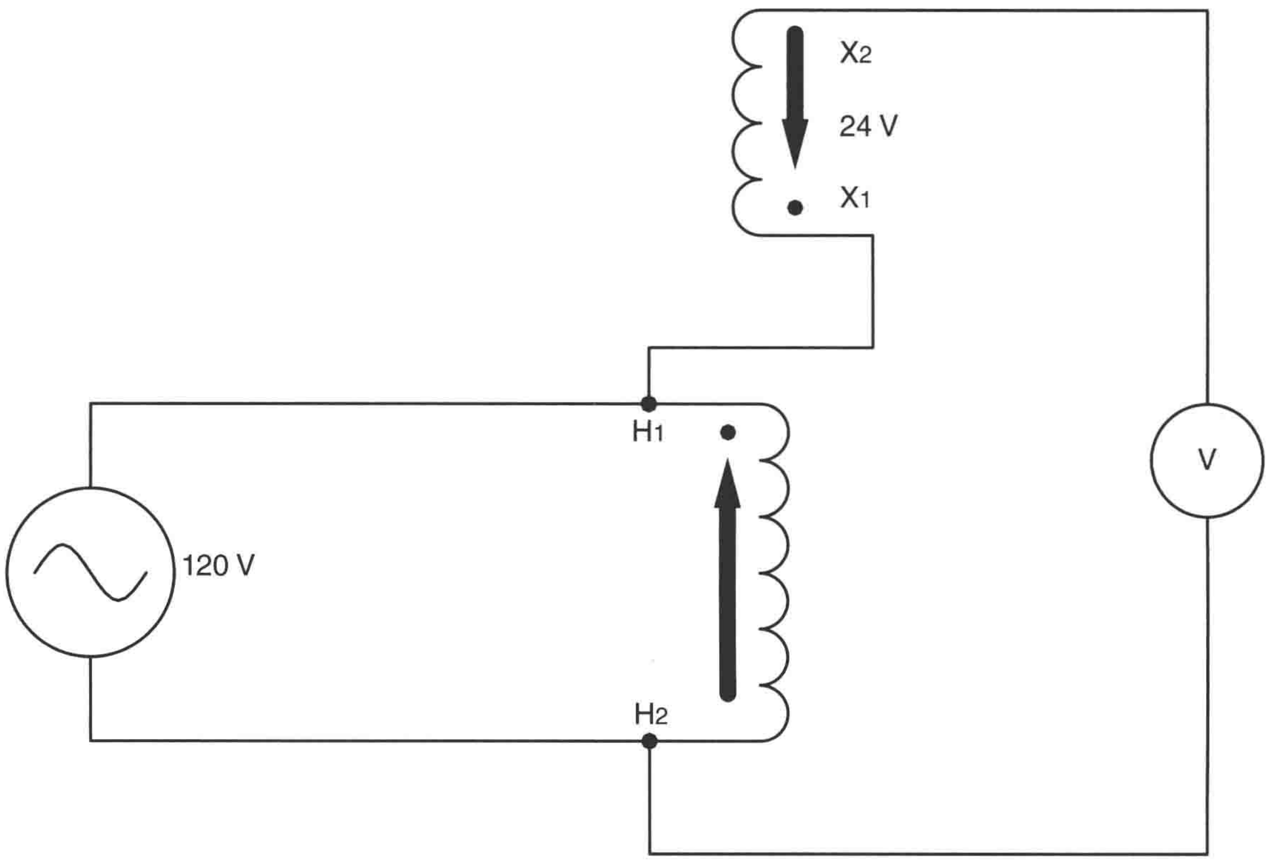

Figure 21-9 The arrows help indicate subtractive polarity.

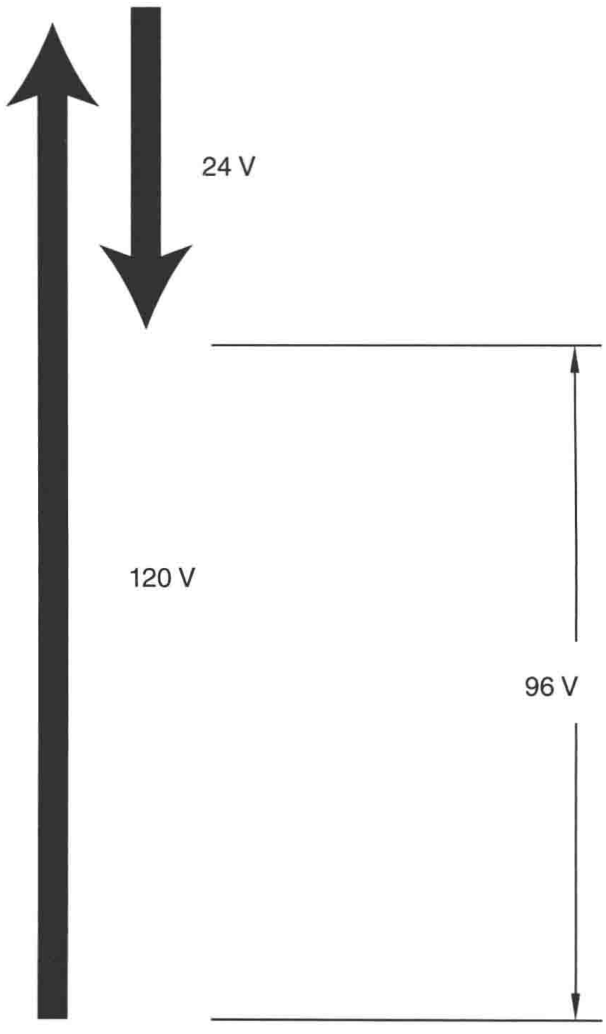

Figure 21-10 The value of the arrows subtract.

LABORATORY EXERCISE

Name ____ Date __________

Materials Required

480-240/120-volt 0.5-kVA control transformer

AC voltmeter

2 AC ammeters, in-line or clamp-on. (If a clamp-on type is used, a 10:1 scale divider is recommended.)

150 ohm resistors

4 100-ohm resistors

In this experiment a control transformer will be connected for both additive (boost) and subtractive (buck) polarity. Buck and boost connections are made by physically connecting the primary and secondary windings together. If they are connected in such a way that the primary and secondary voltages add, the transformer is connected additive, or boost. If the windings are connected in such a way that the primary and secondary voltages subtract, they are connected subtractive, or buck.

In this exercise only one of the high-voltage windings will be used. The other will not be connected.

1. Connect the circuit shown in Figure 21-11.
2. Turn on the power and measure the primary and secondary voltages.

   $E_{(PRIMARY)}$ ____________ volts

   $E_{(SECONDARY)}$ ____________ volts

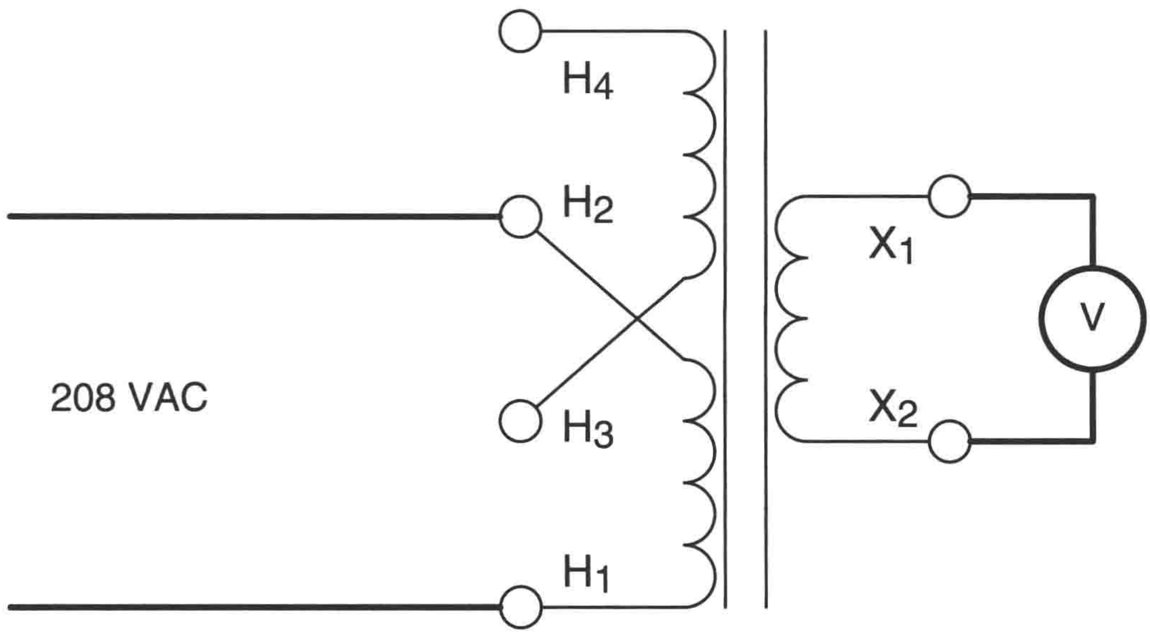

Figure 21-11 Measuring the secondary voltage.

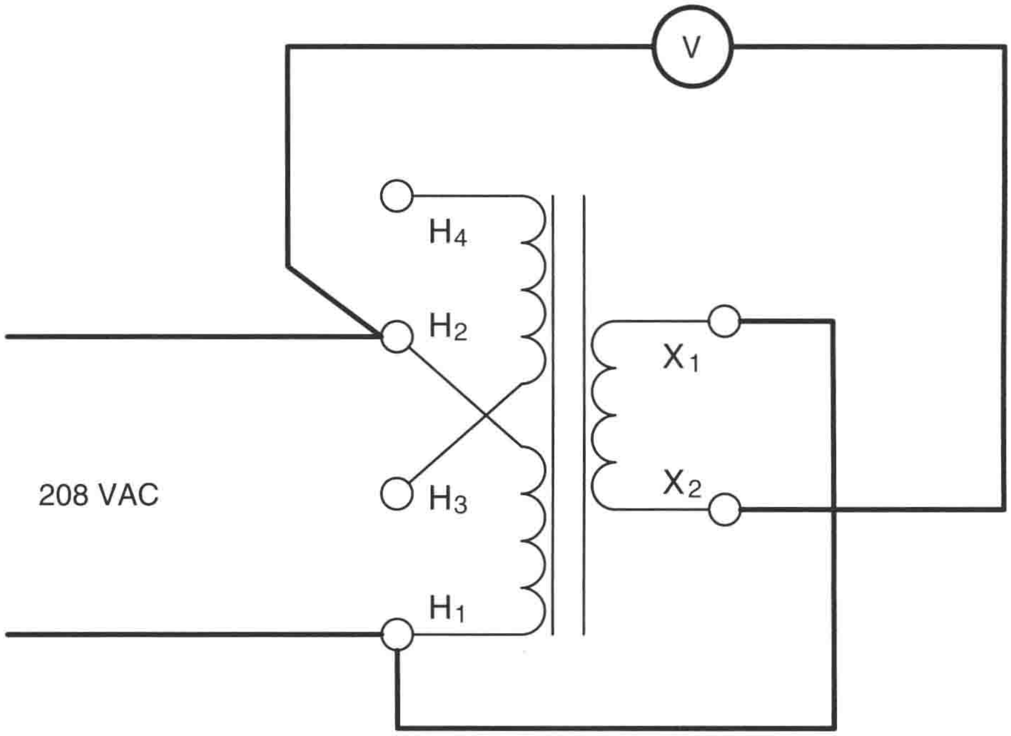

Figure 21-12 Connecting X_2 and H_2.

3. **Turn off the power supply.**
4. Determine the turns-ratio of this transformer connection by dividing the higher voltage by the lower voltage. Recall that if the primary winding has the higher voltage, the higher number will be placed on the left and 1 will be placed on the right. If the secondary has the higher voltage, a 1 will be placed on the left and the higher number will be placed on the right.

$$\text{Turns-ratio} = \frac{\text{Higher voltage}}{\text{Lower voltage}}$$

   Ratio ____________

5. Connect the circuit shown in Figure 21-12 by connecting X_1 to H_1. Connect a voltmeter across terminals X_2 and H_2.
6. Turn on the power supply and measure the voltage across X_2 and H_2.

   ____________ volts

7. **Turn off the power supply.**
8. Determine the turns-ratio of this transformer connection.

   Ratio ____________

9. If the measured voltage is the difference between the applied voltage and the secondary voltage, the transformer is connected subtractive polarity, or buck. If the measured voltage is the sum of the applied voltage and the secondary voltage, the transformer is connected additive, or boost. Is the transformer connected buck or boost?

   ____

10. Connect an AC ammeter in series with one of the power supply lines.
11. Turn on the power supply and measure the excitation current of the transformer.

   $I_{(EXC.)}$ ____________ amp(s)

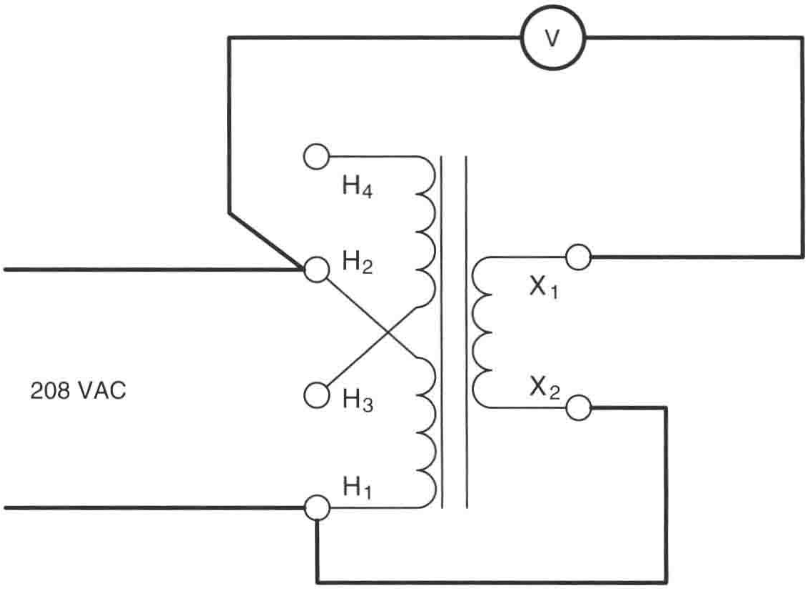

Figure 21-13 Connecting X_1 and H_2.

12. **Turn off the power supply.**
13. Reconnect the transformer as shown in Figure 21-13 by connecting X_2 to H_1. Connect an AC voltmeter across terminals X_1 and H_2.
14. Turn on the power supply and measure the voltage across terminals X_1 and H_2.

    ____________ volts
15. **Turn off the power supply.**
16. Is the transformer connected buck or boost?

    ____
17. Determine the turns-ratio of this transformer connection.

    Ratio ____________
18. Connect an AC ammeter in series with one of the primary leads.
19. Turn on the power supply and measure the excitation current of this connection.

    $I_{(EXC)}$ ____________amp(s)
20. Compare the value of excitation current for the buck and boost connections. Is there any difference between these two values?

    ____
21. **Turn off the power supply.**
22. Figure 21-14 shows the proper location for the placement of polarity dots. Recall that polarity dots are used to indicate which windings of a transformer have the same polarity at the same time. To better understand how the dots are placed, redraw the two transformer windings in a series connection as shown in Figure 21-15. Place a dot beside one of the high-voltage terminals. In this example, a dot has been placed beside the H_1 terminal. Next, draw an arrow pointing to the dot. To place the second dot, draw an arrow in the same direction as the first arrow. This arrow should point to the dot that is to be placed beside the secondary terminal. Since terminal X_2 is connected to H_1, the arrow must point to terminal X_1.
23. Reconnect the transformer for subtractive polarity. If two ammeters are available, place one ammeter in series with one of the primary leads and the second ammeter

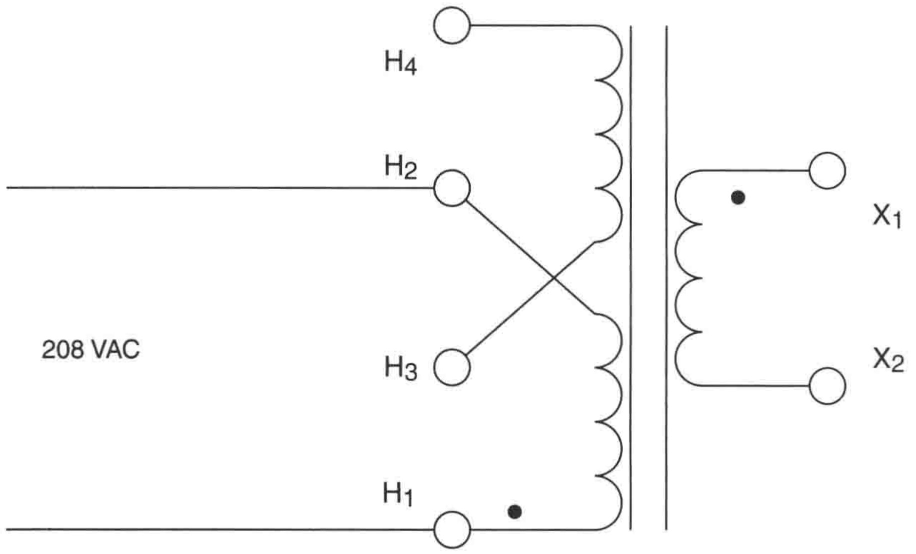

Figure 21-14 Placing polarity dots on the transformer windings.

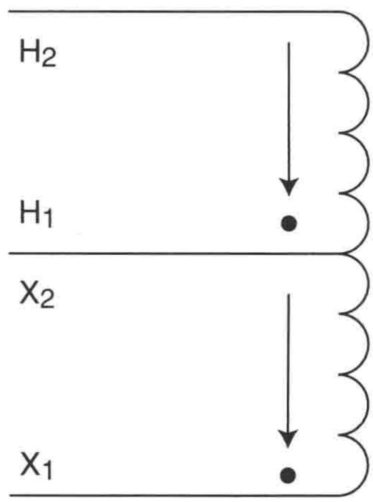

Figure 21-15 Determining the placement of polarity dots.

in series with the secondary lead that is not connected to the H_1 terminal. Connect a 100-ohm resistor in the secondary circuit, and connect a voltmeter in parallel with the resistor, as shown in Figure 21-16.

24. Turn on the power supply and measure the secondary current.

$I_{(SECONDARY)}$ __________ amp(s)

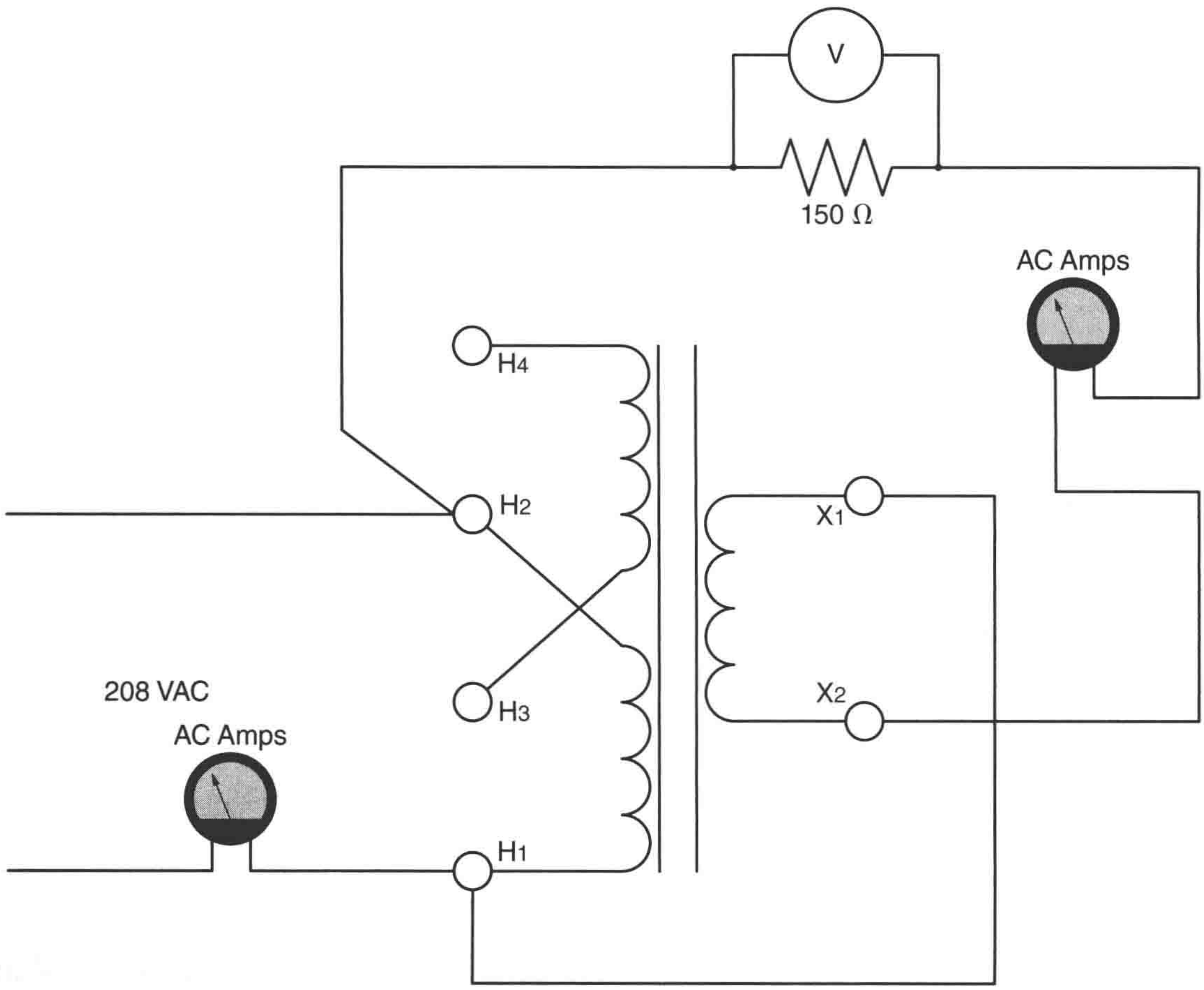

Figure 21-16 Connecting load to a subtractive polarity transformer.

25. Measure the secondary voltage. Since the resistor is the only load connected to the secondary, the voltage drop across the lamp will be the secondary voltage.

$E_{(SECONDARY)}$ __________ volts

26. Calculate the amount of primary current using the measured value of secondary current and the turns-ratio. Be sure to use the turns-ratio for this connection as determined in step 8. Since the primary voltage is greater than the secondary voltage, the primary current should be less. Therefore, divide the secondary current by the turns-ratio and then add the excitation current measured in step 11.

$$I_{(PRIMARY)} = \frac{I_{(SECONDARY)}}{\text{Turns-ratio}} + I_{(EXC)}$$

$I_{(PRIMARY)}$ __________ amp(s)

27. If necessary, **turn off the power supply** and connect an AC ammeter in series with one of the primary leads.

28. Turn on the power supply and measure the primary current. Compare this value with the calculated value.

$I_{(PRIMARY)}$ __________ amp(s)

29. **Turn off the power supply.**

30. Connect a 150-ohm resistor in parallel with the 100-ohm resistor as shown in Figure 21-17. Reconnect the AC ammeter in series with the secondary winding if necessary.

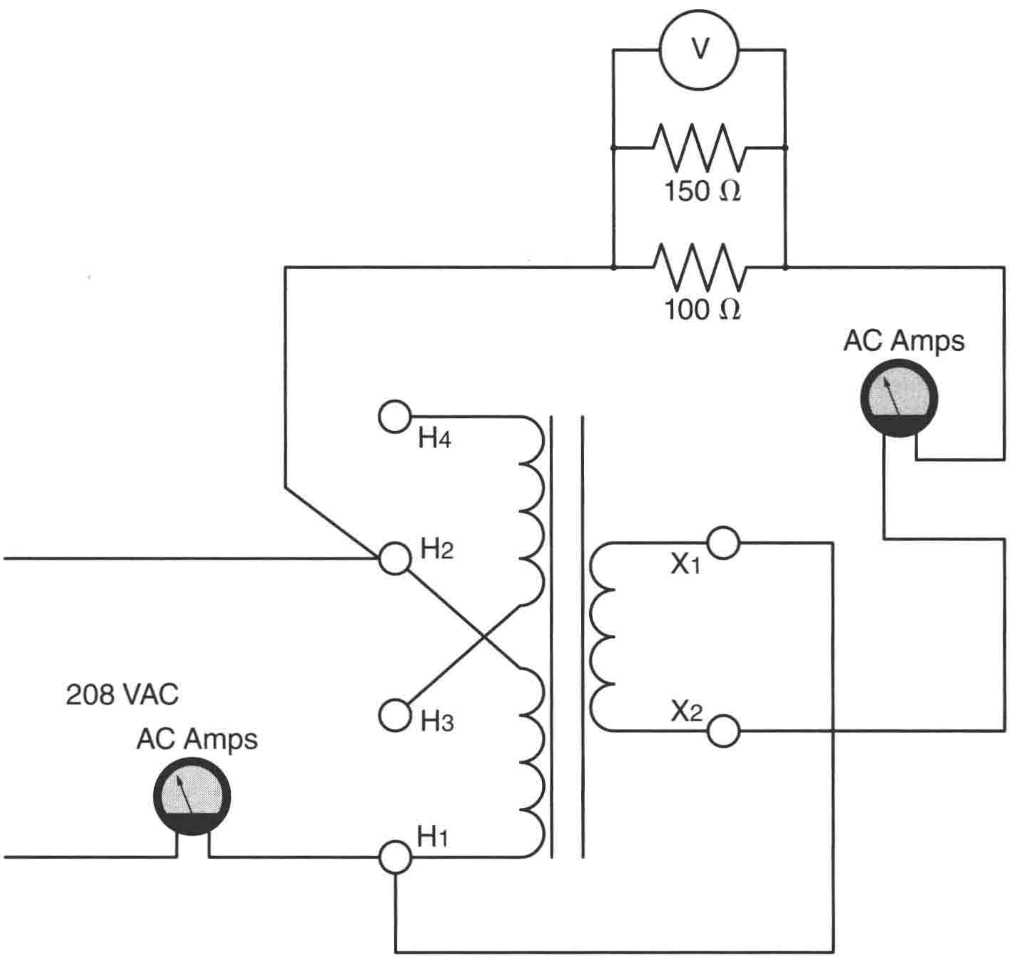

Figure 21-17 Adding load to the transformer.

