TRANSFORMERS

14

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Explain mutual inductance
- Describe how a transformer is constructed and how it operates
- Describe how transformers increase and decrease voltage
- Discuss the effect of a resistive load across the secondary
- Discuss the concept of a reflected load in a transformer
- Discuss impedance matching with transformers
- Describe a practical transformer
- Describe several types of transformers
- Troubleshoot transformers

KEY TERMS

- Mutual inductance (L_M)
- Transformer
- Primary winding
- Secondary winding
- Magnetic coupling
- Turns ratio (n)
- Reflected resistance
- Impedance matching
- Apparent power rating
- Center tap (CT)

APPLICATION ACTIVITY PREVIEW

In this application activity, you will learn how to troubleshoot a type of dc power supply that uses a transformer to couple the ac voltage from a standard electrical outlet. By making voltage measurements at various points, you can determine if there is a fault and be able to specify the part of the power supply that is faulty.

VISIT THE COMPANION WEBSITE

Study aids for this chapter are available at
http://www.pearsonhighered.com/careersresources/

INTRODUCTION

In Chapter 13, you learned about self-inductance. In this chapter, you will study mutual inductance, which is the basis for the operation of transformers. Transformers are used in all types of applications such as power supplies, electrical power distribution, and signal coupling in communications systems.

The operation of the transformer is based on the principle of mutual inductance, which occurs when two or more coils are in close proximity. A simple transformer is actually two coils that are electromagnetically coupled by their mutual inductance. Because there is no electrical contact between two magnetically coupled coils, the transfer of energy from one coil to the other can be achieved in a situation of complete electrical isolation. In relation to transformers, the term *winding* or *coil* is commonly used to describe the primary and secondary.

14–1 MUTUAL INDUCTANCE

When two coils are placed close to each other, a changing electromagnetic field produced by the current in one coil will cause an induced voltage in the second coil because of the mutual inductance between the two coils.

After completing this section, you should be able to

- **Explain mutual inductance**
  - Discuss magnetic coupling
  - Define *electrical isolation*
  - Define *coefficient of coupling*
  - Identify the factors that affect mutual inductance and state the formula

Recall from Chapter 10 that the electromagnetic field surrounding a coil of wire expands, collapses, and reverses as the current increases, decreases, and reverses.

When a second coil is placed very close to the first coil so that the changing magnetic lines of force cut through the second coil, the coils are magnetically coupled and a voltage is induced, as indicated in Figure 14–1. When two coils are magnetically coupled, they provide **electrical isolation,** a condition in which two circuits have no common electrically conductive path between them. If the current in the first coil is sinusoidal, the voltage induced in the second coil is also sinusoidal. The amount of voltage induced in the second coil as a result of the current in the first coil is dependent on the **mutual inductance (L_M)** which is the inductance between the two coils. The mutual inductance is established by the inductance of each coil and by the amount of coupling (k) between the two coils. To maximize coupling, the two coils are wound on a common core.

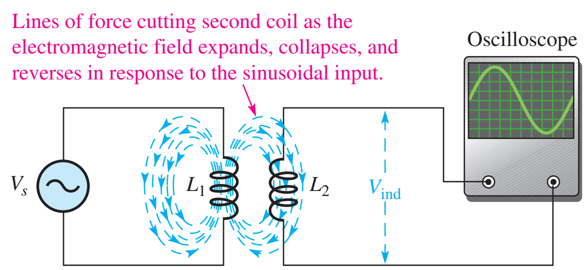


FIGURE 14–1

A voltage is induced in the second coil as a result of the changing current in the first coil, producing a changing electromagnetic field that links the second coil.

Coefficient of Coupling

The **coefficient of coupling, *k***, between two coils is the ratio of the magnetic lines of force (flux) produced by coil 1 linking coil 2(ϕ_{1-2}) to the total flux produced by coil 1(ϕ_1).

Equation 14–1

$$k = \frac{\phi_{1-2}}{\phi_1}$$

For example, if half of the total flux produced by coil 1 links coil 2, then $k = 0.5$. A greater value of k means that more voltage is induced in coil 2 for a certain rate of change of current in coil 1. Note that k has no units. Recall that the unit of magnetic lines of force (flux) is the weber, abbreviated Wb.

The coefficient of coupling, k, depends on the physical closeness of the coils and the type of core material on which they are wound. To maximize the coupling, coils are wound on a single core. The construction and shape of the core is also a factor in the coefficient of coupling.

Formula for Mutual Inductance

The three factors influencing mutual inductance (k, L_1, and L_2) are shown in Figure 14–2. The formula for mutual inductance is

$$L_M = k\sqrt{L_1 L_2}$$

Equation 14–2

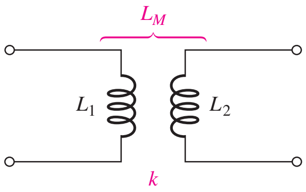


FIGURE 14–2
The mutual inductance of two coils.

EXAMPLE 14–1

One coil produces a total magnetic flux of 50 μWb, and 20 μWb link coil 2. What is the coefficient of coupling, k?

Solution

$$k = \frac{\phi_{1-2}}{\phi_1} = \frac{20\ \mu\text{Wb}}{50\ \mu\text{Wb}} = \mathbf{0.4}$$

*Related Problem** Determine k when $\phi_1 = 500\ \mu$Wb and $\phi_{1-2} = 375\ \mu$Wb.

*Answers are at the end of the chapter.

EXAMPLE 14–2

Two coils are wound on a single core, and the coefficient of coupling is 0.3. The inductance of coil 1 is 10 μH, and the inductance of coil 2 is 15 μH. What is L_M?

Solution

$$L_M = k\sqrt{L_1 L_2} = 0.3\sqrt{(10\ \mu\text{H})(15\ \mu\text{H})} = \mathbf{3.67\ \mu H}$$

Related Problem Determine the mutual inductance when $k = 0.5$, $L_1 = 1$ mH, and $L_2 = 600\ \mu$H.

SECTION 14–1 CHECKUP
Answers are at the end of the chapter.

1. What does the term *electrical isolation* mean?
2. Define *mutual inductance*.
3. Two 50 mH coils have $k = 0.9$. What is L_M?
4. If k is increased, what happens to the voltage induced in one coil as a result of a current change in the other coil?

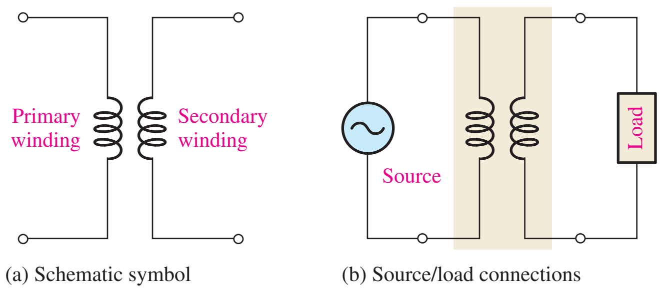
14–2 THE BASIC TRANSFORMER

A **transformer** is an electrical device constructed of two or more coils of wire (windings) magnetically coupled to each other so that there is a mutual inductance for the transfer of power from one winding to the other. Although many transformers have more than two windings, the coverage in this section is restricted to a basic two-winding transformer. Later, more complicated transformers are introduced.

After completing this section, you should be able to

- **Describe how a transformer is constructed and how it operates**
    - Identify the parts of a basic transformer
    - Discuss the importance of the core material
    - Define *primary winding* and *secondary winding*
    - Define *turns ratio*
    - Discuss how the direction of windings affects voltage polarities

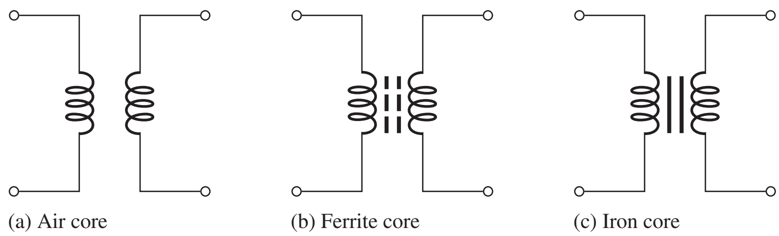
A schematic of a basic transformer is shown in Figure 14–3(a). As shown, one coil is called the **primary winding**, and the other is called the **secondary winding**. The source voltage is applied to the primary winding, and the load is connected to the secondary winding, as shown in Figure 14–3(b). The primary winding is the input winding, and the secondary winding is the output winding. It is common to refer to the side of the transformer that has the source voltage as the *primary*, and the side that has the induced voltage as the *secondary*.



▲ **FIGURE 14–3**

The basic transformer.

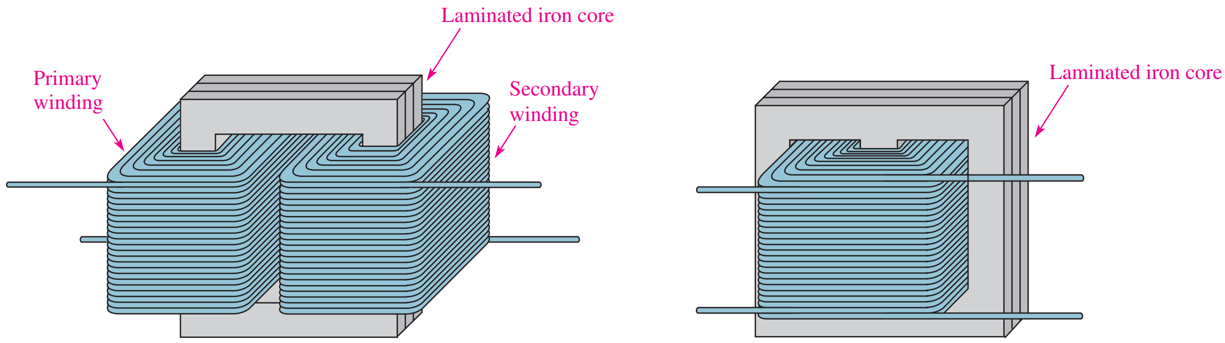
The windings of a transformer are formed around the core. The core provides both a physical structure for placement of the windings and a magnetic path so that the magnetic flux is concentrated close to the coils. There are three general categories of core material: air, ferrite, and iron. The schematic symbol for each type is shown in Figure 14–4.



▲ **FIGURE 14–4**

Schematic symbols based on type of core.

Iron-core transformers generally are used for audio frequency (AF) and power applications. These transformers consist of windings on a core constructed from laminated sheets of ferromagnetic material insulated from each other, as shown in Figure 14–5. This construction provides an easy path for the magnetic flux and increases the amount of coupling between the windings. Figure 14–5 shows the basic



(a) Core type has each winding on a separate leg.

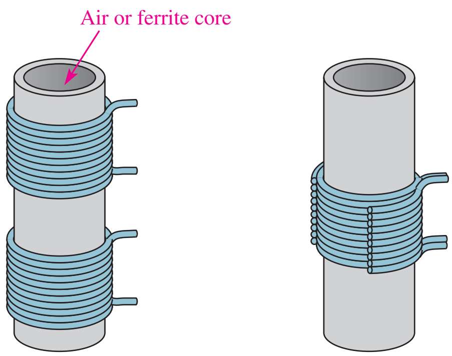
(b) Shell type has both windings on the same leg.

▲ **FIGURE 14–5**

Iron-core transformer construction with multilayer windings.

construction of two major configurations of iron-core transformers. In the core-type construction, shown in part (a), the windings are on separate legs of the laminated core. In the shell-type construction, shown in part (b), both windings are on the same leg. Each type has certain advantages. Generally, the core type has more room for insulation and can handle higher voltages. The shell type can produce higher magnetic fluxes in the core, resulting in the need for fewer turns.

Air-core and ferrite-core transformers generally are used for high-frequency applications and consist of windings on an insulating shell which is hollow (air) or constructed of ferrite, such as depicted in Figure 14–6. The wire is typically covered by a varnish-type coating to prevent the windings from shorting together. The amount of **magnetic coupling** between the primary winding and the secondary winding is set by the type of core material and by the relative positions of the windings. In Figure 14–6(a), the windings are loosely coupled because they are separated, and in part (b) they are tightly coupled because they are overlapping. The tighter the coupling, the greater the induced voltage in the secondary for a given current in the primary.



(a) Loosely coupled windings

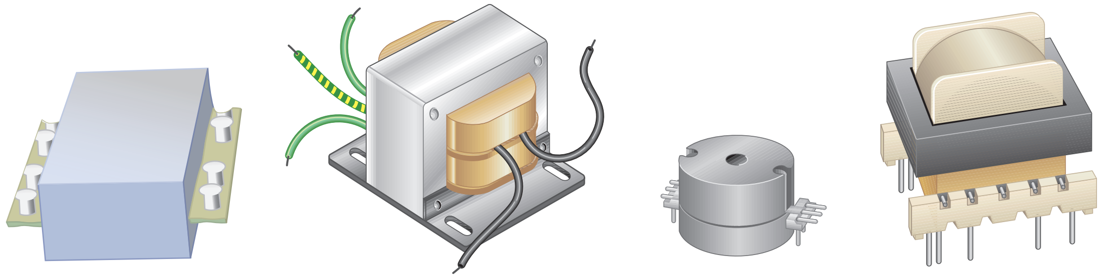
(b) Tightly coupled windings. Cutaway view shows both windings.

◀ **FIGURE 14–6**

Transformers with cylindrical-shaped cores.

High-frequency transformers tend to have fewer windings and smaller inductances than power transformers. A type of high-frequency transformer that has become popular in recent years is the planar transformer. Planar transformers are constructed with printed circuit (PC) board assembly methods (rather than wire winding) that enable them to be produced with high precision and low cost. The windings are actually traces laid out on stacked PC boards. Planar transformers are available in a variety of sizes and wattage ratings. The low profile of a planar transformer (typically less than 0.5 inches) makes it particularly suited to cases where space is critical.

A representative planar transformer is shown in Figure 14–7(a). The transformer in Figure 14–7(b) is a low-voltage transformer commonly used in power supplies. Parts (c) and (d) show other common types of small transformers.



(a) (b) (c) (d)

▲ FIGURE 14–7

Some common types of transformers.

Turns Ratio

A transformer parameter that is useful in understanding how a transformer operates is the turns ratio. In this text, the **turns ratio (n)** is defined as the ratio of the number of turns in the secondary winding (N_{sec}) to the number of turns in the primary winding (N_{pri}).

