2

DIODES

Light-emitting diodes (LEDs) have been developed that incorporate two *pn* junctions inside one lens. This allows the device to produce one color when biased with one polarity, a second color when biased in the opposite polarity, and a third color when the bias is rapidly alternated between polarities.

OUTLINE

OBJECTIVES

After studying the material in this chapter, you should be able to:

1. Identify the terminals of a *pn*-junction diode, given the schematic symbol of the component.
2. Analyze the schematic diagram of a simple diode circuit and determine:
   a. Whether or not the diode is conducting.
   b. The direction of current through a conducting diode.
3. List the three diode models and the applications for each.
4. List the main parameters of the *pn*-junction diode and explain how each limits the use of the component.
5. Determine the suitability of a given diode for a given application, using diode spec sheets and/or selector guides.
6. Identify the schematic symbol of the zener diode and determine the direction of current through the device.
7. Discuss the basic operating principles of the zener diode.
8. List the main zener diode parameters and explain how each limits the use of the component.
9. Discuss the basic operating principles of the light-emitting diode (LED).
10. Calculate the value of the *current-limiting* resistor needed for an LED in a given circuit.
11. Determine whether a given *pn*-junction diode, zener diode, or LED is good or faulty.

In later chapters, you will learn about a type of electronic device called a *transistor*. While the transistor is similar in construction to a *pn*-junction diode, it is actually a more complex component whose operation is based on more complex concepts.

It would seem to the casual observer that the *pn*-junction diode was developed before the transistor. After all, most complex devices are developed as outgrowths of similar, but simpler, devices. This, however, is not the case.

The *pn*-junction diode was actually developed almost six years *after* the development of the first transistor. In fact, the transistor had already been in commercial use for two years when Bell Laboratories announced the development of the *pn*-junction diode! In this instance, the chicken definitely came before the egg.

The diode is the most basic of the solid-state components. There are many diode types, each with its own operating characteristics and applications. The various diode types are easily identified by name, circuit application, and schematic symbol. It should be noted that the term *diode*, used by itself, refers to the basic *pn*-junction diode. All other diode types have other identifying names, such as *zener diode*, *light-emitting diode*, and so on.

Diode
A one-way conductor.

A **diode** is a *two-electrode* (two-terminal) device that acts as a *one-way conductor*. The most basic type of diode is the *pn-junction diode*, which is nothing more than a *pn* junction with a lead connected to each of the semiconductor materials. When forward biased, this type of diode will conduct. When reverse biased, diode conduction will drop to nearly zero.

In this chapter, we will look at the three most commonly used types of diodes: the *pn-junction diode*; the *zener diode*; and the *light-emitting diode*, or *LED*. Many other types of diodes are covered in Chapter 5.

2.1 INTRODUCTION TO THE *pn*-JUNCTION DIODE

OBJECTIVE 1 ►

Cathode
The *n*-type terminal of a diode.

Anode
The *p*-type terminal of a diode.

The schematic symbol for the *pn*-junction diode is shown in Figure 2.1. The *n*-type material is called the **cathode**, and the *p*-type material is called the **anode**.

Recall that a *pn* junction will conduct when the *n*-type material (cathode) is more negative than the *p*-type material (anode). Relating this characteristic to the schematic symbol of the diode, we can make the following statement: A diode will conduct when the two following conditions are met:

1. The arrow points to the more negative of the diode potentials.
2. The voltage differential between the anode and the cathode exceeds the barrier voltage of approximately 0.3 V for a germanium diode and 0.7 V for a silicon diode.

OBJECTIVE 2 ►

This point is illustrated in Figure 2.2, which shows several forward-biased (conducting) diodes. Note that the arrow in the diode schematic symbol points to the more negative potential in each case. Since the arrow in the schematic symbol points to the more negative potential when the diode is conducting, *diode forward current will be in the direction of the arrow*, as is shown in Figure 2.2.

A *pn*-junction diode is reverse biased when the *n*-type material (cathode) is more positive than the *p*-type material (anode). This causes the depletion region to widen and

FIGURE 2.1 ***pn*-junction diode schematic symbol.**

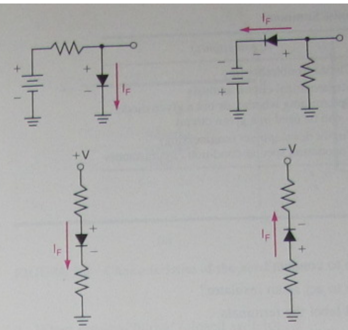


FIGURE 2.2 **Forward-biased diodes.**

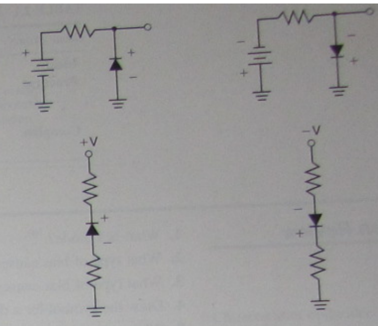


FIGURE 2.3 **Reverse-biased diodes.**

prevent current. Relating this characteristic to the schematic symbol for the diode, we can make the following statement: A diode will not conduct when the arrow points to the more positive of the diode potentials. This point is illustrated in Figure 2.3, which shows several reverse-biased (nonconducting) diodes. Note that the arrow in the diode schematic symbol points to the more positive potential in each case.

Diode Models

Model
A representation of a component or circuit.

In this chapter, you will be introduced to three diode *models*. A **model** is a representation of a component or circuit that contains one or more of the characteristics of that component or circuit. For example, the dc model of a capacitor may represent the component as an open circuit, since a capacitor blocks dc. At the same time, the ac model of a capacitor may represent the component as a variable impedance, since the impedance of a capacitor varies inversely with frequency.

Component models are usually used to represent the component under specific circumstances or in specific applications. As you will see, the diode model that you use depends on what you are trying to do.

Troubleshooting
The process of locating faults in electronic equipment.

The first diode model that we will cover is called the *ideal diode model*. This diode model represents the diode as a simple switch that is either *closed* (conducting) or *open* (nonconducting). This model is used only in the initial stages of **troubleshooting**, as will be explained in Section 2.2.

The *practical diode model* is a bit more complex than the ideal diode model. The practical diode model includes the diode characteristics that must be considered when mathematically analyzing a diode circuit and when determining whether or not a given diode can be used in a given circuit. The practical diode model will be covered in Section 2.3.

The *complete diode model* is the most complex of the diode models. It includes the diode characteristics that are considered only under specific conditions such as *circuit development* (or *engineering*), high-frequency analysis, and so on. As you will see, the characteristics that are included in the complete diode model are not usually considered on a daily basis by the average technician. We will look at the complete diode model in Section 2.5.

The three diode models and their applications are summarized in Table 2.1. ◄ *OBJECTIVE 3*

TABLE 2.1 Diode Model Summary

Diode Model	*Application(s)*
Ideal **Practical**	• Circuit troubleshooting • Mathematical circuit analysis • Determining whether or not a given diode can be used in a given circuit
Complete	• Circuit development (engineering) • Uncommon special-condition circumstances

Section Review

1. What is a diode?
2. What type of bias causes a diode to conduct?
3. What type of bias causes a diode to act as an insulator?
4. Draw the symbol for a diode and label the terminals.
5. What polarity is required to forward bias a diode?
6. When analyzing a schematic diagram, how do you know whether or not a diode is conducting?
7. When analyzing a schematic diagram, how do you determine the direction of diode current? Explain your answer.
8. When is the *ideal diode model* used?
9. When is the *practical diode model* used?
10. When is the *complete diode model* used?

2.2 THE IDEAL DIODE

The ideal diode acts as a switch.

The *ideal* diode has the characteristics of an open switch when it is reverse biased and those of a closed switch when forward biased. You may recall that a switch has the following characteristics:

Condition	*Characteristics*
Open	• Infinite resistance and thus no current • Full applied voltage dropped across the component terminals
Closed	• No resistance and thus maximum current • No voltage dropped across the component terminals

Based on the characteristics of a switch, we can make the following statements about the ideal diode:

Charactistics of the ideal reverse-biased diode.

1. When *reverse biased* (open switch):
   a. The diode will have infinite resistance.
   b. The diode will not pass current.
   c. The diode will drop the entire applied voltage across its terminals.

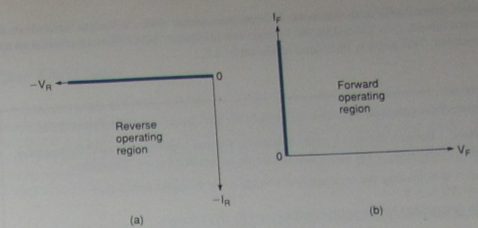


FIGURE 2.4 Characteristics of the ideal diode.

Characteristics of the ideal forward-biased diode.

2. When *forward biased* (closed switch):
   a. The diode will have no resistance.
   b. The diode will have no control over the current through it.
   c. The diode will have no voltage drop across its terminals.

These characteristics of the ideal diode are illustrated in Figure 2.4. Figure 2.4a shows the reverse-bias characteristics of the ideal diode. Note that as **reverse voltage** (V_R) increases, **reverse current** (I_R) remains at zero. This implies that the reverse-biased diode is an *open circuit* (just like an open switch), since there is no current through the device regardless of the value of the applied voltage. *Since the reverse-biased diode is acting as an open, the full applied voltage is dropped across the terminals of the device.* This point is illustrated in Example 2.1.

Reverse voltage (V_R) The voltage across a reverse-biased diode.

Reverse current (I_R) The current through a reverse-biased diode.

EXAMPLE 2.1

Determine the values of V_{D1}, I_T, and V_{R1} for the circuit shown in Figure 2.5a.