31. Turn on the power supply and measure the amount of secondary current.

    $I_{(SECONDARY)}$ ____________ amp(s)

32. Calculate the primary current.

    $I_{(PRIMARY)}$ ____________ amp(s)

33. If necessary, **turn off the power supply** and connect the AC ammeter in series with one of the primary leads.

34. Turn on the power supply and measure the primary current. Compare this value with the computed value.

    $I_{(PRIMARY)}$ ____________ amp(s)

35. **Turn off the power supply.**

36. Reconnect the transformer for the boost connection by connecting terminal X_2 to H_1. If two ammeters are available, connect one AC ammeter in series with one of the power supply leads and the second AC ammeter in series with the secondary. Connect four 150-ohm resistors in series with terminals X_1 and H_2 as shown in Figure 21-18. Connect an AC voltmeter across terminals X_2 and H_1.

37. Turn on the power and measure the secondary current.

    $I_{(SECONDARY)}$ ____________ amp(s)

38. **Turn off the power supply.**

39. Compute the primary current using the turns-ratio. Be sure to use the turns-ratio for this connection as determined in step 17. Since the primary voltage in this connection

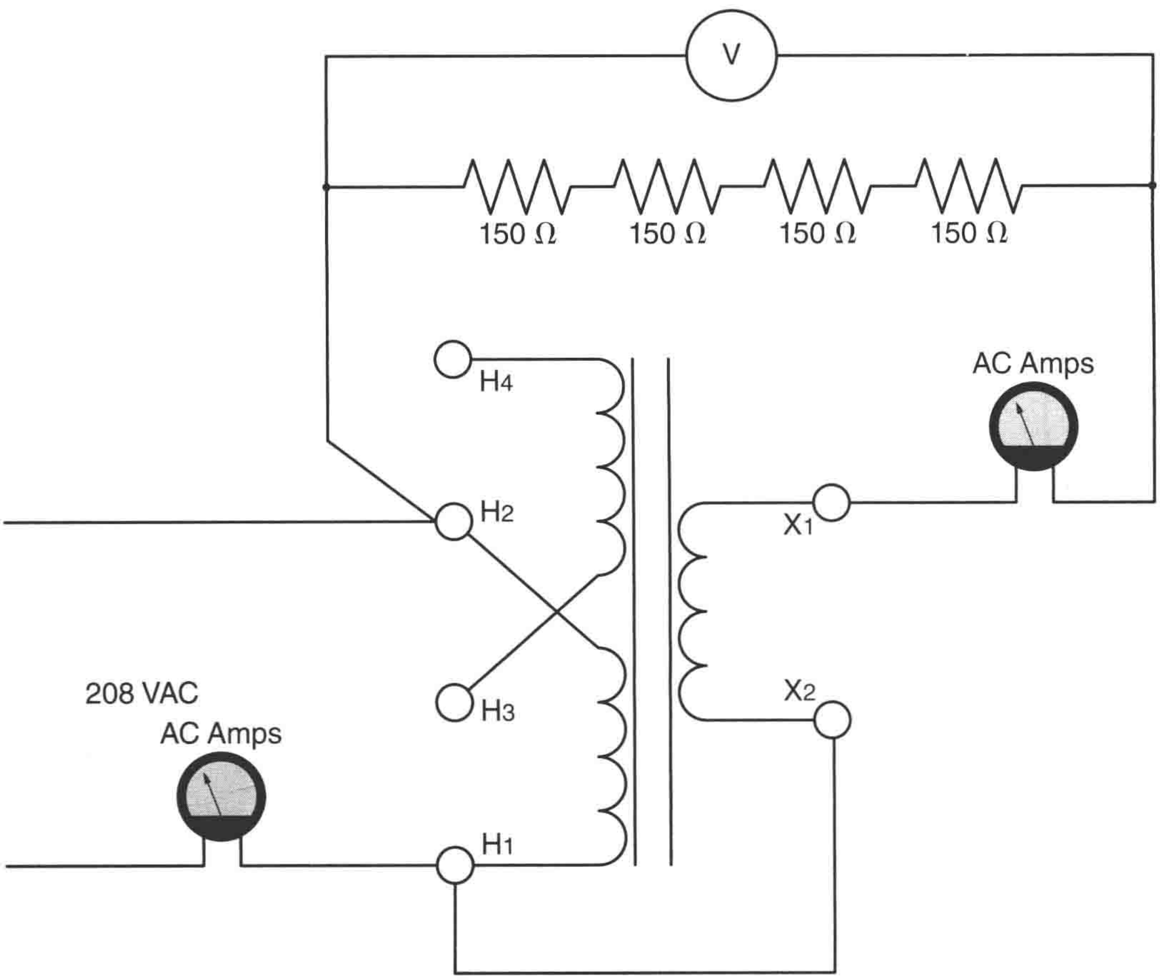

Figure 21-18 Connecting load to the boost connection.

is less than the secondary voltage, the primary current will be greater. To calculate the primary current, multiply the secondary current by the turns-ratio and then add the excitation current.

$$I_{(PRIMARY)} = (I_{(SECONDARY)} \times \text{Turns-ratio}) + I_{(EXC)}$$

$I_{(PRIMARY)}$ ____________ amp(s)

40. If necessary, connect the AC ammeter in series with one of the power supply leads.
41. Turn on the power supply.
42. Measure the primary current. Compare this value with the calculated value.

    $I_{(PRIMARY)}$ ____________ amp(s)
43. **Turn off the power supply.**
44. Disconnect the circuit and return the components to their proper place.

Review Questions

1. What do the dots shown beside the terminal leads of a transformer represent on a schematic?

   ____
2. A transformer has a primary voltage rating of 240 volts and a secondary voltage rating of 80 volts. If the windings are connected subtractive, what voltage would appear across the entire connection?

   ____
3. If the windings of the transformer in question 2 were to be connected additive, what voltage would appear across the entire winding?

   ____
4. The primary leads of a transformer are labeled 1 and 2. The secondary leads are labeled 3 and 4. If polarity dots are placed beside leads 1 and 4, which secondary lead would be connected to terminal 2 to make the connection additive?

   ____

Unit 22 Autotransformers

Objectives

After studying this unit, you should be able to:

- Discuss the operation of an autotransformer.
- Connect a control transformer as an autotransformer.
- Calculate the turns-ratio from measured voltage values.
- Calculate primary current using the secondary current and the turns-ratio.
- Connect an autotransformer as a step-down transformer.
- Connect an autotransformer as a step-up transformer.

The word *auto* means self. An autotransformer is literally a *self-transformer*. It uses the same winding as both the primary and secondary. Recall that the definition of a primary winding is a winding that is connected to the source of power and the definition of a secondary winding is a winding that is connected to a load. Autotransformers have very high efficiencies, most in the range of 95% to 98%.

In Figure 22-1, the entire winding is connected to the power source, and part of the winding is connected to the load. In this illustration all the turns of wire form the primary and part of the turns form the secondary. Since the secondary part of the winding contains fewer turns than the primary section, the secondary will produce less voltage. This autotransformer is a step-down transformer.

In Figure 22-2, the primary section is connected across part of a winding and the secondary is connected across the entire winding. In this illustration the secondary section contains more windings than the primary. This autotransformer is a step-up transformer. Notice that autotransformers, like isolation transformers, can be used as step-up or step-down transformers.

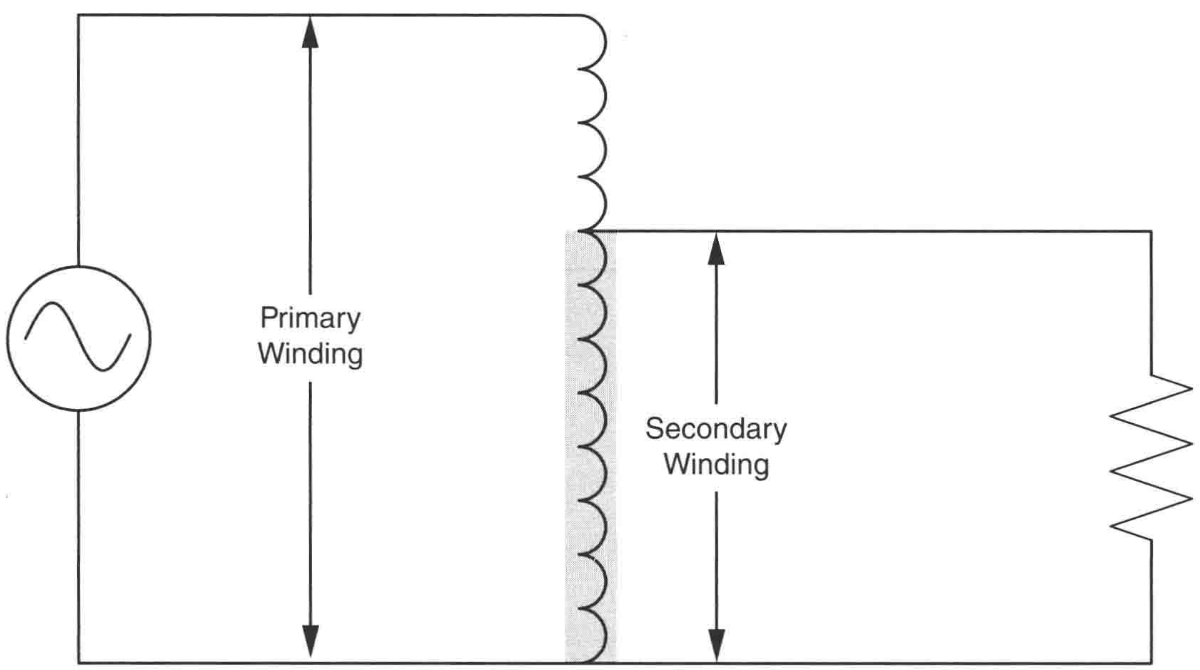

Figure 22-1 Autotransformer used as a step-down transformer.

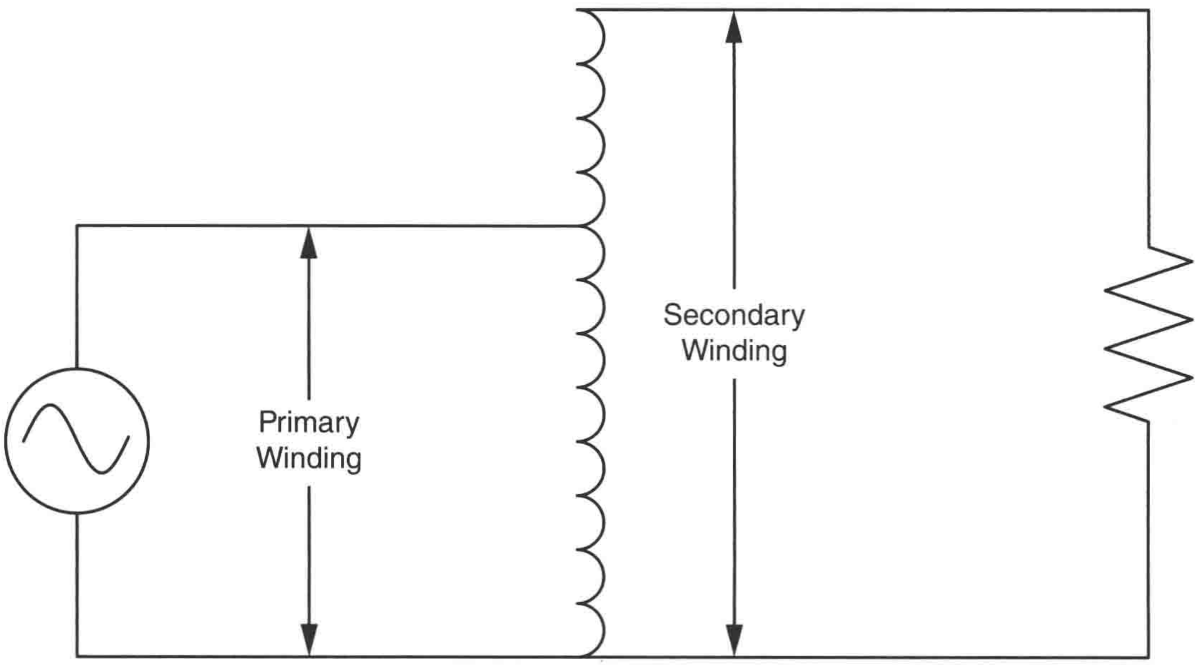

Figure 22-2 Autotransformer used as a step-up transformer.

Determining Voltage Values

Autotransformers are not limited to a single secondary winding. Many autotransformers have multiple taps to provide different voltages as shown in Figure 22-3. In this example there are 40 turns of wire between taps A and B, 80 turns of wire between taps B and C, 100 turns of wire between taps C and D, and 60 turns of wire between taps D and E. The primary section of the windings is connected between taps B and E. It will be assumed that the primary is connected to a source of 120 volts. The voltage across each set of taps will be determined.

There is generally more than one method that can be employed to determine values of a transformer. Since the number of turns between each tap is known, the volts-per-turn

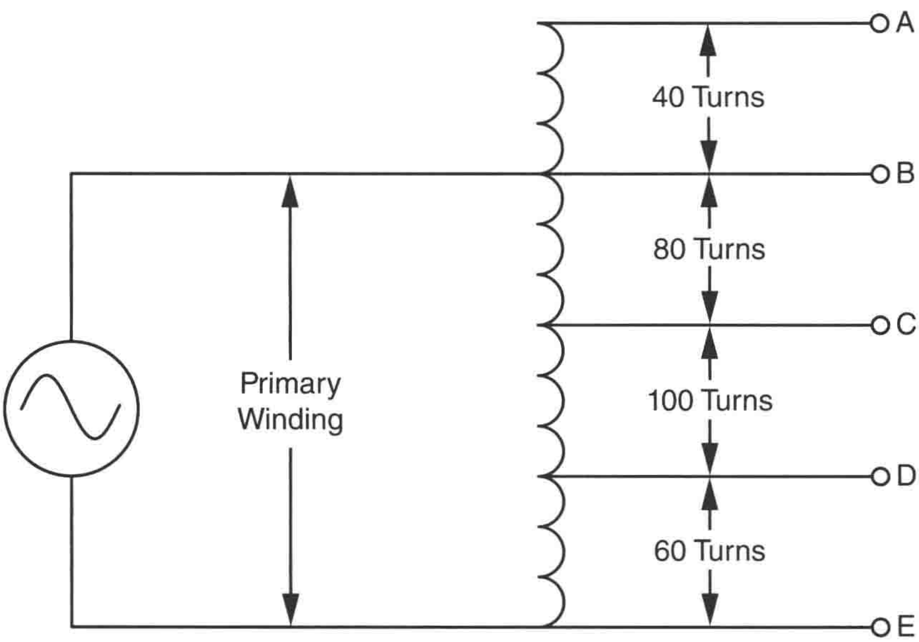

Figure 22-3 Autotransformer with multiple taps.

method will be used in this example. *The volts-per-turn for any transformer is determined by the primary winding.* In this illustration the primary winding is connected across taps B and E. The primary turns are, therefore, the sum of the turns between taps B and E (80 + 100 + 60 = 240 turns). Since 120 volts is connected across 240 turns, this transformer will have a volts-per-turn ratio of 0.5 (240 turns/120 volts = 0.5 volt-per-turn). To determine the amount of voltage between each set of taps, it becomes a simple matter of multiplying the number of turns by the volts-per-turn.

A-B (40 turns × 0.5 = 20 volts)

A-C (120 turns × 0.5 = 60 volts)

A-D (220 turns × 0.5 = 110 volts)

A-E (280 turns × 0.5 = 140 volts)

B-C (80 turns × 0.5 = 40 volts)

B-D (180 turns × 0.5 = 90 volts)

B-E (240 turns × 0.5 = 120 volts)

C-D (100 turns × 0.5 = 50 volts)

C-E (160 turns × 0.5 = 80 volts)

D-E (60 turns × 0.5 = 30 volts)

Using Transformer Formulas

The values of voltage and current for autotransformers can also be determined by using standard transformer formulas. The primary winding of the transformer shown in Figure 22-4 is between points B and N and has a voltage of 120 volts applied to it. If the turns of wire are counted between points B and N, it can be seen there are 120 turns of wire. Now assume that the selector switch is set to point D. The load is now connected between points

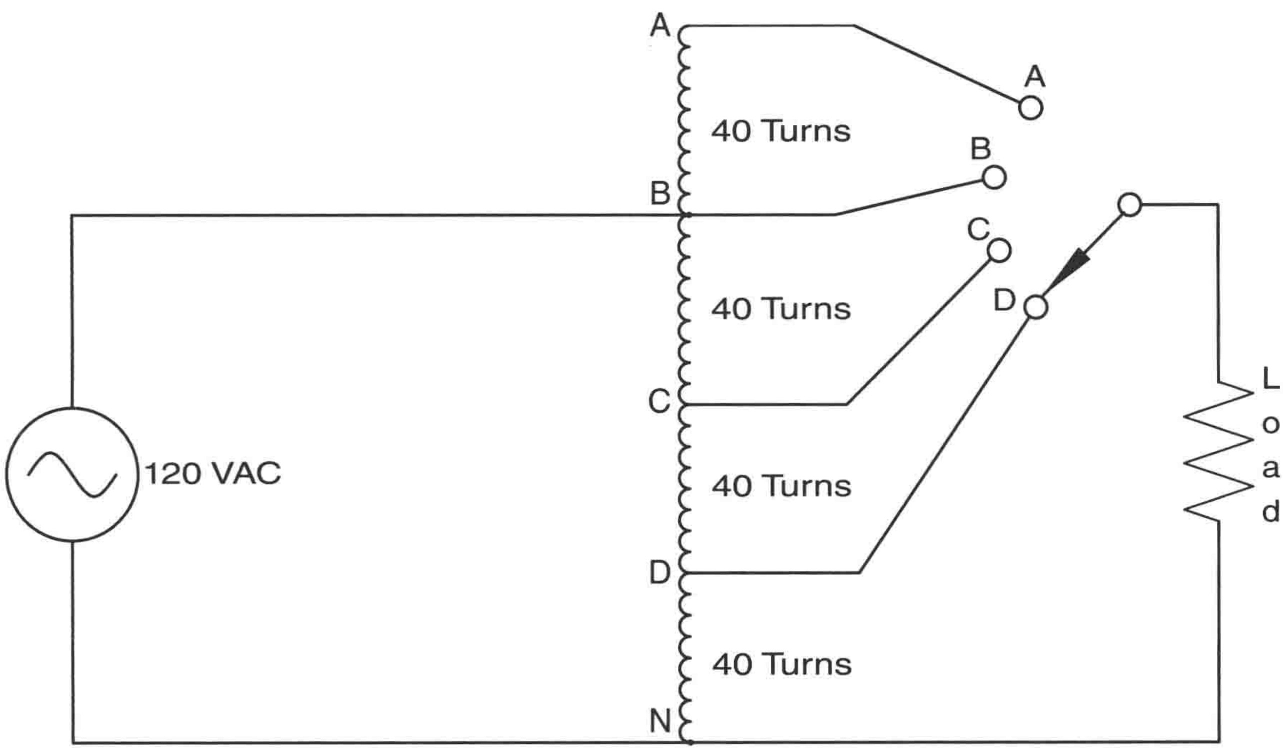

Figure 22-4 Determining voltage and current values.

D and N. The secondary of this transformer contains 40 turns of wire. If the amount of voltage applied to the load is to be computed, the following formula can be used:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{120}{40}$$

$$120E_S = 4{,}800$$

$$E_S = 40 \text{ volts}$$

Assume that the load connected to the secondary has an impedance of 10 Ω. The amount of current flow in the secondary circuit can be computed using the following formula:

$$I = \frac{E}{Z}$$

$$I = \frac{40}{10}$$

$$I = 4 \text{ amps}$$

The primary current can be computed by using the same formula that was used to compute primary current for an isolation type of transformer.

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{40} = \frac{4}{I_P}$$

$$I_P = 1.333 \text{ amps}$$

The amount of power input and output for the autotransformer must also be the same.

Primary	Secondary
$120 \times 1.333 = 160$ volt-amps	$40 \times 4 = 160$ volt-amps

Now assume that the rotary switch is connected to point A. The load is now connected to 160 turns of wire. The voltage applied to the load can be computed by:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{120}{60}$$

$$120E_S = 19{,}200$$

$$E_S = 160 \text{ volts}$$

The amount of secondary current can be computed using the formula:

$$I = \frac{E}{Z}$$

$$I = \frac{160}{10}$$

$$I = 16 \text{ amps}$$

The primary current can be computed using the formula:

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{160} = \frac{16}{I_P}$$

$$120I_P = 2{,}560$$

$$I_P = 21.333 \text{ amps}$$

The answers can be checked by determining if the power in and power out are the same.

Primary	Secondary
120 × 21.333 = 2,560 volt-amps	160 × 16 = 2,560 volt-amps

Current Relationships

An autotransformer with a 2:1 turns-ratio is shown in Figure 22-5. It is assumed that a voltage of 480 volts is connected across the entire winding. Since the transformer has a turns-ratio of 2:1, a voltage of 240 volts will be supplied to the load. Ammeters connected in series with each winding indicate the current flow in the circuit. It is assumed that the load produces a current flow of 4 amperes on the secondary. Note that a current flow of 2 amperes is supplied to the primary.

$$I_{PRIMARY} = \frac{I_{SECONDARY}}{\text{Ratio}}$$

$$I_P = \frac{4}{2}$$

$$I_P = 2 \text{ amperes}$$

If the rotary switch shown in Figure 22-4 were to be removed and replaced with a sliding tap that made contact directly to the transformer winding, the turns-ratio could be adjusted continuously. This type of transformer is commonly referred to as a Variac or Powerstat depending on the manufacturer. The windings are wrapped around a tape-wound torroid core inside a plastic case. The tops of the windings have been milled flat similar to a commutator. A carbon brush makes contact with the windings. When the

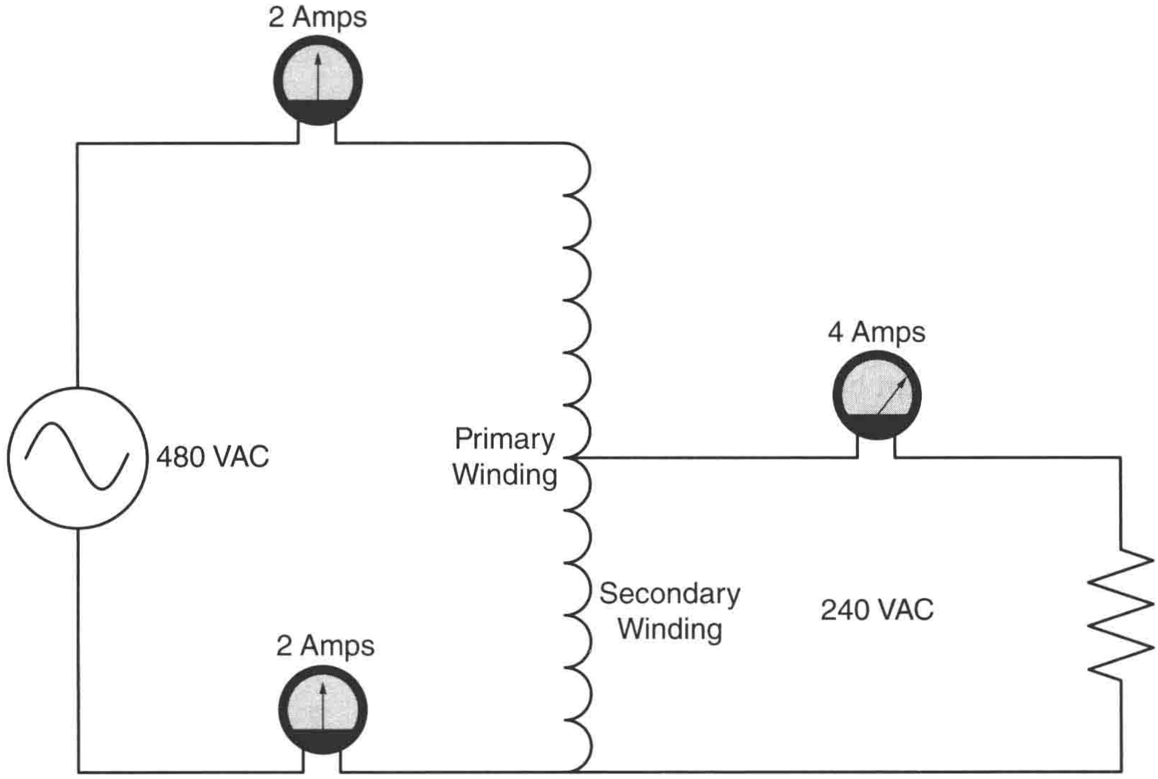

Figure 22-5 Current divides between primary and secondary.

brush is moved across the windings, the turns-ratio changes, which changes the output voltage. This type of autotransformer provides a very efficient means of controlling AC voltage. Autotransformers are often used by power companies to provide a small increase or decrease to the line voltage. They help provide voltage regulation to large power lines.