Equation 14–3

$$n = \frac{N_{sec}}{N_{pri}}$$

This definition of turns ratio is based on the IEEE standard for electronics power transformers as specified in the IEEE dictionary. Other categories of transformer may have a different definition, so some sources define the turns ratio as N_{pri}/N_{sec}. Either definition is correct as long as it is clearly stated and used consistently. The turns ratio of a transformer is rarely if ever given as a transformer specification. Generally, the input and output voltages and the power rating are the key specifications. However, the turns ratio is useful in studying the operating principle of a transformer.

EXAMPLE 14–3

A transformer primary winding has 100 turns, and the secondary winding has 400 turns. What is the turns ratio?

Solution $N_{sec} = 400$ and $N_{pri} = 100$; therefore, the turns ratio is

$$n = \frac{N_{sec}}{N_{pri}} = \frac{400}{100} = \mathbf{4}$$

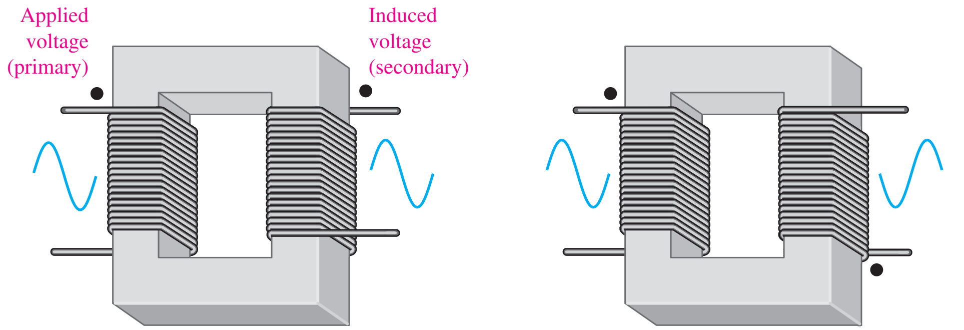
Related Problem A certain transformer has a turns ratio of 10. If $N_{pri} = 500$, what is N_{sec}?

Direction of Windings

Another important transformer parameter is the direction in which the windings are placed around the core. As illustrated in Figure 14–8, the direction of the windings determines the polarity of the voltage across the secondary winding (secondary voltage) with respect to the voltage across the primary winding (primary voltage). Phase dots are sometimes used on the schematic symbols to indicate polarities, as shown in Figure 14–9.

FIGURE 14–8

The direction of the windings determines the relative polarities of the voltages.

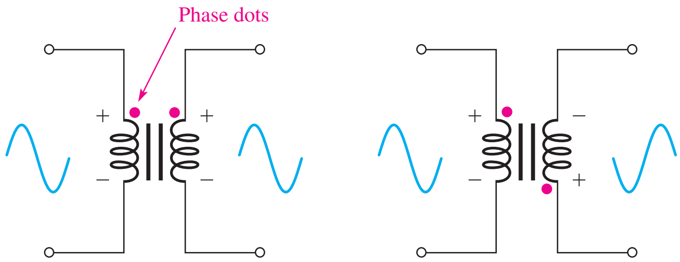


(a) The primary and secondary voltages are in phase when the windings are in the same effective direction around the magnetic path.

(b) The primary and secondary voltages are 180° out of phase when the windings are in the opposite direction.

FIGURE 14–9

Phase dots indicate relative polarities of primary and secondary voltages.



(a) Voltages are in phase.

(b) Voltages are out of phase.

SECTION 14–2 CHECKUP

1. Upon what principle is the operation of a transformer based?
2. Define *turns ratio*.
3. Why are the directions of the windings of a transformer important?
4. A certain transformer has a primary winding with 500 turns and a secondary winding with 250 turns. What is the turns ratio?
5. How do the windings in a planar transformer differ from other transformers?

14–3 STEP-UP AND STEP-DOWN TRANSFORMERS

A step-up transformer has more turns in its secondary winding than in its primary winding and is used to increase ac voltage. A step-down transformer has more turns in its primary winding than in its secondary winding and is used to decrease ac voltage.

After completing this section, you should be able to

- **Describe how transformers increase and decrease voltage**
  - Explain how a step-up transformer works
  - Identify a step-up transformer by its turns ratio
  - State the relationship between primary and secondary voltages and the turns ratio
  - Explain how a step-down transformer works
  - Identify a step-down transformer by its turns ratio
  - Describe dc isolation

The Step-Up Transformer

A transformer in which the secondary voltage is greater than the primary voltage is called a **step-up transformer**. The amount that the voltage is stepped up depends on the turns ratio.

The ratio of secondary voltage (V_{sec}) to primary voltage (V_{pri}) is equal to the ratio of the number of turns in the secondary winding (N_{sec}) to the number of turns in the primary winding (N_{pri}).

Equation 14–4

$$\frac{V_{sec}}{V_{pri}} = \frac{N_{sec}}{N_{pri}}$$

Recall that N_{sec}/N_{pri} defines the turns ratio, n. Therefore, from this relationship,

Equation 14–5

$$V_{sec} = nV_{pri}$$

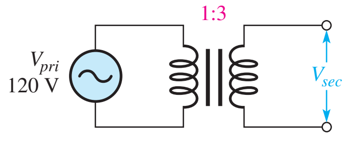
Equation 14–5 shows that the secondary voltage is equal to the turns ratio times the primary voltage. This condition assumes that the coefficient of coupling is 1, and a good iron-core transformer approaches this value.

The turns ratio for a step-up transformer is always greater than 1 because the number of turns in the secondary winding (N_{sec}) is always greater than the number of turns in the primary winding (N_{pri}).

EXAMPLE 14–4

The transformer in Figure 14–10 has a turns ratio of 3. What is the voltage across the secondary winding? RMS voltage is assumed.

► FIGURE 14–10



Solution The secondary voltage is

$$V_{sec} = nV_{pri} = (3)120\text{ V} = \mathbf{360\text{ V}}$$

Note that the turns ratio of 3 is indicated on the schematic as 1:3, meaning that there are three secondary turns for each primary turn.

Related Problem The transformer in Figure 14–10 is changed to one with a turns ratio of 4. Determine V_{sec}.

Use Multisim file E14-04 to verify the calculated results in this example and to confirm your calculation for the related problem.

The Step-Down Transformer

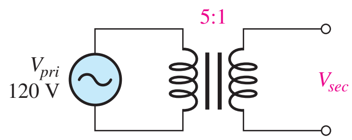
A transformer in which the secondary voltage is less than the primary voltage is called a **step-down transformer**. The amount by which the voltage is stepped down depends on the turns ratio. Equation 14–5 also applies to a step-down transformer.

The turns ratio of a step-down transformer is always less than 1 because the number of turns in the secondary winding is always fewer than the number of turns in the primary winding.

EXAMPLE 14–5

The transformer in Figure 14–11 has a turns ratio of 0.2. What is the secondary voltage?

▶ FIGURE 14–11



Solution The secondary voltage is

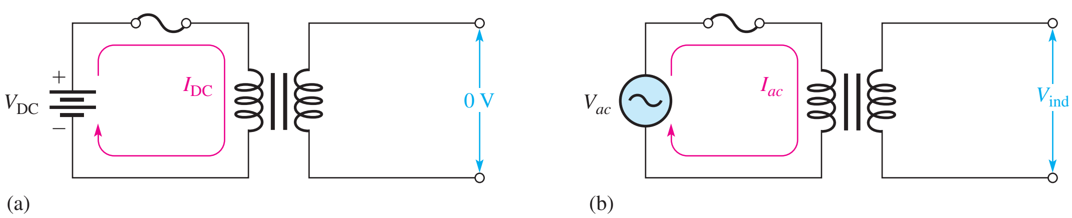
$$V_{sec} = nV_{pri} = (0.2)120\text{ V} = \mathbf{24\ V}$$

Related Problem The transformer in Figure 14–11 is changed to one with a turns ratio of 0.48. Determine the secondary voltage.

Use Multisim file E14-05 to verify the calculated results in this example and to confirm your calculation for the related problem.

DC Isolation

As illustrated in Figure 14–12(a), if there is dc in the primary of a transformer, nothing happens in the secondary. The reason is that a changing current in the primary winding is necessary to induce a voltage in the secondary winding, as shown in part (b). Therefore, the transformer isolates the secondary circuit from any dc in the primary circuit. A transformer that is used strictly for isolation has a turns ratio of 1.



▲ FIGURE 14–12

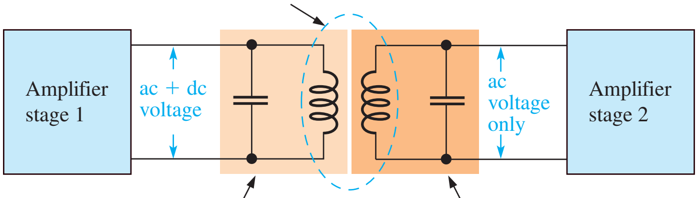
DC isolation and ac coupling.

Isolation transformers are often packaged as part of a total ac line-conditioning device. In addition to the isolation transformer, the line conditioning includes surge protection, filters to eliminate interference, and sometimes automatic voltage regulation. Line conditioning is useful to isolate sensitive equipment such as microprocessor-based controllers. Specialized line conditioners for patient-monitoring equipment in hospitals provide a high degree of electrical isolation and protection from shock.

Small transformers that are used to isolate the dc bias from one stage of an amplifier to the next stage are called coupling transformers because the ac signal is passed ("coupled") but the dc is blocked. Coupling transformers are widely used at high frequencies where they are designed to pass only a selected band of frequencies by making the primary and secondary coils part of a parallel tuned circuit (resonant circuit). (Tuned circuits are discussed in Chapter 17.) A typical transformer-coupled amplifier arrangement is shown in Figure 14–13. Frequently, the core of a coupling transformer can be adjusted to fine-tune the frequency response. Coupling transformers are also commonly used to couple a signal from an amplifier to a speaker.

▶ FIGURE 14–13

Amplifier stages with transformer coupling for dc isolation. Also, the coupling transformer is used to pass high frequencies in the band determined by the tuned circuits.



SECTION 14–3 CHECKUP

1. What does a step-up transformer do?
2. If the turns ratio is 5, how much greater is the secondary voltage than the primary voltage?
3. When 240 V ac are applied to the primary winding of a transformer with a turns ratio of 10, what is the secondary voltage?
4. What does a step-down transformer do?
5. A voltage of 120 V ac is applied to the primary winding of a transformer with a turns ratio of 0.5. What is the secondary voltage?
6. A primary voltage of 120 V ac is reduced to 12 V ac. What is the turns ratio?

14–4 LOADING THE SECONDARY

When a resistive load is connected to the secondary winding of a transformer, the relationship of the load (secondary) current and the current in the primary circuit is determined by the turns ratio.

After completing this section, you should be able to

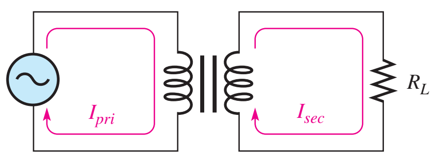
- **Discuss the effect of a resistive load across the secondary**
  - Determine the current delivered by the secondary when a step-up transformer is loaded
  - Determine the current delivered by the secondary when a step-down transformer is loaded
  - Discuss power in a transformer

When a load resistor is connected to the secondary winding, as shown in Figure 14–14, there is current through the resulting secondary circuit because of the voltage induced in the secondary coil. It can be shown that the ratio of the primary current, I_{pri}, to the secondary current, I_{sec}, is equal to the turns ratio, as expressed in the following equation:

Equation 14–6
$$\frac{I_{pri}}{I_{sec}} = n$$

▶ FIGURE 14–14

Induced current in the secondary of a transformer.



A manipulation of the terms in Equation 14–6 gives Equation 14–7, which shows that I_{sec} is equal to I_{pri} times the reciprocal of the turns ratio.

$$I_{sec} = \left(\frac{1}{n}\right)I_{pri}$$

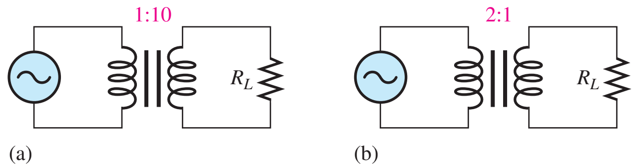
Equation 14–7

Thus, for a step-up transformer, in which n is greater than 1, the secondary current is less than the primary current. For a step-down transformer, n is less than 1, and I_{sec} is greater than I_{pri}. When the secondary voltage is greater than the primary voltage, the secondary current is lower than the primary current and vice versa.

EXAMPLE 14–6

The two ideal transformers in Figure 14–15 have loaded secondary windings. If the primary current is 100 mA in each case, what is the load current?

► FIGURE 14–15



Solution In Figure 14–15(a), the turns ratio is 10. The current through the load is

$$I_{sec} = \left(\frac{1}{n}\right)I_{pri} = (0.1)100\text{ mA} = \mathbf{10\text{ mA}}$$

In Figure 14–15(b), the turns ratio is 0.5. The current through the load is

$$I_{sec} = \left(\frac{1}{n}\right)I_{pri} = (2)100\text{ mA} = \mathbf{200\text{ mA}}$$

Related Problem What is the secondary current in Figure 14–15(a) if the turns ratio is doubled? What is the secondary current in Figure 14–15(b) if the turns ratio is halved? Assume I_{pri} remains the same in both circuits.

Primary Power Equals Load Power

When a load is connected to the secondary winding of a transformer, the power transferred to the load can never be greater than the power in the primary winding. For an ideal transformer, the power delivered to the primary equals the power delivered by the secondary to the load. When losses are considered, some of the power is dissipated in the transformer rather than the load; therefore, the load power is always less than the power delivered to the primary.

Power is dependent on voltage and current, and there can be no increase in power in a transformer. Therefore, if the voltage is stepped up, the current is stepped down and vice versa. In an ideal transformer, the secondary power is equal to the primary power regardless of the turns ratio, as the following equations show. The power delivered to the primary is

$$P_{pri} = V_{pri}I_{pri}$$

and the power delivered to the load is

$$P_{sec} = V_{sec}I_{sec}$$

From Equations 14–7 and 14–5,

$$I_{sec} = \left(\frac{1}{n}\right)I_{pri} \quad \text{and} \quad V_{sec} = nV_{pri}$$

By substitution,

$$P_{sec} = \left(\frac{1}{\cancel{n}}\right)\cancel{n}V_{pri}I_{pri}$$

Canceling terms yields

$$P_{sec} = V_{pri}I_{pri} = P_{pri}$$

This result is closely approached in practice by power transformers because of the very high efficiencies.