Solution: Because the arrow in the schematic symbol is pointing toward the positive terminal of the source, we know that the diode is reverse biased. Therefore:

a. The full applied voltage is dropped across D_1.

$$V_{D1} = V_S = 5\text{ V}$$

b. D_1 will not allow conduction. Therefore, $I_T = 0$ A.
c. Since there is no current through R_1, there is no voltage drop across the component ($V_R = 0$ V).

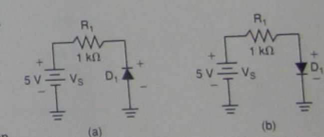


FIGURE 2.5

PRACTICE PROBLEM 2.1

A series circuit consists of a 12-V source, a 470-Ω resistor (R_1), a 330-Ω resistor (R_2), and a diode. If the diode is reverse biased, what is the value of V_{R1}? What is the value of V_{R2}?

What determines the value of diode forward current?

Figure 2.4b shows the forward-bias characteristics of the ideal diode. Note that the forward voltage (V_F) across the diode is assumed to be 0 V for this diode model, while forward current (I_F) is shown to be at some measurable value. When the ideal diode is forward biased, I_F is limited by the voltage and resistance values that are external to the component. This point is illustrated in Example 2.2.

EXAMPLE 2.2

Determine the values of V_{D1}, and V_{R1}, and I_T for the circuit shown in Figure 2.5b.

Solution: Because the arrow in the schematic symbol is pointing toward the negative terminal of the source, we know that the diode is forward biased. Therefore:

a. $V_{D1} = 0$ V, leaving the total applied voltage to be dropped across R_1.
b. $V_R = V_S = 5$ V.
c. I_T is determined by the source voltage and R_1. By formula,

$$I_T = \frac{V_R}{R_1} = \frac{5\text{ V}}{1\text{ k}\Omega} = 5\text{ mA}$$

PRACTICE PROBLEM 2.2

A series circuit consists of a 12-V source, a 470-Ω resistor, 330-Ω resistor, and a diode. If the diode is forward biased, what is the value of I_T for the circuit?

If you compare the values found in Examples 2.1 and 2.2 to the switch characteristics described earlier, you will see that the diode acted as an ideal switch in both cases. The forward and reverse characteristics of the ideal diode are summarized in Figure 2.6.

When Do We Use the Ideal Diode Model?

Normally, the ideal model of the diode is used in the initial stages of circuit troubleshooting. When troubleshooting most diode circuits, your initial concern is only

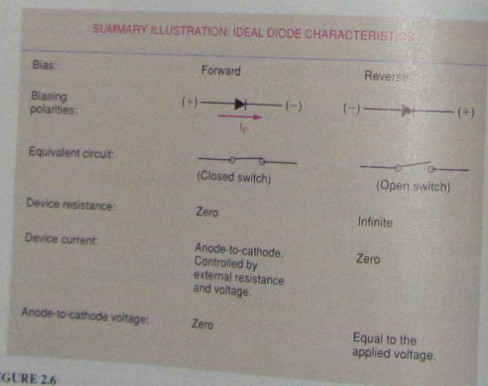


FIGURE 2.6

whether or not a given diode is acting as a one-way conductor. If it is, the component is assumed to be good. If not, it is faulty and must be replaced.

One Final Note

It was stated earlier in the chapter that the ideal model of the diode is used only for a non-detailed analysis of a diode circuit. Then we used this model to mathematically analyze the circuits in Figure 2.5. Why? We did this only to illustrate how the ideal model of the diode is treated as a perfect switch: either *on* (closed) with no resistance or *off* (open) with infinite resistance. In the next section, you will be shown how the *practical diode model* is used to calculate current and voltage values.

Section Review

1. What are the forward characteristics of the ideal diode model?
2. What are the reverse characteristics of the ideal diode model?
3. When do we use the ideal diode model?

2.3 THE PRACTICAL DIODE MODEL

In our discussion of the ideal diode, we did not consider many of the diode characteristics that must be dealt with by working technicians on a regular basis. One of these characteristics, *forward voltage*, is normally considered in the mathematical analysis of a diode circuit. Many other practical diode characteristics are used when determining whether or not one diode may be used in place of another or in a specific circuit. These characteristics include *peak reverse voltage*, *average forward current*, and *forward power dissipation*.

In this section, we will take a look at *forward voltage* (V_F) and the effect that it has on the mathematical analysis of basic diode circuits. The other characteristics listed are covered in detail in Section 2.4.

Whenever the term *diode* is used, we will assume that it is a silicon type. As we learned in Chapter 1, one difference between a silicon *pn* junction and a germanium *pn* junction is the difference in their values of V_F when forward biased. Therefore, to work a given example as you would for a circuit containing a germanium diode, just reduce the forward voltage drop to approximately 0.3 V from 0.7 V.

Forward Voltage (V_F)

In Chapter 1, we established the fact that there is a slight voltage developed across a forward-biased *pn* junction. The effect of this V_F on the diode characteristic curve is illustrated in Figure 2.7.

Figure 2.7a is a composite of the ideal diode characteristic graphs that were shown in Figure 2.4. Note that the point where I_F suddenly increases is labeled V_k in the figure. This label is commonly used to identify what is called the *knee voltage* in a voltage-versus-current graph. The term **knee voltage (V_k)** is often used to describe the point in a voltage-versus-current graph where current suddenly increases or decreases. As you can see, the ideal diode model assumes a knee voltage of 0 V.

Knee voltage (V_k) The voltage at which device current suddenly increases or decreases.

In Figure 2.7b, we see the characteristic curve for the practical diode model. The only difference between this curve and the one shown for the ideal diode model is the value of V_F. In the practical diode model, the value of V_k is shown to be equal to the approximated value of V_F for a silicon *pn* junction, 0.7 V. In an actual circuit, the V_F may fall between 0.7 V and 1.1 V, depending on the current through the device.

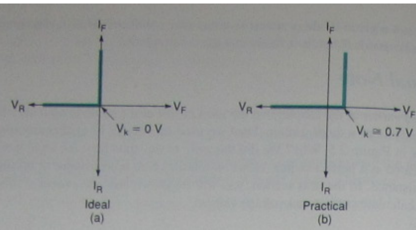


FIGURE 2.7 Diode characteristic curves.

Using the curve shown in Figure 2.7b, we can make the following statements about the forward operating characteristics of the practical diode:

1. Diode current remains at zero until the knee voltage is reached.
2. Once the applied voltage reaches the value of V_k, the diode turns *on* and forward conduction occurs.
3. As long as the diode is conducting, the value of V_F is approximately equal to V_k. In other words, V_F is assumed to be approximately 0.7 V, regardless of the value of I_F.

Figure 2.8 will help you to see the difference between the forward operating characteristics of the ideal diode model and the practical diode model. Note the addition of the battery in the equivalent circuit for the practical diode model. This battery is used to represent the 0.7-V value of V_F for the component.

The Effect of V_F on Circuit Analysis

So, how does including the value of V_F change the analysis of a diode circuit? To answer this question, let's take a look at the circuit shown in Figure 2.9. According to Kirchhoff's voltage law, the sum of the component voltages in the circuit must equal the applied voltage. By formula,

$$V_S = V_F + V_R$$

If we substitute the value of V_k (0.7 V) for V_F and rearrange the equation to solve for V_R, we get

$$V_R = V_S - 0.7\text{ V} \tag{2.1}$$

SUMMARY ILLUSTRATION

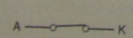
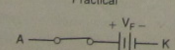
Diode model:	Ideal	Practical
Equivalent circuit:		
Knee voltage:	0 V	0.7 V (Silicon) 0.3 V (Germanium)
Assumed V_F:	Same as V_k	Same as V_k

FIGURE 2.8

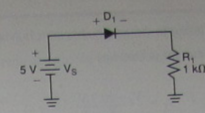


FIGURE 2.9

According to Ohm's law,

$$I_T = \frac{V_R}{R_1}$$

Substituting equation (2.1) in place of V_R in the above equation, we get

$$I_T = \frac{V_S - 0.7\text{ V}}{R_1} \tag{2.2}$$

Thus, for the circuit shown,

$$V_R = V_S - 0.7\text{ V} = 4.3\text{ V}$$

and

$$I_T = \frac{V_S - 0.7\text{ V}}{R_1} = \frac{5\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega} = 4.3\text{ mA}$$

If you compare these values with those obtained for the same circuit in Example 2.2, you will see how including the value of V_F in the circuit analysis changes the results. The two sets of values are summarized as follows:

Value	*Ideal*	*Practical*
V_F	0 V	0.7 V
V_R	5 V	4.3 V
I_T	5 mA	4.3 mA

Examples 2.3 and 2.4 further demonstrate the use of V_F in circuit calculations.

EXAMPLE 2.3

Determine the voltage across R_1 in Figure 2.10.

Solution: The voltage across the diode is assumed to be 0.7 V. Thus, the voltage across the resistor will be equal to the difference between the source voltage and the value of V_F. By formula,

$$V_R = V_S - 0.7\text{ V} = 5.3\text{ V}$$

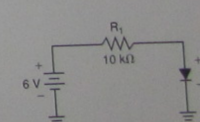


FIGURE 2.10

EXAMPLE 2.4

Determine the total circuit current in the circuit shown in Figure 2.10.

Solution: The total circuit current is found as

$$I_T = \frac{V_S - 0.7\ \text{V}}{R_1}$$
$$= \frac{6\ \text{V} - 0.7\ \text{V}}{10\ \text{k}\Omega}$$
$$= 530\ \mu\text{A}$$

PRACTICE PROBLEM 2.4

A circuit like the one shown in Figure 2.10 has a 5-V source and a 510-Ω resistor. Determine the value of I_T for the circuit.