The autotransformer does have one disadvantage. Since the load is connected to one side of the power line, there is no line isolation between the incoming power and the load. This can cause problems with certain types of equipment and must be a consideration when designing a power system.

LABORATORY EXERCISE

Name ______________________________________ Date __________

Materials Required

480-240/120-volt, 0.5-kVA control transformer

AC voltmeter

2 AC ammeter, in-line or clamp-on. (If the clamp-on type is used, a 10:1 scale divider is recommended.)

4 150-ohm resistors

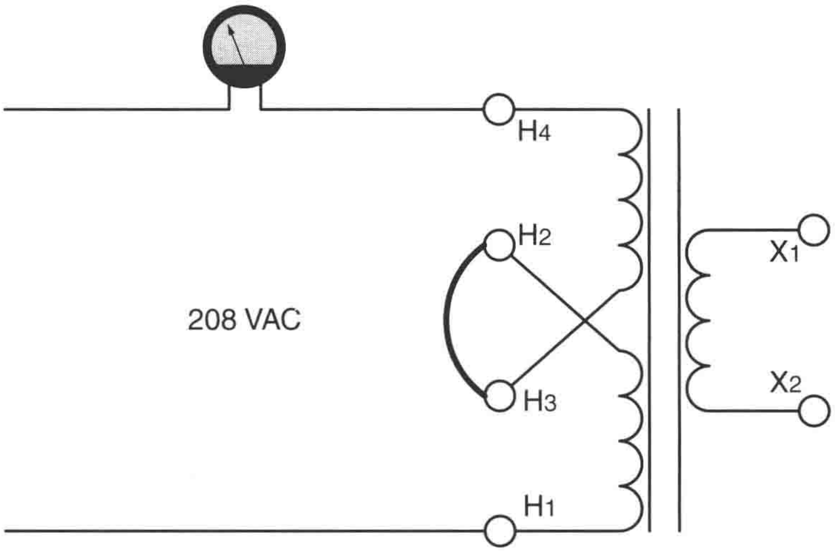

Figure 22-6 Connecting the high-voltage windings as an autotransformer.

In this experiment the control transformer will be connected for operation as an autotransformer. The low-voltage winding will not be used in this experiment. The two high-voltage windings will be connected in series to form one continuous winding. The transformer will be connected as both a step-down and a step-up transformer.

1. Series connect the two high-voltage windings by connecting terminals H_2 and H_3 together. The H_1 and H_4 terminals will be connected to a source of 208 VAC. Connect an ammeter in series with one of the power supply lines, as shown in Figure 22-6.
2. Turn on the power supply and measure the excitation current. The current will be small, and it may be difficult to determine this current value.

   $I_{(EXC)}$ ____________ amp(s)
3. Measure the primary voltage across terminals H_1 and H_4.

   $E_{(PRIMARY)}$ ____________ volts
4. Measure the secondary voltage across terminals H_1 and H_2. (Note: It is also possible to use terminals H_3 and H_4 as the secondary winding.)

   $E_{(SECONDARY)}$ ____________ volts
5. Determine the turns-ratio of this transformer connection.

$$\text{Turns-ratio} = \frac{\text{Higher voltage}}{\text{Lower voltage}}$$

   Ratio ____________
6. **Turn off the power supply.**
7. Connect an AC ammeter in series with the H_2 terminal and a 150-ohm resistor as shown in Figure 22-7. The secondary winding of the transformer will be between terminals H_2 and H_1.
8. Calculate the secondary current using Ohm's law.

   $I_{(SECONDERY)} =$ __________ A
9. Calculate the primary current using the turns-ratio.

$$I_{PRIMARY} = \frac{I_{SECONDARY}}{\text{Turns-Ratio}} + E_{EXC}$$

   $I_{(PRIMARY)} =$ __________ A

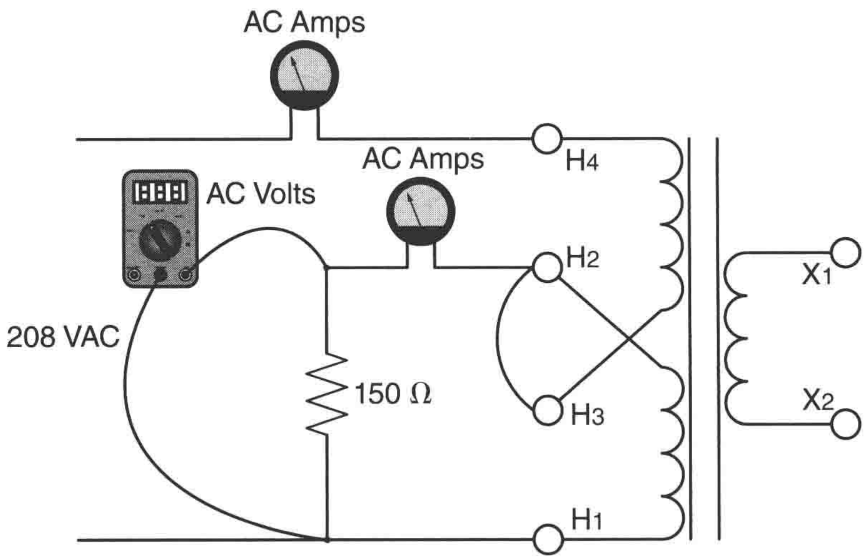

Figure 22-7 Connecting a load to the autotransformer.

10. Turn on the power and measure the secondary current, primary current, and voltage drop across the secondary. **Turn off the power.**

    $I_{(SECONDARY)}$ ________ A

    $I_{(PRIMARY)}$ ________ A

    $E_{(SECONDARY)}$ ________ volts

11. Compare the measured values with the calculated values in steps 8 and 9. Are they within 5% of each other?

    ____

12. Connect a second 150-ohm resistor in parallel with the first as shown in Figure 22-8. This should provide a total resistance of 75 ohms (150/2). Calculate the secondary current and primary current.

    $I_{(SECONDARY)}$ = ________ A

    $I_{(PRIMARY)}$ = ________ A

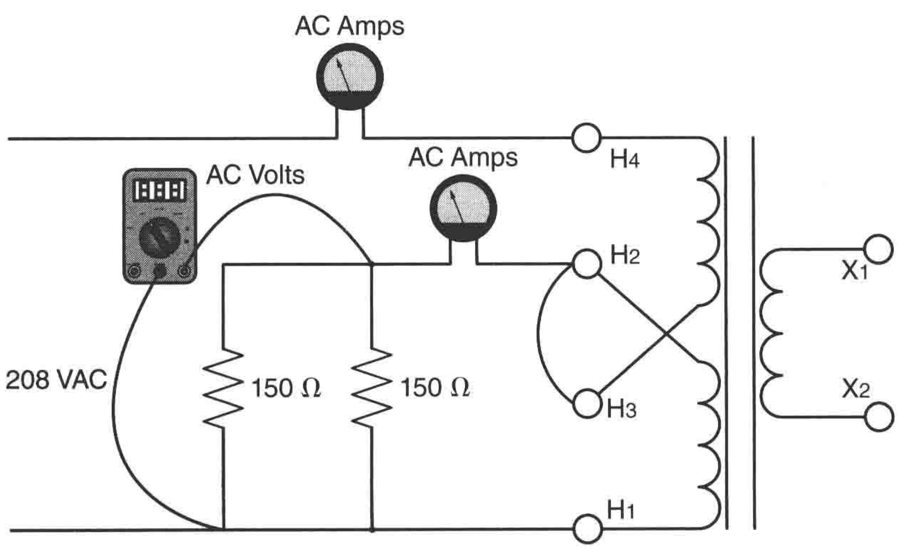

Figure 22-8 Adding load to the autotransformer.

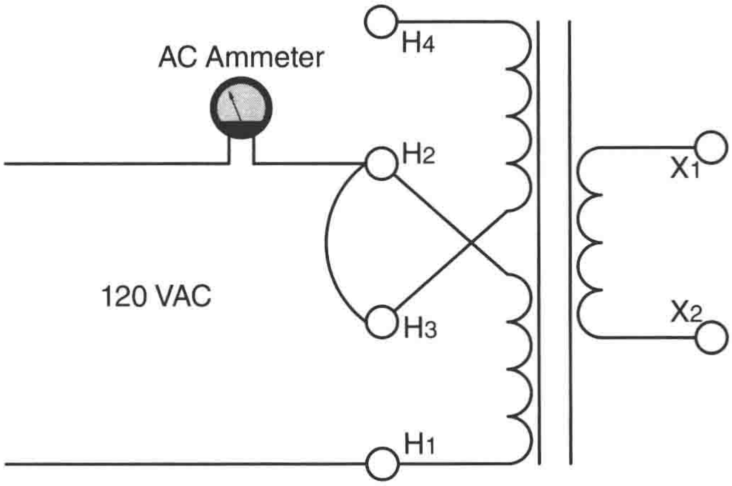

Figure 22-9 The autotransformer connected for high voltage.

13. Turn on the power and measure the secondary current, primary current, and voltage drop across the secondary. **Turn off the power.**

    $I_{(SECONDARY)}$ __________ A

    $I_{(PRIMARY)}$ __________ A

    $E_{(SECONDARY)}$ __________ volts

14. Compare the measured values with the calculated values in step 12. Are they within 5% of each other?

    ____

15. The transformer will now be connected as a step-up autotransformer. Connect the circuit shown in Figure 22-9. Turn on the power and measure the excitation current of the primary. **Turn off the power.**

    $I_{(EXC)}$ = __________ A

16. Connect an AC voltmeter across terminals H1 and H4 of the transformer. Turn on the power and measure the secondary voltage. **Turn off the power.**

    $E_{(SECONDARY)}$ = __________ volts

17. Determine the turns-ratio of the transformer.

    Ratio __________

18. Connect the circuit shown in Figure 22-10.
19. Calculate the secondary current and the primary current.

    $I_{(SECONDARY)}$ __________ A

    $I_{(PRIMARY)}$ __________ A

20. Turn on the power and measure the secondary current, primary current, and voltage drop across the transformer secondary winding. **Turn off the power.**

    $I_{(SECONDARY)}$ __________ A

    $I_{(PRIMARY)}$ __________ A

    $E_{(SECONDARY)}$ __________ volts

21. Compare the measured values with the calculated values in step 19. Are they within 5% of each other?

    ____

22. Disconnect the circuit and return the components to their proper place.

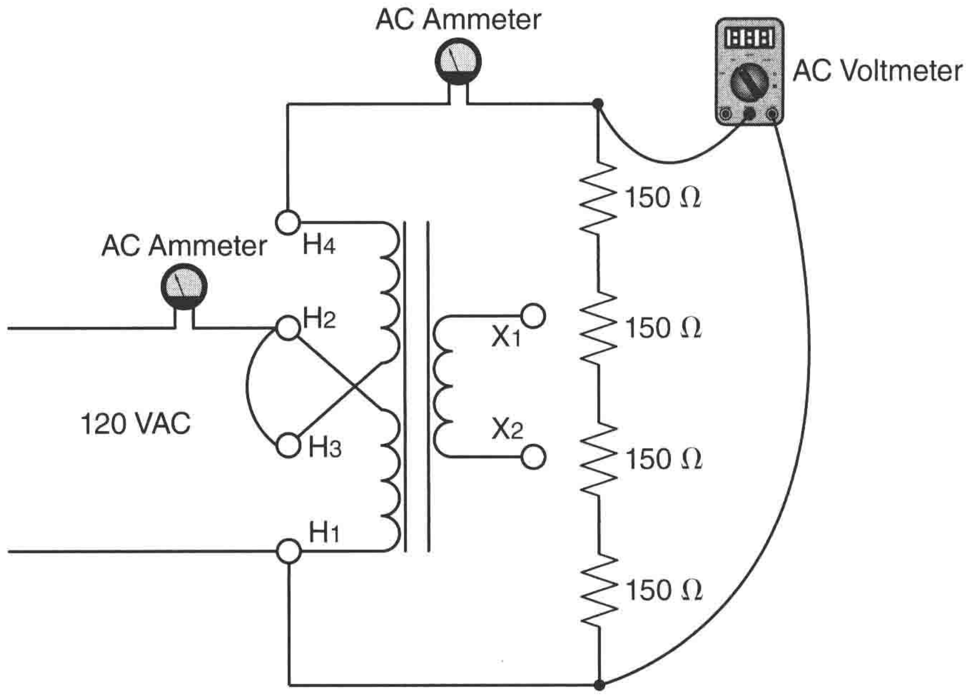

Figure 22-10 Adding load to the secondary winding.

Review Questions

1. An AC power source is connected across 325 turns of an autotransformer and the load is connected across 260 turns. What is the turns-ratio of this transformer?

____

2. Is the transformer in question 1 a step-up or step-down transformer?

____

3. An autotransformer has a turns-ratio of 3.2:1. A voltage of 208 volts is connected across the primary. What is the voltage of the secondary?

____

4. A load impedance of 52 Ω is connected to the secondary winding of the transformer in question 3. How much current will flow in the secondary?

____

5. How much current will flow in the primary of the transformer in question 4?

____

6. The autotransformer shown in Figure 22-3 has the following number of turns between windings: A-B (120 turns), B-C (180 turns), C-D (250 turns), and D-E (300 turns). A voltage of 240 volts is connected across B and E. Find the voltages between each of the following points:

A-B _____ A-C _____ A-D _____ A-E _____ B-C _____ B-D _____
B-E _____ C-D _____ C-E _____ D-E _____

Unit 23 Three-Phase Circuits

Objectives

After studying this unit, you should be able to:

- Connect a wye connected, three-phase load.
- Calculate and measure voltage and current values for a wye connected load.
- Connect a delta connected load.
- Calculate and measure voltage and current values for a delta connected load.

Before beginning the study of three-phase transformers, it is appropriate to discuss three-phase power connections and basic circuit calculations. This unit may be review for some students and new ground for others. Whichever is the case, a working knowledge of three-phase circuits is essential before beginning the study of three-phase transformers.

Most of the power generated in the world today is three-phase. Three-phase power was first conceived by a man named Nikola Tesla. There are several reasons why three-phase power is superior to single-phase power.

1. The kVA rating of three-phase transformers is about 150% greater than for a single-phase transformer with a similar core size.
2. The power delivered by a single-phase system pulsates (Figure 23-1). The power falls to zero three times during each cycle. The power delivered by a three-phase circuit pulsates also, but the power never falls to zero (Figure 23-2). In a three-phase system, the power delivered to the load is the same at any instant.

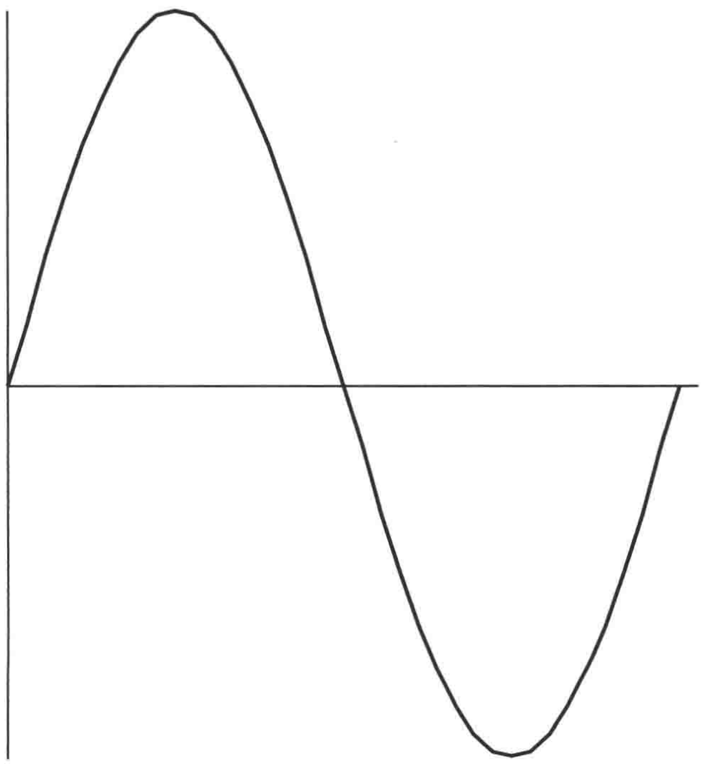

Figure 23-1 Single-phase power falls to zero three times each cycle.

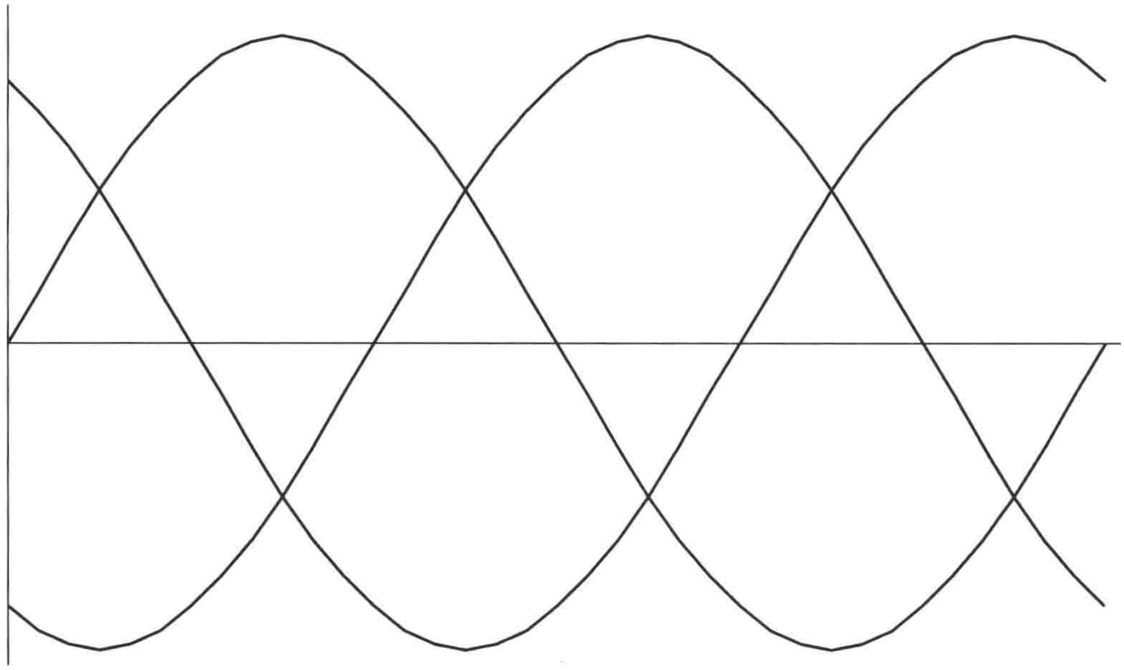

Figure 23-2 Three-phase power never falls to zero.

3. In a balanced three-phase system, the conductors need be only about 75% the size of conductors for a single-phase two-wire system of the same kVA rating. This helps offset the cost of supplying the third conductor required by three-phase systems.

A single-phase alternating voltage can be produced by rotating a magnetic field through the conductors of a stationary coil as shown in Figure 23-3. Since alternate polarities of the magnetic field cut through the conductors of the stationary coil, the induced voltage will change polarity at the same speed as the rotation of the magnetic field. The alternator shown in Figure 23-3 is single-phase because it produces only one AC voltage.

If three separate coils are spaced 120° apart as shown in Figure 23-4, three voltages 120° out of phase with each other will be produced when the magnetic field cuts through the coils. This is the manner in which a three-phase voltage is produced. There are two basic three-phase connections, the *wye* or *star,* and the *delta.*

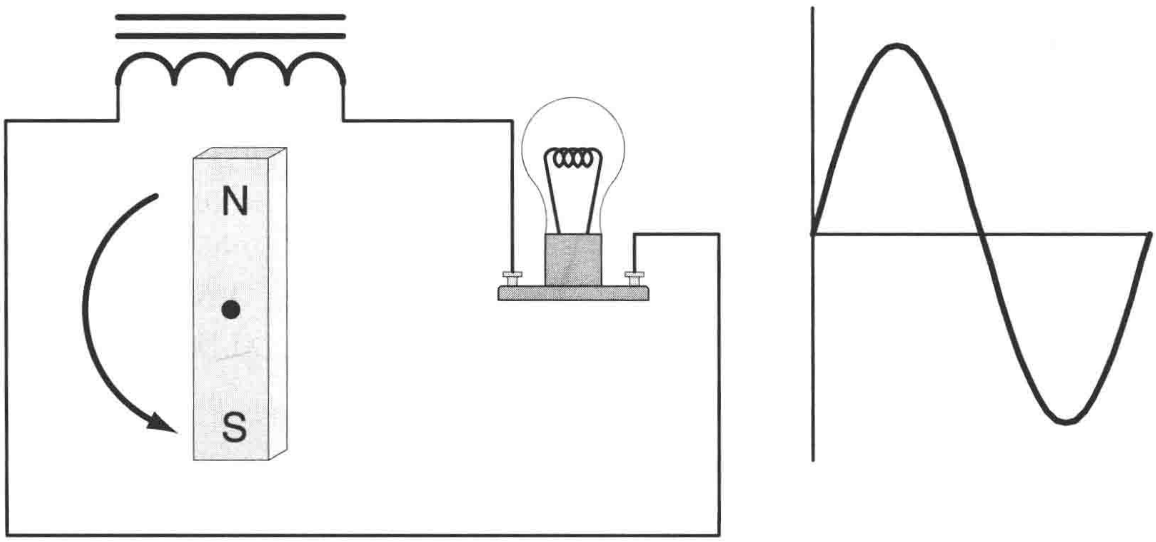

Figure 23-3 Producing a single-phase voltage.

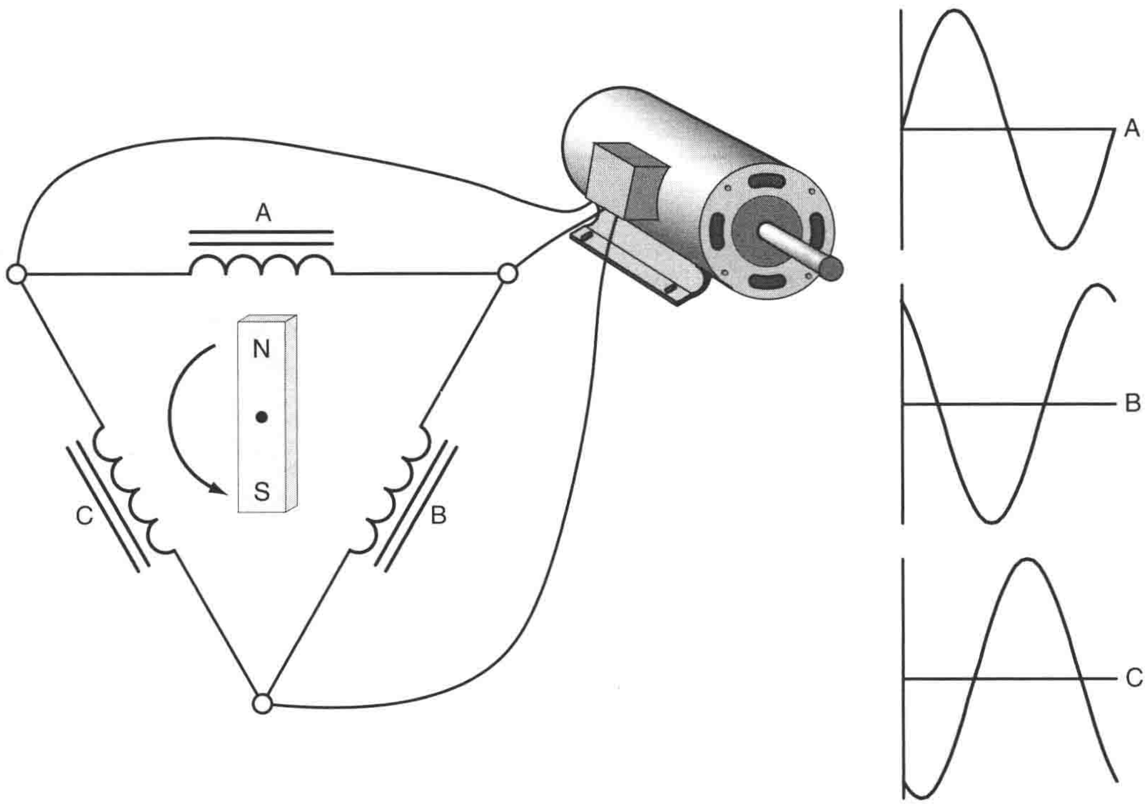

Figure 23-4 The voltages of a three-phase system are 120° out of phase with each other.