SECTION 14–4 CHECKUP

1. If the turns ratio of a transformer is 2, is the secondary current greater than or less than the primary current? By how much?
2. A transformer has 1,000 turns in its primary winding and 250 turns in its secondary winding, and I_{pri} is 0.5 A. What is the value of I_{sec}?
3. In Problem 2, how much primary current is necessary to produce a secondary load current of 10 A?

14–5 REFLECTED LOAD

Resistance (by Ohm's law) is voltage divided by current. Because a transformer can change both the voltage and current, the resistance "seen" by the primary is not necessarily equal to the actual resistance of the load. The actual load is "reflected" into the primary as determined by the turns ratio. This reflected load is what the primary source effectively sees, and it determines the amount of primary current.

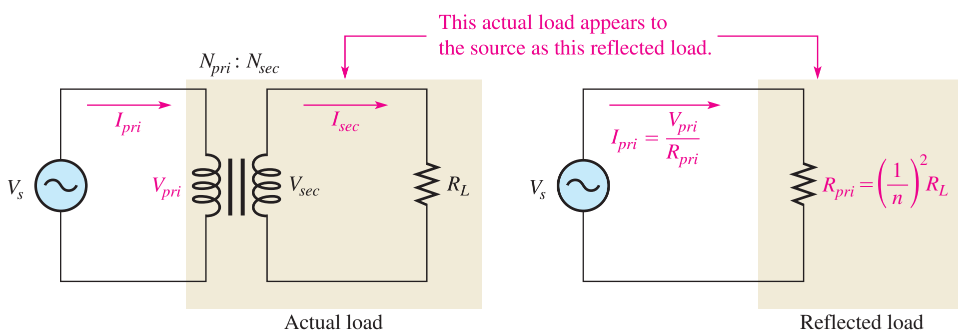
After completing this section, you should be able to

- **Discuss the concept of a reflected load in a transformer**
  - Define *reflected resistance*
  - Explain how the turns ratio affects the reflected resistance
  - Calculate reflected resistance

The concept of the **reflected load** is illustrated in Figure 14–16. The load (R_L) in the secondary of a transformer is reflected into the primary by transformer action. Ideally, the load appears to the source in the primary to be a resistance (R_{pri}) with a value determined by the turns ratio and the actual value of the load resistance. The resistance (R_{pri}) is called the **reflected resistance**.

▶ FIGURE 14–16

Reflected load in a transformer circuit.



The resistance in the primary of Figure 14–16 is $R_{pri} = V_{pri}/I_{pri}$. The resistance in the secondary is $R_L = V_{sec}/I_{sec}$. From Equations 14–4 and 14–6, you know that $V_{sec}/V_{pri} = n$ and $I_{pri}/I_{sec} = n$. Using these relationships, a formula for R_{pri} in terms of R_L is determined as follows:

$$\frac{R_{pri}}{R_L} = \frac{V_{pri}/I_{pri}}{V_{sec}/I_{sec}} = \left(\frac{V_{pri}}{V_{sec}}\right)\left(\frac{I_{sec}}{I_{pri}}\right) = \left(\frac{1}{n}\right)\left(\frac{1}{n}\right) = \left(\frac{1}{n}\right)^2$$

Solving for R_{pri} yields

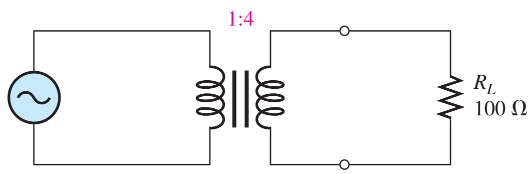
$$R_{pri} = \left(\frac{1}{n}\right)^2 R_L \qquad \textbf{Equation 14–8}$$

Equation 14–8 shows that the resistance reflected into the primary circuit is the square of the reciprocal of the turns ratio times the load resistance.

EXAMPLE 14–7

Figure 14–17 shows a source that is transformer-coupled to a load resistor of 100 Ω. The transformer has a turns ratio of 4. What is the reflected resistance seen by the source?

FIGURE 14–17

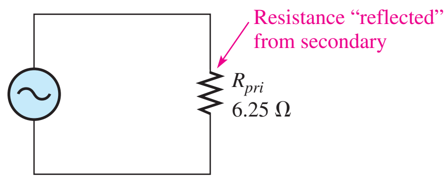


Solution The reflected resistance is determined by Equation 14–8.

$$R_{pri} = \left(\frac{1}{n}\right)^2 R_L = \left(\frac{1}{4}\right)^2 R_L = \left(\frac{1}{16}\right)100\ \Omega = \mathbf{6.25\ \Omega}$$

The source sees a resistance of 6.25 Ω just as if it were connected directly, as shown in the equivalent circuit of Figure 14–18.

FIGURE 14–18



Related Problem If the turns ratio in Figure 14–17 is 10 and R_L is 600 Ω, what is the reflected resistance?

EXAMPLE 14–8

In Figure 14–17, if a transformer is used having a turns ratio of 0.25, what is the reflected resistance?

Solution The reflected resistance is

$$R_{pri} = \left(\frac{1}{n}\right)^2 R_L = \left(\frac{1}{0.25}\right)^2 100\ \Omega = (4)^2 100\ \Omega = \mathbf{1{,}600\ \Omega}$$

This result illustrates the difference that the turns ratio makes.

Related Problem To achieve a reflected resistance of 800 Ω, what turns ratio is required in Figure 14–17?

In a step-up transformer ($n > 1$), the reflected resistance is less than the actual load resistance; in a step-down transformer ($n < 1$), the reflected resistance is greater than the load resistance. This was illustrated in Examples 14–7 and 14–8, respectively.

SECTION 14–5 CHECKUP

1. Define *reflected resistance*.
2. What transformer characteristic determines the reflected resistance?
3. A given transformer has a turns ratio of 10, and the load is 50 Ω How much resistance is reflected into the primary?
4. What is the turns ratio required to reflect a 4 Ω load resistance into the primary as 400 Ω?

14–6 Impedance Matching

One application of transformers is in the matching of a load impedance to a source impedance to achieve maximum transfer of power or other results. This technique is called impedance matching. In audio systems, special wide-band transformers are often used to get the maximum amount of available power from the amplifier to the speaker by proper selection of the turns ratio. Transformers designed specifically for impedance matching usually show the input and output impedance they are designed to match. A special type of impedance-matching transformer called the balun is introduced.

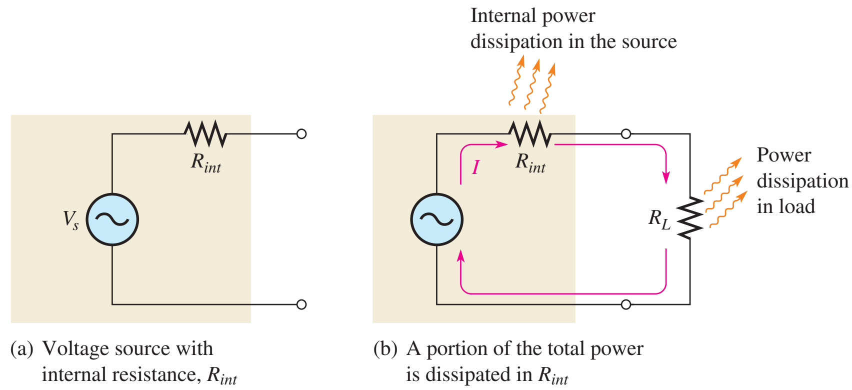
After completing this section, you should be able to

- **Discuss impedance matching with transformers**
    - Discuss the maximum power transfer theorem
    - Define *impedance matching*
    - Explain the purpose of impedance matching
    - Describe a balun transformer

Recall that the maximum power transfer theorem (discussed in Section 8–7) states that maximum power is transferred from a source to a load when the load resistance is equal to the source resistance. In ac circuits, the total opposition to current is referred to as impedance, which can be resistance, reactance, or a combination of both. The term **impedance matching** is used to show that the source and load impedances are effectively equal. For this section, we will confine our usage to resistance only.

Figure 14–19(a) shows an ac source with a fixed internal resistance. Some fixed internal resistance is inherent in all sources due to their internal circuitry. Part (b) shows a load connected to the source. In this case, the objective is often to transfer as much power to the load as possible. It is important to verify that the impedance-matching transformer is rated for this power.

In most practical situations, the internal source resistance of various types of sources is fixed. Also, in many cases, the resistance of a device that acts as a load is fixed and cannot be altered. If you need to connect a given source to a given load, remember that only by chance will their resistances match. In this situation, a special type of wide band transformer comes in handy. You can use the reflected-resistance characteristic provided by a transformer to make the load resistance appear to have the same value as the source resistance. This technique is called impedance matching, and the transformer is called an impedance-matching transformer because it also transforms reactances as well as resistances.



◀ FIGURE 14–19

Power transfer from a nonideal voltage source to a load.

Figure 14–20 illustrates a specific example of an impedance-matching transformer. In this example, a source with an internal resistance of 75 Ω is driving a 300 Ω load. The impedance-matching transformer needs to make the load resistance look like a 75 Ω resistance to the source in order to deliver maximum power to the load. To select the right transformer, you need to know how the turns ratio affects the impedance. You can use Equation 14–8 to determine the turns ratio, n, to achieve impedance matching when you know the values for R_L and R_{pri}.

$$R_{pri} = \left(\frac{1}{n}\right)^2 R_L$$

Transpose terms and divide both sides by R_L.

$$\left(\frac{1}{n}\right)^2 = \frac{R_{pri}}{R_L}$$

Then take the square root of both sides.

$$\frac{1}{n} = \sqrt{\frac{R_{pri}}{R_L}}$$

Invert both sides to get the following formula for the turns ratio:

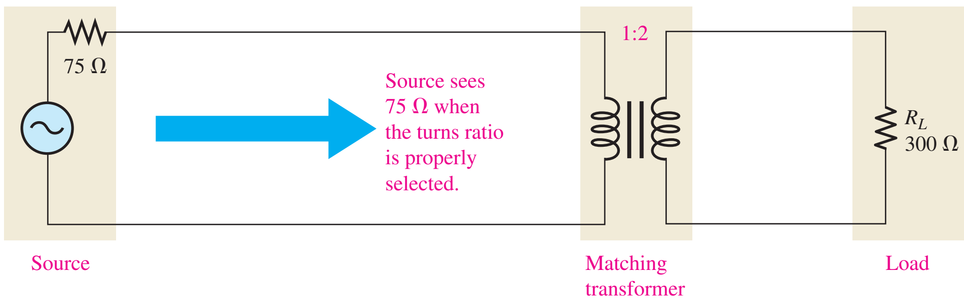
$$n = \sqrt{\frac{R_L}{R_{pri}}}$$

Equation 14–9

Finally, solve for the particular turns ratio to match a 300 Ω load to a 75 Ω source.

$$n = \sqrt{\frac{300\ \Omega}{75\ \Omega}} = \sqrt{4} = 2$$

Therefore, a matching transformer with a turns ratio of 2 must be used in this application.



◀ FIGURE 14–20

Example of a load matched to a source by transformer coupling for maximum power transfer.

EXAMPLE 14–9

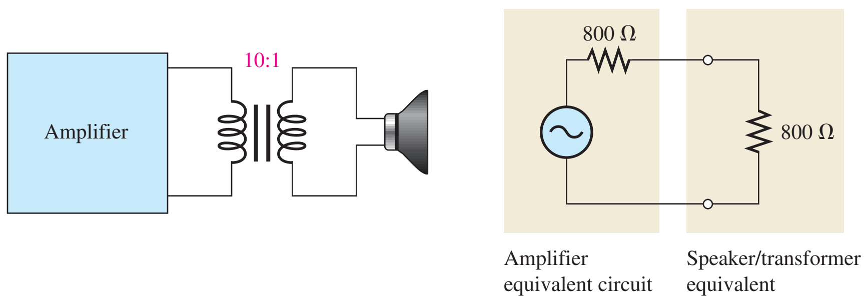
An amplifier has an 800 Ω internal resistance. In order to provide maximum power to an 8 Ω speaker, what turns ratio must be used in the coupling transformer?

Solution The reflected resistance must equal 800 Ω. Thus, from Equation 14–9, the turns ratio can be determined.

$$n = \sqrt{\frac{R_L}{R_{pri}}} = \sqrt{\frac{8\ \Omega}{800\ \Omega}} = \sqrt{0.01} = \mathbf{0.1}$$

The diagram and its equivalent reflected circuit are shown in Figure 14–21.

▶ FIGURE 14–21



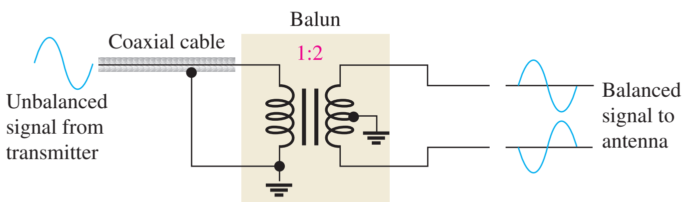
Related Problem What must be the turns ratio in Figure 14–21 to provide maximum power to two 8 Ω speakers in parallel?

Frequently, the specification sheet for an impedance-matching transformer simply shows the primary and secondary impedances that are designed to be matched, rather than the turns ratio. For example, an audio amplifier that is designed to match the high impedance output of an amplifier to a low impedance speaker will show the primary impedance, the secondary impedance it matches, and the wattage rating. The frequency range and physical characteristics are also on the specification sheet.

The Balun Transformer An application for impedance matching is used in high-frequency antennas. In addition to impedance matching, many transmitting antennas also require that an unbalanced signal from the transmitter be converted to a balanced signal. A *balanced signal* is composed of two equal-amplitude signals that are 180° out-of-phase with each other. An *unbalanced signal* is one that is referenced to ground. A special type of transformer called a **balun,** a contraction of the words "*bal*anced-*un*balanced" is used to convert the unbalanced signal from the transmitter to a balanced signal at the antenna, as shown in Figure 14–22.