Percentage of Error

Lab Reference: Percentage of error calculations appear throughout the lab manual, beginning in Exercise 3.

In most circuit analysis problems, a calculated value is considered to be accurate enough if it is within ±10% of the actual measured value. The percentage of error of a given calculation is determined using

$$\%\ \text{of error} = \frac{|X - X'|}{X} \times 100 \qquad (2.3)$$

where X = the actual measured value
X' = the calculated value

How accurate must circuit calculation be?

Using the ideal diode model in circuit calculations can introduce a percentage of error in the results that is not acceptable (that is, not within ±10%). For example, we used the ideal and practical diode models to determine the value of V_R for the circuit shown in Figure 2.9. The percentage of error introduced by using the ideal diode model in this case would be found as

$$\%\ \text{of error} = \frac{|4.3\ \text{V} - 5\ \text{V}|}{4.3\ \text{V}} \times 100$$
$$= 16.28\%$$

As you can see, the percentage of error is greater than 10% and therefore is not acceptable. This is why we use the practical diode model in circuit analysis problems.

If there is more than one resistor in a simple diode circuit, the *total* resistance (R_T) must be used in determining the value of I_T, as was the case in all the circuits you studied in basic electronics. This point is illustrated in Example 2.5.

EXAMPLE 2.5

Determine the value of I_T for the circuit shown in Figure 2.11.

Solution: For the circuit shown, we can calculate the total circuit current using

$$I_T = \frac{V_S - 0.7\ \text{V}}{R_T}$$
$$= \frac{5\ \text{V} - 0.7\ \text{V}}{3.4\ \text{k}\Omega}$$
$$= 1.26\ \text{mA}$$

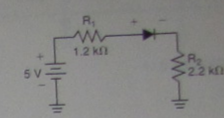


FIGURE 2.11

Note that we used R_T in place of R_1 in equation (2.2) to solve the circuit in Example 2.5.

Just as you must consider the total resistance in the analysis of a diode circuit, you must consider the *sum of the diode voltage drops* if there are several *series-connected* diodes in a circuit. This point is illustrated in Example 2.6.

EXAMPLE 2.6

Determine the value of I_T for the circuit shown in Figure 2.12.

Solution: With two diodes in the circuit, the total value of V_F is assumed to be 1.4 V. Using this value in the place of 0.7 V in equation (2.2) allows us to accurately determine the value of I_T as follows:

$$I_T = \frac{V_S - 1.4\ \text{V}}{R_1}$$
$$= \frac{4\ \text{V} - 1.4\ \text{V}}{5.1\ \text{k}\Omega}$$
$$= 509.8\ \mu\text{A}$$

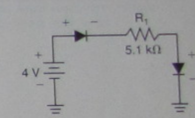


FIGURE 2.12

PRACTICE PROBLEM 2.6

A series circuit consists of two forward-biased diodes, a 470-Ω resistor, a 330-Ω resistor, and a 6-V source. What is the value of I_T for the circuit?

Now, let's do one more example to tie everything together.

EXAMPLE 2.7

Determine the value of I_T for the circuit shown in Figure 2.13 *using the ideal diode model*. Then recalculate the value *using the practical diode model*. What is the percentage of error introduced by using the ideal diode model?

Solution: The ideal diode model assumes that V_F = 0 V. Therefore, the total applied voltage is dropped across the two resistors, and I_T is found as

$$I_T = \frac{V_S}{R_T}$$
$$= \frac{10\ \text{V}}{3.3\ \text{k}\Omega}$$
$$= 3.03\ \text{mA}$$

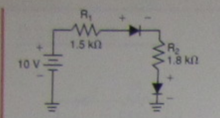


FIGURE 2.13

The practical diode model assumes that $V_F = 0.7$ V for each diode. Therefore, the value of I_T is found as

$$I_T = \frac{V_S - 1.4\text{ V}}{R_T} = \frac{10\text{ V} - 1.4\text{ V}}{3.3\text{ k}\Omega} = 2.61\text{ mA}$$

The percentage of error between the two calculations is found as

$$\%\text{ of error} = \frac{|2.61\text{ mA} - 3.03\text{ mA}|}{2.61\text{ mA}} \times 100 = 16.1\%$$

Note that the value of I_T found using the *practical diode model* was used in the denominator of the fraction in the percentage of error calculation. This value was used because the practical value is always assumed to be closer than the ideal to the actual value of I_T.

PRACTICE PROBLEM 2.7

Refer to Practice Problem 2.6. Recalculate the value of total circuit current using the *ideal diode model*. Then determine the percentage of error introduced by using this diode model.

One Final Note

It can be argued that it isn't always necessary to include the 0.7 V drop across a diode in the mathematical analysis of a diode circuit. For example, if we had a diode and resistor in series with a 100-V source, ignoring the 0.7 V diode drop would cause a percentage of error of less than 1%, which is well within the acceptable limits for accuracy.

While this argument is valid, there are two other considerations. First, many diode circuits contain more than one diode. When this is the case, the percentage of error introduced by using the ideal diode model becomes much larger. Second, we are always interested in getting the most accurate results possible (within reason) in the mathematical analysis of any circuit. For these reasons, we will always use the practical diode model in the mathematical analysis of any diode circuit. Remember, the only difference in using this model for analysis purposes is that you must take the value of V_F for each diode into account. Otherwise, the component is assumed to work just like the ideal model.

In the next section, we will look at the factors that must be considered when determining whether or not a specific diode can be used in a given situation. While these factors are not normally considered in voltage and current calculations, they are very important when it comes to actually working on a circuit.

Section Review

1. What diode characteristic must be considered in the mathematical analysis of a diode circuit?
2. Which diode characteristics are normally considered when replacing one diode with another?
3. What is the assumed value of a knee voltage for a silicon diode?
4. List the characteristics of the practical forward-biased diode.
5. How does including the value of V_F affect the accuracy of circuit calculations?

6. How accurate must a calculation be to be considered acceptable?
7. A circuit voltage is calculated to be 10 V. The actual value of this voltage is 12.2 V. What is the percentage of error in the calculation?

2.4 OTHER PRACTICAL CONSIDERATIONS

Assume that you have just finished troubleshooting a circuit. While troubleshooting, you found that the diode in the circuit is faulty and must be replaced. Now you discover that you have a wide variety of diodes in stock, but none of them has the same part number as the one that needs replacing. How can you determine whether or not a specific diode can be used in place of the faulty one? Several diode characteristics must be considered when determining whether or not a specific diode can be used in a given circuit. These characteristics are *peak reverse voltage*, *average forward current*, and *forward power dissipation*.

◂ *OBJECTIVE 4*

Peak Reverse Voltage (V_{RRM})

Any insulator will conduct if the applied voltage is high enough to cause the insulator to break down. For a reverse-biased diode, the *maximum* reverse voltage that *won't* force the diode to conduct is called the **peak reverse voltage (V_{RRM})**. When V_{RRM} is exceeded, the depletion layer will break down, and the diode will conduct in the reverse direction. Typical values of V_{RRM} range from a few volts (for zener diodes) to thousands of volts.

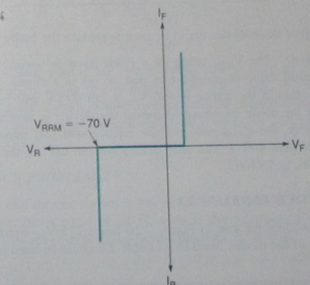
Peak reverse voltage (V_{RRM}) The *maximum* reverse voltage allowable for a diode.

The effect that V_{RRM} has on the diode characteristic curve is illustrated in Figure 2.14. Note that the value of reverse current (I_R) is shown to be zero until the value of V_{RRM} (−70 V, in this case) is exceeded. When $V_R > V_{RRM}$, the value of I_R increases rapidly as the depletion layer breaks down. Normally, when a *pn* junction is forced to conduct in the reverse direction, the device is destroyed. A *zener diode*, on the other hand, is designed to work in the reverse direction without harming the diode. This point is discussed in detail later in this chapter.

The current that occurs when $V_R > V_{RRM}$ is called **avalanche current**. This name comes from the fact that one free electron bumps other electrons in the diode, causing them to break free from their covalent bonds, which then rapidly causes even more electrons to be broken free, and so on. The result is that the diode is destroyed by excessive current and the heat it produces.

Avalanche current The current that occurs when V_{RRM} is reached. Avalanche current can destroy a *pn* junction diode.