Wye Connection

The wye or star connection is made by connecting one end of each of the three-phase windings together, as shown is Figure 23-5. The voltage measured across a single winding or phase is known as the *phase* voltage as shown in Figure 23-6. The voltage measured between the lines is known as the line-to-line voltage or simply as the *line* voltage.

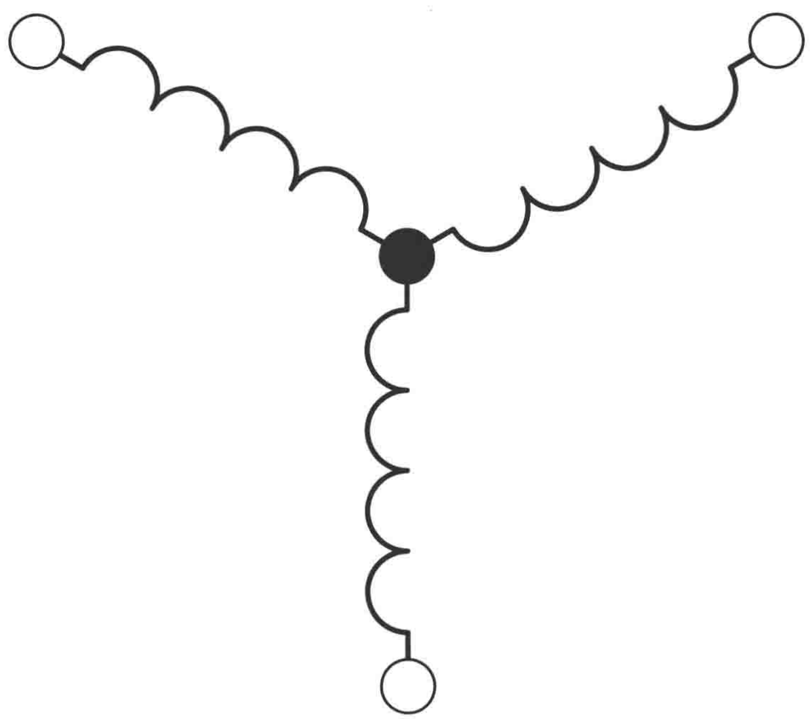

Figure 23-5 A wye connection is formed by joining one end of each winding together.

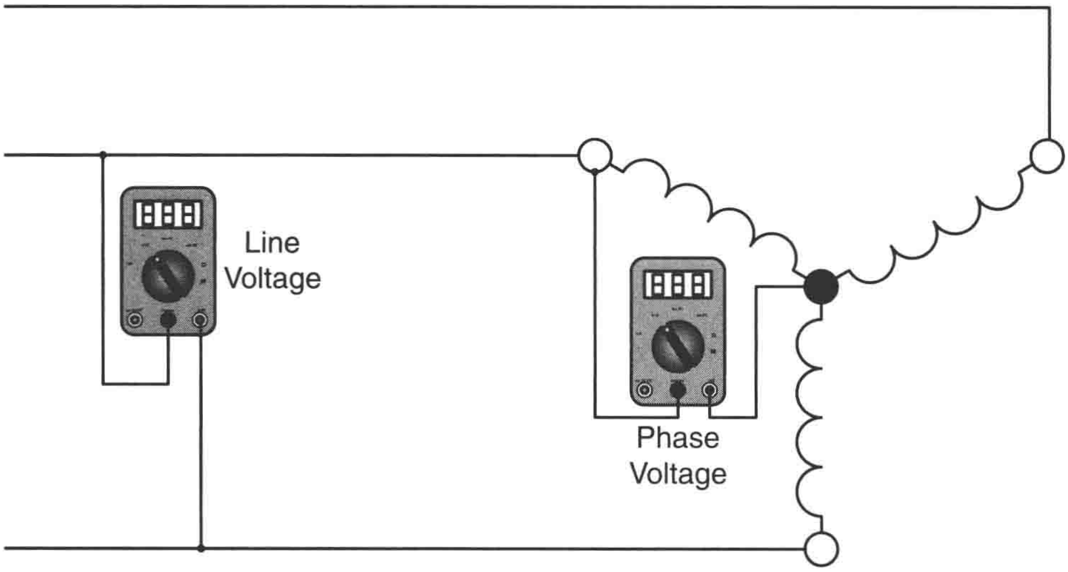

Figure 23-6 Line and phase voltages are different in a wye connection.

In Figure 23-7, ammeters have been placed in the phase winding of a wye connected load and in the line supplying power to the load. Voltmeters have been connected across the input to the load and across the phase. A line voltage of 208 volts has been applied to the load. Notice that the voltmeter connected across the lines indicates a value of 208 volts, but the voltmeter connected across the phase indicates a value of 120 volts.

In a wye connected system, the line voltage is higher than the phase voltage by a factor of $\sqrt{3}$ (1.732). Two formulas used to compute the voltage in a wye connected system are:

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

or

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

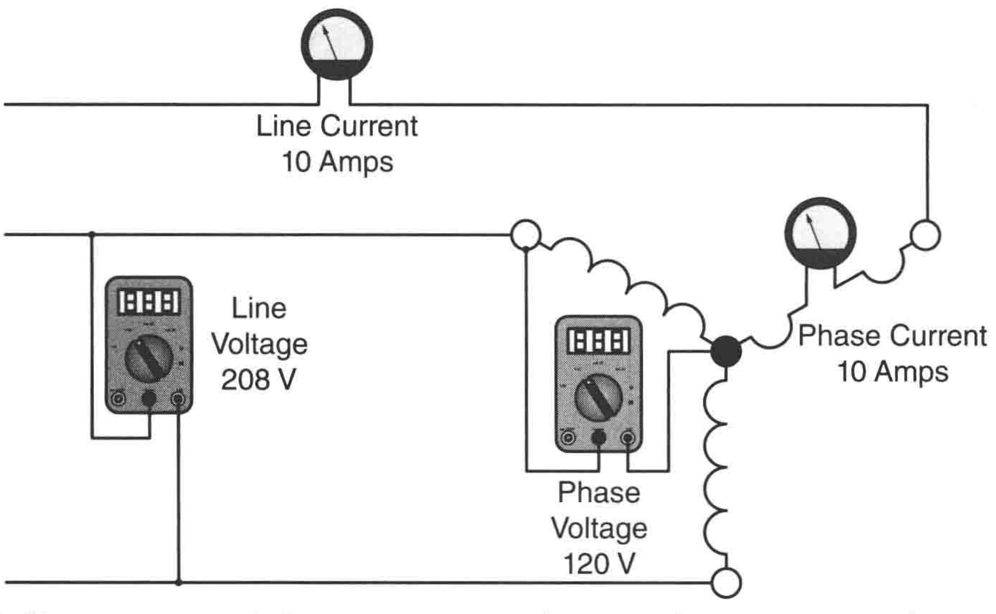

Figure 23-7 Line current and phase current are the same in a wye connection.

Also, notice in Figure 23-7 that there is 10 amps of current flow in both the phase and the line. In a wye connected system, phase current and line current are the same.

$$I_{LINE} = I_{PHASE}$$

Helpful Hint

In a wye connected system, the line voltage is higher than the phase voltage by a factor of $\sqrt{3}$ (1.732).

In a wye connected system, phase current and line current are the same.

$$I_{LINE} = I_{PHASE}$$

Voltage Relationships in a Wye Connection

Many students of electricity have difficulty at first understanding why the line voltage of the wye connection used in this illustration is 208 volts instead of 240 volts. Since line voltage is measured across two phases that have a voltage of 120 volts each, it would appear that the sum of the two voltages should be 240 volts. One cause of this misconception is that many students are familiar with the 240/120 volt connection supplied to most homes. If voltage is measured across the two incoming lines, a voltage of 240 volts will be seen. If voltage is measured from either of the two lines to the neutral, a voltage of 120 volts will be seen. The reason for this is that this connection is derived from the center tap of an isolation transformer, as shown in Figure 23-8. If the center tap is used as a common point, the two line voltages on either side of it will

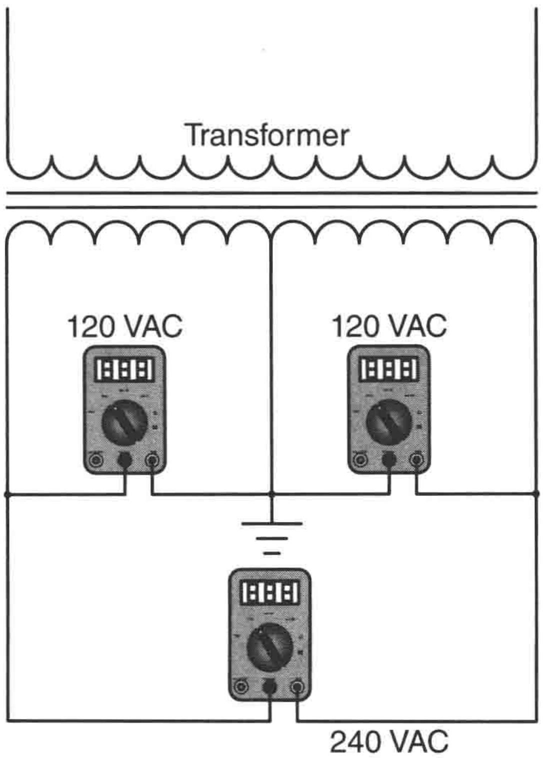

Figure 23-8 Single-phase transformer with grounded center tap.

be in phase with each other. Since the two voltages are in phase, they add similar to a boost connected transformer, as shown in Figure 23-9. The vector sum of these two voltages would be 240 volts.

Three-phase voltages are 120° apart, not in phase. If the three voltages are drawn 120° apart, it will be seen that the vector sum of these voltages is 208 volts, as shown in Figure 23-10. Another illustration of vector addition is shown in Figure 23-11. In this illustration, two-phase voltage vectors are added and the resultant is drawn from the starting point of one vector to the end point of the other. The parallelogram method of vector addition for the voltages in a wye connected three-phase system is shown in Figure 23-12.

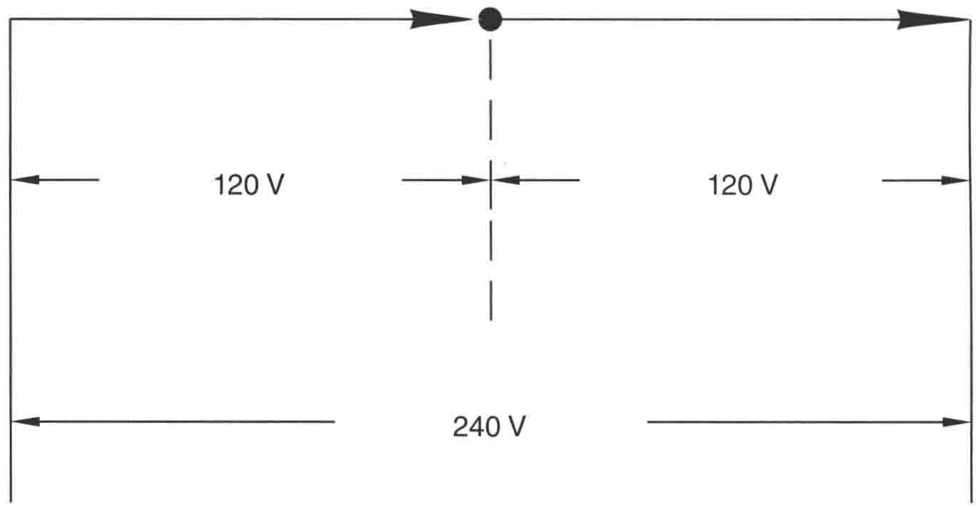

Figure 23-9 The two voltages are in phase with each other.

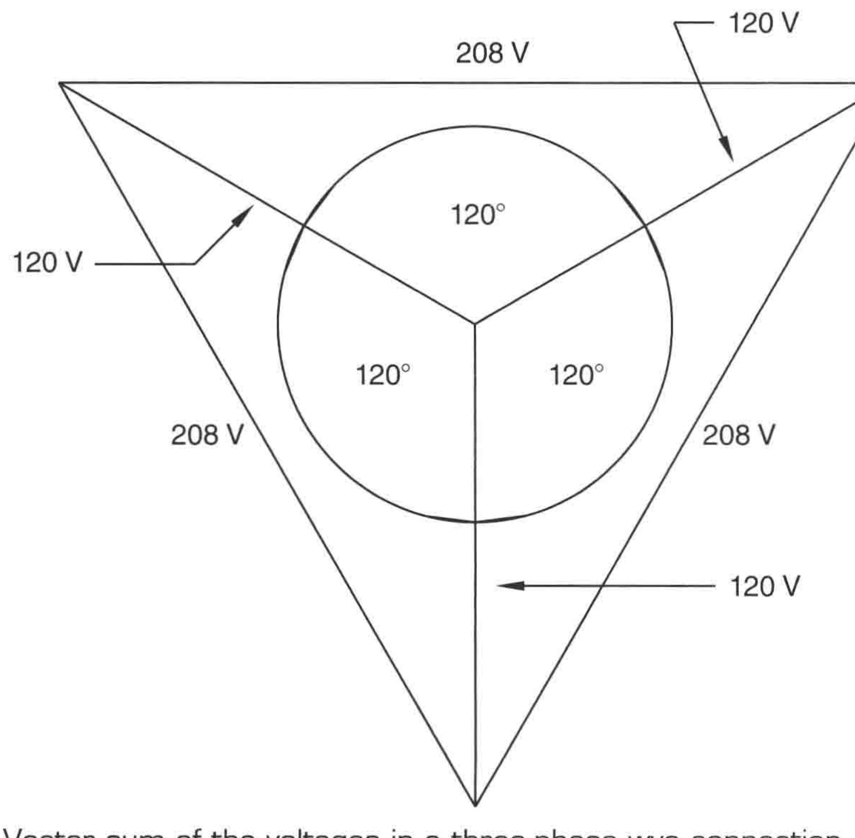

Figure 23-10 Vector sum of the voltages in a three-phase wye connection.

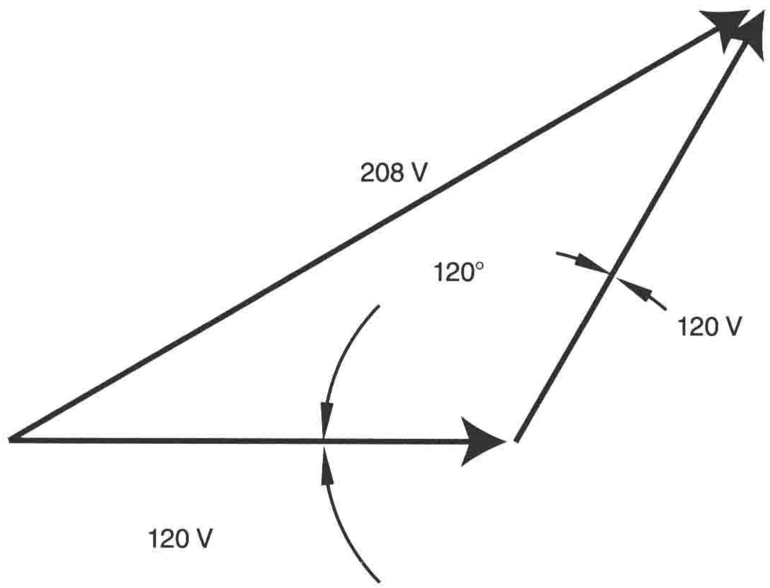

Figure 23-11 Adding voltage vectors of two-phase voltage values.

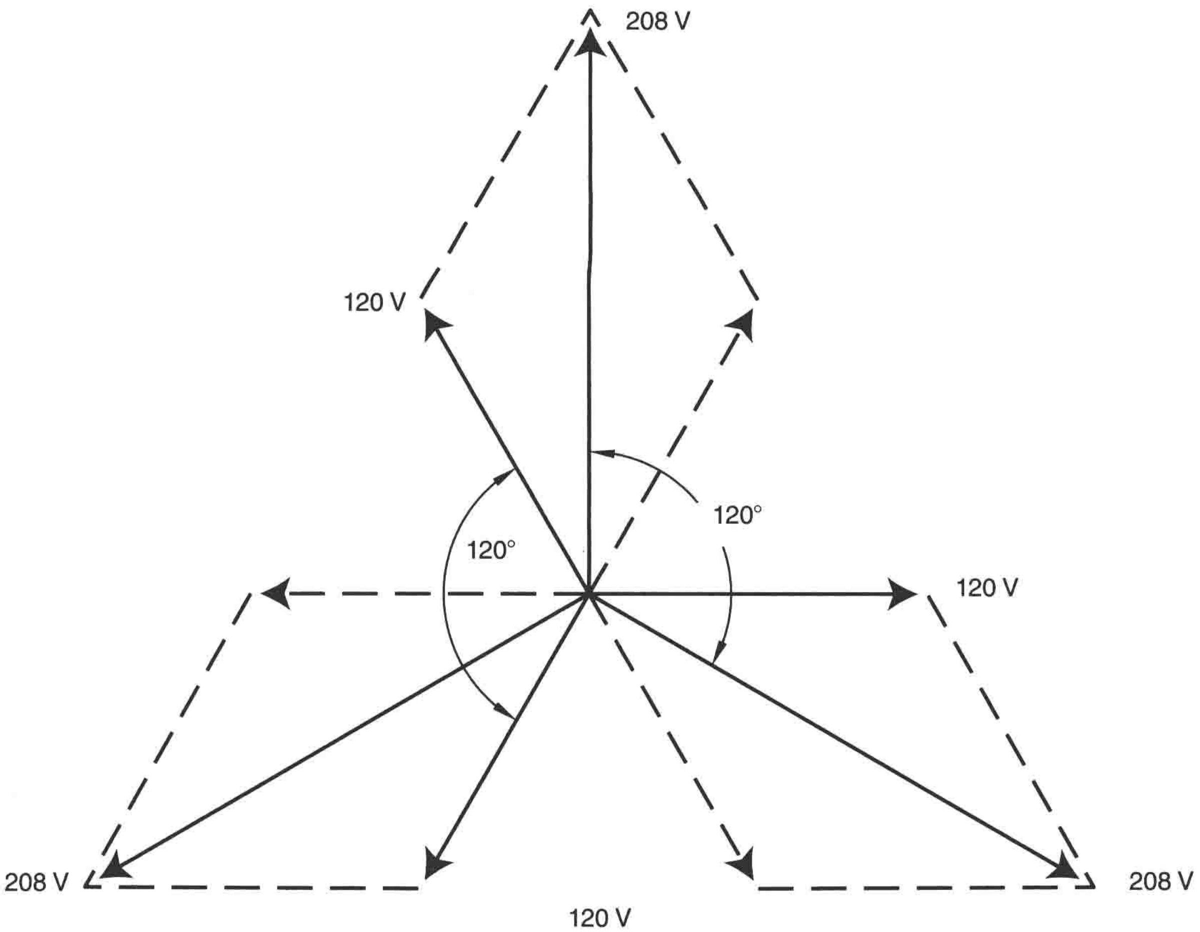

Figure 23-12 The parallelogram method of adding three-phase vectors.

Delta Connection

In Figure 23-13, three separate inductive loads have been connected to form a delta connection. This connection receives its name from the fact that a schematic diagram of this connection resembles the Greek letter delta (Δ). In Figure 23-14, voltmeters have been connected across the lines and across the phase. Ammeters have been connected in the

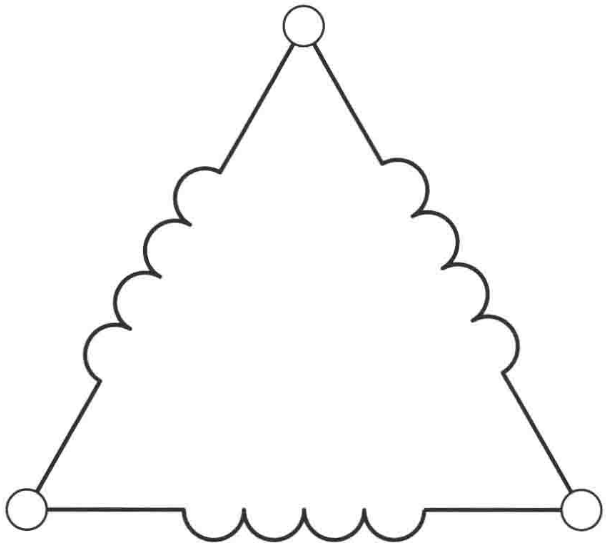

Figure 23-13 Three-phase delta connection.

line and in the phase. In the delta connection, line voltage and phase voltage are the same. Notice that both voltmeters indicated a value of 480 volts.

$$E_{LINE} = E_{PHASE}$$

Helpful Hint

In the delta connection, line voltage and phase voltage are the same.

Notice that the line current and phase current are different, however. The line current of a delta connection is higher than the phase current by a factor of $\sqrt{3}$ (1.732). In the example shown, it is assumed that each of the phase windings has a current flow of 10 amperes. The current in each of the lines, however, is 17.32 amperes. The reason for this

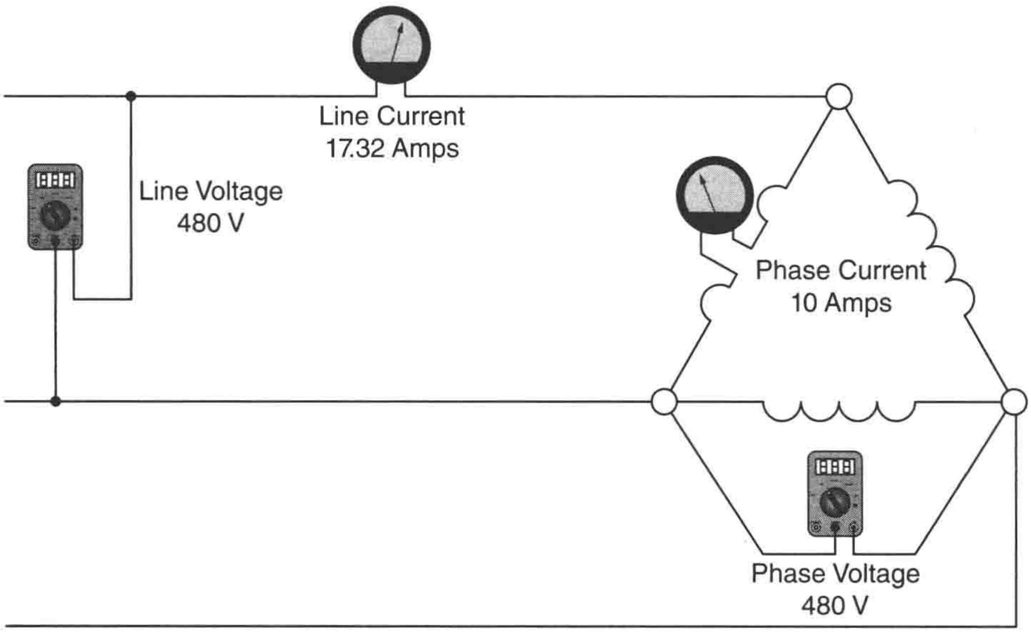

Figure 23-14 Voltage and current relationships in a delta connection.