▶ FIGURE 14–22

Illustration of a balun transformer converting an unbalanced signal to a balanced signal.



The transmitter is usually connected to the balun with a coaxial cable (coax). A coax is basically a conductor surrounded by an insulating region and an outer conductor called the shield. In Figure 14–22, the signal from the transmitter is referenced to ground, which is connected to the outer shield of the coax, so it is an unbalanced signal. The shield on the coax minimizes pickup of radiated noise.

The coax has a certain characteristic impedance associated with it. The turns ratio of the balun is set to match the coax impedance to the antenna impedance. For example, if the transmitting antenna represents a 300 Ω impedance and the coax has a characteristic impedance of 75 Ω, the balun can provide the impedance match with a turns ratio of 2, as was shown earlier. Baluns can also be used to convert from balanced signals to unbalanced signals.

SECTION 14–6 CHECKUP

1. What does impedance matching mean?
2. What is the advantage of matching the load resistance to the resistance of a source?
3. A transformer has a turns ratio of 0.5. What is the reflected resistance with 100 Ω across the secondary?
4. What is the function of a balun?

14–7 TRANSFORMER RATINGS AND CHARACTERISTICS

Transformer operation has been discussed from an ideal point of view. That is, the winding resistance, the winding capacitance, and nonideal core characteristics were all neglected and the transformer was treated as if it had an efficiency of 100%. For studying the basic concepts and in many applications, the ideal model is valid. However, the practical transformer has several nonideal characteristics.

After completing this section, you should be able to

- **Describe a practical transformer**
  - List and describe the nonideal characteristics
  - Explain power rating of a transformer
  - Define *efficiency* of a transformer

Ratings

Power Rating A power transformer is typically rated in volt-amperes (VA), primary/secondary voltage, and operating frequency. For example, a given transformer rating may be specified as 2 kVA, 500/50, 60 Hz. The 2 kVA value is the **apparent power rating**. The 500 and the 50 can be either secondary or primary voltages. The 60 Hz is the operating frequency.

The transformer rating can be helpful in selecting the proper transformer for a given application. Let's assume, for example, that 50 V is the secondary voltage. In this case the load current is

$$I_L = \frac{P_{sec}}{V_{sec}} = \frac{2\text{ kVA}}{50\text{ V}} = 40\text{ A}$$

On the other hand, if 500 V is the secondary voltage, then

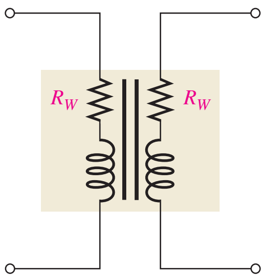
$$I_L = \frac{P_{sec}}{V_{sec}} = \frac{2\text{ kVA}}{500\text{ V}} = 4\text{ A}$$

These are the maximum currents that the secondary can handle in either case.

The reason that the power rating is in volt-amperes (apparent power) rather than in watts (true power) is as follows: If the transformer load is purely capacitive or purely inductive, the true power (watts) delivered to the load is zero. However, the current for $V_{sec} = 500$ V and $X_C = 100\ \Omega$ at 60 Hz, for example, is 5 A. This current exceeds the maximum that the 2 kVA secondary can handle, and the transformer may be damaged. So it is meaningless to specify power in watts for transformers.

Voltage and Frequency Ratings In addition to the apparent power rating, most power transformers will have voltage and frequency ratings placed on the transformer. The voltage ratings include the primary voltage for which it is designed and the secondary voltage that is present when the rated load is connected to the secondary and the primary is connected to the rated input voltage. Frequently, there will be a small schematic drawing showing the windings and voltage rating for each winding. The frequency for which the transformer is designed will also be specified; for power transformers this is generally 50/60 Hz. A transformer operated on the wrong frequency can be damaged, so it is important to note the frequency specification. These are minimum specifications you need to know in order to select a power transformer for an application.

Characteristics



▲ FIGURE 14–23

Winding resistances in a practical transformer.

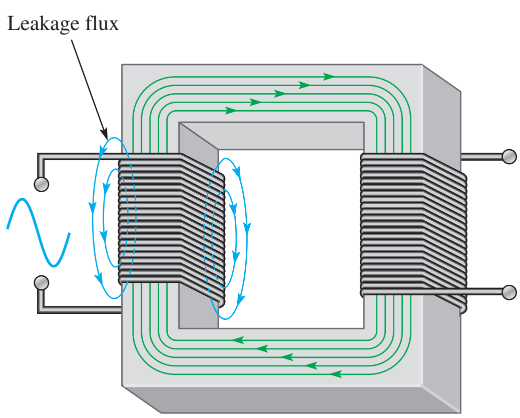
Winding Resistance Both the primary and the secondary windings of a practical transformer have winding resistance. You learned about the winding resistance of inductors in Chapter 13. The winding resistances of a practical transformer are represented as resistors in series with the windings as shown in Figure 14–23.

Winding resistance in a practical transformer results in less voltage across a secondary load. Voltage drops due to the winding resistance effectively subtract from the primary and secondary voltages and result in load voltage that is less than that predicted by the relationship $V_{sec} = nV_{pri}$. In many cases, the effect is relatively small and can be neglected.

Losses in the Core There is always some energy conversion in the core material of a practical transformer. This conversion is seen as a heating of ferrite and iron cores, but it does not occur in air cores. Part of this energy conversion is because of the continuous reversal of the magnetic field due to the changing direction of the primary current; this component of the energy conversion is called *hysteresis loss.* The rest of the energy conversion to heat is caused by eddy currents produced when voltage is induced in the core material by the changing magnetic flux, according to Faraday's law. The eddy currents occur in circular patterns in the core resistance, thus producing heat. This conversion to heat is greatly reduced by the use of laminated construction of iron cores. The thin layers of ferromagnetic material are insulated from each other to minimize the buildup of eddy currents by confining them to a small area and to keep core losses to a minimum.

Magnetic Flux Leakage In an ideal transformer, all of the magnetic flux produced by the primary current is assumed to pass through the core to the secondary winding, and vice versa. In a practical transformer, some of the magnetic flux lines break out of the core and pass through the surrounding air back to the other end of the winding, as illustrated in Figure 14–24 for the magnetic field produced by the primary current. Magnetic flux leakage results in a reduced secondary voltage.

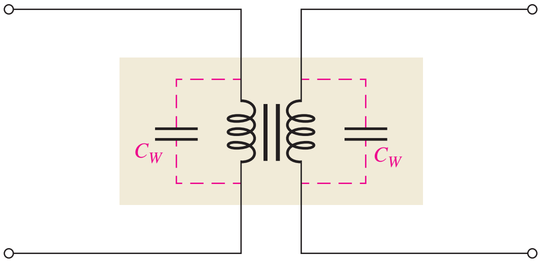
The percentage of magnetic flux that actually reaches the secondary winding determines the coefficient of coupling of the transformer. For example, if nine out of ten flux lines remain inside the core, the coefficient of coupling is 0.90 or 90%. Most iron-core transformers have very high coefficients of coupling (greater than 0.99), while ferrite-core and air-core devices have lower values.



► FIGURE 14–24

Flux leakage in a practical transformer.

Winding Capacitance As you learned in Chapter 13, there is always some stray capacitance between adjacent turns of a winding. These stray capacitances result in an effective capacitance in parallel with each winding of a transformer, as indicated in Figure 14–25.



◄ FIGURE 14–25

Winding capacitance in a practical transformer.

These stray capacitances have very little effect on the transformer's operation at low frequencies (such as power line frequencies) because the reactances (X_C) are very high. However, at higher frequencies, the reactances decrease and begin to produce a bypassing effect across the primary winding and across the secondary load. As a result, less of the total primary current is through the primary winding, and less of the total secondary current is through the load. This effect reduces the load voltage as the frequency goes up.

Transformer Efficiency Recall that the power delivered to the load is equal to the power delivered to the primary in an ideal transformer. Because the nonideal characteristics just discussed result in a power loss in the transformer, the secondary (output) power is always less than the primary (input) power. The **efficiency** ($\boldsymbol{\eta}$) of a transformer is a measure of the percentage of the input power that is delivered to the output.

$$\eta = \left(\frac{P_{out}}{P_{in}}\right)100\%$$

Equation 14–10

Most power transformers have efficiencies in excess of 95% under load.

EXAMPLE 14–10

A certain type of transformer has a primary current of 5 A and a primary voltage of 4,800 V. The secondary current is 90 A, and the secondary voltage is 240 V. Determine the efficiency of this transformer.

Solution The input power is

$$P_{in} = V_{pri}I_{pri} = (4{,}800\text{ V})(5\text{ A}) = 24\text{ kVA}$$

The output power is

$$P_{out} = V_{sec}I_{sec} = (240\text{ V})(90\text{ A}) = 21.6\text{ kVA}$$

The efficiency is

$$\eta = \left(\frac{P_{out}}{P_{in}}\right)100\% = \left(\frac{21.6\text{ kVA}}{24\text{ kVA}}\right)100\% = \mathbf{90\%}$$

Related Problem A transformer has a primary current of 8 A with a primary voltage of 440 V. The secondary current is 30 A and the secondary voltage is 100 V. What is the efficiency?

SECTION 14–7 CHECKUP

1. Explain how a practical transformer differs from the ideal model.
2. The coefficient of coupling of a certain transformer is 0.85. What does this mean?
3. A certain transformer has a rating of 10 kVA. If the secondary voltage is 250 V, how much load current can the transformer handle?

14–8 TAPPED AND MULTIPLE-WINDING TRANSFORMERS

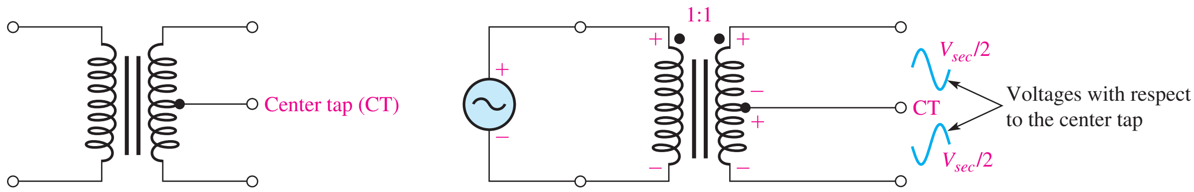
The basic transformer has several important variations. They include tapped transformers, multiple-winding transformers, and autotransformers. Three-phase transformers, which are types of multiple-winding transformers, are introduced in this section.

After completing this section, you should be able to

- **Describe several types of transformers**
  - Describe center-tapped transformers
  - Describe multiple-winding transformers
  - Describe autotransformers
  - Describe three-phase transformers

Tapped Transformers

A schematic of a transformer with a center-tapped secondary winding is shown in Figure 14–26(a). The **center tap (CT)** is equivalent to two secondary windings with half the total voltage across each.



(a) Center-tapped transformer

(b) Output voltages with respect to the center tap are 180° out of phase with each other and are one-half the magnitude of the secondary voltage.

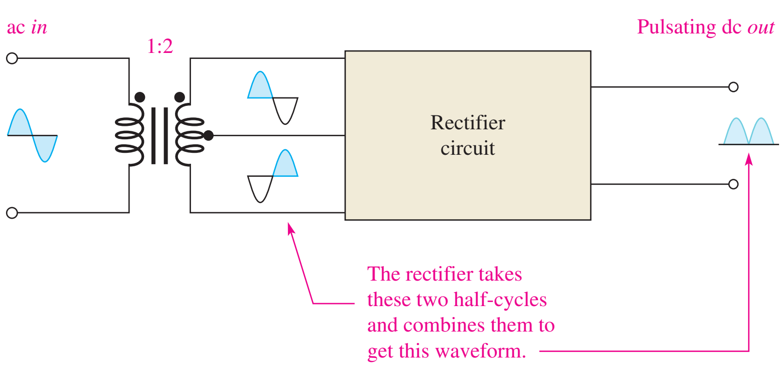
▲ FIGURE 14–26

Operation of a center-tapped transformer.

The voltages between either end of the secondary winding and the center tap are, at any instant, equal in magnitude but opposite in polarity, as illustrated in Figure 14–26(b). Here, for example, at some instant on the sinusoidal voltage, the polarity across the entire secondary winding is as shown (top end +, bottom −). At the center tap, the voltage is less positive than the top end but more positive than the bottom end of the secondary. Therefore, measured with respect to the center tap, the top end of the secondary is positive, and the bottom end is negative. This center-tapped feature is used in many power supply rectifiers in which the ac voltage is converted to dc, as illustrated in Figure 14–27.

► FIGURE 14–27

Application of a center-tapped transformer in ac-to-dc conversion.



Some tapped transformers have taps on the secondary winding at points other than the electrical center. Also, single and multiple primary and secondary taps are sometimes used in certain applications, such as impedance-matching transformers that normally have a center-tapped primary. Examples of these types of transformers are shown in Figure 14–28.

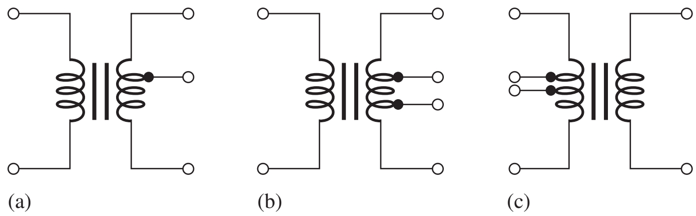


FIGURE 14–28

Tapped transformers.

Utility companies use many tapped transformers in distribution systems. Normally, power is generated and transmitted as three-phase power. At some point, the three-phase power is converted to single-phase for residential use. An example of a utility-pole transformer is shown in Figure 14–29 for the case where the high-voltage three-phase power has previously been converted to single-phase power (by tapping one of the three phases). It still needs to be converted to 120 V/240 V for residential customers, so a single-phase tapped transformer is used. By selecting the appropriate tap on the primary side, the utility company can make minor adjustments in the voltage that is delivered to the customer. The center tap on the secondary side is the neutral conductor that is the return line for current. Within the building, the wires are identified by color. For a 120 V Romex cable, the hot wire in a multiple sheathed cable is in black (or red if there is a second hot wire), neutral is in white or gray color, and the safety ground is either green or bare.