FIGURE 2.14



surface-leakage current
troubleshooting
voltage regulator
zener breakdown
zener diode
zener impedence
zener knee current
zener test current
zener voltage

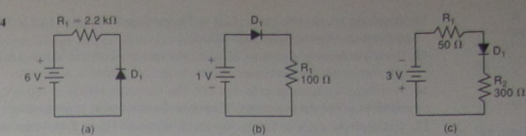
Equation Summary

Equation Number	Equation	Section Number
(2.1)	$V_R = V_S - 0.7\text{V}$	2.3
(2.2)	$I_T = \dfrac{V_S - 0.7\text{V}}{R_1}$	2.3
(2.3)	$\% \text{ of error} = \dfrac{\lvert X - X' \rvert}{X} \times 100$	2.3
(2.4)	$I_{F(\max)} = \dfrac{P_{D(\max)}}{V_F}$	2.4
(2.5)	$V_F = 0.7\text{ V} + I_F R_B$	2.5
(2.6)	$I_R = I_S + I_{SL}$	2.5
(2.7)	$I'_R = I_R\,(2^X)$	2.5
(2.8)	$Z_Z = \dfrac{\Delta V_Z}{\Delta I_Z} \mid \Delta V_Z = \text{the change in } V_Z$	2.7
(2.9)	$I_{ZM} = \dfrac{P_{D(\max)}}{V_Z}$	2.8
(2.10)	$R_S = \dfrac{V_{\text{out(pk)}} - V_F}{I_F}$	2.9

Answers to the Example Practice Problems

2.1. The diode acts as an open, and an open drops the full applied voltage. Therefore, $V_{R1} = V_{R2} = 0$ V.
2.2. Using the ideal diode model, $I_T = 15$ mA.
2.4. $I_T = 8.43$ mA.
2.6. $I_T = 5.75$ mA.
2.7. I_T (ideal) = 7.5 mA: % of error = 30.4%.
2.8. Any diode with $V_{RRM} > 210$ V. Therefore, you could use any diode from 1N4004–07.
2.9. The value of I_T for the circuit is 1.95 A. The rating for the diode would have to be 20% greater than this value, or 2.34A.
2.10. $P_{D(\min)} = 198.7$ mW × 1.20 = 238.4 mW
2.11. P_D = (750 mA) (0.7 V) = 525 mW. This exceeds the 500-mW limit.
2.12. 0.796 V (or 796 mV).
2.13. $x = 3.5$, $I'_R = 22.63\mu$A
2.14. $I_{ZM} = 37$ mA.
2.15. P_D (at 125°C) = 250.25 mW.
2.16. The 1N5374A.
2.17. P_D for the device is 1.19 W. Therefore, any diode in the 6.8-V row with a P_D of 1.5 W or higher could be used. (The 1N5921A or 1N5342A could be used.)
2.18. $R_S = 1.1$ kΩ minimum standard value; the calculated value is 1050 Ω.

FIGURE 2.44



Practice Problems

§2.1

1. Draw a circuit containing a dc voltage source, a resistor, and a forward-biased diode.
2. Add an arrow to the circuit you drew in Problem 1 to indicate the direction of diode current.
3. Draw a circuit containing a dc voltage source, a resistor, and a reverse-biased diode.
4. For each of the circuits shown in Figure 2.44, determine the direction (if any) of diode forward current.
5. For each of the circuits shown in Figure 2.45, determine the direction (if any) of diode forward current.

§2.2

6. Using the *ideal diode model*, determine the voltage drop across each of the diodes in Figure 2.44.
7. Using the *ideal diode model*, determine the voltage drop across each of the components in Figure 2.45a.

§2.3

8. Using the *practical diode model*, determine the values of V_{D1}, V_{R1}, and I_T for the circuit shown in Figure 2.44a.
9. Using the *practical diode model*, determine the values of V_{D1}, V_{R1}, and I_T for the circuit shown in Figure 2.44b.
10. Using the *practical diode model*, determine the values of V_{D1}, V_{R1}, V_{R2}, and I_2 for the circuit shown in Figure 2.44c.
11. Determine the values of V_{D1}, V_{R1}, I_1, V_{D2}, V_{R2}, and I_2 for the circuit shown in Figure 2.45a.*
12. Determine the values of V_{D1}, V_{D2}, V_{R1}, and I_T for the circuit shown in Figure 2.45b.
13. Determine the values of V_{D1}, V_{D2}, V_{R1}, V_{R2}, and I_T for the circuit shown in Figure 2.45c.

*From now on, the practical diode model will be assumed unless indicated otherwise.

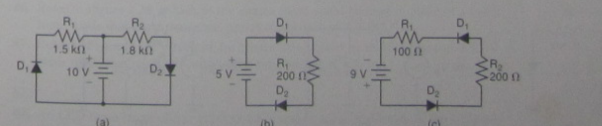


FIGURE 2.45

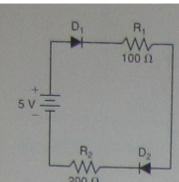


FIGURE 2.46

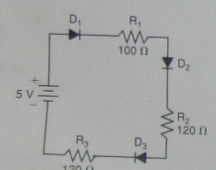


FIGURE 2.47

14. A voltage is calculated to be 12.8 V. The measured voltage is 13.2 V. What is the percentage of error in the calculation?
15. A current is calculated to be 750 μA. The measured current is 880 μA. Determine whether or not the percentage of error in the calculation is acceptable.
16. A voltage is calculated to be 144 mV. The measured voltage is 160 mV. Determine whether or not the percentage of error in the calculation is acceptable.
17. Calculate the value of V_{R2} for the circuit shown in Figure 2.46. When measured, V_{R2} is found to be 2.54 V. What is the percentage of error between your calculated value of V_{R2} and the measured value?
18. Calculate the value of V_{R2} for the circuit shown in Figure 2.47. When measured, V_{R2} is found to be 970 mV. What is the percentage of error between your calculated value of V_{R2} and the measured value?

§2.4

19. What is the minimum required peak reverse voltage rating for the diode in Figure 2.48a?
20. What is the minimum required peak reverse voltage rating for the diode in Figure 2.48b? (*Hint*: Don't forget how to work with voltage dividers!)
21. It was stated in section 2.4 that practical V_{RRM} ratings are usually multiples of 50 or 100 V. With this in mind, what would be the minimum acceptable V_{RRM} rating for the diode in Figure 2.48c?
22. What is the minimum acceptable average forward current rating for the diode shown in Figure 2.49?
23. What is the minimum acceptable average forward power dissipation rating for the diode shown in Figure 2.49?
24. A diode has a $P_{D(MAX)}$ rating of 1.2 W. What is the maximum allowable value of forward current for the device?
25. A diode has a $P_{D(MAX)}$ rating of 750 mW. What is the maximum allowable value of forward current for the device?

§2.5

26. A small-signal diode (silicon) has a forward current of 10 mA and a bulk resistance (R_B) of 5 Ω. What is the actual value of V_F for the device?
27. A small-signal diode (silicon) has a forward current of 8.2 mA and a bulk resistance (R_B) of 12 Ω. What is the actual value of V_F for the device?
28. A diode (silicon) has a bulk resistance of 20 Ω. At what value of I_F will the value of V_F actually *equal* 0.8 V?
29. Refer to Figure 2.48a. The diode in the circuit has a maximum rated value of I_R = 10 μA at 25°C. Assuming that I_R reaches its maximum value at each negative peak of the input cycle, what value of voltage will be measured across R_1 when I_R peaks? (Assume that T = 25°C.)
30. The circuit described in Problem 29 is operated at a temperature of 75°C. What is the voltage across R_1 when I_R peaks?

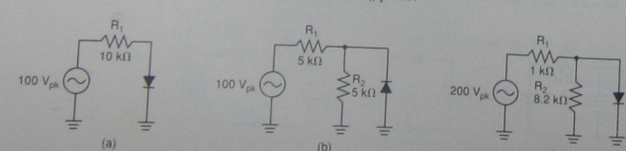


FIGURE 2.48

31. A 150-Ω resistor is in series with a diode that has a rating of I_R = 20 μA at 25°C. What reverse voltage will be measured across the resistor if the diode is reversed biased and T = 120°C? (Assume that I_R reaches its maximum possible value.)

§2.6

32. Refer to the diode spec sheet shown in Figure 2.50. In terms of maximum reverse voltage ratings, which of the diodes listed could be used in the circuit shown in Figure 2.48a?
33. Refer to the spec sheet shown in Figure 2.50. What is the maximum value of I_R for the 1N5398 at T = 150°C?
34. Refer to the spec sheet in Figure 2.50. What is the surge current rating for the 1N5391?
35. Refer to Figure 2.27. A circuit has an average forward current of 24.5 A and a 225-V_{pk} source. Which of the diodes listed has the *minimum* acceptable ratings for use in this circuit?
36. Refer to Figure 2.27. A circuit has an average forward current of 3.6 A and a 170-V_{pk} source. Which diode has the *minimum* acceptable ratings for use in this circuit?
37. Refer to Figure 2.27. A circuit has an average forward power dissipation (for the diode) of 2.8 W and a 470-V_{pk} source. Which diode has the *minimum* acceptable ratings for use in this circuit?

§2.7

38. A zener diode spec sheet lists values of I_{ZT} = 20 mA and I_{zt} = 1 mA. If the measured change in V_Z (at I_{zt}) is 25 mV, what is the value of zener impedance for the device?
39. Refer to Figure 2.51. In each circuit, determine whether or not the biasing voltage has the correct polarity for *normal* zener operation.
40. For each of the properly biased zener diodes in Figure 2.51, draw an arrow indicating the direction of zener current.

§2.8

41. A 6.8-V zener diode has a $P_{D(MAX)}$ rating of 1 W. What is the value of I_{ZM} for the device?
42. A 24-V zener diode has a $P_{D(MAX)}$ rating of 10 W. What is the value of I_{ZM} for the device?
43. A zener diode with a $P_{D(MAX)}$ rating of 5 W has a derating factor of 8 mW/°C above 50°C. What is the maximum allowable value of P_D for the device if it is operating at 120°C?
44. The MLL4678 zener diode has a $P_{D(MAX)}$ rating of 250 mW and a derating factor of 1.67 mW/°C above 50°C. What is the maximum allowable value of P_D for the device if it is operating at 150°C?
45. Refer to Figure 2.34. Which of the diodes could be used in place of a 28-V zener diode that has a maximum power dissipation of 1.8 W?
46. Refer to Figure 2.34. Which of the diodes listed could be used in place of a 6.8-V zener diode that has a maximum power dissipation of 1.2 W?
47. Refer to Figure 2.34. Which of the diodes listed could be used in place of a 12-V zener diode that has a maximum operating current of 150 mA?