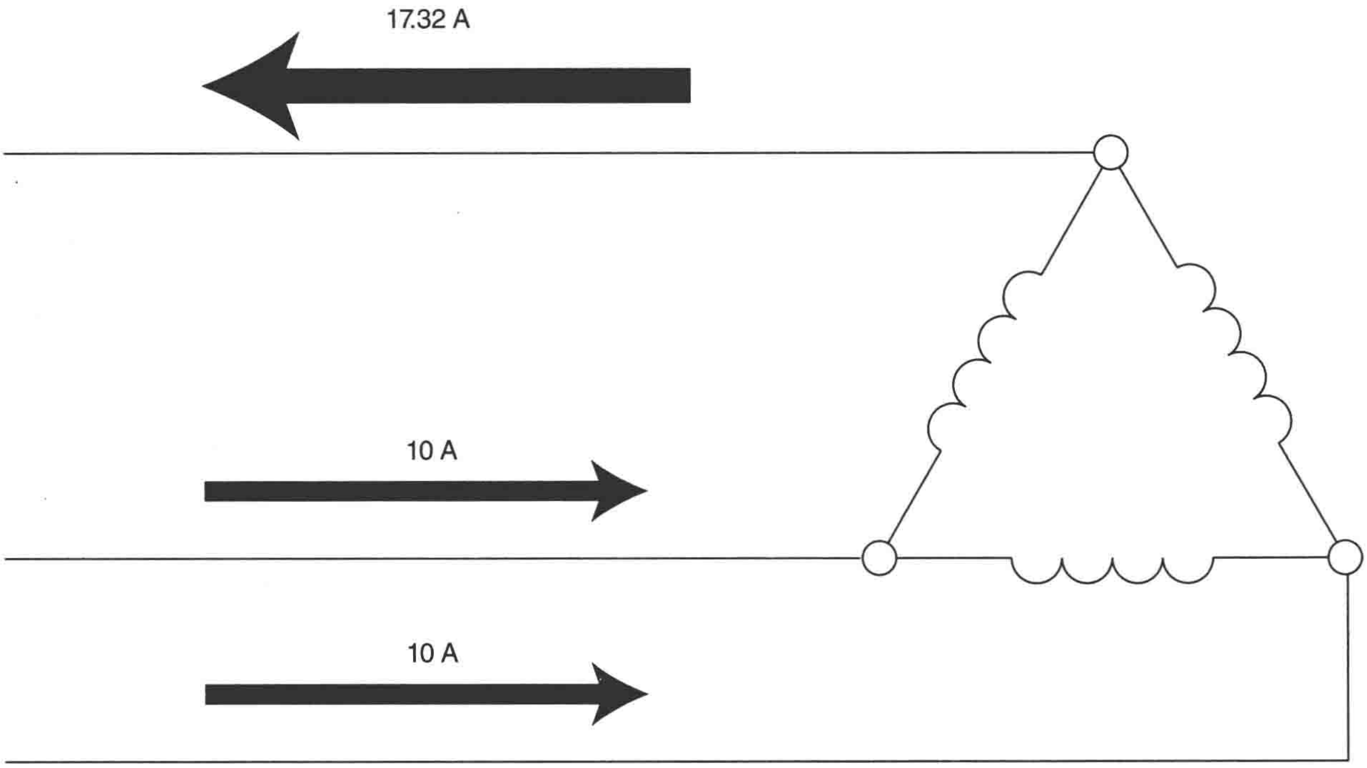

Figure 23-15 Division of currents in a delta connection.

difference in current is that current flows through different windings at different times in a three-phase circuit. During some periods of time, current will flow between two lines only. At other times, current will flow from two lines to the third, seen in Figure 23-15. The delta connection is similar to a parallel connection because there is always more than one path for current flow. Since these currents are 120° out of phase with each other, vector addition must be used when finding the sum of the currents (Figure 23-16). Formulas for determining the current in a delta connection are:

$$I_{PHASE} = \frac{I_{LINE}}{\sqrt{3}}$$

or

$$I_{LINE} = I_{PHASE} \times \sqrt{3}$$

Three-Phase Power

Students sometimes become confused when computing values of power in three-phase circuits. One reason for this confusion is because there are actually two formulas that can be used. If LINE values of voltage and current are known, the apparent power of the circuit can be computed using the formula:

$$VA = \sqrt{3} \times E_{LINE} \times I_{LINE}$$

If the PHASE values of voltage and current are known, the apparent power can be computed using the formula:

$$VA = 3 \times E_{PHASE} \times I_{PHASE}$$

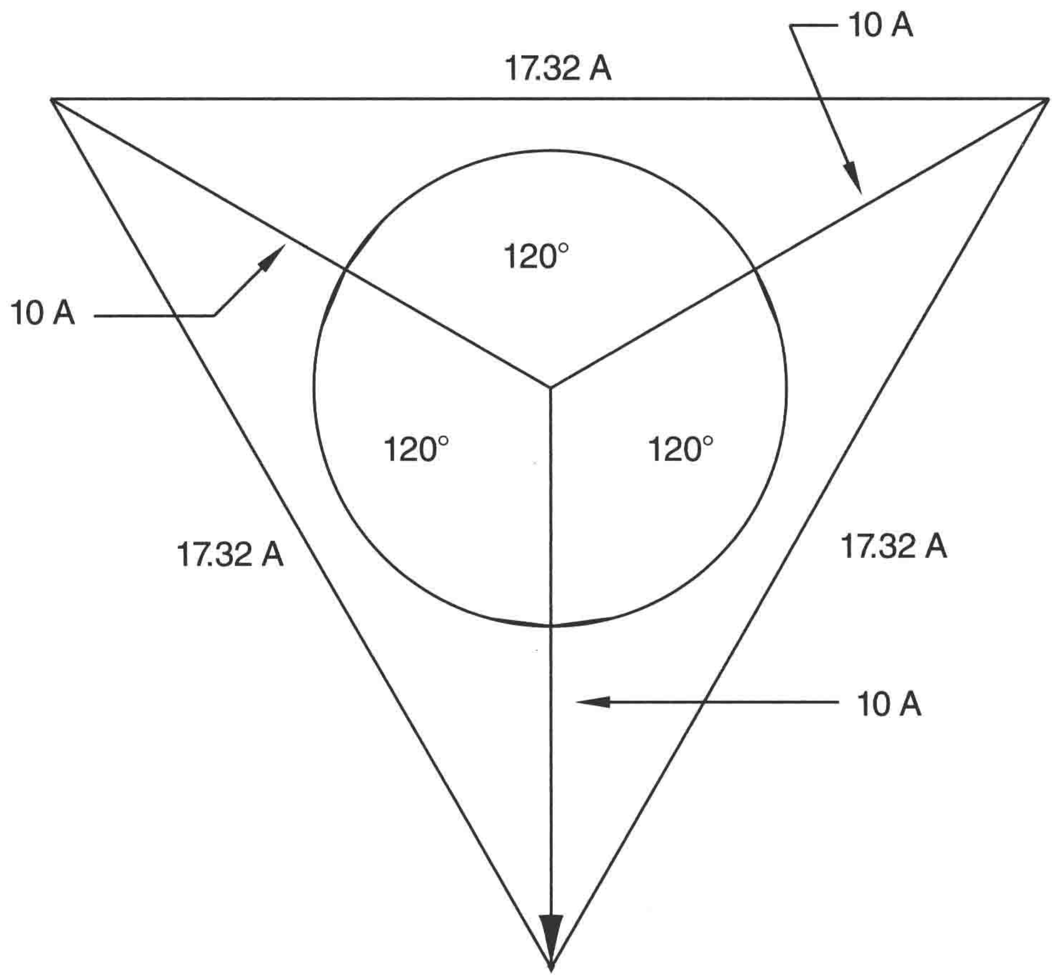

Figure 23-16 Vector addition is used to compute the sum of the currents in a delta connection.

Notice that in the first formula, the line values of voltage and current are multiplied by the square root of 3. In the second formula, the phase values of voltage and current are multiplied by 3. The first formula is the most used because it is generally more convenient to obtain line values of voltage and current because they can be measured with a voltmeter and clamp-on ammeter.

Watts and VARs

Watts and VARs can be computed in a similar manner. Watts can be computed by multiplying the apparent power by the power factor:

$$P = \sqrt{3} \times E_{LINE} \times I_{LINE} \times PF$$

or

$$P = 3 \times E_{PHASE} \times I_{PHASE} \times PF$$

Note: When computing the power of a pure resistive load, the voltage and current are in phase with each other and the power factor is 1.

VARs can be computed in a similar manner, except that voltage and current values of a pure reactive load are used. For example, a pure capacitive load is shown in Figure 23-17.

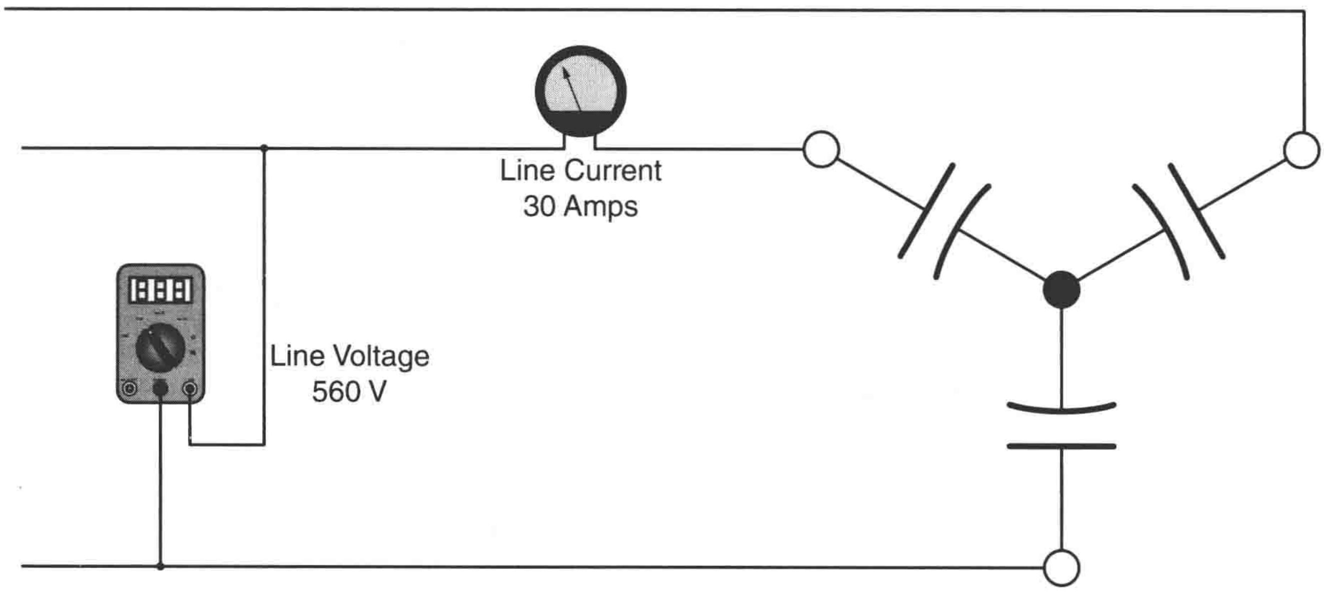

Figure 23-17 Pure capacitive three-phase load.

In this example, it is assumed that the line voltage is 480 volts and the line current is 30 amperes. Capacitive VARs can be computed using the formula:

$$VARs_C = \sqrt{3} \times E_{LINE(CAPACITIVE)} \times I_{LINE(CAPACITIVE)}$$

$$VARs_C = 1.732 \times 560 \times 30$$

$$VARs_C = 29{,}097.6$$

Three-Phase Circuit Calculations

In the following examples, values of line and phase voltage, line and phase current, and power will be computed for different types of three-phase connections.

Example #1. A wye connected, three-phase alternator supplies power to a delta connected resistive load, as shown in Figure 23-18. The alternator has a line voltage of 480 volts. Each resistor of the delta load has 8 Ω of resistance. Find the following values:

$E_{L(LOAD)}$ - Line voltage of the load

$E_{P(LOAD)}$ - Phase voltage of the load

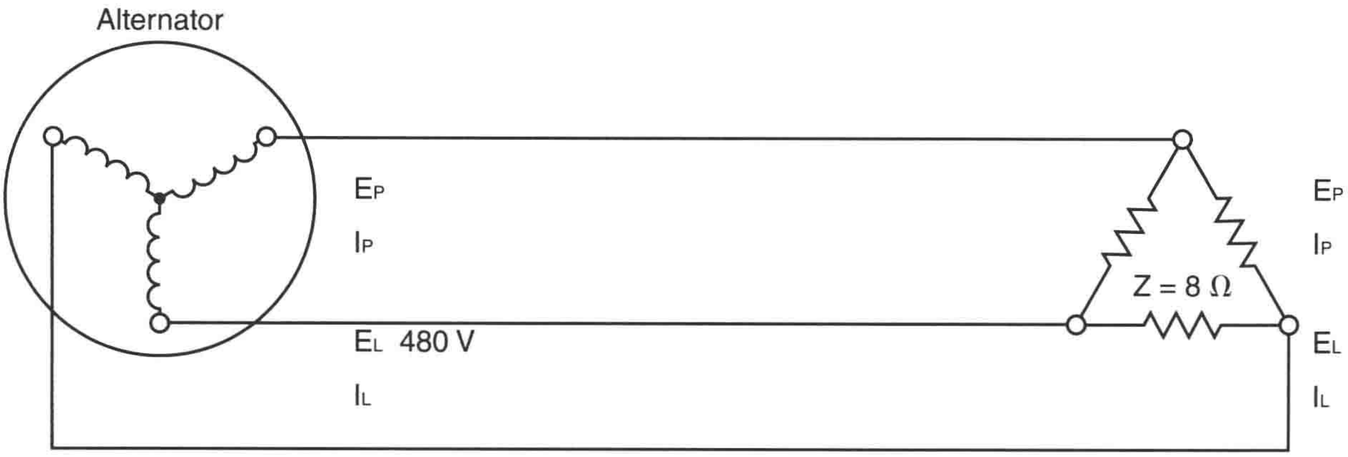

Figure 23-18 Computing three-phase values: Example Circuit #1.

$I_{P(LOAD)}$ - Phase current of the load
$I_{L(LOAD)}$ - Line current to the load
$I_{L(ALT)}$ - Line current delivered by the alternator
$E_{P(ALT)}$ - Phase voltage of the alternator
P - True power

Solution: The load is connected directly to the alternator. Therefore, the line voltage supplied by the alternator is the line voltage of the load.

$$E_{L(LOAD)} = 480 \text{ volts}$$

The three resistors of the load are connected in a delta connection. In a delta connection, the phase voltage is the same as the line voltage.

$$E_{P(LOAD)} = E_{I(LOAD)}$$

$$E_{P(LOAD)} = 480 \text{ volts}$$

Each of the three resistors in the load comprises one phase of the load. Now that the phase voltage is known (480 volts), the amount of phase current can be computed using Ohm's law.

$$I_{P(LOAD)} = \frac{E_{P(LOAD)}}{Z}$$

$$I_{P(LOAD)} = \frac{480}{8}$$

$$I_{P(LOAD)} = 60 \text{ amps}$$

In this example the three load resistors are connected as a delta with 60 amperes of current flow in each phase. The line current supplying a delta connection must be 1.732 times greater than the phase current.

$$I_{L(LOAD)} = I_{P(LOAD)} \times 1.732$$

$$I_{L(LOAD)} = 60 \times 1.732$$

$$I_{L(LOAD)} = 103.92 \text{ amps}$$

The alternator must supply the line current to the load or loads to which it is connected. In this example, there is only one load connected to the alternator. Therefore, the line current of the load will be the same as the line current of the alternator.

$$I_{L(ALT)} = 103.92 \text{ amps}$$

The phase windings of the alternator are connected in a wye connection. In a wye connection, the phase current and line current are equal. The phase current of the alternator will, therefore, be the same as the alternator line current.

$$I_{P(ALT)} = 103.92 \text{ amps}$$

The phase voltage of a wye connection is less than the line voltage by a factor of the square root of 3 ($\sqrt{3}$). The phase voltage of the alternator will be:

$$E_{P(ALT)} = \frac{E_{L(ALT)}}{\sqrt{3}}$$

$$E_{P(ALT)} = \frac{480}{1.732}$$

$$E_{P(ALT)} = 277.13 \text{ volts}$$

In this circuit the load is pure resistive. The voltage and current are in phase with each other, which produces a unity power factor of 1. The true power in this circuit will be computed using the formula:

$$P = 1.732 \times E_{L(ALT)} \times I_{L(ALT)} \times PF$$

$$P = 1.732 \times 480 \times 103.92 \times 1$$

$$P = 86{,}394.93 \text{ watts}$$

Example #2. In the next example, a delta connected alternator is connected to a wye connected resistive load, as shown in Figure 23-19. The alternator produces a line voltage of 240 volts and the resistors have a value of 6 Ω each. The following values will be found:

$E_{L(LOAD)}$ - Line voltage of the load
$E_{P(LOAD)}$ - Phase voltage of the load
$I_{P(LOAD)}$ - Phase current of the load
$I_{L(LOAD)}$ - Line current to the load
$I_{L(ALT)}$ - Line current delivered by the alternator
$E_{P(ALT)}$ - Phase voltage of the alternator
P - True power

As in the first example, the load is connected directly to the output of the alternator. The line voltage of the load must, therefore, be the same as the line voltage of the alternator.

$$E_{L(LOAD)} = 240 \text{ volts}$$

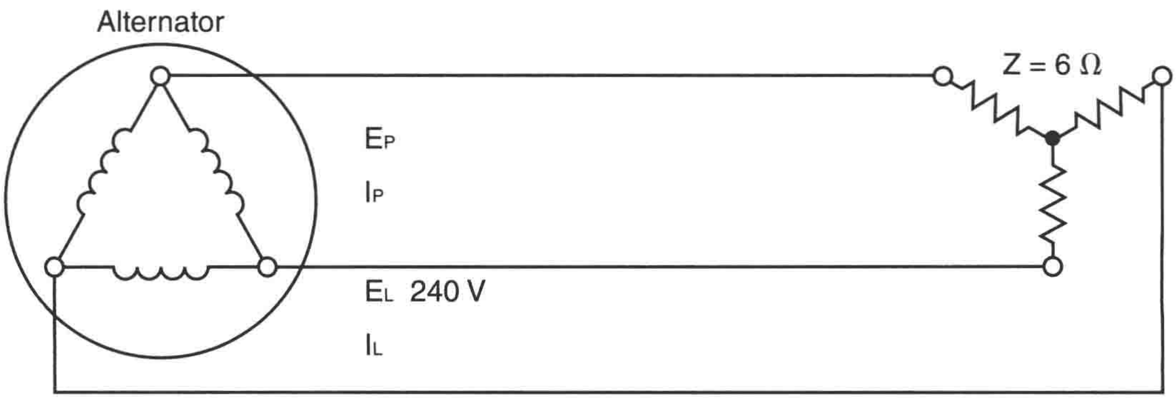

Figure 23-19 Example #2.

The phase voltage of a wye connection is less than the line voltage by a factor of 1.732.

$$E_{P(LOAD)} = \frac{240}{1.732}$$

$$E_{P(LOAD)} = 138.57 \text{ volts}$$

Each of the three 6 Ω resistors comprises one phase of the wye connected load. Since the phase voltage is 138.57 volts, this voltage is applied to each of the three resistors. The amount of phase current can now be determined using Ohm's law.

$$I_{P(LOAD)} = \frac{E_{P(LOAD)}}{Z}$$

$$I_{P(LOAD)} = \frac{138.57}{6}$$

$$I_{P(LOAD)} = 23.1 \text{ amps}$$

The amount of line current needed to supply a wye connected load is the same as the phase current of the load.

$$I_{L(LOAD)} = 23.1 \text{ amps}$$

In this example there is only one load connected to the alternator. The line current supplied to the load is the same as the line current of the alternator.

$$I_{L(ALT)} = 23.1 \text{ amps}$$

The phase windings of the alternator are connected in delta. In a delta connection the phase current is less than the line current by a factor of 1.732.

$$I_{P(ALT)} = \frac{I_{P(ALT)}}{1.732}$$

$$I_{P(ALT)} = \frac{23.1}{1.732}$$

$$I_{P(ALT)} = 13.34 \text{ amps}$$

The phase voltage of a delta is the same as the line voltage.

$$E_{P(ALT)} = 240 \text{ volts}$$

Since the load in this example is pure resistive, the power factor has a value of unity or 1. Power will be computed by using the line values of voltage and current.

$$P = 1.732 \times E_L \times I_L \times PF$$

$$P = 1.732 \times 240 \times 23.1 \times 1$$

$$P = 9{,}602.21 \text{ watts}$$

LABORATORY EXERCISE

Name ______________________________ Date __________

Materials Required

2 AC voltmeters

AC ammeter, in-line or clamp-on. (If a clamp-on type is used, it is recommended to use a 10:1 scale divider.)

6 150-ohm resistors

In this experiment six 150-ohm resistors will be connected to form different three-phase loads. Two lamps will be connected in series to form three separate loads. These loads will be connected to form wye or delta connections.

1. Connect the two 150-ohm resistors in series to form three separated load banks. Connect the load banks in wye by connecting one end of each bank together to form a center point, as shown in Figure 23-20. It is assumed that this load is to be connected to a 208 VAC three-phase line. Connect an AC ammeter in series with the line supplying power to the load.

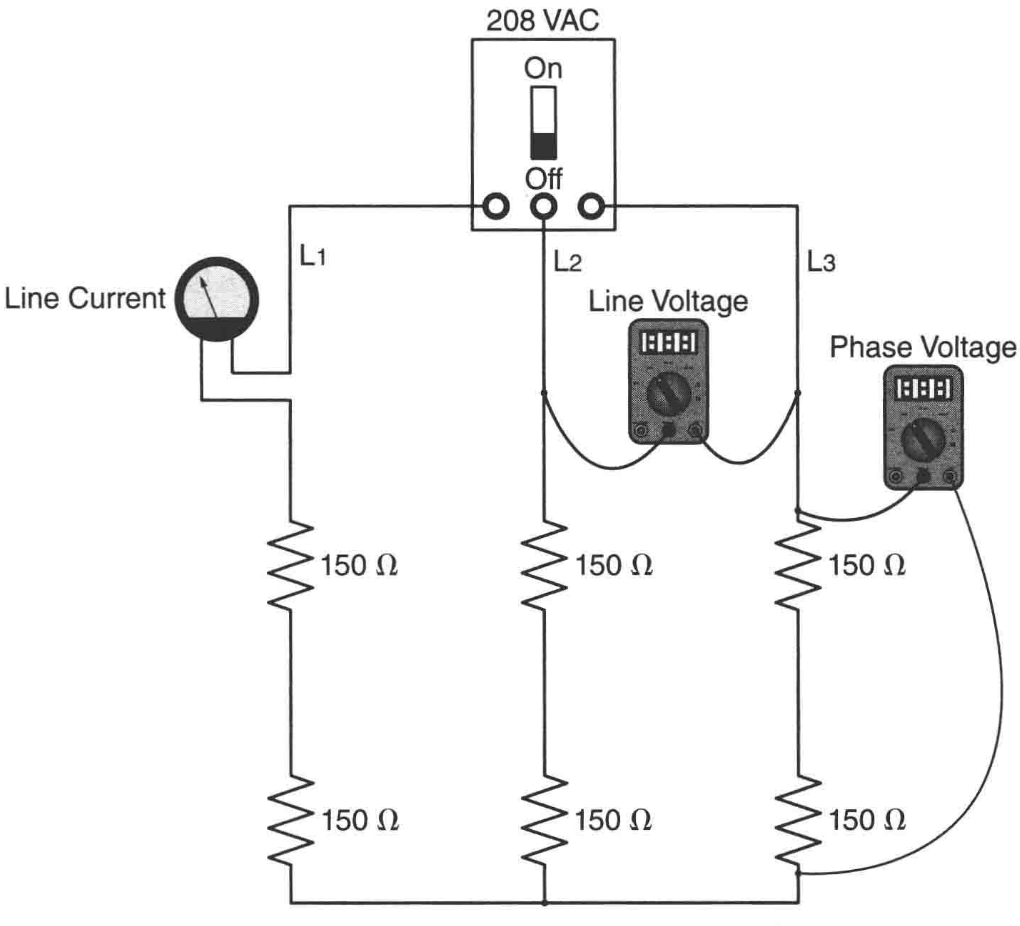

Figure 23-20 Measuring the line current in a wye connected load.

2. Turn on the power and measure the line voltage supplied to the load.

   $E_{(LINE)}$ ____________ volts

3. Calculate the value of phase voltage for a wye connected load.

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

   $E_{(PHASE)}$ ____________ volts

4. Measure the phase voltage and compare this value with the computed value.

   $E_{(PHASE)}$ ____________ volts

5. Measure the line current.

   $I_{(LINE)}$ ____________ amp(s)

6. **Turn off the power supply.**
7. In a wye connected system, the line current and phase current are the same. Reconnect the circuit as shown in Figure 23-21.
8. Turn on the power and measure the phase current.

   $I_{(PHASE)}$ ____________ amp(s)

9. **Turn off the power supply.**
10. Reconnect the three banks of lamps to form a delta connected load, as shown in Figure 23-22.
11. Turn on the power and measure the line voltage supplied to the load.