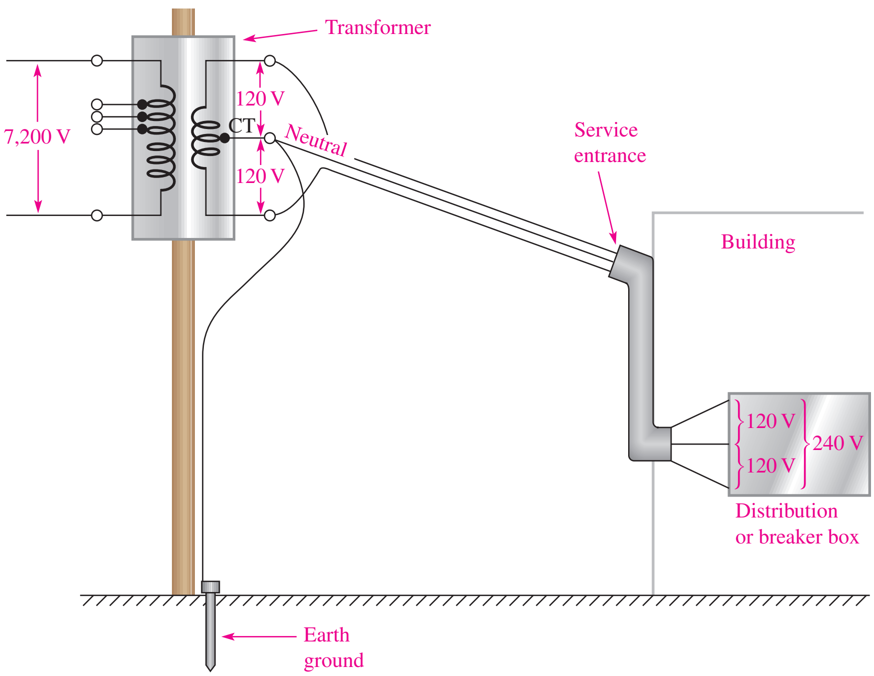


FIGURE 14–29

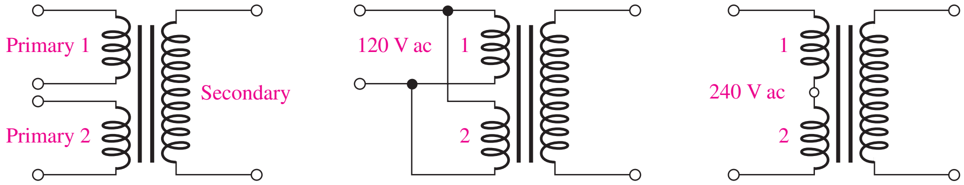
Utility-pole transformer in a typical power distribution system.

Multiple-Winding Transformers

Some transformers are designed to operate from either 120 V ac or 240 V ac lines. These transformers usually have two primary windings, each of which is designed for 120 V ac. When the two are connected in series, the transformer can be used for 240 V ac operations, as illustrated in Figure 14–30.

▶ **FIGURE 14–30**

Multiple-primary transformers.



(a) Two primary windings

(b) Primary windings in parallel for 120 V ac operation

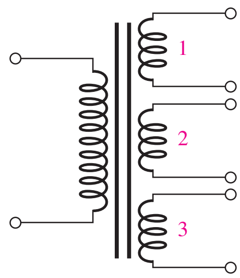
(c) Primary windings in series for 240 V ac operation

More than one secondary can be wound on a common core. Transformers with several secondary windings are often used to achieve several voltages by either stepping up or stepping down the primary voltage. These types are commonly used in power supply applications in which several voltage levels are required for the operation of an electronic instrument.

A typical schematic of a multiple-secondary transformer is shown in Figure 14–31; this transformer has three secondaries. Sometimes you will find combinations of multiple-primary, multiple-secondary, and tapped transformers all in one unit.

▶ **FIGURE 14–31**

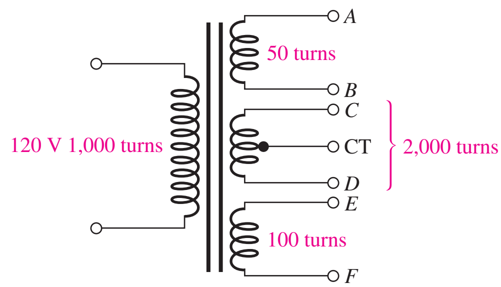
A multiple-secondary transformer.



EXAMPLE 14–11

The transformer shown in Figure 14–32 has the numbers of turns indicated. One of the secondaries is also center tapped. If 120 V ac are connected to the primary, determine each secondary voltage and the voltages with respect to the center tap (CT) on the middle secondary.

▶ **FIGURE 14–32**



Solution

$$V_{AB} = n_{AB}V_{pri} = (0.05)120\text{ V} = \mathbf{6.0\ V}$$

$$V_{CD} = n_{CD}V_{pri} = (2)120\text{ V} = \mathbf{240\ V}$$

$$V_{(\text{CT})C} = V_{(\text{CT})D} = \frac{240\text{ V}}{2} = \mathbf{120\ V}$$

$$V_{EF} = n_{EF}V_{pri} = (0.1)120\text{ V} = \mathbf{12\ V}$$

Related Problem Repeat the calculations for a primary with 500 turns.

Autotransformers

In an **autotransformer**, one winding serves as both the primary and the secondary. The winding is tapped at the proper points to achieve the desired turns ratio for stepping up or stepping down the voltage. The primary and secondary have some or all of their turns in common.

Autotransformers differ from conventional transformers in that there is no electrical isolation between the primary and the secondary because both share a common winding. Autotransformers normally are smaller and lighter than equivalent conventional transformers because they require a much lower kVA rating for a given load. Many autotransformers provide an adjustable tap using a sliding contact mechanism so that the output voltage can be varied (these are often called *variacs*). Figure 14–33 shows schematic symbols for various types of autotransformers. Autotransformers are used in starting industrial induction motors and regulating transmission line voltages.

Example 14–12 illustrates why an autotransformer has a kVA requirement that is less than the input or output kVA.

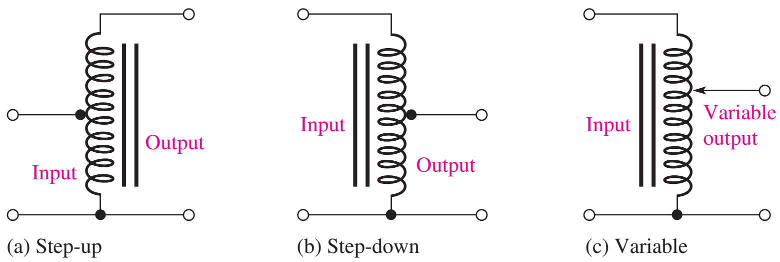


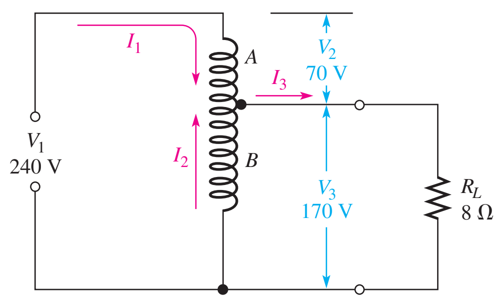
FIGURE 14–33
Types of autotransformers.

EXAMPLE 14–12

A certain autotransformer is used to change a source voltage of 240 V to a load voltage of 170 V across an 8 Ω load resistance. Determine the input and output power in kilovolt-amperes, and show that the actual kVA requirement is less than this value. Assume that this transformer is ideal.

Solution The circuit is shown in Figure 14–34 with voltages and currents indicated.

FIGURE 14–34



The load current, I_3, is determined as

$$I_3 = \frac{V_3}{R_L} = \frac{170\text{ V}}{8\ \Omega} = 21.3\text{ A}$$

The input power is the total source voltage (V_1) times the total current from the source (I_1).

$$P_{in} = V_1 I_1$$

The output power is the load voltage, V_3, times the load current, I_3.

$$P_{out} = V_3 I_3$$

For an ideal transformer, $P_{in} = P_{out}$; thus,

$$V_1 I_1 = V_3 I_3$$

Solving for I_1 yields

$$I_1 = \frac{V_3 I_3}{V_1} = \frac{(170\text{ V})(21.3\text{ A})}{240\text{ V}} = 15.1\text{ A}$$

Applying Kirchhoff's current law at the tap junction,

$$I_1 = I_2 + I_3$$

Solving for I_2, the current through winding B, yields

$$I_2 = I_1 - I_3 = 15.1\text{ A} - 21.3\text{ A} = -6.2\text{ A}$$

The minus sign indicates I_2 is out of phase with I_1.

The input and output power are

$$P_{in} = P_{out} = V_3 I_3 = (170\text{ V})(21.3\text{ A}) = \mathbf{3.62\text{ kVA}}$$

The power in winding A is

$$P_A = V_2 I_1 = (70\text{ V})(15.1\text{ A}) = 1.05\text{ kVA}$$

The power in winding B is

$$P_B = V_3 I_2 = (170\text{ V})(6.2\text{ A}) = 1.05\text{ kVA}$$

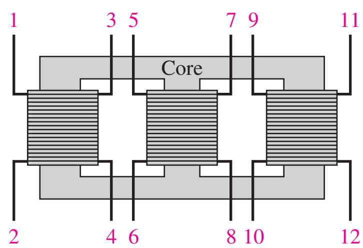
Thus, the power rating required for each winding is less than the power that is delivered to the load.

Related Problem What happens to the kVA requirement if the load is changed to 4 Ω?

Three-Phase Transformers

Three-phase power was introduced in Chapter 11 in relation to generators and motors. Three-phase transformers are widely used in power distribution systems. Three-phase power is the most common way in which power is produced, transmitted, and used. Although widely used in commercial and industrial applications, three-phase power is generally not used in residential applications.

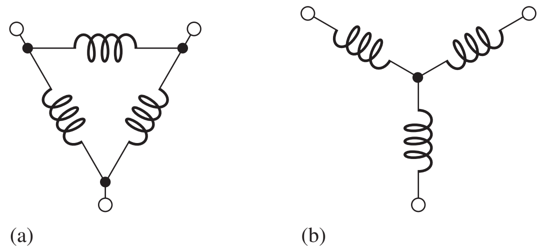
A three-phase transformer consists of three sets of primary and secondary windings. Each set is wound on one leg of an iron-core assembly. Basically, it is three single-phase transformers sharing a common core, as shown in Figure 14–35. It is possible (but more expensive) to connect three single-phase transformers together to achieve the same result. In a three-phase transformer, the three identical primary



► FIGURE 14–35

Three-phase transformer.

windings and the three identical secondary windings are connected in either of two ways, a delta (Δ) configuration or a wye (Y) configuration, to form a complete transformer unit. Delta and wye connections are shown in Figure 14–36.



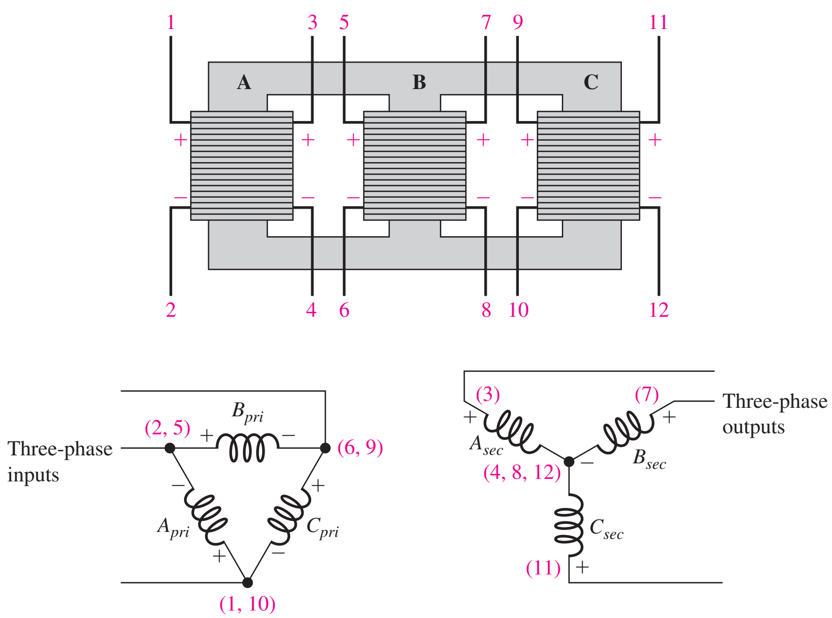
◀ **FIGURE 14–36**

Delta and wye configurations.

In a three-phase transformer the possible combinations of delta and wye configurations are

1. *Delta-to-wye* (Δ-Y). The primary winding is a delta and the secondary winding is a wye. This common configuration is used in commercial and industrial applications.
2. *Delta-to-delta* (Δ-Δ). The primary and secondary windings are both connected in the delta configuration. This is also commonly used in industrial applications.
3. *Wye-to-delta* (Y-Δ). The primary winding is a wye and the secondary winding is a delta. This is used in high-voltage transmission applications.
4. *Wye-to-wye* (Y-Y). The primary and secondary windings are both connected in the wye configuration. It is used in high-voltage, low kVA applications.

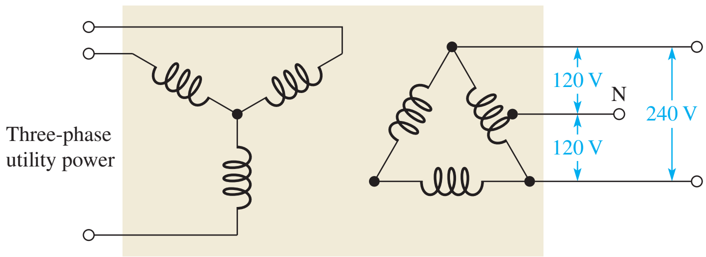
The delta-to-wye connections are shown in Figure 14–37. The proper winding phasing must be observed when connecting the transformers. The windings in the delta must be + to −; the polarity for each winding in the wye must be the same at the center point.



▲ **FIGURE 14–37**

Connections for a delta-to-wye transformer. The primary windings are designated A_{pri}, B_{pri}, and C_{pri}, the secondary windings are designated A_{sec}, B_{sec}, and C_{sec}. The numbers in parentheses correspond to the transformer leads.

The wye configuration has an advantage in that a neutral connection can be made at the center junction point. The delta configuration normally does not have a neutral. One exception is the special case for changing three-phase transmission-line voltage to single-phase power for residential use. In this case, a Y-Δ transformer with a center-tapped delta configuration is used, as shown in Figure 14–38. This configuration is referred to as a four-wire delta and can be used in applications where single phase is not available.