§2.9

48. An LED has a range of V_F = 1.5 to 1.8 V and $I_{F(desired)}$ = 18 mA. If the LED is driven by a 20-V_{pk} source, what standard value of current-limiting resistor is needed to protect the LED?

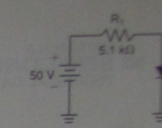


FIGURE 2.49

The Role of Power Supplies in Semiconductor Development

Power supplies are the most commonly used circuits in electronics. Virtually every electronic system requires the use of a power supply to convert the ac line voltage to the dc voltages needed for the system's internal operation.

In addition to being the most commonly used type of circuit, the power supply also played a major role in the development of today's electronic devices. Early power supplies used vacuum tubes to *rectify* ac, that is, to convert ac to pulsating dc. These vacuum tubes wasted a tremendous amount of power.

Early semiconductor research was centered around the use of *germanium*, a semiconductor material that cannot withstand any significant amount of current and heat. With the development of the commercial *pn*-junction diode in 1954, researchers turned to the problem of developing rectifier diodes, diodes that could withstand large current values and the heat produced by those currents.

In 1955, *silicon pn*-junction rectifier diodes had been developed that could handle current values up to 2 amperes. From that point on, research centered around the use of silicon rather than germanium. At this point in time, silicon is used for most semiconductor applications. Germanium is rarely used in the production of semiconductor devices.

It would take several volumes to discuss every diode application in modern electronics. In this chapter, we will concentrate on the most common diode application, the power supply. In Chapter 4, we will look at several additional diode applications.

OBJECTIVE 1 ►

Power supply
Converts ac to dc.

The **power supply** of an electronic system is used to convert the ac energy provided by the wall outlet to dc energy. The power cord of any electronic system supplies the line power to the system power supply, which then provides all internal dc voltages needed for proper circuit operation.

There are two basic types of power supplies. The *linear* power supply is the original and simpler of the two, and it is the focus of this chapter. The *switching* power supply is a newer and more complex circuit that is used in an increasing number of electronic systems. Switching supplies are covered in Chapter 21.

Rectifier
A circuit that converts ac to pulsating dc.

Filter
A circuit that reduces the variations in the output of a rectifier.

Voltage regulator
A circuit used to maintain a constant output voltage.

The basic power supply can be broken down into four circuit groups, as shown in Figure 3.1. The incoming ac line voltage is usually applied to a *transformer*. This transformer may either step up or step down the line voltage; depending on the needs of the power supply. The alternating voltage out of the transformer is then applied to a rectifier. A **rectifier** is a diode circuit that converts the ac to what is called *pulsating dc*. This pulsating dc is then applied to a *filter*, which reduces the variations in dc voltage. The **filter** is usually made up of passive components, such as resistors, capacitors, and inductors. The final stage is the **voltage regulator**. A voltage regulator is used to maintain a constant output voltage.

At one time, voltage regulators were designed using zener diodes as the regulating element. However, the development of the IC (integrated-circuit) voltage regulator has led to the replacement of zener diodes as regulating elements. IC voltage regulators are far more efficient than zener diodes, so power supply design currently emphasizes their use. At the same time, zener regulators are easier to understand and they serve as valuable educational circuits. We will therefore concentrate on the zener regulator in this chapter. The IC voltage regulator is covered in detail in Chapter 21.

3.1 TRANSFORMERS

Transformers are not considered solid-state devices, but they *do* play an integral role in the operation of most power supplies. Therefore, we will begin our discussion on power supply operation by reviewing the basics of transformer operation.

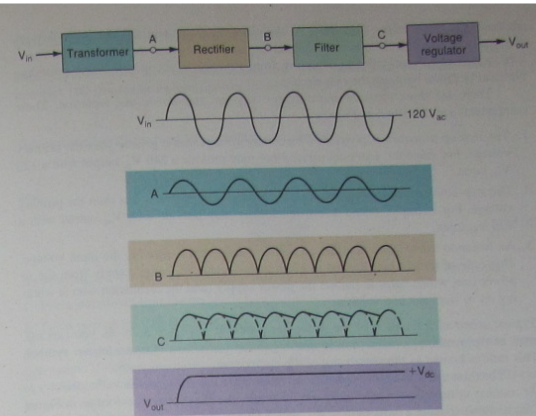


FIGURE 3.1 Basic power supply block diagram and waveforms.

The basic schematic symbol for the transformer is shown in Figure 3.2a. The component consists of two windings, called the *primary* and the *secondary*. The input to the transformer is applied to the primary and the output is taken from the secondary.

Transformers are made up of inductors that are in close proximity to each other, yet are not physically connected. An alternating voltage applied to the primary induces an

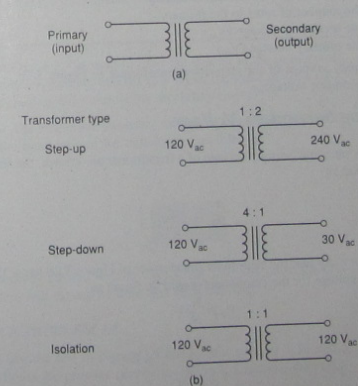


FIGURE 3.2 Transformer symbols.

alternating voltage in the secondary. At the same time, the primary and secondary are physically isolated, so there is no actual current transfer between the two circuits. Therefore, a transformer provides ac coupling from primary to secondary, while providing physical isolation between the two circuits.

There are three types of transformers: *step-up*, *step-down*, and *isolation*. These components are described as follows:

1. The *step-up transformer* provides a secondary voltage that is *greater than* the primary voltage. For example, a step-up transformer may provide a 240 V_{ac} output with a 120 V_{ac} input.
2. The *step-down transformer* provides a secondary voltage that is *less than* the primary voltage. For example, a step-down transformer may provide a 30 V_{ac} output with a 120 V_{ac} input.
3. An *isolation transformer* provides an output voltage that is *equal to* the input voltage. This type of transformer is used to electrically isolate the power supply from the ac power line, which helps to protect the power supply (and the technician who is working on it) from the line voltage.

Typical schematics for each of the above are provided in Figure 3.2b. As you can see, each of the symbols contains a ratio that is printed just above the transformer symbol. This ratio is known as the *turns ratio* of the component.

The turns ratio of a transformer is *the ratio of the number of turns in the primary to the number of turns in the secondary*. For example, the step-down transformer in Figure 3.2b is shown to have a turns ratio of 4:1, which means that there are four turns in the primary for each turn in the secondary.

The turns ratio of a transformer is equal to the voltage ratio of the component. By formula,

$$\frac{N_2}{N_1} = \frac{V_2}{V_1} \tag{3.1}$$

where N_2 = the number of turns in the secondary
N_1 = the number of turns in the primary
V_2 = the secondary voltage (V_{ac})
V_1 = the primary voltage (V_{ac})

Thus, the primary voltage of the step-down transformer in Figure 3.2b is four times as great as the secondary voltage.

Calculating Secondary Voltage

When the turns ratio and primary voltage of a transformer are known, the secondary voltage can be found as

$$V_2 = \frac{N_2}{N_1}V_1 \tag{3.2}$$

For example, let's say that the step-down transformer in Figure 3.2b has a 120 V_{ac} input. The secondary voltage for the component would be found as

$$V_2 = \frac{N_2}{N_1}V_1$$
$$= \frac{1}{4}(120\ V_{ac})$$
$$= 30\ V_{ac}$$

As you can see, the primary voltage (120 V_{ac}) is four times the secondary voltage (30 V_{ac}).

Calculating Secondary Current

Ideally, transformers are 100 percent efficient. This means that the ideal transformer transfers 100 percent of its input power to the secondary. By formula,

$$P_2 = P_1$$

Since power equals the product of voltage and current,

$$V_2I_2 = V_1I_1$$

and

$$\frac{I_1}{I_2} = \frac{V_2}{V_1} \tag{3.3}$$

As you can see, the current ratio is the inverse of the voltage ratio. This means that

1. For a step-down transformer, $I_2 > I_1$.
2. For a step-up transformer, $I_2 < I_1$.

In other words, current varies (from primary to secondary) in the opposite way that voltage varies. If voltage increases, current decreases, and vice versa.

Since the voltage ratio of a transformer is equal to its turns ratio, equation (3.3) can be rewritten as

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

or

$$I_2 = \frac{N_1}{N_2}I_1 \tag{3.4}$$

The following example demonstrates a practical application of this relationship.

EXAMPLE 3.1

The fuse in Figure 3.3 is used to limit the current in the primary of the transformer. Assuming that the fuse limits the value of I_1 to 1 A, what is the limit on the value of the secondary current?

Solution: The maximum secondary current is found using the limit on I_1 and the turns ratio of the transformer, as follows:

$$I_2 = \frac{N_1}{N_2}I_1$$
$$= \frac{1}{4}(1\ A)$$
$$= 250\ mA$$

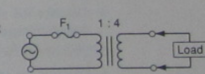


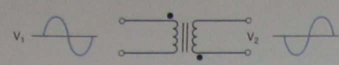
FIGURE 3.3

If the secondary current tries to exceed the 250 mA limit, the primary current will exceed its limit and blow the fuse.

PRACTICE PROBLEM 3.1

A circuit like the one in Figure 3.3 has a turns ratio of 1:12 and a fuse that limits the primary current to 250 mA. Calculate the maximum allowable value of I_2.

FIGURE 3.4



The current relationships developed here have been based on the idea that a transformer is 100 percent efficient. In reality, there are a number of losses within a transformer that cause the secondary power to be somewhat lower than the primary power. However, the difference between primary power and secondary power is small enough to have little effect on the relationships covered in this section.