   $E_{(LINE)}$ ____________ volts

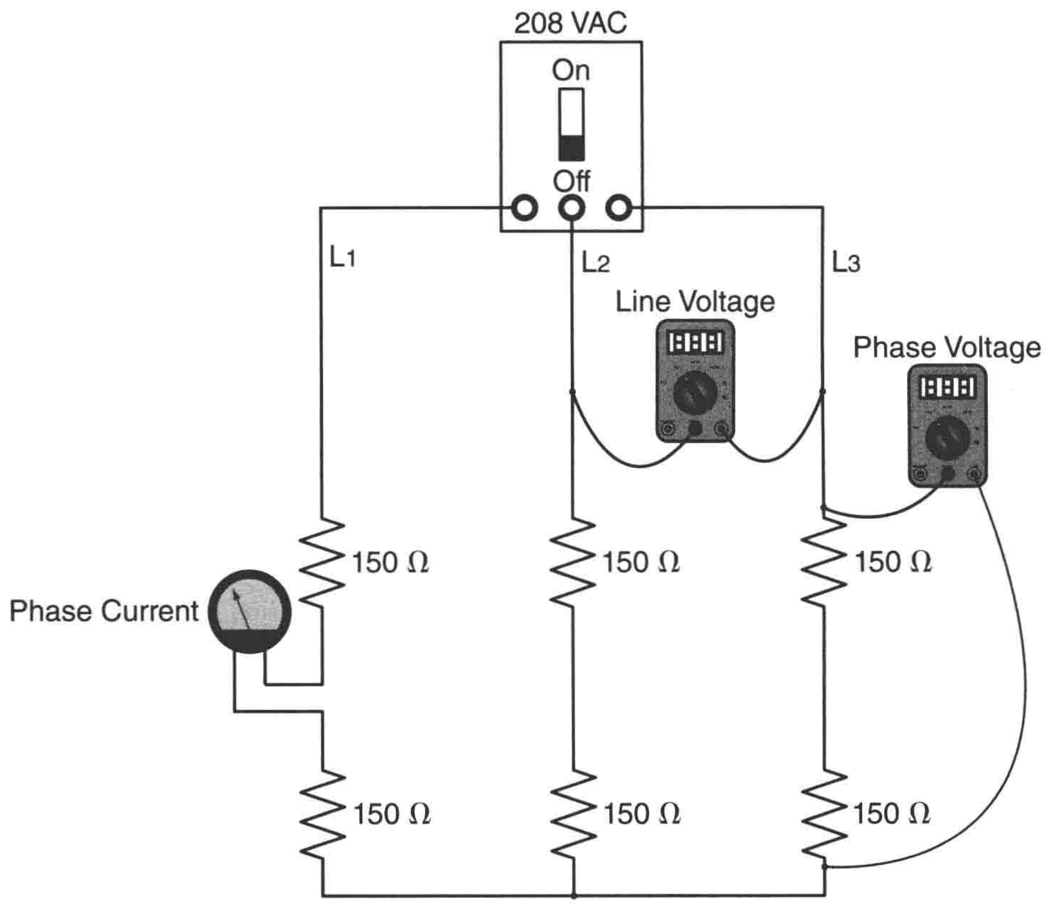

Figure 23-21 Measuring the phase current in a wye connected load.

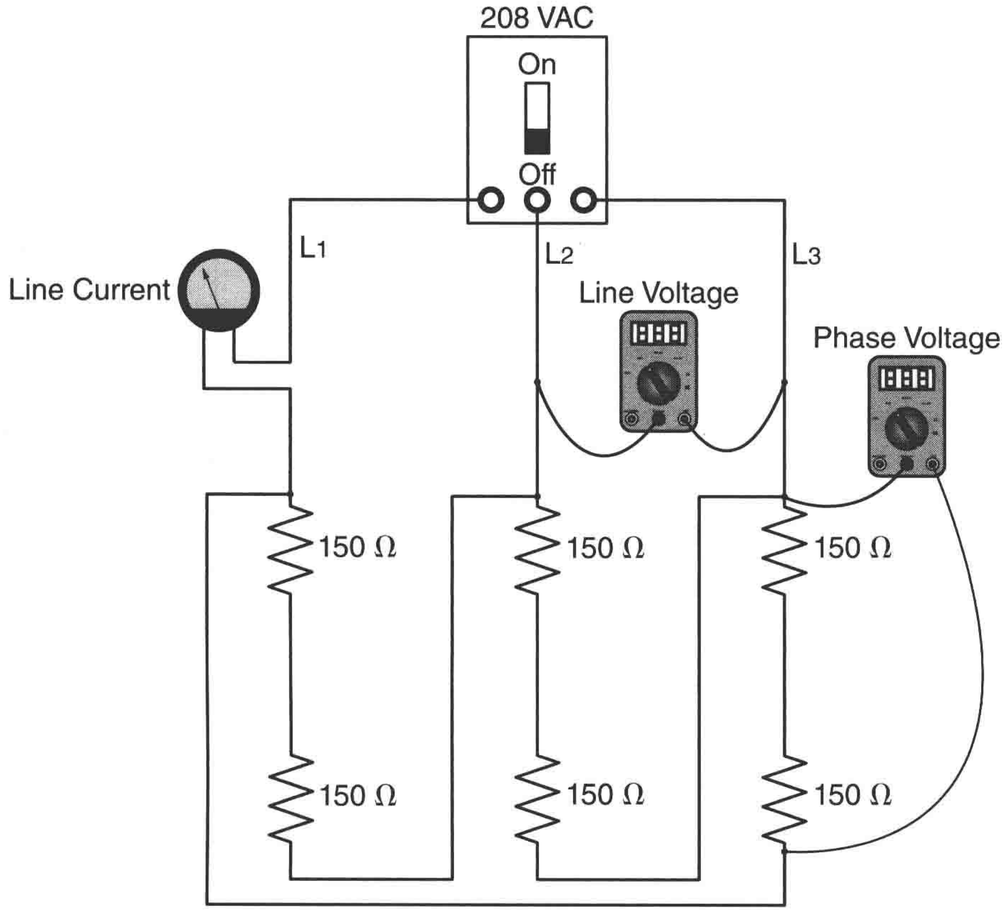

Figure 23-22 Measuring the voltage and line current values of a delta connected load.

12. Measure the phase value of voltage.

    $E_{(PHASE)}$ ____________ volts

13. Are the line and phase voltage values the same or different?

    ____

14. Measure the line current.

    $I_{(LINE)}$ ____________ amp(s)

15. **Turn off the power supply.**

16. In a delta connected system, the phase current will be less than the line current by a factor of 1.732. Calculate the phase current value for this connection.

$$I_{PHASE} = \frac{I_{LINE}}{1.732}$$

    $I_{(PHASE)}$ ____________ amp(s)

17. Reconnect the circuit as shown in Figure 23-23.

18. Turn on the power supply and measure the phase current. Compare this value with the computed value.

    $I_{(PHASE)}$ ____________ amp(s)

19. **Turn off the power supply.**

20. Disconnect the circuit and return the components to their proper place.

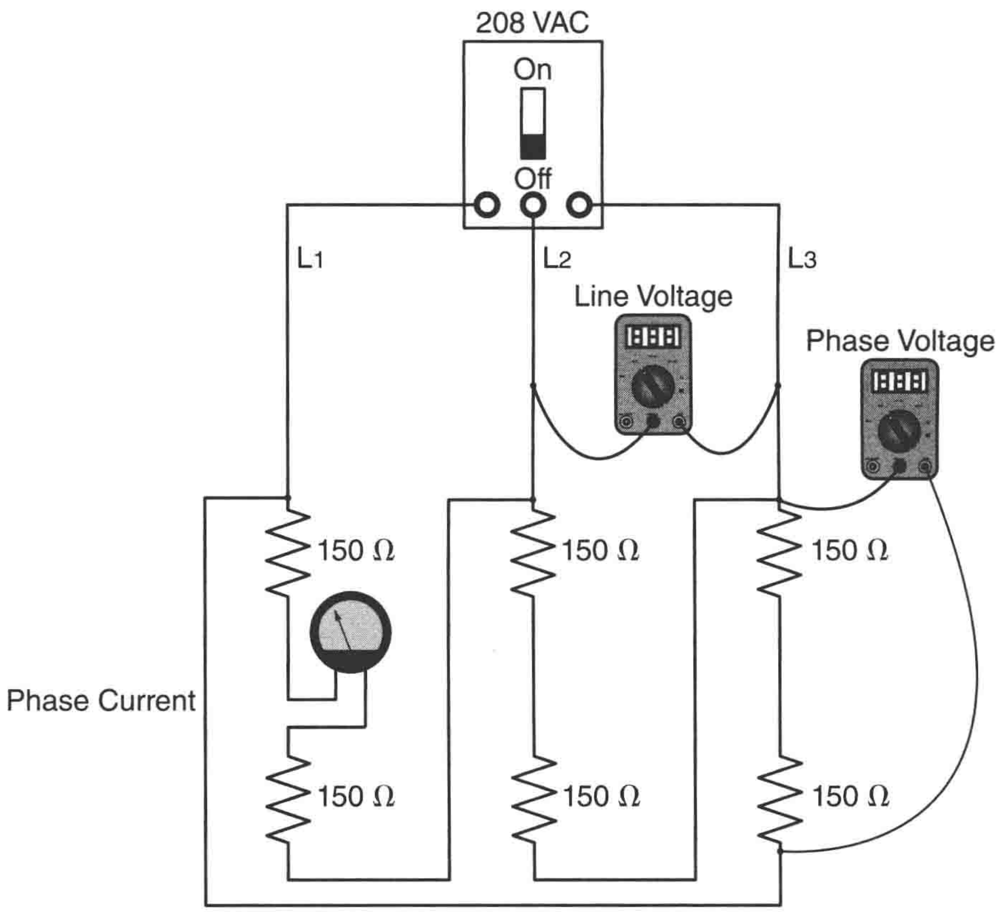

Figure 23-23 Measuring the voltage and phase current values of a delta connected load.

Review Questions

1. How many degrees out of phase with each other are the voltages of a three-phase system?

2. What are the two main types of three-phase connections?

3. A wye connected load has a voltage of 480 volts applied to it. What is the voltage dropped across each phase?

4. A wye connected load has a phase current of 25 amps. How much current is flowing through the lines supplying the load?

5. A delta connection has a voltage of 560 volts connected to it. How much voltage is dropped across each phase?

6. A delta connection has 30 amps of current flowing through each phase winding. How much current is flowing through each of the lines supplying power to the load?

7. A three-phase load has a phase voltage of 240 volts and a phase current of 18 amperes. What is the apparent power of this load?

8. If the load in question 7 is connected in a wye, what would be the line voltage and line current supplying the load?

____

9. An alternator with a line voltage of 2,400 volts supplies a delta connected load. The line current supplied to the load is 40 amperes. Assuming the load is a balanced three-phase load, what is the impedance of each phase?

____

10. What is the apparent power of the circuit in question 9?

____

Unit 24 Three-Phase Transformers

Objectives

After studying this unit, you should be able to:

- Connect three single-phase transformers to form a three-phase bank.
- Connect transformer windings in a delta configuration.
- Connect transformer windings in a wye configuration.
- Compute values of voltage, current, and turns-ratio for different three-phase connections.
- Compute the values for an open delta connected transformer bank.

Three-phase transformers are used throughout industry to change values of three-phase voltage and current. Since three-phase power is the major way in which power is produced, transmitted, and used, an understanding of how three-phase transformer connections are made is essential. This unit discusses different types of three-phase transformer connections and presents examples of how values of voltage and current for these connections are computed.

A three-phase transformer is constructed by winding three single-phase transformers on a single core, as shown in Figure 24-1. The transformer is enclosed in a case and may be dry or mounted in an enclosure that will be filled with a dielectric oil. The dielectric oil performs several functions. Since it is a dielectric, it provides electrical insulation between the windings and the case. It is also used to help provide cooling and to prevent the formation of moisture, which can deteriorate the winding insulation.

Three-Phase Transformer Connections

Three-phase transformers are connected in delta or wye configurations. A wye-delta transformer, for example, has its primary winding connected in a wye and its secondary winding

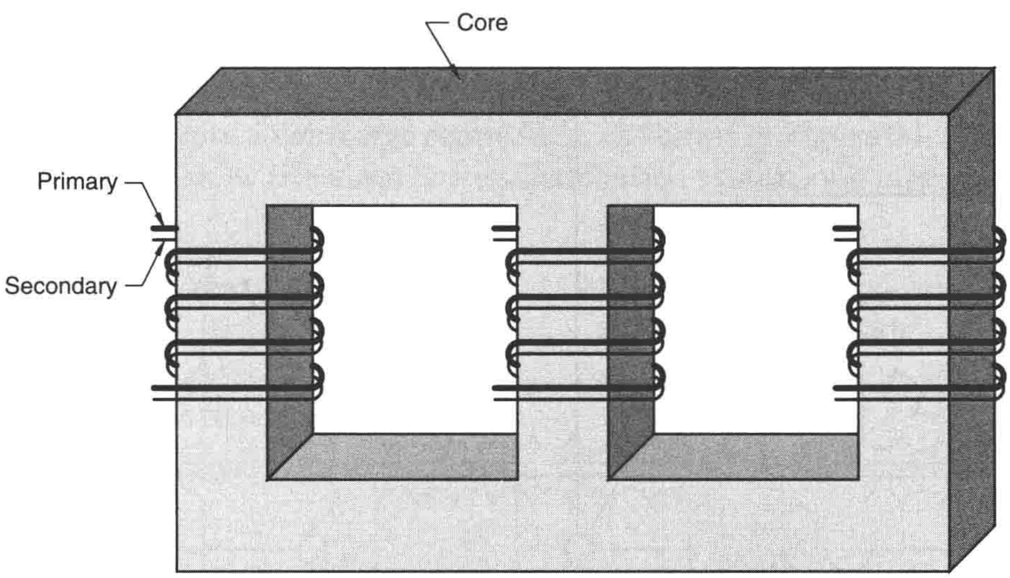

Figure 24-1 Basic construction of a three-phase transformer.

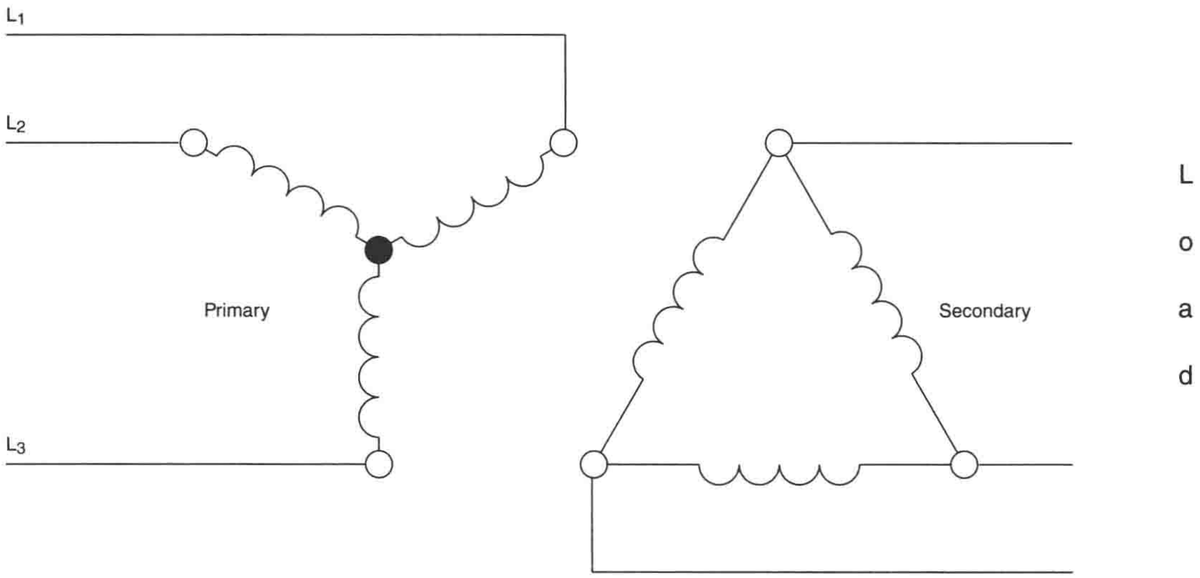

Figure 24-2 Wye-delta connected three-phase transformer.

connected in a delta, as shown in Figure 24-2. A delta-wye transformer would have its primary winding connected in delta and its secondary connected in wye, as shown in Figure 24-3.

Connecting Single-Phase Transformers into a Three-Phase Bank

If three-phase transformer is needed, and a three-phase transformer of the proper size and turns-ratio is not available, three single-phase transformers can be connected to form a three-phase bank. When three single-phase transformers are used to make a three-phase transformer bank, their primary and secondary windings are connected in a wye or delta connection. The three transformer windings in Figure 24-4 have been labeled A, B, and C. One end of each primary lead has been labeled H_1 and the other end has been labeled H_2. One end of each secondary lead has been labeled X_1 and the other end has been labeled X_2.

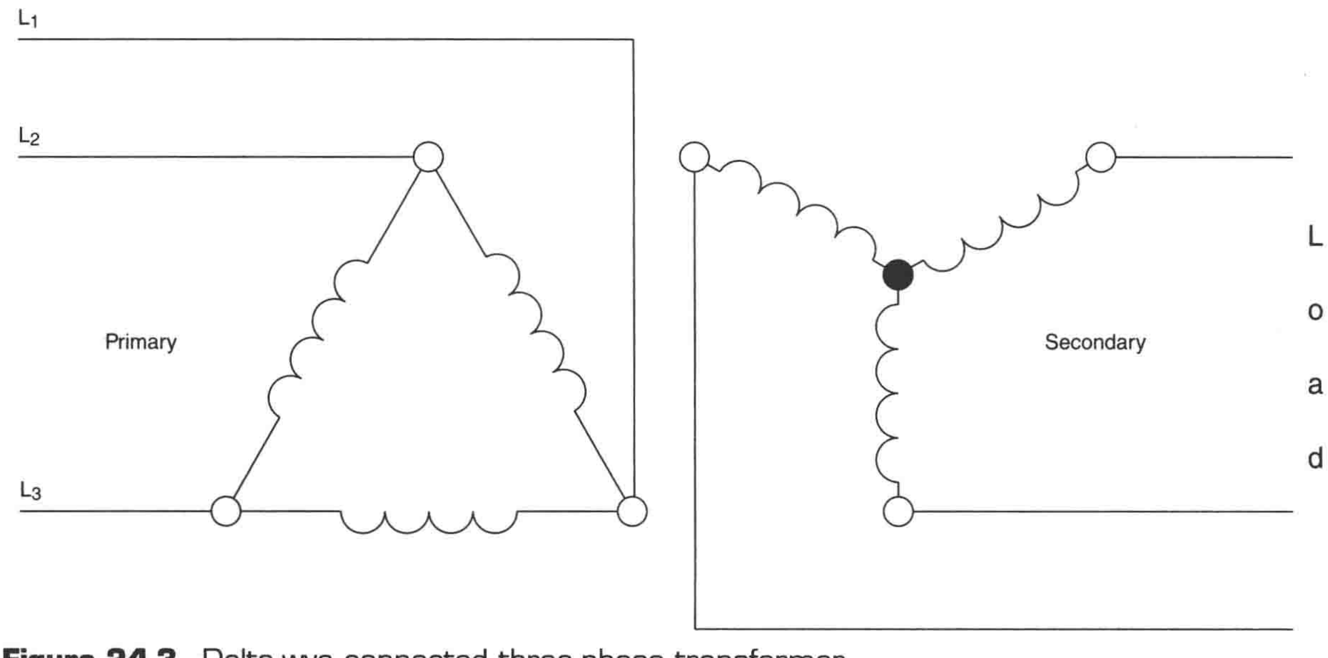

Figure 24-3 Delta-wye connected three-phase transformer.

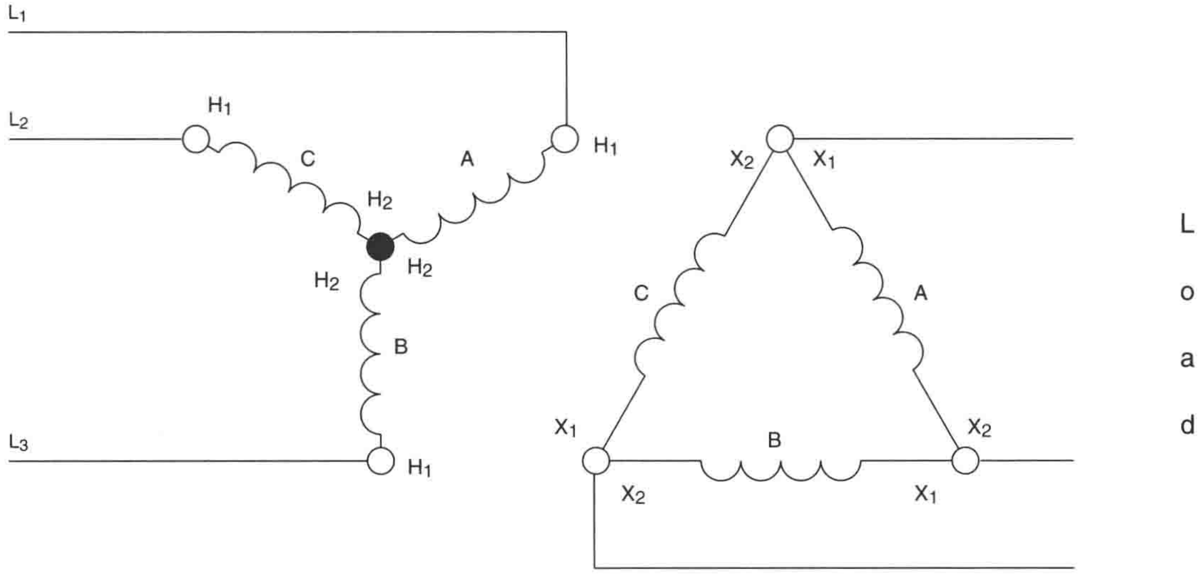

Figure 24-4 Identifying the windings.

Figure 24-5 shows three single-phase transformers labeled A, B, and C. The primary leads of each transformer have been labeled H_1 and H_2, and the secondary leads have been labeled X_1 and X_2. The schematic diagram of Figure 24-4 will be used to connect the three single-phase transformers into a three-phase wye-delta connection, as shown in Figure 24-6.

The primary winding will be tied into a wye connection first. The schematic in Figure 24-4 shows that the H_2 lead of each primary winding is connected together, and the H_1 lead of each winding is open for connection to the incoming power line. Notice in Figure 24-6 that the H_2 lead of each primary winding has been connected together, and the H_1 lead of each winding has been connected to the incoming power line.

Figure 24-4 also shows the X_1 lead of transformer A is connected to the X_2 lead of transformer C. Notice that this same connection has been made in Figure 24-6. The X_1 lead of transformer B is connected to the X_2 lead of transformer A, and the X_1 lead to transformer C is connected to the X_2 lead of transformer B. The load is connected to the points of the delta connection.

Although Figure 24-4 illustrates the proper schematic symbology for a three-phase transformer connection, some electrical schematics and wiring diagrams do not illustrate three-phase transformer connections in this manner. One type of diagram, called the one line diagram, would illustrate a delta-wye connection, as shown in Figure 24-7. These diagrams are generally used to show the main power distribution system of a large industrial plant.

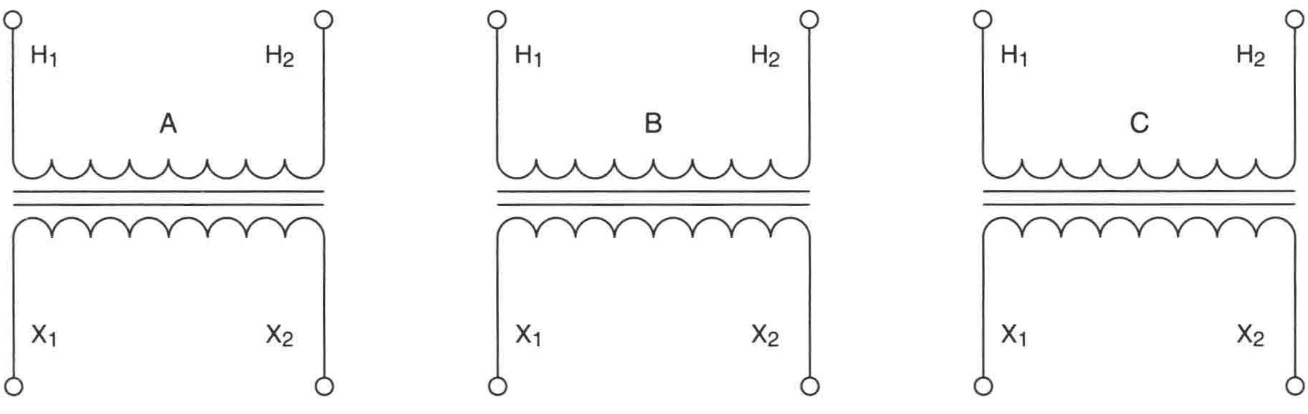

Figure 24-5 Three single-phase transformers.