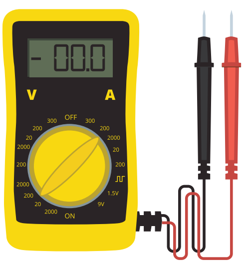
▲ FIGURE 14–38

A tapped wye-delta transformer that can be used to convert three-phase utility voltages to single-phase residential voltages.

SECTION 14–8 CHECKUP

1. A certain transformer has two secondary windings. The turns ratio from the primary winding to the first secondary is 10. The turns ratio from the primary to the other secondary is 0.2. If 240 V ac are applied to the primary, what are the secondary voltages?
2. Name one advantage and one disadvantage of an autotransformer over a conventional transformer.
3. In what form is electrical power most commonly produced and transmitted?

14–9 Troubleshooting



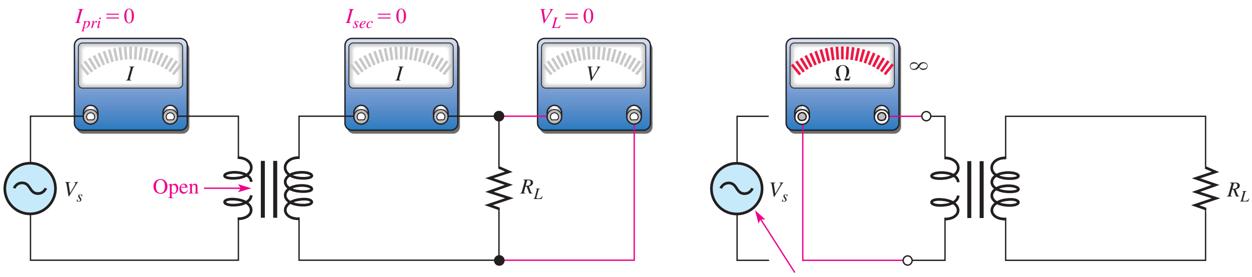
Transformers are reliable devices when they are operated within their specified range. Common failures in transformers are opens in either the primary or the secondary windings. One cause of such failures is the operation of the device under conditions that exceed its ratings. Normally, when a transformer fails, it is difficult to repair and therefore the simplest procedure is to replace it. A few transformer failures and the associated symptoms are covered in this section.

After completing this section, you should be able to

- **Troubleshoot transformers**
  - Find an open primary or secondary winding
  - Find a shorted or partially shorted primary or secondary winding

Open Primary Winding

When there is an open primary winding, there is no primary current and, therefore, no induced voltage or current in the secondary. This condition is illustrated in Figure 14–39(a), and the method of checking with an ohmmeter is shown in part (b).



(a) Conditions when the primary winding is open

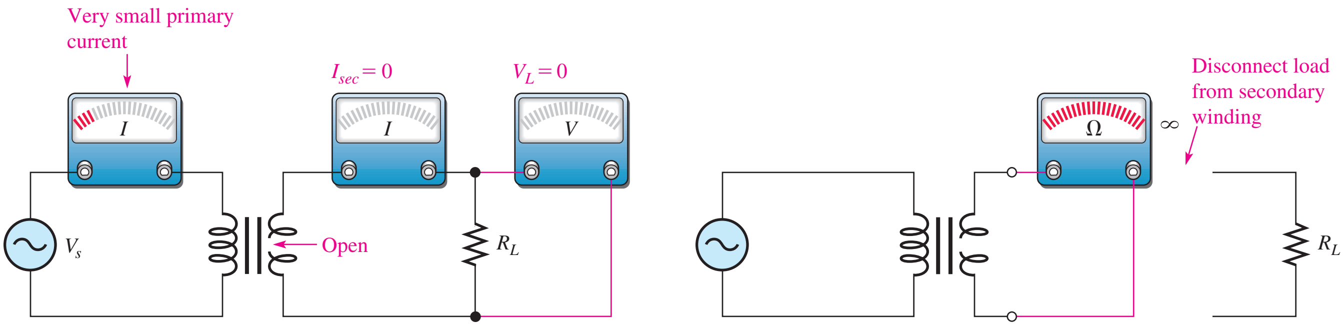
(b) Checking the primary winding with an ohmmeter

▲ **FIGURE 14–39**

Open primary winding.

Open Secondary Winding

When there is an open secondary winding, there is no current in the secondary circuit and, as a result, no voltage across the load. Also, an open secondary causes the primary current to be very small (there is only a small magnetizing current). This condition is illustrated in Figure 14–40(a), and the ohmmeter check is shown in part (b).



(a) Conditions when the secondary winding is open

(b) Checking the secondary winding with the ohmmeter

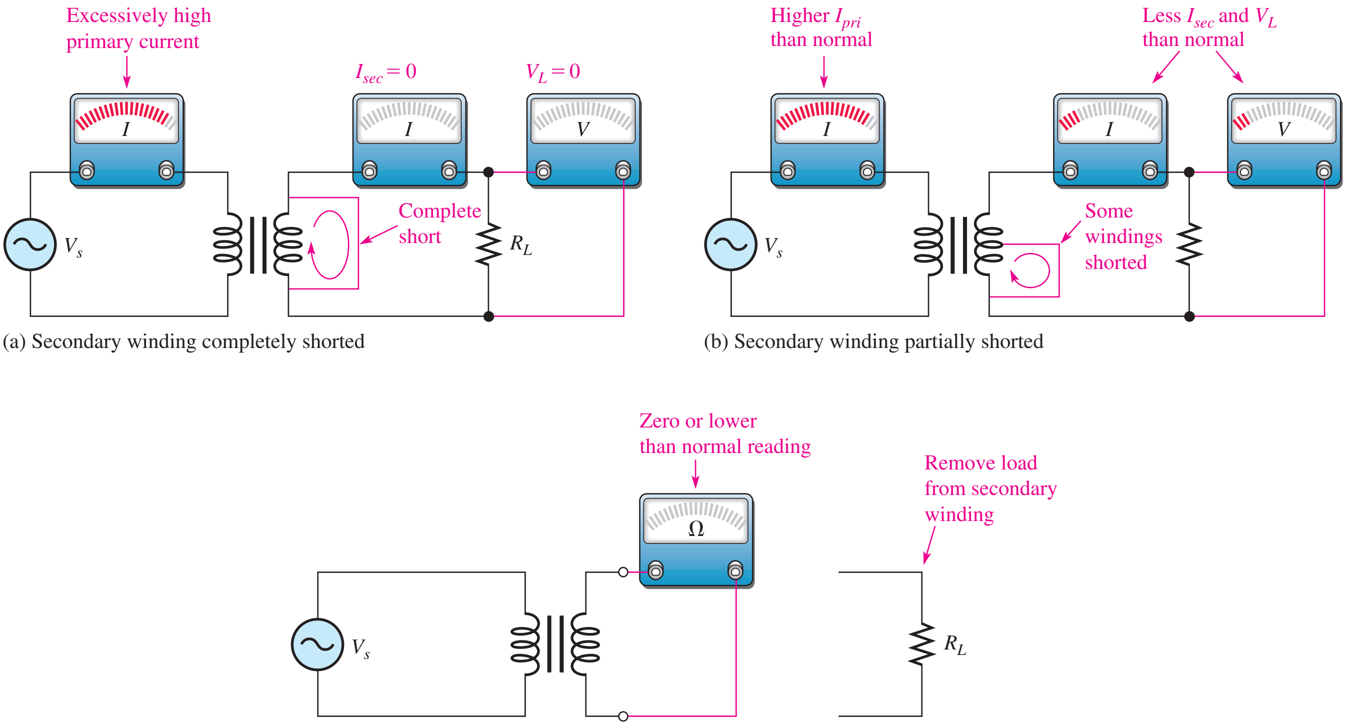
▲ **FIGURE 14–40**

Open secondary winding.

Shorted or Partially Shorted Windings

Shorted windings are very rare, and if they do occur they are very difficult to find unless there is a visual indication or a large number of windings are shorted. A completely shorted primary winding will draw excessive current from the source; unless there is a breaker or a fuse in the circuit, either the source or the transformer or both will burn out. A partial short in the primary winding can cause higher than normal or even excessive primary current.

In the case of a shorted or partially shorted secondary winding, there is an excessive primary current because of the low reflected resistance due to the short. Often, this excessive current will burn out the primary winding and result in an open. The short-circuit current in the secondary winding causes the load current to be zero (full short) or smaller than normal (partial short), as demonstrated in Figure 14–41(a) and (b). The ohmmeter check for this condition is shown in part (c).



(a) Secondary winding completely shorted

(b) Secondary winding partially shorted

(c) Checking the secondary winding with the ohmmeter

▲ **FIGURE 14–41**

Shorted secondary winding.

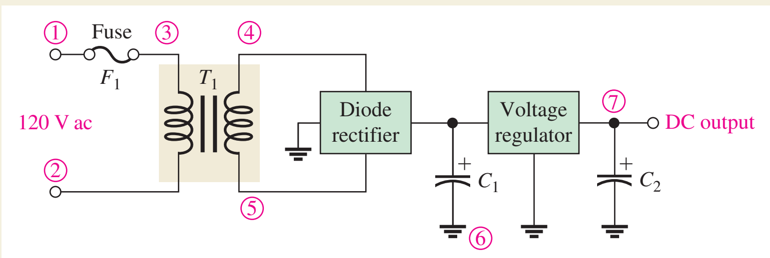
SECTION 14–9 CHECKUP

1. Name two possible failures in a transformer and state the most likely one.
2. What is often the cause of transformer failure?

Application Activity

A common application of the transformer is in dc power supplies. The transformer is used to change and couple the ac line voltage into the power supply circuitry where it is converted to a dc voltage. You will troubleshoot four identical transformer-coupled dc power supplies and, based on a series of measurements, determine the fault, if any, in each.

The transformer (T_1) in the power supply schematic of Figure 14–42 steps the 120 V from the ac outlet down to 10 V that can be converted by the diode bridge rectifier, filtered, and regulated to obtain a 6 V dc output. The diode rectifier



◄ **FIGURE 14–42**

Basic transformer-coupled dc power supply.

changes the ac to a pulsating full-wave dc voltage that is smoothed by the capacitor filter C_1. The voltage regulator is an integrated circuit that takes the filtered voltage and provides a constant 6 V dc over a range of load values and line voltage variations. Additional filtering is provided by capacitor C_2. You will learn about these circuits in a later course. The circled numbers in Figure 14–42 correspond to measurement points on the power supply board.

The Power Supply

There are four identical power supply boards to troubleshoot like the one shown in Figure 14–43. The power line to the primary winding of transformer T_1 is protected by the fuse. The secondary winding is connected to the circuit board containing the rectifier, filter, and regulator. Measurement points are indicated by the circled numbers.

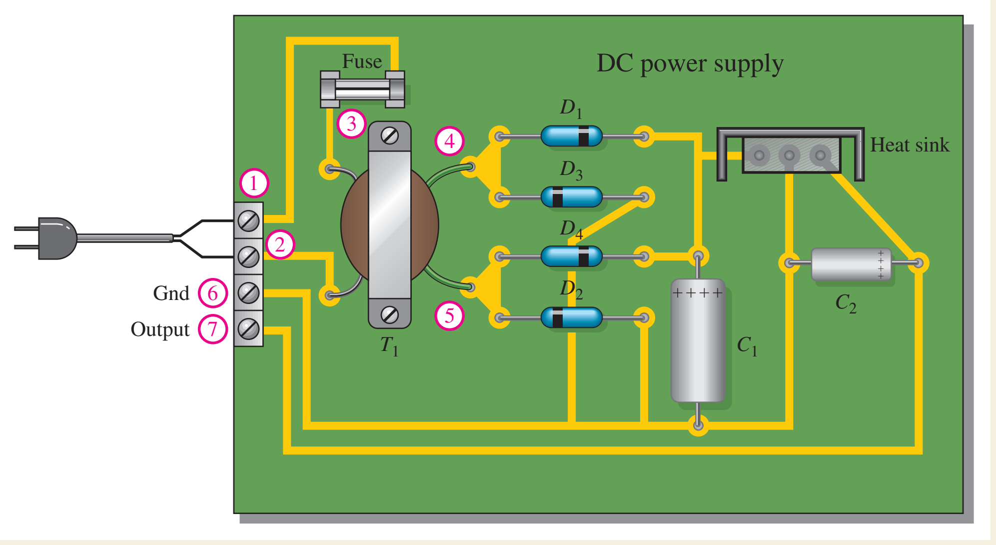
Measuring Voltages on Power Supply Board 1

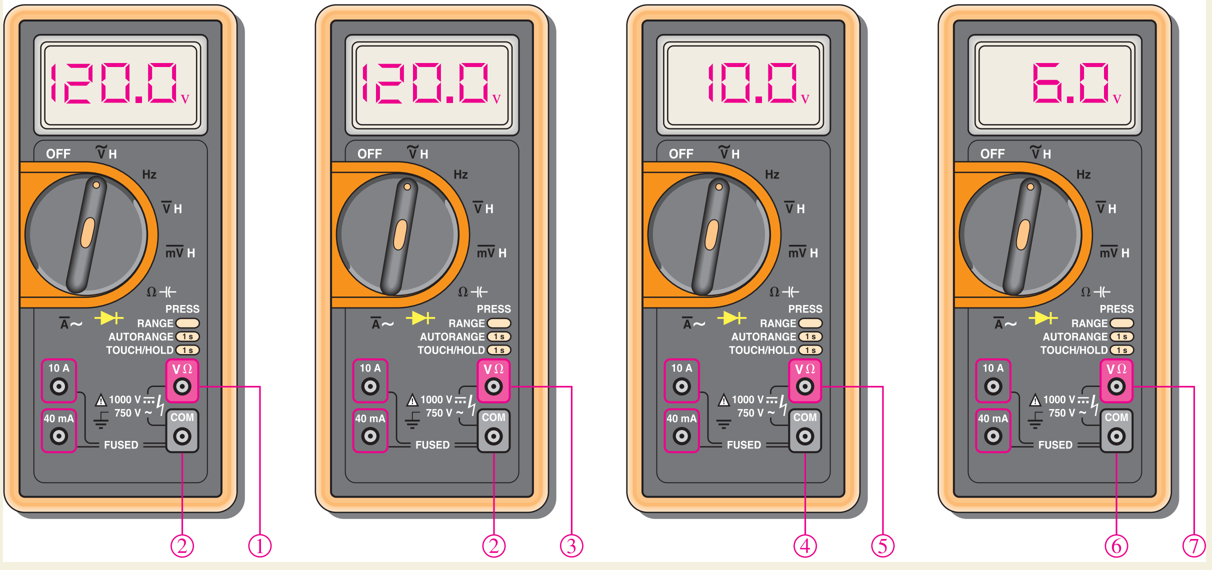
After plugging the power supply into a standard wall outlet, an autoranging portable multimeter is used to measure the voltages. In an autoranging meter, the appropriate measurement range is automatically selected instead of being manually selected as in a standard multimeter.