Transformer Input/Output Phase Relationships

Some transformers provide a 180° phase shift from input to output; others do not. The input/output phase relationship of a transformer is not an important factor in the analysis of a power supply. However, you should be aware that a transformer with a 180° phase shift is identified as follows: In the schematic symbol, there are two dots: one on the top side of the primary and one on the bottom side of the secondary. When you see these dots, you are working with a transformer whose output voltage is 180° out of phase with its input voltage, as shown in Figure 3.4.

Transformer Ratings

Some manufacturers' catalogs rate transformers by their turns ratios, while others list them by *secondary voltage ratings*. For example, a transformer may be listed as a 40 V_{ac} transformer. When this rating is used, *it indicates the ac secondary voltage produced by a 120 V_{ac} input to the primary*. In other words, it gives you the rms output from the transformer when it is supplied by a standard 120 V_{ac} line input. Throughout this chapter, we will use both of these methods of rating transformers.

Section Review

1. What are names of the transformer input and output circuits?
2. List and describe the three types of transformers.
3. What is the *turns ratio* of a transformer?
4. Describe the relationship between the turns ratio of a transformer and its input and output voltages.
5. Describe the relationship between the transformer primary and secondary power.
6. Describe the relationship between the voltage ratio of a transformer and its current ratio.
7. Describe the two means by which transformers are normally listed in parts catalogs.

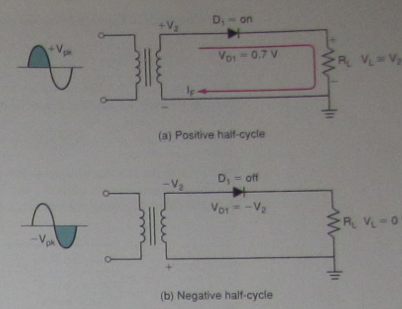
3.2 HALF-WAVE RECTIFIERS

There are three basic types of rectifier circuits: the *half-wave*, *full-wave*, and *bridge* rectifiers. Of the three, the bridge rectifier is the most commonly used, followed by the full-wave rectifier. Our discussion on rectifiers begins with the half-wave rectifier simply because it is the easiest to understand.

What does a half-wave rectifier do?

The half-wave rectifier is made up of a *diode* and a *resistor*, as shown in Figure 3.5. The half-wave rectifier is used to eliminate either the negative alternation of the input or

FIGURE 3.5 Ideal half-wave rectifier operation.



the positive alternation of the input. As you will see, the diode direction determines which half-cycle will be eliminated.

Because the half-wave rectifier configuration requires the least number of parts, it is the cheapest to produce. However, it is the least efficient of the three different types of rectifiers. Because of this, it is normally used for noncritical, low-current applications.

Basic Circuit Operation

The negative half-cycle of the input to the rectifier in Figure 3.5 is eliminated by the one-way conduction of the diode. Figure 3.6 details the operation of the circuit for one complete cycle of the input signal. During the positive half-cycle of the input, D_1 is forward biased and provides a path for current. This allows a voltage (V_L) to be developed across R_L that is approximately equal to the voltage across the secondary of the transformer (V_2).

When the polarity of the input signal reverses, D_1 is reverse biased, preventing conduction in the circuit. With no current through R_L, no voltage is developed across the load. In this case, the output voltage remains at approximately 0 V, and the voltage across the diode (V_D) is approximately equal to V_2.

If all this seems confusing, remember the *ideal diode model*. This diode model was shown in Chapter 2 to represent the component as either an *open* (reverse-biased) or *closed* (forward-biased) switch. When forward biased, this ideal switch drops no voltage. When reverse biased, this ideal switch drops all the applied voltage.

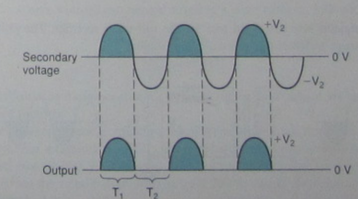


FIGURE 3.6 Input and output waveforms.

Lab Reference: These waveforms are observed in Exercise 4.

The diode in Figure 3.5a can be viewed as a closed switch. Therefore:

$$V_L = V_2 \quad \text{(forward operation)} \tag{3.5}$$

This is due to the fact that no voltage is dropped across a closed switch. By the same token, if we view the diode in Figure 3.5b as an *open* switch, we see that

$$V_{D1} = V_2 \quad \text{(reverse operation)} \tag{3.6}$$

This is due to the fact that an open switch drops all the applied voltage. This would leave no voltage to be dropped across R_L, and V_L would equal 0 V, as is shown in the figure. The *ideal* circuit operating characteristics are summarized as follows:

Diode Condition	V_{D1}	V_L
Forward biased	0 V	Equal to V_2
Reverse biased	Equal to V_2	0 V

Using these relationships, it is easy to understand the input/output waveforms shown in Figure 3.6. During T_1, the diode is forward biased, and the output (V_L) is approximately equal to the input (V_2). During T_2, the diode is reverse biased, and the output drops to 0 V. This is the way half-wave rectifiers work.

Negative Half-Wave Rectifiers

A Practical Consideration: When we talk about the *positive* and *negative* half-cycles of the input, we are referring to the polarity of the transformer secondary voltage measured from the top of the secondary to the bottom of the secondary.

Determining the output polarity of a half-wave rectifier.

Figure 3.7 shows a half-wave rectifier with the diode direction reversed. In this circuit, the diode will conduct on the *negative* half-cycle of the input, and equation (3.5) will apply. The diode will be reverse biased on the *positive* half-cycle of the input, and equation (3.6) will apply. As a result, the positive half-cycle of the input is eliminated. Note that the operating principles for this circuit are *exactly* the same as those for the *positive* half-wave rectifier shown in Figure 3.5. The only difference is that the polarity of the output has been reversed.

As you can see, the *direction* of the diode determines whether the output from the rectifier is positive or negative. For circuit recognition, the following statements will generally hold true:

1. When the diode points toward the load (R_L), the output from the rectifier will be *positive*.
2. When the diode points toward the transformer, the output from the rectifier will be *negative*.

These two statements will also hold true for the full-wave rectifier. The points made so far about half-wave rectifiers are summarized in Figure 3.8.

Lab Reference: The effects of diode direction are demonstrated in Exercise 4.

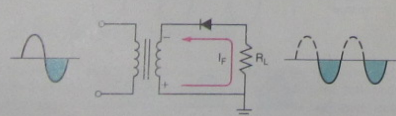


FIGURE 3.7 **Negative half-wave rectifier.**

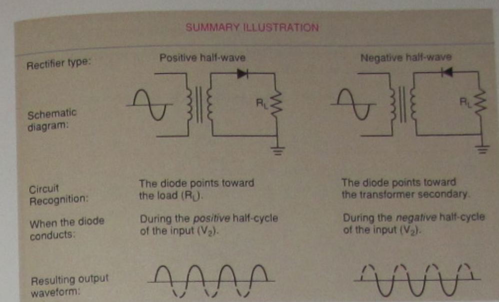


FIGURE 3.8

Calculating Load Voltage and Current Values

OBJECTIVE 2

In our discussion of the *ideal* half-wave rectifier, we ignored the value of V_F for the diode. When we take this value into account, the *peak load voltage*, $V_{L(pk)}$ is found as

$$V_{L(pk)} = V_{2(pk)} - V_F \tag{3.7}$$

You shouldn't have any difficulty with this equation. It is simply a variation on equation (2.1). $V_{2(pk)}$ is the *peak secondary voltage* of the transformer, found as

Equation (2.1): $V_R = V_S - 0.7\text{ V}$

$$V_{2(pk)} = \frac{N_2}{N_1} V_{1(pk)} \tag{3.8}$$

where $\frac{N_2}{N_1}$ = the ratio of transformer secondary turns to primary turns

$V_{1(pk)}$ = the peak transformer primary voltage

A word of caution: Equation (3.8) assumes that the input to the transformer is given as a *peak* value. More often than not, source voltages are given as rms values. When this is the case, the source voltage can be converted to a peak value as follows:

$$V_{pk} = \frac{V_{rms}}{0.707} \tag{3.9}$$

Example 3.2 illustrates the procedure for calculating the peak output voltage from a positive half-wave rectifier.

Note: You will be shown later in this section how to calculate the output values for a *negative* half-wave rectifier.

Here is another practical situation: Most transformers are rated for a specific rms output voltage. For example, a 25 V_{ac} transformer would have an rms output of 25 V when supplied from a 120 V wall outlet. When a transformer has an output voltage rating, simply divide the rated output voltage by 0.707 to obtain the value of $V_{2(pk)}$. This is shown in Example 3.3.

EXAMPLE 3.2

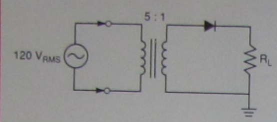


FIGURE 3.9

Determine the peak load voltage for the circuit shown in Figure 3.9.

Solution: First, the ac input to the transformer is converted to a peak value, as follows:

$$V_{1(pk)} = \frac{V_{1(rms)}}{0.707} = \frac{120\ V_{ac}}{0.707} = 169.7\ V_{pk}$$

Now, the voltage values in the secondary circuit are found as

$$V_{2(pk)} = \frac{N_2}{N_1}V_{1(pk)} = \frac{1}{5}(169.7\ V_{(pk)}) = 33.94\ V_{pk}$$

and

$$\begin{aligned} V_{L(pk)} &= V_{2(pk)} - V_F \\ &= 33.94\ V_{pk} - 0.7\ V \\ &= 33.24\ V_{pk} \end{aligned}$$

PRACTICE PROBLEM 3.2

A half-wave rectifier has values of $N_1 = 10$, $N_2 = 1$, and $V_{1(pk)} = 180\ V_{pk}$. What is the peak load voltage for the circuit?