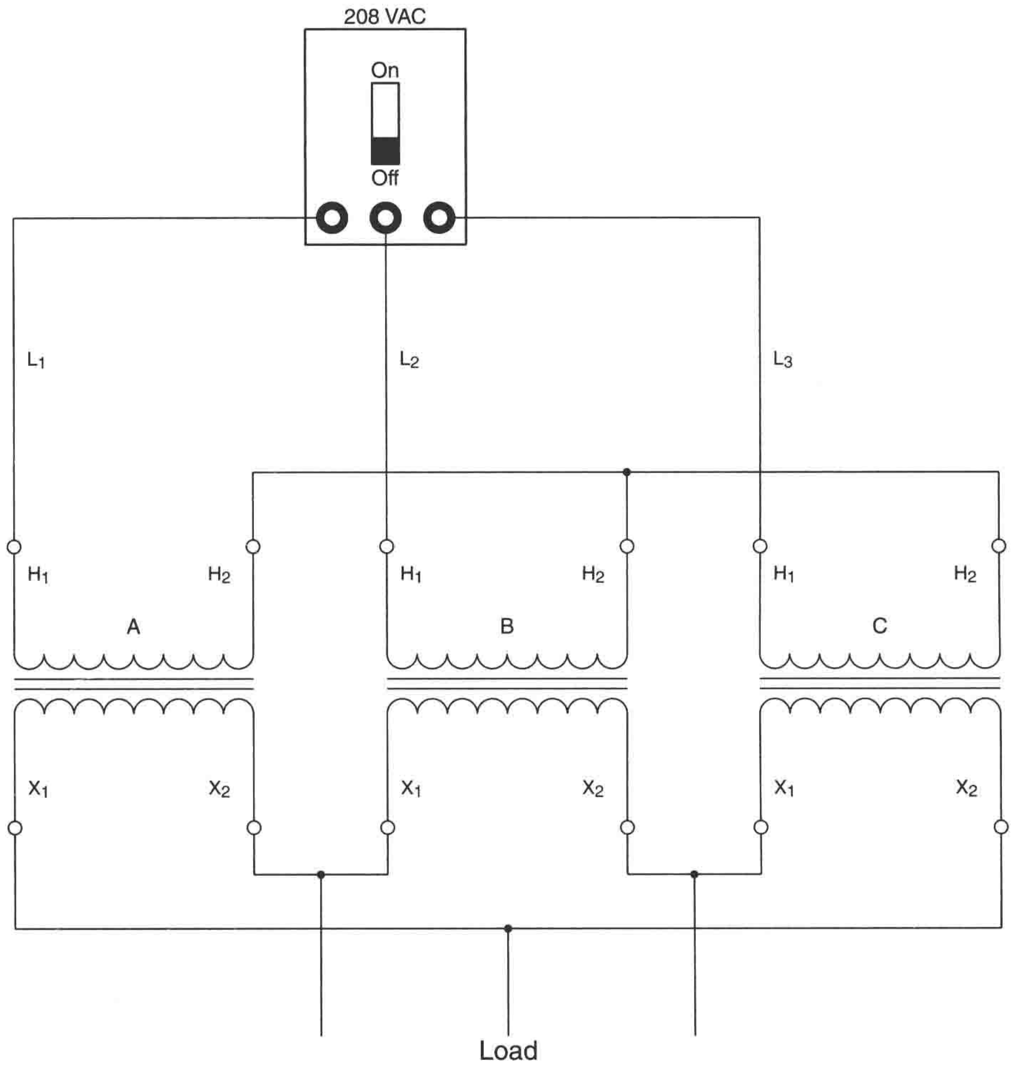

Figure 24-6 Connecting three single-phase transformers to form a wye-delta three-phase bank.

The one line diagram in Figure 24-8 shows the main power to the plant and the transformation of voltages to different subfeeders. Notice that each transformer shows whether the primary and secondary are connected as a wye or delta, and the secondary voltage of the subfeeder.

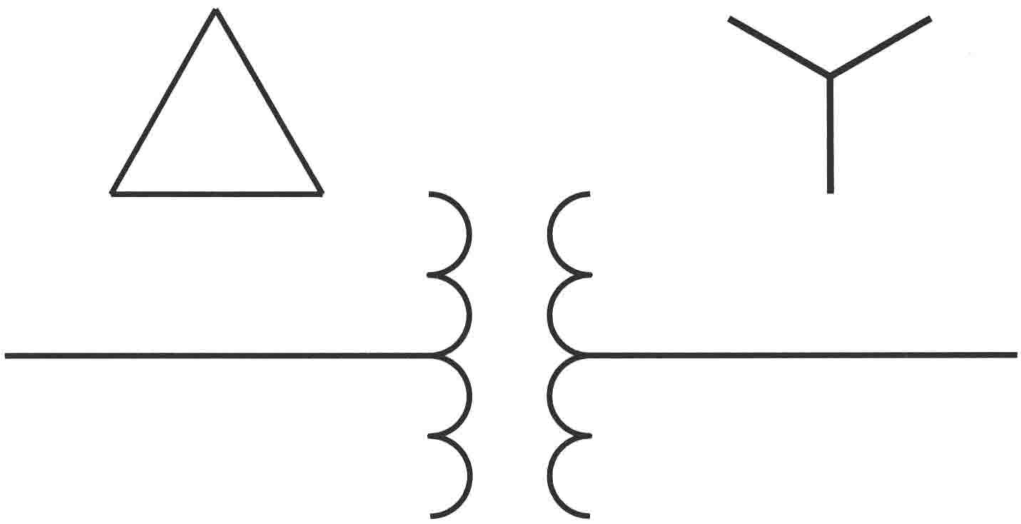

Figure 24-7 One line diagram symbol used to represent a delta-wye three-phase transformer connection.

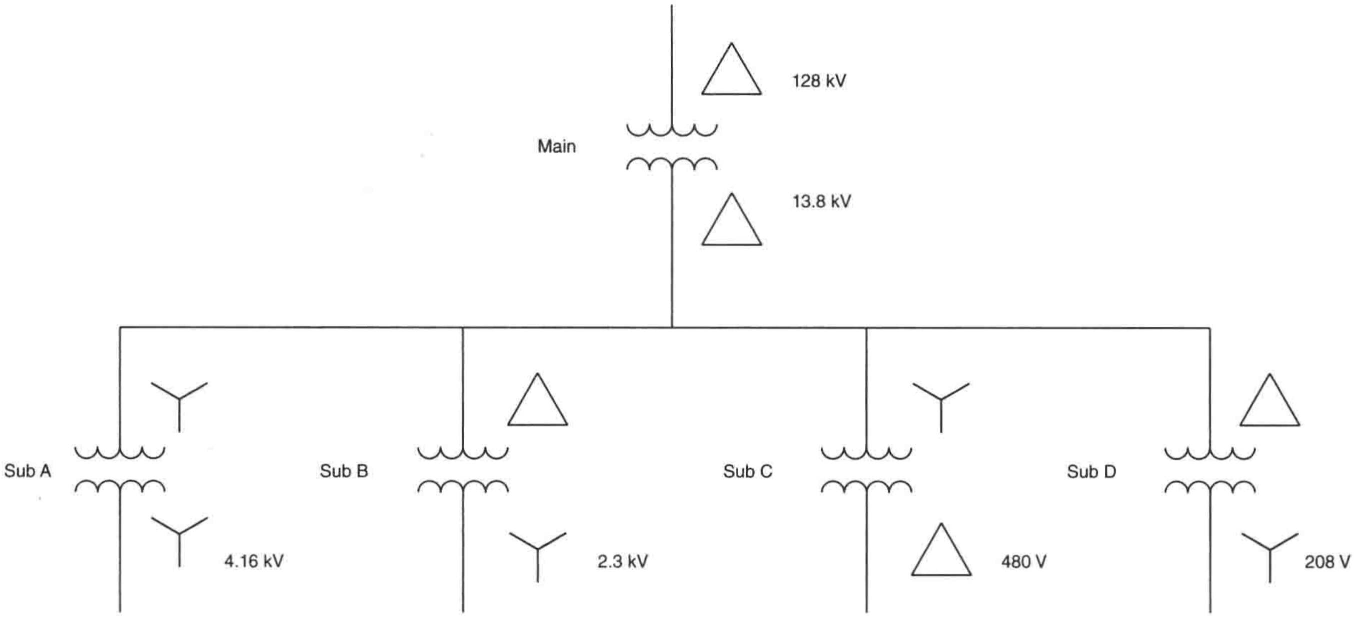

Figure 24-8 One line diagrams are generally used to show the main power distribution of a plant.

Closing a Delta

Delta connections should be checked for proper polarity before making the final connection and applying power. If the phase winding of one transformer is reversed, an extremely high current will flow when power is applied. Proper phasing can be checked with a voltmeter, as shown in Figure 24-9. If power is applied to the transformer bank before the delta connection is closed, the voltmeter should indicate 0 volt. If one phase winding has been reversed, however, the voltmeter will indicate double the amount of voltage. For example, assume the output voltage of a delta secondary is 240 volts. If the voltage is checked

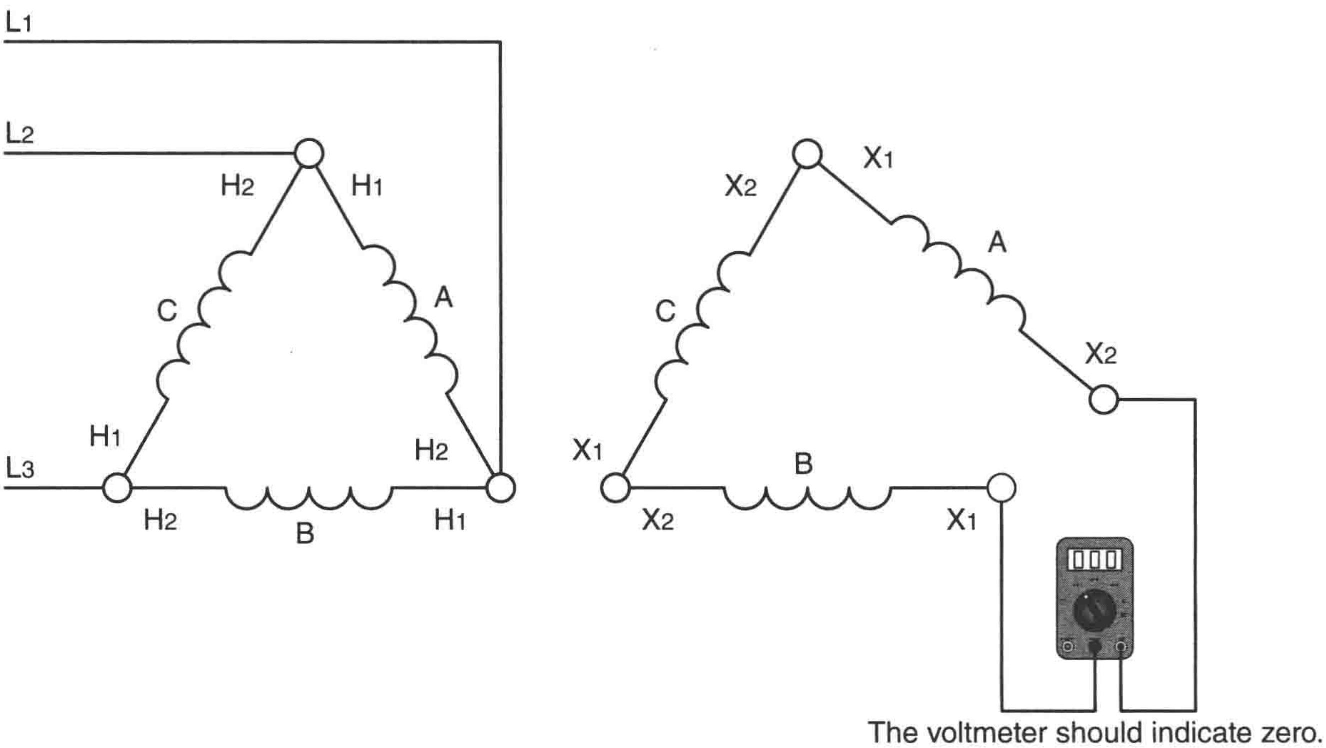

Figure 24-9 Testing for proper transformer polarity before closing the delta.

before the delta is closed, the voltmeter should indicate a voltage of 0 volt if all windings have been phased properly. If one winding has been reversed, however, the voltmeter will indicate a voltage of 480 volts (240 + 240). This test will confirm whether a phase winding has been reversed, but it will not indicate if the reversed winding is located in the primary or secondary. If either primary or secondary windings have been reversed, the voltmeter will indicate double the output voltage.

It should be noted, however, that a voltmeter is a high impedance device. It is not unusual for a voltmeter to indicate some amount of voltage before the delta is closed, especially if the primary has been connected as a wye and the secondary as a delta. When this is the case, however, the voltmeter will generally indicate close to the normal output voltage if the connection is correct and double the output voltage if the connection is incorrect. Regardless of whether the primary is connected as a delta or wye, the voltmeter will indicate twice the normal output voltage of the secondary if the connection is incorrect.

Three-Phase Transformer Calculations

When computing the values of voltage and current for three-phase transformers, the formulas used for making transformer calculations and three-phase calculations must be followed. Another very important rule that must be understood is that only phase values of voltage and current can be used when computing transformer values. When three-phase transformers are connected as a wye or delta, the primary and secondary windings themselves become the phases of a three-phase connection. This is true whether a three-phase transformer is used or whether three single-phase transformers are employed to form a three-phase bank. Refer to transformer A in Figure 24-5. All transformation of voltage and current takes place between the primary and secondary windings. Since these windings form the phase values of the three-phase connection, only phase, not line, values can be used when calculating transformed voltages and currents.

Helpful Hint

Only phase values of voltage and current can be used when computing transformer values.

Example #1: A three-phase transformer connection is shown in Figure 24-10. Three single-phase transformers have been connected to form a wye-delta bank. The primary is connected to a three-phase line of 13,800 volts, and the secondary voltage is 480. A three-phase resistive load with an impedance of 2.77 Ω per phase is connected to the secondary of the transformer. The following values will be computed for this circuit.

$E_{P(PRIMARY)}$ = Phase voltage of the primary

$E_{P(SECONDARY)}$ = Phase voltage of the secondary

Ratio = Turns-ratio of the transformer

$E_{P(LOAD)}$ = Phase voltage of the load bank

$I_{P(LOAD)}$ = Phase current of the load bank

$I_{L(SECONDARY)}$ = Secondary line current

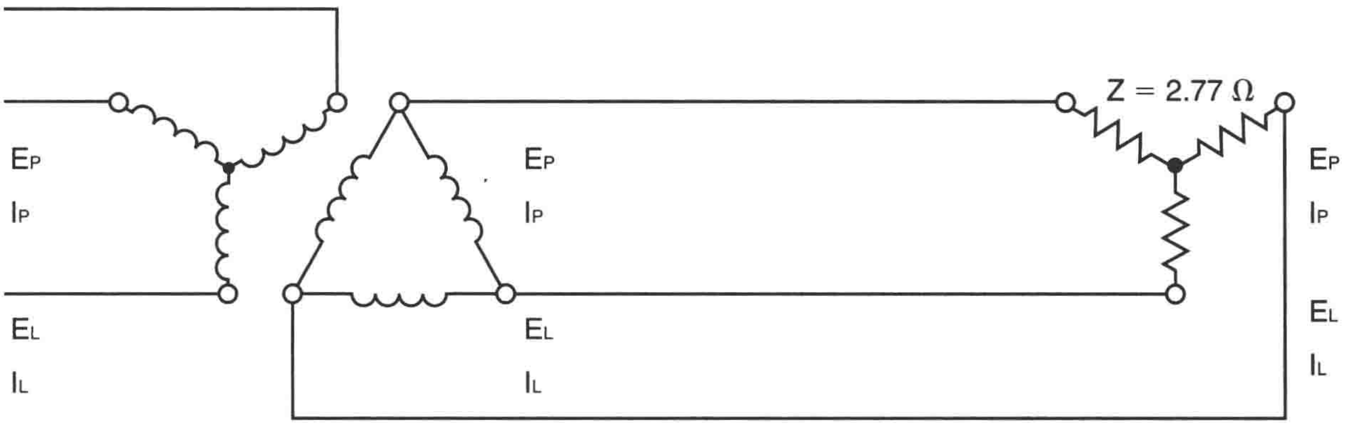

Figure 24-10 Example #1: Three-phase transformer calculations.

$I_{P(SECONDARY)}$ = Phase current of the secondary
$I_{P(PRIMARY)}$ = Phase current of the primary
$I_{L(PRIMARY)}$ = Line current of the primary

The primary windings of the three single-phase transformers have been connected to form a wye connection. In a wye connection, the phase voltage is less than the line voltage by a factor of 1.732 ($\sqrt{3}$). Therefore, the phase value of voltage can be computed using the following formula:

$$E_{P(PRIMARY)} = \frac{E_L}{1.732}$$

$$E_{P(PRIMARY)} = \frac{13{,}800}{1.732}$$

$$E_{P(PRIMARY)} = 7{,}967.67 \text{ volts}$$

The secondary windings are connected as a delta. In a delta connection, the phase voltage and line voltage are the same.

$$E_{P(SECONDARY)} = E_{L(SECONDARY)}$$

$$E_{P(SECONDARY)} = 480 \text{ volts}$$

The turns-ratio can be computed by comparing the phase voltage of the primary to the phase voltage of the secondary.

$$\text{Ratio} = \frac{\text{Primary phase voltage}}{\text{Secondary phase voltage}}$$

$$\text{Ratio} = \frac{7{,}967.67}{480}$$

$$\text{Ratio} = 16.6{:}1$$

The load bank is connected in a wye connection. The voltage across the phase of the load bank will be less than the line voltage by a factor of 1.732.

$$E_{P(LOAD)} = \frac{E_{L(LOAD)}}{1.732}$$

$$E_{P(LOAD)} = \frac{480}{1.732}$$

$$E_{P(LOAD)} = 277 \text{ volts}$$

Now that the voltage across each of the load resistors is known, the current flow through the phase of the load can be computed using Ohm's law.

$$I_{P(LOAD)} = \frac{E_{P(LOAD)}}{R}$$

$$I_{P(LOAD)} = \frac{277}{2.77}$$

$$I_{P(LOAD)} = 100 \text{ amperes}$$

Since the load is connected as a wye connection, the line current will be the same as the phase current. Therefore, the line current supplied by the secondary of the transformer is equal to the phase current of the load.

$$I_{L(SECONDARY)} = 100 \text{ amperes}$$

The secondary of the transformer bank is connected as a delta. The phase current of the delta is less than the line current by a factor of 1.732.

$$I_{P(SECONDARY)} = \frac{I_{L(SECONDARY)}}{1.732}$$

$$I_{P(SECONDARY)} = \frac{100}{1.732}$$

$$I_{P(SECONDARY)} = 57.74 \text{ amps}$$

The amount of current flow through the primary can be computed using the turns-ratio. Since the primary has a higher voltage, it will have a lower current. (Volts × Amps input must equal Volts × Amps output.)

$$I_{P(PRIMARY)} = \frac{I_{P(SECONDARY)}}{\text{Ratio}}$$

$$I_{P(PRIMARY)} = \frac{57.74}{16.6}$$

$$I_{P(PRIMARY)} = 3.48 \text{ amperes}$$

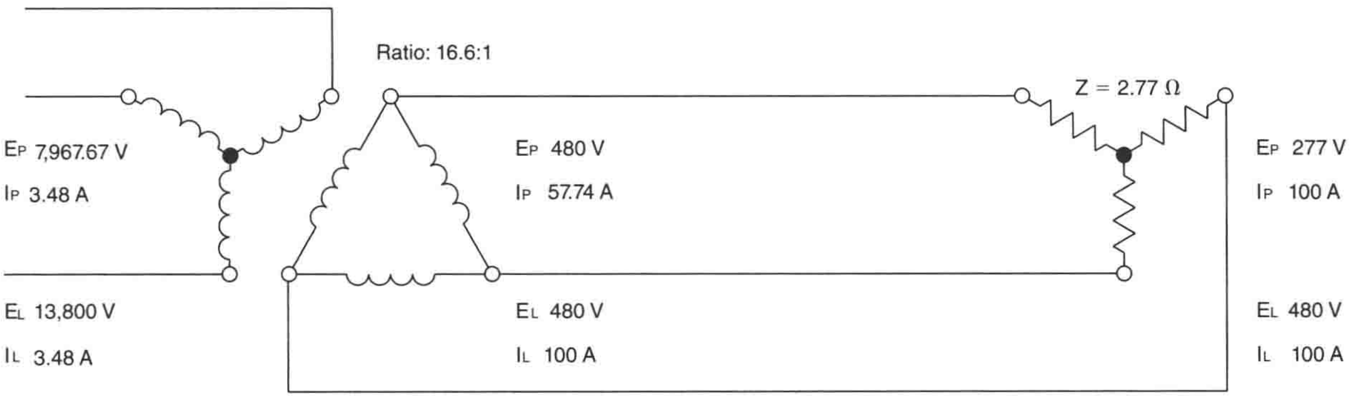

Figure 24-11 Example #1 with all missing values.

Recall that all transformed values of voltage and current take place across the phases; the primary has a phase current of 3.48 amps.

In a wye connection, the phase current is the same as the line current.

$$I_{L(PRIMARY)} = 3.48 \text{ amps}$$

The transformer connection with all computed values is shown in Figure 24-11.

Example #2: In the next example, a three-phase transformer is connected in a delta-delta configuration (Figure 24-12). The load is connected as a wye and each phase has an impedance of 7 Ω. The primary is connected to a line voltage of 4,160 volts and the secondary line voltage is 440 volts. The following values will be found:

$E_{P(PRIMARY)}$ = Phase voltage of the primary
$E_{P(SECONDARY)}$ = Phase voltage of the secondary
Ratio = Turns-ratio of the transformer
$E_{P(LOAD)}$ = Phase voltage of the load bank
$I_{P(LOAD)}$ = Phase current of the load bank
$I_{L(SECONDARY)}$ = Secondary line current
$I_{P(SECONDARY)}$ = Phase current of the secondary
$I_{P(PRIMARY)}$ = Phase current of the primary
$I_{L(PRIMARY)}$ = Line current of the primary

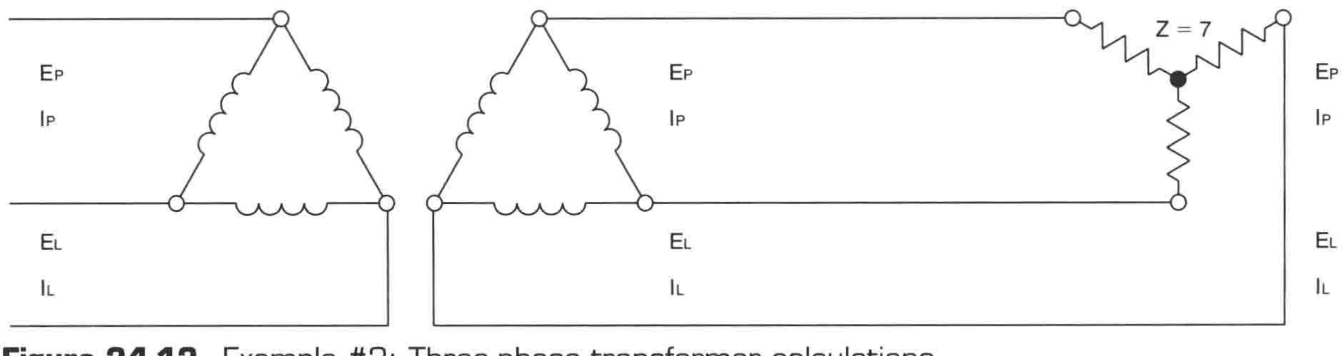

Figure 24-12 Example #2: Three-phase transformer calculations.

The primary is connected as a delta. The phase voltage will be the same as the applied line voltage.

$$E_{P(PRIMARY)} = E_{L(PRIMARY)}$$

$$E_{P(PRIMARY)} = 4{,}160 \text{ volts}$$

The secondary of the transformer is connected as a delta, also. Therefore, the phase voltage of the secondary will be the same as the line voltage of the secondary.

$$E_{P(SECONDARY)} = 440 \text{ volts}$$

All transformer values must be computed using phase values of voltage and current. The turns-ratio can be found by dividing the phase voltage of the primary by the phase voltage of the secondary.

$$\text{Ratio} = \frac{\text{Primary phase voltage}}{\text{Secondary phase voltage}}$$

$$\text{Ratio} = \frac{4{,}160}{440}$$

$$\text{Ratio} = 9.45{:}1$$

The load is connected directly to the output of the secondary. The line voltage applied to the load must, therefore, be the same as the line voltage of the secondary.

$$E_{L(LOAD)} = 440 \text{ volts}$$

The load is connected in a wye. The voltage applied across each phase will be less than the line voltage by a factor of 1.732.

$$E_{P(LOAD)} = \frac{E_{L(LOAD)}}{1.732}$$

$$E_{P(LOAD)} = \frac{440}{1.732}$$

$$E_{P(LOAD)} = 254 \text{ volts}$$

The phase current of the load can be computed using Ohm's law.

$$I_{P(LOAD)} = \frac{E_{P(LOAD)}}{Z}$$

$$I_{P(LOAD)} = \frac{254}{7}$$

$$I_{P(LOAD)} = 36.29 \text{ amps}$$

The amount of line current supplying a wye connected load will be the same as the phase current of the load.

$$I_{L(LOAD)} = 36.39 \text{ amps}$$

Since the secondary of the transformer is supplying current to only one load, the line current of the secondary will be the same as the line current of the load.

$$I_{L(SECONDARY)} = 36.29 \text{ amps}$$

The phase current in a delta connection is less than the line current by a factor of 1.732.

$$I_{P(SECONDARY)} = \frac{I_{L(SECONDARY)}}{1.732}$$

$$I_{P(SECONDARY)} = \frac{36.29}{1.732}$$

$$I_{P(SECONDARY)} = 20.95 \text{ amps}$$

The phase current of the transformer primary can now be computed using the phase current of the secondary and the turns-ratio.

$$I_{P(PRIMARY)} = \frac{I_{P(SECONDARY)}}{\text{Ratio}}$$

$$I_{P(PRIMARY)} = \frac{20.95}{9.45}$$

$$I_{P(PRIMARY)} = 2.27 \text{ amps}$$

In this example, the primary of the transformer is connected as a delta. The line current supplying the transformer will be higher than the phase current by a factor of 1.732.

$$I_{L(PRIMARY)} = I_{P(PRIMARY)} \times 1.732$$

$$I_{L(PRIMARY)} = 2.27 \times 1.732$$

$$I_{L(PRIMARY)} = 3.93 \text{ amps}$$

The circuit with all computed values is shown in Figure 24-13.