1. Determine from the meter readings in Figure 14–44 whether or not the power supply is operating properly. If it is not, isolate the problem to one of the following:

► FIGURE 14–43

Power supply board (top view).





▲ FIGURE 14–44

Voltage measurements on power supply board 1.

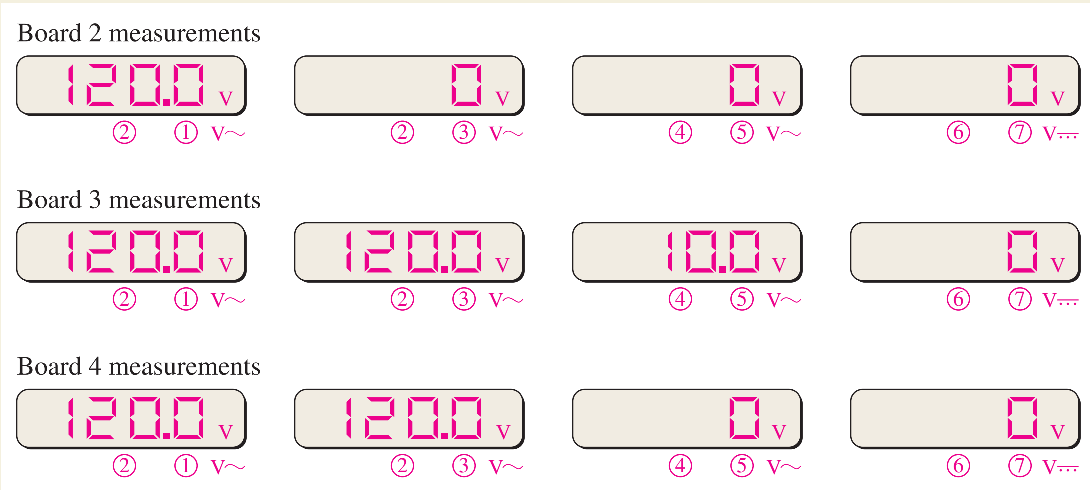
the circuit board containing the rectifier, filter, and regulator; the transformer; the fuse; or the power source. The circled numbers on the meter inputs correspond to the numbered points on the power supply in Figure 14–43.

Measuring Voltages on Power Supply Boards 2, 3, and 4

2. Determine from the meter readings for boards 2, 3, and 4 in Figure 14–45 whether or not each power supply is operating properly. If it is not, isolate the problem to one of the following: the circuit board containing the rectifier, filter, and regulator; the transformer; the fuse; or the power source. Only the meter displays and corresponding measurement points are shown.

Review

3. In the case where the transformer was found to be faulty, how can you determine the specific fault (open windings or shorted windings)?
4. What type of fault could cause the fuse to blow?



▲ FIGURE 14–45

Measurements for power supply boards 2, 3, and 4.

SUMMARY

- A normal transformer consists of two or more coils that are magnetically coupled on a common core.
- There is mutual inductance between two magnetically coupled coils.
- When current in one coil changes, voltage is induced in the other coil.
- The primary is the winding connected to the source, and the secondary is the winding connected to the load.
- The number of turns in the primary and the number of turns in the secondary determine the turns ratio.
- The relative polarities of the primary and secondary voltages are determined by the direction of the windings around the core.
- A step-up transformer has a turns ratio greater than 1.
- A step-down transformer has a turns ratio less than 1.
- In an ideal transformer, the power from the source (input power) is equal to the power delivered to the load (output power).
- In a practical transformer, the power delivered to the load is always less than the power delivered to the primary.

- If the voltage is stepped up, the current is stepped down, and vice versa.
- A load across the secondary winding of a transformer appears to the source as a reflected load having a value dependent on the reciprocal of the turns ratio squared.
- Certain transformers can match a load resistance to a source resistance to achieve maximum power transfer to the load by selecting the proper turns ratio.
- A balun is a type of transformer used to convert a balanced line (such as twisted pair wiring) to an unbalanced line (such as coaxial cable) or vice versa.
- A typical transformer does not respond to dc.
- Conversion of electrical energy to heat in an actual transformer results from winding resistances, hysteresis loss in the core, eddy currents in the core, and flux leakage.
- Three-phase transformers are commonly used in power distribution applications.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Apparent power rating The method of rating transformers in which the power capability is expressed in volt-amperes (VA).

Center tap (CT) A connection at the midpoint of a winding in a transformer.

Impedance matching A technique used to match a load resistance to a source resistance in order to achieve maximum transfer of power.

Magnetic coupling The magnetic connection between two coils as a result of the changing magnetic flux lines of one coil cutting through the second coil.

Mutual inductance (L_M) The inductance between two separate coils, such as in a transformer.

Primary winding The input winding of a transformer; also called *primary*.

Reflected resistance The resistance in the secondary circuit reflected into the primary circuit.

Secondary winding The output winding of a transformer; also called *secondary*.

Transformer An electrical device constructed of two or more coils (windings) that are electromagnetically coupled to each other to provide a transfer of power from one coil to another.

Turns ratio (n) The ratio of turns in the secondary winding to turns in the primary winding.

FORMULAS

14–1	$k = \dfrac{\phi_{1-2}}{\phi_1}$	Coefficient of coupling
14–2	$L_M = k\sqrt{L_1 L_2}$	Mutual inductance
14–3	$n = \dfrac{N_{sec}}{N_{pri}}$	Turns ratio
14–4	$\dfrac{V_{sec}}{V_{pri}} = \dfrac{N_{sec}}{N_{pri}}$	Voltage ratio
14–5	$V_{sec} = nV_{pri}$	Secondary voltage
14–6	$\dfrac{I_{pri}}{I_{sec}} = n$	Current ratio
14–7	$I_{sec} = \left(\dfrac{1}{n}\right)I_{pri}$	Secondary current

14–8	$R_{pri} = \left(\frac{1}{n}\right)^2 R_L$	Reflected resistance
14–9	$n = \sqrt{\frac{R_L}{R_{pri}}}$	Turns ratio for impedance matching
14–10	$\eta = \left(\frac{P_{out}}{P_{in}}\right)100\%$	Transformer efficiency

TRUE/FALSE QUIZ

Answers are at the end of the chapter.

1. A transformer is based on the principle of mutual inductance.
2. The two windings in a basic transformer are called the primary and the tertiary.
3. Transformers are used only for ac voltages.
4. The turns ratio of a transformer determines the ratio of the output voltage to the input voltage.
5. If there is direct current in the transformer primary, there will also be direct current in the secondary.
6. When a load is connected to a transformer, the power in the load is ideally equal to the power in the primary.
7. Impedance matching is based on the principle of reflected load.
8. The apparent power rating of a transformer is expressed in watts.
9. A transformer can have more than two windings.
10. Three-phase transformers consist of delta and/or wye connections of the windings.

SELF-TEST

Answers are at the end of the chapter.

1. A transformer is used for
   (a) dc voltages **(b)** ac voltages **(c)** both dc and ac
2. Which one of the following is affected by the turns ratio of a transformer?
   (a) primary voltage **(b)** dc voltage
   (c) secondary voltage **(d)** none of these
3. If the windings of a certain transformer with a turns ratio of 1 are in opposite directions around the core, the secondary voltage is
   (a) in phase with the primary voltage **(b)** less than the primary voltage
   (c) greater than the primary voltage **(d)** out of phase with the primary voltage
4. When the turns ratio of a transformer is 10 and the primary ac voltage is 6 V, the secondary voltage is
   (a) 60 V **(b)** 0.6 V **(c)** 6 V **(d)** 36 V
5. When the turns ratio of a transformer is 0.5 and the primary ac voltage is 100 V, the secondary voltage is
   (a) 200 V **(b)** 50 V **(c)** 10 V **(d)** 100 V
6. A certain transformer has 500 turns in the primary winding and 2,500 turns in the secondary winding. The turns ratio is
   (a) 0.2 **(b)** 2.5 **(c)** 5 **(d)** 0.5
7. If 10 W of power are applied to the primary of an ideal transformer with a turns ratio of 5, the power delivered to the secondary load is
   (a) 50 W **(b)** 0.5 W **(c)** 0 W **(d)** 10 W
8. In a certain loaded transformer, the secondary voltage is one-third the primary voltage. The secondary current is
   (a) one-third the primary current **(b)** three times the primary current
   (c) equal to the primary current **(d)** less than the primary current

9. When a 1.0 kΩ load resistor is connected across the secondary winding of a transformer with a turns ratio of 2, the source "sees" a reflected load of
   (a) 250 Ω **(b)** 2 kΩ **(c)** 4 kΩ **(d)** 1.0 kΩ
10. In Question 9, if the turns ratio is 0.5, the source "sees" a reflected load of
   (a) 1.0 kΩ **(b)** 2 kΩ **(c)** 4 kΩ **(d)** 500 Ω
11. The turns required to match a 50 Ω source to a 200 Ω load is
   (a) 0.25 **(b)** 0.5 **(c)** 4 **(d)** 2
12. Maximum power is transferred from a source to a load in a transformer coupled circuit when
   (a) $R_L > R_{int}$ **(b)** $R_L < R_{int}$ **(c)** $(1/n)^2 R_L = R_{int}$ **(d)** $R_L = nR_{int}$
13. When a 12 V battery is connected across the primary of a transformer with a turns ratio of 4, the secondary voltage is
   (a) 0 V **(b)** 12 V **(c)** 48 V **(d)** 3 V
14. A certain transformer has a turns ratio of 1 and a 0.95 coefficient of coupling. When 1 V ac is applied to the primary, the secondary voltage is
   (a) 1 V **(b)** 1.95 V **(c)** 0.95 V

CIRCUIT DYNAMICS QUIZ

Answers are at the end of the chapter.

Refer to Figure 14–47(c).

1. If the ac source shorts out, the voltage across R_L
   (a) increases **(b)** decreases **(c)** stays the same
2. If the dc source shorts out, the voltage across R_L
   (a) increases **(b)** decreases **(c)** stays the same
3. If R_L opens, the voltage across it
   (a) increases **(b)** decreases **(c)** stays the same

Refer to Figure 14–49.

4. If the fuse opens, the voltage across R_L
   (a) increases **(b)** decreases **(c)** stays the same
5. If the turns ratio is changed to 2, the current through R_L
   (a) increases **(b)** decreases **(c)** stays the same
6. If the frequency of the source voltage is increased, the voltage across R_L
   (a) increases **(b)** decreases **(c)** stays the same

Refer to Figure 14–53.

7. If the source voltage is increased, the loudness of the sound from the speaker
   (a) increases **(b)** decreases **(c)** stays the same
8. If the turns ratio is increased, the loudness of the sound from the speaker
   (a) increases **(b)** decreases **(c)** stays the same

Refer to Figure 14–54.

9. 10 V rms are applied across the primary. If the left switch is moved form position 1 to position 2, the voltage from the top of R_1 to ground
   (a) increases **(b)** decreases **(c)** stays the same
10. Again, 10 V rms are applied across the primary. With both switches in position 1 as shown and if R_1 opens, the voltage across R_1
   (a) increases **(b)** decreases **(c)** stays the same

PROBLEMS

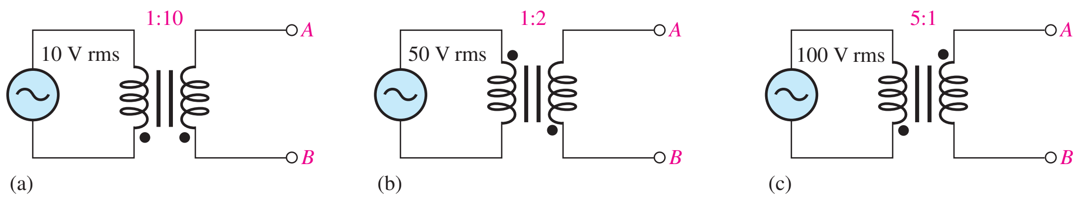
More difficult problems are indicated by an asterisk (*).
Answers to odd-numbered problems are at the end of the book.

SECTION 14–1 Mutual Inductance

1. What is the mutual inductance when $k = 0.75$, $L_1 = 1\ \mu H$, and $L_2 = 4\ \mu H$?
2. Determine the coefficient of coupling when $L_M = 1\ \mu H$, $L_1 = 8\ \mu H$, and $L_2 = 2\ \mu H$.

SECTION 14–2 The Basic Transformer

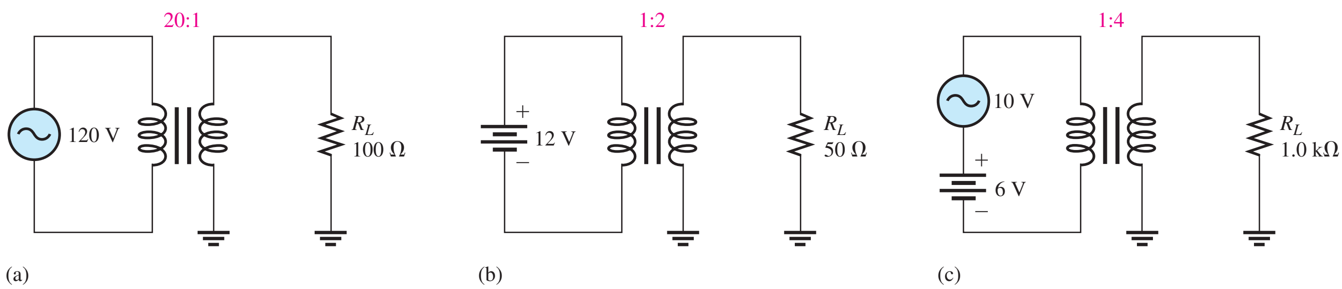
3. What is the turns ratio of a transformer having 250 primary turns and 1,000 secondary turns? What is the turns ratio when the primary winding has 400 turns and the secondary winding has 100 turns?
4. A certain transformer has 250 turns in its primary winding. In order to double the voltage, how many turns must be in the secondary winding?
5. For each transformer in Figure 14–46, draw the secondary voltage showing its relationship to the primary voltage. Also indicate the amplitude.