EXAMPLE 3.3

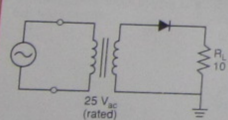


FIGURE 3.10

Determine the peak load voltage for the circuit shown in Figure 3.10.

Solution: The transformer is shown to have a 25 V_{ac} rating. This value of V_2 is converted to peak form as follows:

$$V_{2(pk)} = \frac{V_{2(rms)}}{0.707} = \frac{25\ V_{rms}}{0.707} = 35.36\ V_{pk}$$

Now the value of $V_{L(pk)}$ is found as

$$\begin{aligned} V_{L(pk)} &= V_{2(pk)} - 0.7\ V \\ &= 35.36\ V_{pk} - 0.7\ V \\ &= 34.66\ V_{pk} \end{aligned}$$

PRACTICE PROBLEM 3.3

A 24 V_{ac} transformer is being used in a positive half-wave rectifier. What is the peak load voltage for the circuit?

Once the peak load voltage is determined, the peak load current is found as

$$I_{L(pk)} = \frac{V_{L(pk)}}{R_L} \tag{3.10}$$

Example 3.4 demonstrates the calculation of peak load current.

EXAMPLE 3.4

Question and Answer: At this point, you may be wondering why we are so concerned with *peak* values. Wouldn't it just be easier to leave everything in *rms* form since ac voltmeters measure *rms*? There are two reasons for dealing with peak voltages: First, we measure peak voltages when using an oscilloscope. Second (and perhaps most important) is the fact that *average* (dc) voltage and current values are easier to determine when peak values are known.

What is the peak load current for the circuit shown in Figure 3.11?

Solution: The input voltage is given as an rms value. This value is converted to a *peak* value as follows:

$$V_{1(pk)} = \frac{V_{1(rms)}}{0.707} = \frac{200\ V_{ac}}{0.707} = 282.9\ V_{pk}$$

Now, the value of $V_{2(pk)}$ is found as

$$V_{2(pk)} = \frac{N_2}{N_1}V_{1(pk)} = \frac{1}{5}(282.9\ V_{pk}) = 56.6\ V_{pk}$$

Finally, the load voltage and current values are found as:

$$\begin{aligned} V_{L(pk)} &= V_{2(pk)} - V_F \\ &= 56.6\ V_{pk} - 0.7\ V \\ &= 55.9\ V_{pk} \end{aligned}$$

and

$$I_{L(pk)} = \frac{V_{L(pk)}}{R_L} = \frac{55.9\ V_{pk}}{10\ k\Omega} = 5.59\ mA_{pk}$$

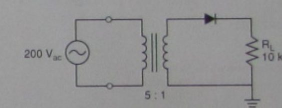


FIGURE 3.11

PRACTICE PROBLEM 3.4

A circuit like the one shown in Figure 3.11 has values of $N_1 = 12$, $N_2 = 1$, $V_1 = 150\ V_{ac}$, and $R_L = 8.2\ k\Omega$. What is the peak load current for the circuit?

Average Load Voltage and Current

The **average load voltage,** V_{ave}, from an ac circuit indicates *the reading you would get if the voltage was measured with a dc voltmeter.* In other words, V_{ave} is the *dc equivalent* of an ac signal. In most cases, V_{ave} and V_{dc} will be used to describe the same value. Since

Average load voltage
The dc equivalent of an ac signal. V_{ave} is measured with a dc voltmeter.

rectifiers are used to convert ac to dc, V_{ave} is a very important value. For a half-wave rectifier, V_{ave} is found as

$$V_{ave} = \frac{V_{pk}}{\pi} \quad \text{(half-wave rectified)} \tag{3.11}$$

Another form of this equation is

$$V_{ave} = 0.318(V_{pk}) \quad \text{(half-wave rectified)} \tag{3.12}$$

where $0.318 \cong 1/\pi$. Either of these equations can be used to determine the *dc equivalent* load voltage for a *half-wave* rectifier. Example 3.5 demonstrates the process for determining the value of V_{ave} for a half-wave rectifier.

EXAMPLE 3.5

Determine the value of V_{ave} for the circuit shown in Figure 3.12.

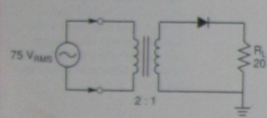


FIGURE 3.12

Lab Reference: These values are calculated and measured as part of Exercise 4.

Solution:

$$V_{1(pk)} = \frac{V_{1(rms)}}{0.707} = \frac{75\ V_{ac}}{0.707} = 106.1\ V_{pk}$$

$$V_{2(pk)} = \frac{N_2}{N_1}V_{1(pk)} = \frac{1}{2}(106.1\ V_{pk}) = 53.04\ V_{pk}$$

$$V_{L(pk)} = 53.04\ V_{pk} - 0.7\ V = 52.34\ V_{pk}$$

$$V_{ave} = \frac{V_{pk}}{\pi} = \frac{52.34\ V_{pk}}{\pi} = 16.66\ V_{dc}$$

PRACTICE PROBLEM 3.5

A half-wave rectifier like the one in Figure 3.12 has values of $N_1 = 14$, $N_2 = 1$, and $V_1 = 150\ V_{ac}$. What is the dc load voltage for the circuit?

Average load current
The dc equivalent current of an ac signal. I_{ave} is measured with a dc ammeter.

Just as we can convert a *peak* voltage to *average* voltage, we can also convert a *peak* current to an *average* current. The value of the **average load current** for an ac waveform is the value that would be measured with a *dc ammeter*. Thus, the value of I_{ave} for a waveform gives us an *equivalent dc current*. This is another very important value

that we need to know for any circuit used to convert ac to dc. The value of I_{ave} can be calculated in one of two ways:

Question and Answer: Where did equations (3.11) through (3.14) come from? These are the equations that are taught in an ac circuits course for converting *peak* values to *average* values. You may want to review your basic electronics text for a complete explanation of the equations.

1. We can determine the value of V_{ave} and then use Ohm's law as follows:

$$I_{ave} = \frac{V_{ave}}{R_L}$$

2. We can convert I_{pk} to average form using the same basic equations, (3.11) and (3.12), that we used to convert V_{pk} to V_{ave}. The current forms of these equations are

$$I_{ave} = \frac{I_{pk}}{\pi} \quad \text{(half-wave rectified)} \tag{3.13}$$

and

$$I_{ave} = 0.318(I_{pk}) \quad \text{(half-wave rectified)} \tag{3.14}$$

Example 3.6 demonstrates the first method for determining the value of I_{ave}.

EXAMPLE 3.6

Determine the value of I_{ave} for the circuit shown in Figure 3.12.

Solution: In Example 3.5, we determined the value of V_{ave} to be 16.66 V_{dc}. Using this value and the value of R_L, the value of I_{ave} is found to be

$$I_{ave} = \frac{V_{ave}}{R_L} = \frac{16.66\ V_{ave}}{20\ k\Omega} = 833\ \mu A_{dc}$$

PRACTICE PROBLEM 3.6

A half-wave rectifier has an average output voltage that is equal to 24 V_{dc}. The load resistance is 2.2 kΩ. What is the value of the dc load current for the circuit?

Example 3.7 demonstrates the second method of determining the value of I_{ave}.

EXAMPLE 3.7

Determine the dc load current for the rectifier shown in Figure 3.13.

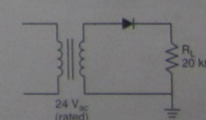


FIGURE 3.13

Solution: The transformer has a 24 V_{ac} rating. Thus, the peak secondary voltage is found as

$$V_{2(pk)} = \frac{24\ V_{ac}}{0.707} = 33.9\ V_{pk}$$

The peak load voltage is now found as

$$V_{L(pk)} = V_{2(pk)} - 0.7\ V = 33.2\ V_{pk}$$

The peak load current is found as

$$I_{L(pk)} = \frac{V_{L(pk)}}{R_L} = \frac{33.2\ V_{pk}}{20\ k\Omega} = 1.66\ mA_{pk}$$

Finally,

$$I_{ave} = \frac{I_{pk}}{\pi} = \frac{1.66\ mA_{pk}}{\pi} = 529.13\ \mu A_{dc}$$

PRACTICE PROBLEM 3.7

A half-wave rectifier is fed by a 48 V_{ac} transformer. If the load resistance for the circuit is 12 kΩ, what is the dc load current for the circuit?

Negative Half-Wave Rectifiers

The analysis of a *negative* half-wave rectifier is nearly identical to that for a positive half-wave rectifier. The only difference is that all the voltage polarities will be reversed.

You can use a simple method for performing the mathematical analysis of a negative half-wave rectifier:

1. Analyze the circuit as if it were a positive half-wave rectifier.
2. After completing your calculations, change all your voltage polarity signs from positive to negative.

This method for analyzing a negative half-wave rectifier is demonstrated in Example 3.8.

EXAMPLE 3.8

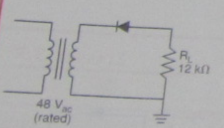


FIGURE 3.14

Determine the dc output voltage for the circuit shown in Figure 3.14.