Open Delta Connections

The open delta transformer connection can be made with only two transformers instead of three (Figure 24-14). This connection is often used when the amount of three-phase power needed is not excessive, such as in a small business. It should be noted that the

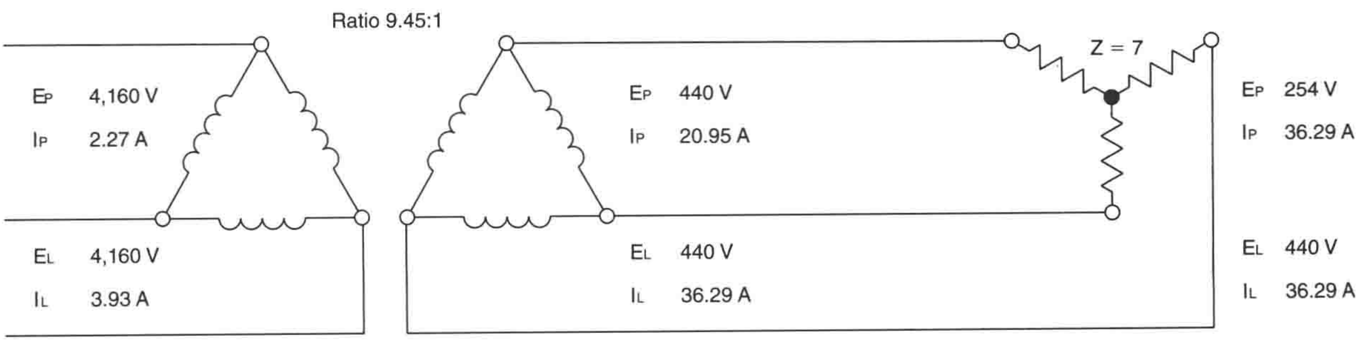

Figure 24-13 Example #2 with all the missing values.

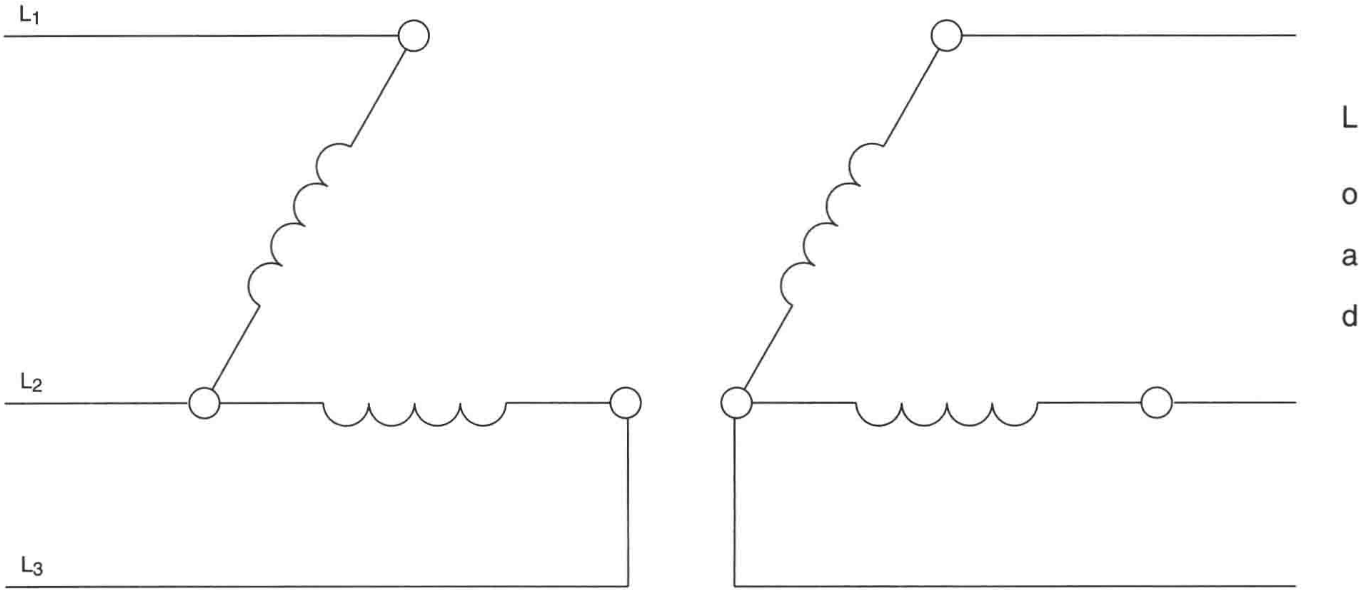

Figure 24-14 Open delta connection.

output power of an open delta connection is only 86.6% of the rated power of the two transformers. For example, assume two transformers, each having a capacity of 25 kVA (kilovolt-amperes), are connected in an open delta connection. The total output power of this connection is 43.3 kVA (50 kVA × 0.866 = 43.3 kVA).

Another figure given for this calculation is 57.7%. This percentage assumes a closed delta bank containing three transformers. If three 25 kVA transformers were connected to form a closed delta connection, the total output power would be 75 kVA (3 × 25 kVA = 75 kVA). If one of these transformers were to be removed, and the transformer bank operated as an open delta connection, the output power would be reduced to 57.7% of its original capacity of 75 kVA. The output capacity of the open delta bank is 43.3 kVA (75 kVA × 0.577 = 43.3 kVA).

The voltage and current values of an open delta connection are computed in the same manner as a standard delta-delta connection when three transformers are employed. The voltage and current rules for a delta connection must be used when determining line and phase values of voltage and current.

LABORATORY EXERCISE

Name ______________________________ Date __________

Note: Due to the length of this laboratory exercise it has been divided into two parts.

Materials Required

3 480-240/120-volt, 0.5-kVA control transformers

AC voltmeter

2 AC ammeter, in-line or clamp-on. (If the clamp-on type is used, it is recommended to use a 10:1 scale divider.)

6 150-ohm resistors

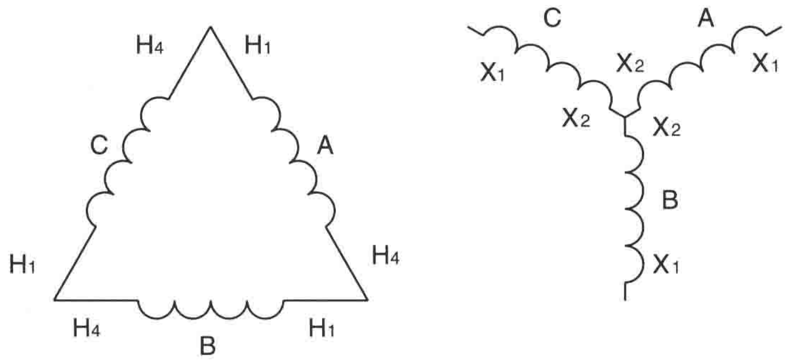

Figure 24-15 A delta-wye transformer connection.

In this experiment, three single-phase control transformers will be connected to form different three-phase transformer banks. Values of voltage, current, and turns-ratios will be computed and then measured. The three transformers will be operated with their high-voltage windings connected in parallel for low-voltage operation. The high-voltage windings are used as the primary for each connection.

The Delta-Wye Connection (PART 1)

A delta-wye connected three-phase transformer bank has its primary windings connected in a delta configuration and its secondary windings connected in a wye configuration (Figure 24-15). Notice that the three primary windings have been labeled A, B, and C. The H_1 terminal of transformer A is connected to the H_4 terminal of transformer C. The H_4 terminal of transformer A is connected to the H_1 terminal of transformer B, and the H_4 terminal of transformer B is connected to the H_1 terminal of transformer C. The secondary windings form a wye by connecting all the X_2 terminals together.

1. Connect the circuit shown in Figure 24-16. Notice that the three transformers have been labeled A, B, and C. The H_1 terminal of transformer A is connected to the H_4 terminal of transformer C, the H_4 terminal of transformer A is connected to the H_1 terminal of transformer B, and the H_4 terminal of transformer B is connected to the H_1 terminal of transformer C. This is the same connection shown in the schematic drawing of Figure 24-15. Also, notice that the X_2 terminal of each transformer is connected together to form a wye connected secondary.

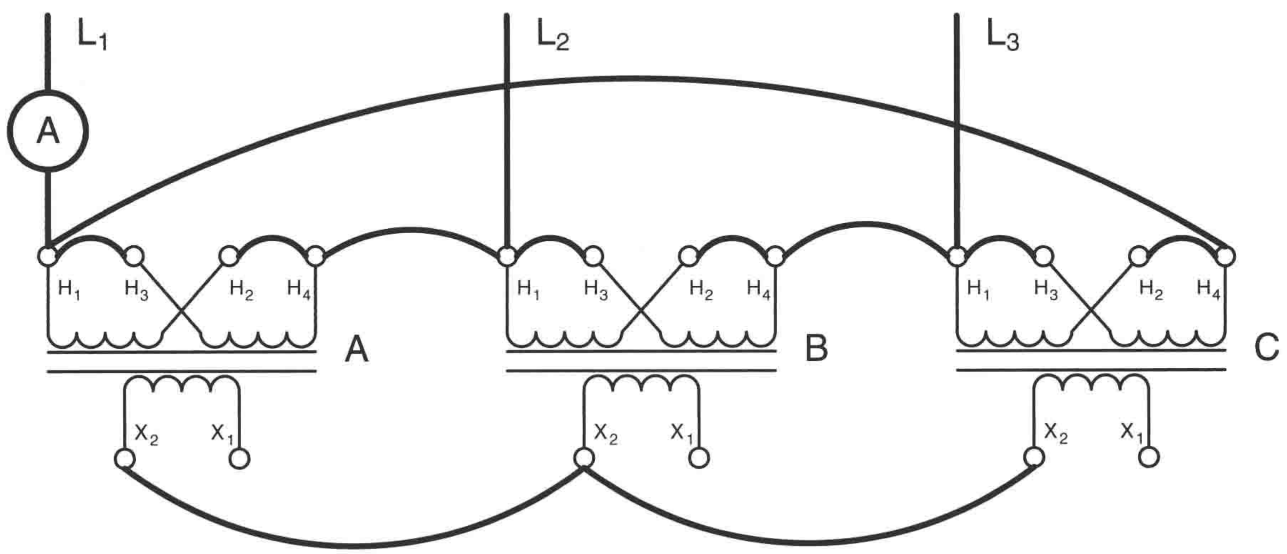

Figure 24-16 Connecting three single-phase transformers to form a wye-delta three-phase bank.

Helpful Hint

When calculating three-phase transformer values, draw the circuit as illustrated in Figures 24-10, 24-11, 24-12, and 24-13. Insert the known quantities in the drawing. This method helps avoid confusion when dealing with wye and delta connections.

2. The transformers in this exercise have a turns ratio of 2:1. Assuming that 208 volts is applied to the primary windings, calculate the phase voltage of the secondary windings.

   $E_{(SECONDARY\ PHASE)}$ = __________ volts.
3. Calculate the line voltage of the secondary.

   $E_{(SECONDARY\ LINE)}$ = __________ volts.
4. Turn on the power and measure the excitation current of the transformers. The excitation current should remain constant as long as the transformers are connected in this configuration.

   $E_{(EXC)}$ = __________ A
5. Measure the phase voltage of the primary winding with an AC voltmeter. This can be accomplished by measuring the voltage across H_1 and H_4 of any transformer.

   $E_{(PHASE\ PRIMARY)}$ = __________ volts
6. Measure the phase voltage of the secondary winding. This can be accomplished by measuring the voltage across X_1 and X_2 of any transformer.

   $E_{(PHASE\ SECONDARY)}$ = __________ volts
7. Measure the line voltage of the secondary winding. This can be accomplished by measuring the voltage across any two X_1 terminals of the three transformers. **Turn off the power.**

   $E_{(LINE\ SECONDARY)}$ = __________ volts
8. Compare the measured values with the computed values above. Are they within 5% of each other?

   ____
9. Connect the circuit shown in Figure 24-17. In this circuit, three 150-ohm resistors have been connected to form a wye load. A wye connection can be readily identified because one end of each load is connected together to form a center point.
10. Calculate the phase voltage of the wye connected load.

    $E_{(PHASE\ LOAD)}$ __________ volts
11. Using Ohm's law, calculate the phase current in the load.

    $I_{(PHASE\ LOAD)}$ = __________ A
12. Calculate the line current supplied by the transformer secondary to the load.

    $I_{(LINE\ SECONDARY)}$ = __________ A
13. Calculate the current in the phase winding of the transformer secondary.

    $I_{(PHASE\ SECONDARY)}$ = __________ A

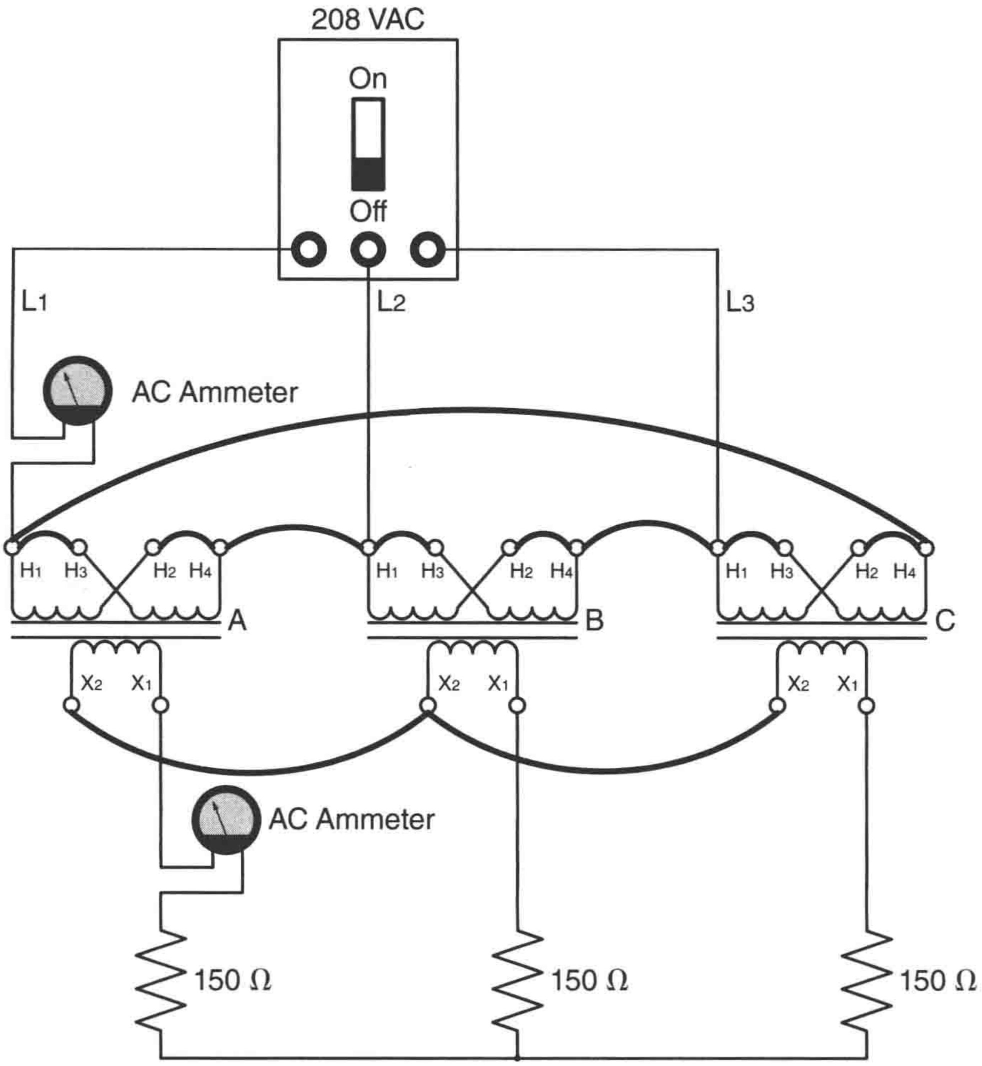

Figure 24-17 Adding load to the connection.

14. Calculate the current in the phase winding of the primary using the turns ratio. Because this is a step-down transformer, the primary current will be less than the secondary current by a factor of the turns-ratio.

    $I_{(PHASE\ PRIMARY)}$ = __________ A

15. Calculate the line current of the primary. Make sure to add the excitation current to the calculation.

    $I_{(LINE\ PRIMARY)}$ = __________ A

16. Turn on the power and measure the line current of the secondary and primary. **Turn off the power**.

    $I_{(LINE\ SECONDARY)}$ = __________ A

    $I_{(LINE\ PRIMARY)}$ = __________ A

    Compare these measured values with the computed values in step 12 and step 15. Are the values within 5% of each other?

____

17. Connect a second 150-ohm resistor in parallel with each of the load resistors, as shown in Figure 24-18. This will provide a resistance of 75 ohms for each phase of the load.

$$R_T = \frac{R}{N} \qquad R_T = \frac{150}{2} \qquad R_T = 75\ \Omega$$

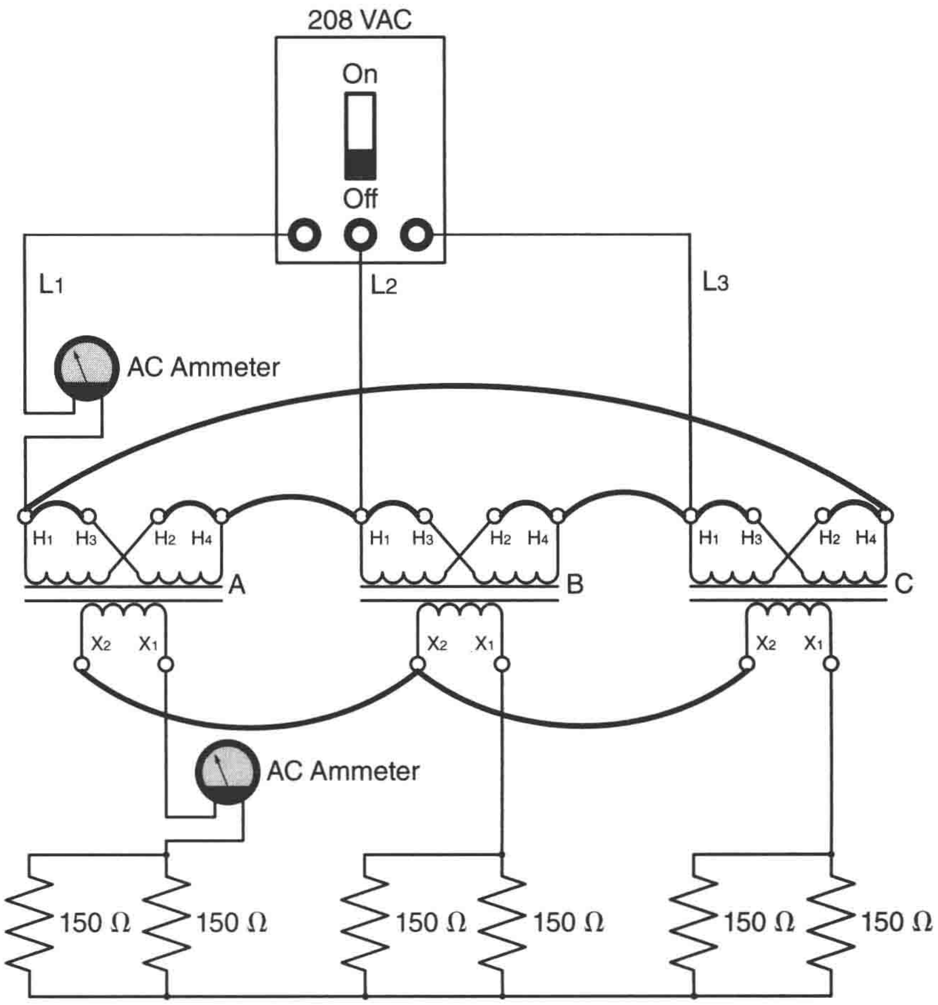

Figure 24-18 Adding load to the transformers.

18. Using the value of phase voltage for the load determined in step 10, calculate the phase current of the load using Ohm's law.

    $I_{(\text{PHASE LOAD})}$ = ________ A

19. Calculate the line current supplied by the transformer secondary to the load.

    $I_{(\text{LINE SECONDARY})}$ = ________ A

20. Calculate the current in the phase winding of the transformer secondary.

    $I_{(\text{PHASE SECONDARY})}$ = ________ A

21. Calculate the current in the phase winding of the primary using the turns-ratio. Because this is a step-down transformer, the primary current will be less than the secondary current by a factor of the turns-ratio.

$$I_{(\text{PHASE PRIMARY})} = \frac{I_{(\text{PHASE SECONDARY})}}{\text{Turns-ratio}}$$

$I_{(\text{PHASE PRIMARY})}$ = ________ A

Helpful Hint

When calculating primary current using the secondary current and the turns-ratio, the phase value of secondary current must be used to determine the phase value of the primary current.

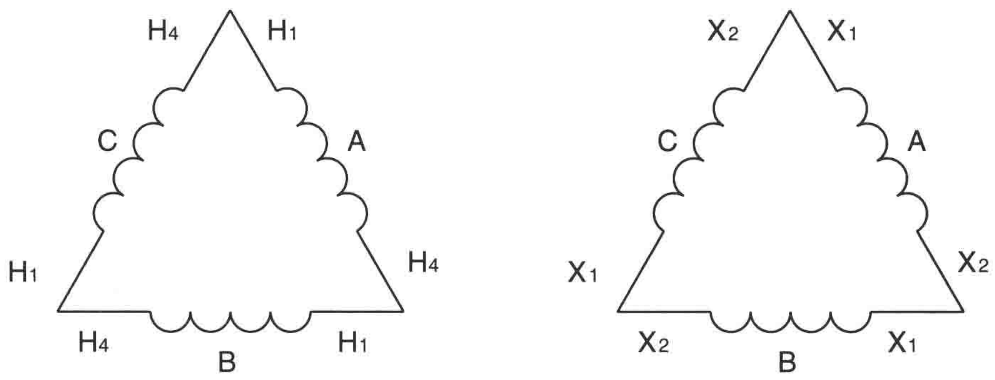

Figure 24-19 Delta-wye transformer connection.

22. Calculate the line current of the primary. Make sure to add the excitation current to the calculation.

    $I_{(LINE\ PRIMARY)}$ = __________ A

23. Turn on the power and measure the line current of the secondary and primary. **Turn off the power**.

    $I_{(LINE\ SECONDARY)}$ = __________ A

    $I_{(LINE\ PRIMARY)}$ = __________ A

    Compare these measured values with the computed values in step 12 and step 15. Are the values within 5% of each other?

    ____

Delta-Delta Connection

The three transformers will now be reconnected to form a delta-delta connection. The schematic diagram for a delta-delta connection is shown in Figure 24-19.

24. Reconnect the transformers as shown in Figure 24-20. In this connection, the primary windings remain connected in a delta configuration, but the secondary windings have been reconnected from a wye to a delta. Because the primary windings have not been changed, the excitation current will remain the same.
25. Assuming a primary voltage of 208 volts, calculate the phase voltage of the secondary. The transformers have a ratio of 2:1.

    $E_{(PHASE\ SECONDARY)}$ __________ volts

26. Calculate the line voltage of the secondary.

    $E_{(LINE\ SECONDARY)}$ __________ volts

27. Calculate the phase voltage of the wye connected load resistors.

    $E_{(PHASE\ LOAD)}$ __________ volts

28. Calculate the phase current of the load using Ohm's law.

    $I_{(PHASE\ LOAD)}$ __________ A

29. Calculate the line current supplied to the load by the secondary of the transformer.

    $I_{(LINE\ SECONDARY)}$ __________ A

30. Calculate the phase current of the secondary winding.

    $I_{(PHASE\ SECONDARY)}$ __________ A