▲ FIGURE 14–46

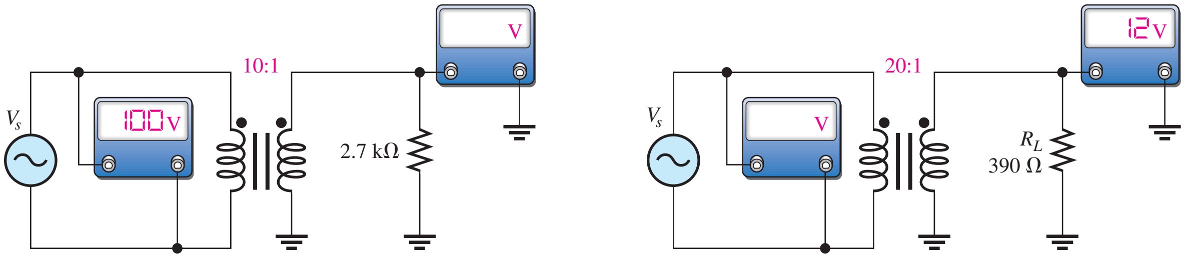
SECTION 14–3 Step-Up and Step-Down Transformers

6. To step 240 V ac up to 720 V, what must the turns ratio be?
7. The primary winding of a transformer has 120 V ac across it. What is the secondary voltage if the turns ratio is 5?
8. How many primary volts must be applied to a transformer with a turns ratio of 10 to obtain a secondary voltage of 60 V ac?
9. To step 120 V down to 30 V, what must the turns ratio be?
10. The primary winding of a transformer has 1,200 V across it. What is the secondary voltage if the turns ratio is 0.2?
11. How many primary volts must be applied to a transformer with a turns ratio of 0.1 to obtain a secondary voltage of 6 V ac?
12. What is the voltage across the load in each circuit of Figure 14–47?



▲ FIGURE 14–47

13. Determine the unspecified meter readings in Figure 14–48.



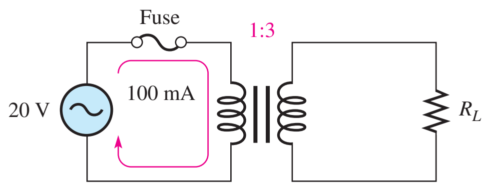
(a) (b)

▲ FIGURE 14–48

SECTION 14–4 Loading the Secondary

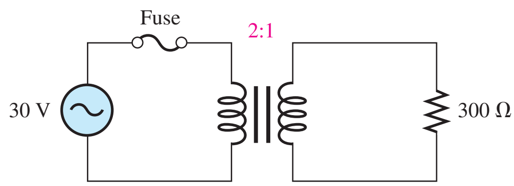
14. Determine I_{sec} in Figure 14–49. What is the value of R_L?

► FIGURE 14–49



15. Determine the following quantities in Figure 14–50.
   - **(a)** Primary current
   - **(b)** Secondary current
   - **(c)** Secondary voltage
   - **(d)** Power in the load

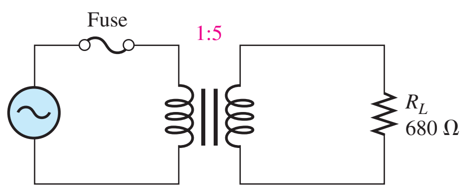
► FIGURE 14–50



SECTION 14–5 Reflected Load

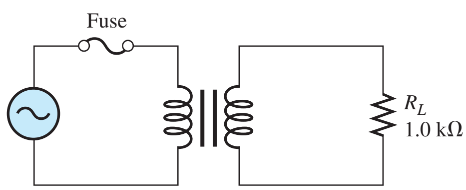
16. What is the load resistance as seen by the source in Figure 14–51?

► FIGURE 14–51



17. What must the turns ratio be in Figure 14–52 in order to reflect 300 Ω into the primary circuit?

► FIGURE 14–52

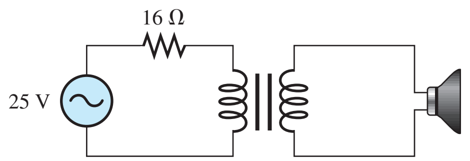


SECTION 14–6 Impedance Matching

18. For the circuit in Figure 14–53, find the turns ratio required to deliver maximum power to the 4 Ω speaker.

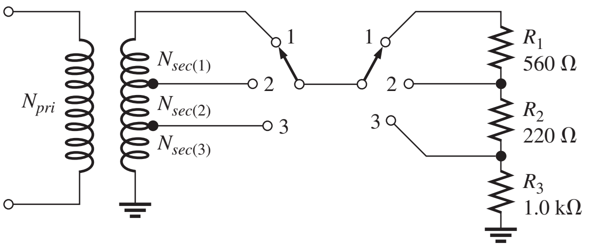
19. In Figure 14–53, what is the maximum power that can be delivered to the 4 Ω speaker?

▶ FIGURE 14–53



***20.** Find the appropriate turns ratio for each switch position in Figure 14–54 in order to transfer the maximum power to each load when the source resistance is 10 Ω. Specify the number of turns for the secondary winding if the primary winding has 1,000 turns.

▶ FIGURE 14–54



SECTION 14–7 Transformer Ratings and Characteristics

21. In a certain transformer, the input power to the primary is 100 W. If 5.5 W are lost in the winding resistances, what is the output power to the load, neglecting any other losses?

22. What is the efficiency of the transformer in Problem 21?

23. Determine the coefficient of coupling for a transformer in which 2% of the total flux generated in the primary does not pass through the secondary.

***24.** A certain transformer is rated at 1 kVA. It operates on 60 Hz, 120 V ac. The secondary voltage is 600 V.

(a) What is the maximum load current?

(b) What is the smallest R_L that you can drive?

(c) What is the largest capacitor that can be connected as a load?

25. What kVA rating is required for a transformer that must handle a maximum load current of 10 A with a secondary voltage of 2.5 kV?

***26.** A certain transformer is rated at 5 kVA, 2,400/120 V, at 60 Hz.

(a) What is the turns ratio if the 120 V is the secondary voltage?

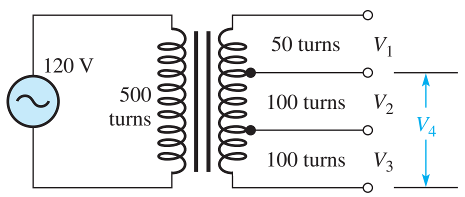
(b) What is the current rating of the secondary if 2,400 V is the primary voltage?

(c) What is the current rating of the primary winding if 2,400 V is the primary voltage?

SECTION 14–8 Tapped and Multiple-Winding Transformers

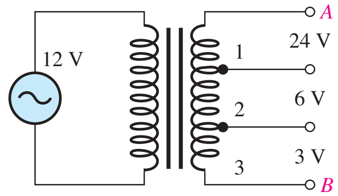
27. Determine each unknown voltage indicated in Figure 14–55.

▶ FIGURE 14–55

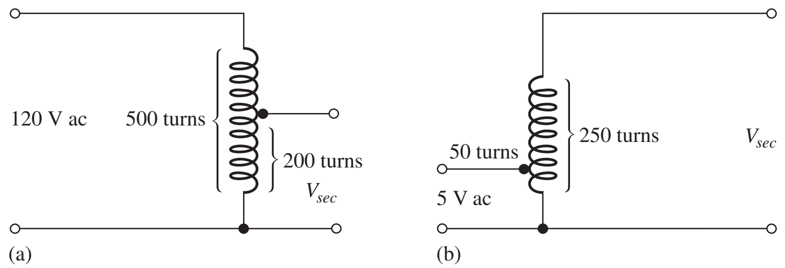


28. Using the indicated secondary voltages in Figure 14–56, determine the turns ratio of each tapped section of the secondary winding to the primary winding.

▶ FIGURE 14–56



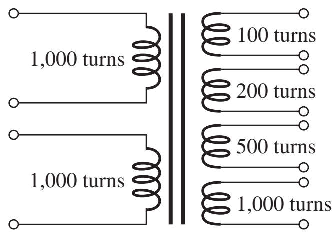
29. Find the secondary voltage for each autotransformer in Figure 14–57.



▲ FIGURE 14–57

30. In Figure 14–58, each primary can accommodate 120 V ac. How should the primaries be connected for 240 V ac operation? Determine each secondary voltage for 240 V operation.

▶ FIGURE 14–58

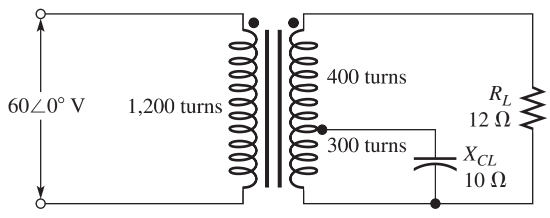


***31.** For the loaded, tapped-secondary transformer in Figure 14–59, determine the following:

(a) All load voltages and currents

(b) The resistance reflected into the primary

▶ FIGURE 14–59



SECTION 14–9 Troubleshooting

32. When you apply 120 V ac across the primary winding of a transformer and check the voltage across the secondary winding, you get 0 V. Further investigation shows no primary or secondary currents. List the possible faults. What is your next step in investigating the problem?

33. What is likely to happen if the primary winding of a transformer shorts?
34. While checking out a transformer, you find that the secondary voltage is less than it should be although it is not zero. What is the most likely fault?

Multisim Troubleshooting and Analysis

These problems require Multisim.

35. Open file P14-35 and measure the secondary voltage. Determine the turns ratio.
36. Open file P14-36 and determine by measurement if there is an open winding.
37. Open file P14-37 and determine if there is a fault in the circuit.

ANSWERS

SECTION CHECKUPS

SECTION 14–1 Mutual Inductance

1. Electrical isolation is the condition in which two circuits have no electrically conductive path between them.
2. Mutual inductance is the inductance between two coils.
3. $L_M = k\sqrt{L_1L_2} = 45$ mH
4. The induced voltage increases if k increases.

SECTION 14–2 The Basic Transformer

1. Transformer operation is based on mutual inductance.
2. The turns ratio is the ratio of turns in the secondary winding to turns in the primary winding.
3. The directions of the windings determine the relative polarities of the voltages.
4. $n = 250/500 = 0.5$
5. The windings are formed on a printed circuit board.

SECTION 14–3 Step-Up and Step-Down Transformers

1. A step-up transformer produces a secondary voltage that is greater than the primary voltage.
2. V_{sec} is five times greater than V_{pri}.
3. $V_{sec} = nV_{pri} = 10(240\text{ V}) = 2{,}400\text{ V}$
4. A step-down transformer produces a secondary voltage that is less than the primary voltage.
5. $V_{sec} = (0.5)120\text{ V} = 60\text{ V}$
6. $n = 12\text{ V}/120\text{ V} = 0.1$

SECTION 14–4 Loading the Secondary

1. I_{sec} is less than I_{pri} by half.
2. $I_{sec} = (1{,}000/250)0.5\text{ A} = 2\text{ A}$
3. $I_{pri} = (250/1{,}000)10\text{ A} = 2.5\text{ A}$

SECTION 14–5 Reflected Load

1. Reflected resistance is the resistance in the secondary, altered by the reciprocal of the turns ratio squared, as it appears to the primary.
2. The turns ratio determines reflected resistance.
3. $R_{pri} = (0.1)^2 50\ \Omega = 0.5\ \Omega$
4. $n = 0.1$

SECTION 14–6 Impedance Matching

1. Impedance matching makes the load resistance equal the source resistance.
2. Maximum power is delivered to the load when $R_L = R_s$.
3. $R_{pri} = (100/50)^2 100\ \Omega = 400\ \Omega$
4. To convert unbalanced signals to balanced signals and provide impedance matching.

SECTION 14–7 Transformer Ratings and Characteristics

1. A practical transformer does not have the 100% efficiency of an ideal transformer due to less than 100% coupling, winding capacitance, winding resistance, flux leakage, eddy currents, and other nonideal characteristics.

2. When $k = 0.85$, 85% of the magnetic flux generated in the primary winding passes through the secondary winding.
3. $I_L = 10\text{ kVA}/250\text{ V} = 40\text{ A}$

SECTION 14–8 **Tapped and Multiple-Winding Transformers**

1. $V_{sec} = (10)240\text{ V} = 2{,}400\text{ V}$, $V_{sec} = (0.2)240\text{ V} = 48\text{ V}$
2. *Advantage:* An autotransformer is smaller and lighter for the same rating than a conventional transformer.
   Disadvantage: An autotransformer has no electrical isolation.
3. Three-phase

SECTION 14–9 **Troubleshooting**

1. Transformer faults: open windings are the most common, shorted windings are much less common.
2. Operating above rated values will cause a failure.

RELATED PROBLEMS FOR EXAMPLES

14–1	0.75
14–2	387 μH
14–3	5,000 turns
14–4	480 V
14–5	57.6 V
14–6	5 mA; 400 mA
14–7	6 Ω
14–8	0.354
14–9	0.0707 or 14.14:1
14–10	85.2%
14–11	$V_{AB} = 12\text{ V}$, $V_{CD} = 480\text{ V}$, $V_{(\text{CT})C} = V_{(\text{CT})D} = 240\text{ V}$, $V_{EF} = 24\text{ V}$
14–12	Doubles to 2.11 kVA

TRUE/FALSE QUIZ

1. T **2.** F **3.** T **4.** T **5.** F **6.** T **7.** T **8.** F **9.** T **10.** T

SELF-TEST

1. (b) **2.** (c) **3.** (d) **4.** (a) **5.** (b) **6.** (c) **7.** (d)
8. (b) **9.** (a) **10.** (c) **11.** (d) **12.** (c) **13.** (a) **14.** (c)

CIRCUIT DYNAMICS QUIZ

1. (b) **2.** (c) **3.** (c) **4.** (b) **5.** (a)
6. (c) **7.** (a) **8.** (a) **9.** (b) **10.** (a)