Solution: We'll start by solving the circuit as if it were a positive half-wave rectifier. First,

$$V_{2(pk)} = \frac{48\ V_{ac}}{0.707} = 67.9\ V_{pk}$$

and

$$V_{L(pk)} = V_{2(pk)} - 0.7\ V = 67.2\ V_{pk}$$

Finally,

$$V_{ave} = \frac{V_{pk}}{\pi} = 21.39\ V_{dc}$$

Now we simply convert all the positive voltage values to negative voltage values. Thus, for the circuit shown in Figure 3.14,

$$V_{2(pk)} = -67.9\ V_{pk}$$
$$V_{L(pk)} = -67.2\ V_{pk}$$
$$V_{ave} = -21.39\ V_{dc}$$

PRACTICE PROBLEM 3.8

A negative half-wave rectifier is fed by a 36 V_{ac} transformer. Using the method illustrated in this example, calculate the values of $V_{2(pk)}$, $V_{L(pk)}$, and the dc output voltage.

As you can see, there isn't really a whole lot of difference between the analysis of a negative half-wave rectifier and that of a positive half-wave rectifier.

Component Substitution

The value of I_{ave} is important for another reason. You may recall from Chapter 2 that the *maximum dc forward current* that can be drawn through a diode is equal to the *average forward current* (I_0) rating of the device. When working with rectifiers, you may need at some point to substitute one diode for another. When this is the case, you must make sure that the value of I_{ave} for the diode in the circuit is less than the I_0 rating of the substitute component. This point will be demonstrated in Section 3.5.

Why knowing the value of I_{ave} is important.

Peak Inverse Voltage (PIV)

The maximum amount of reverse bias that a diode will be exposed to in a rectifier is called the **peak inverse voltage** or **PIV** of the rectifier. For the half-wave rectifier, the value of PIV is found as

Peak inverse voltage (PIV) The maximum reverse bias that a diode will be exposed to in a rectifier.

$$PIV = V_{2(pk)} \quad \text{(half-wave rectifier)} \qquad (3.15)$$

The basis for this equation can be seen by referring to Figure 3.5. When the diode is reverse biased (Figure 3.5b), there is no voltage dropped across the load. Therefore, all of V_2 is dropped across the diode in the rectifier.

The PIV of a given rectifier is important because it determines the *minimum allowable value* of V_{RRM} for any diode used in the circuit. This point is demonstrated in Section 3.5.

Why PIV is important.

Section Review

1. Briefly explain the forward and reverse operation of a half-wave rectifier.
2. Describe the difference between the output waveforms of a positive and a negative half-wave rectifier.
3. How can you tell the output polarity of a half-wave rectifier?
4. List, in order, the steps you would take to calculate the dc output voltage from a rectifier if you were given the turns ratio of the transformer and the rms primary voltage.
5. List, in order, the steps you would take to calculate the dc output voltage from a rectifier if you knew the rated rms output voltage.

6. You have calculated the value of V_{ave} for a half-wave rectifier. What piece of test equipment would you use to measure it?
7. You have calculated the value of I_{ave} for a half-wave rectifier. What piece of test equipment would you use to measure it?
8. Describe the two methods for analyzing a *negative* half-wave rectifier.
9. Why is PIV important?
10. How do you determine the value of PIV for a half-wave rectifier?

3.3 FULL-WAVE RECTIFIERS

The full-wave rectifier consists of *two diodes* and a *resistor*, as shown in Figure 3.15a. The result of this change in circuit construction is illustrated in Figure 3.15b.

In Figure 3.15b, the output from the full-wave rectifier is compared with that of a half-wave rectifier. Note that the full-wave rectifier has two positive half-cycles out for every one produced by the half-wave rectifier.

Center-tapped transformer Transformer with an output lead connected to the center of the secondary winding.

The transformer shown in Figure 3.15 is a **center-tapped transformer**. This type of transformer has a lead connected to the center of the secondary winding. The voltage from the center tap to each of the outer winding terminals is equal to one-half of the secondary voltage. For example, let's say we have a 24 V center-tapped transformer. The voltage from the center tap to each of the outer winding terminals is 12 V.

As you will see, the operation of the center-tapped transformer plays a major role in the operation of the full-wave rectifier. For this reason, the full-wave rectifier cannot be "line operated"; that is, it cannot be connected directly to the ac power input like the half-wave rectifier can.

Basic Circuit Operation

OBJECTIVE 3 ►

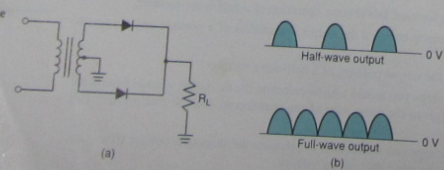
Figure 3.16 shows the operation of the full-wave rectifier during one complete cycle of the input signal. During the positive half-cycle of the input, D_1 is forward biased and D_2 is reverse biased. Note the direction of current through the load (R_L). Using the ideal operating characteristics of the diode, V_L can be found as

$$V_{L(pk)} = \frac{V_{2(pk)}}{2} \tag{3.16}$$

Why the load voltage is only half the value of the transformer secondary voltage.

V_L is equal to half of the secondary voltage because the transformer is center tapped. The voltage from one end of a center-tapped transformer to the center tap is *always* one-half of the total secondary voltage.

FIGURE 3.15 Full-wave rectifier.



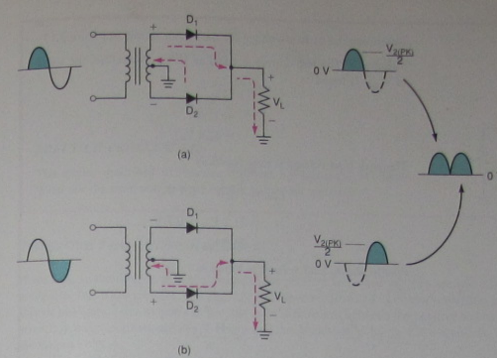


FIGURE 3.16 Full-wave operation.

Lab Reference: Full-wave operation is demonstrated in Exercise 4.

When the polarity of the input reverses, D_2 is forward biased, and D_1 is reverse biased. Note that the direction of current through the load *has not changed*, even though the polarity of the transformer secondary has. Thus, another positive half-cycle is produced across the load. This gives the output waveform shown in Figure 3.15b.

Calculating Load Voltage and Current Values

◄ OBJECTIVE 4

Using the *practical diode model*, the peak load voltage for a full-wave rectifier is found as

$$V_{L(pk)} = \frac{V_{2(pk)}}{2} - 0.7\text{ V} \tag{3.17}$$

The full-wave rectifier has twice the output frequency of the half-wave rectifier.

The full-wave rectifier will produce twice as many output pulses (per input cycle) as the half-wave rectifier. In other words, for every output pulse produced by a half-wave rectifier, two will be produced by a full-wave rectifier. For this reason, the *average load voltage* for the full-wave rectifier is found as

$$V_{ave} = \frac{2V_{L(pk)}}{\pi} \tag{3.18}$$

or

$$V_{ave} = 0.636\, V_{L(pk)} \tag{3.19}$$

where $0.636 \cong 2/\pi$. Note that the value 0.636 used in equation (3.19) is twice the value of 0.318 that was used in equation (3.12) to find the value of V_{ave} for a half-wave rectifier. The procedure for determining the dc load voltage for a full-wave rectifier is illustrated in Example 3.9.

EXAMPLE 3.9

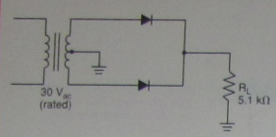


FIGURE 3.17

Lab Reference: These values are calculated and measured as part of Exercise 4.

Determine the dc load voltage for the circuit shown in Figure 3.17.

Solution: The transformer is rated at 30 V_{ac}. Therefore, the value of $V_{2(pk)}$ is found as

$$V_{2(pk)} = \frac{30\ V_{ac}}{0.707} = 42.4\ V_{pk}$$

The peak load voltage is now found as

$$V_{L(pk)} = \frac{V_{2(pk)}}{2} - 0.7\ V = 21.2\ V_{pk} - 0.7\ V = 20.5\ V_{pk}$$

Finally, the dc load voltage is found as

$$V_{ave} = \frac{2\,V_{L(pk)}}{\pi} = \frac{41\ V_{pk}}{\pi} = 13.05\ V_{dc}$$

PRACTICE PROBLEM 3.9

A full-wave rectifier is fed by a 24 V_{ac} center-tapped transformer. What is the dc load voltage for the circuit?

Once the peak and average load voltage values are known, it is easy to determine the values of $I_{L(pk)}$ and I_{ave}. Just use the known values and Ohm's law, as demonstrated in Example 3.10.

EXAMPLE 3.10

Determine the values $I_{L(pk)}$ and I_{ave} for the circuit shown in Figure 3.17.

Solution: In Example 3.9, we calculated the peak and average output voltages for the circuit. Using these calculated values and the value of R_L shown in the circuit, we determine the circuit current values as follows:

$$I_{L(pk)} = \frac{V_{L(pk)}}{R_L} = \frac{20.5\ V_{pk}}{5.1\ k\Omega} = 4.02\ mA_{pk}$$

and

$$I_{ave} = \frac{V_{ave}}{R_L} = \frac{13.05\ V_{dc}}{5.1\ k\Omega} = 2.56\ mA\ dc$$

PRACTICE PROBLEM 3.10

The circuit described in Practice Problem 3.9 has a 2.2-kΩ load. What are the peak and dc load current values for the circuit?

Negative Full-Wave Rectifiers

If we reverse the directions of the diodes in the positive full-wave rectifier, we will have a *negative* full-wave rectifier. The negative full-wave rectifier and its output waveform are shown in Figure 3.18. As you can see, the main differences between the positive and negative full-wave rectifiers are the direction that the diodes are pointing and the polarity of the output voltage.

The method you were shown for analyzing a negative half-wave rectifier will also work for analyzing a negative full-wave rectifier: simply change the voltage polarity signs from positive to negative. We will not go through these analysis procedures again, but you should have no problem making the transition from the negative half-wave to the negative full-wave rectifier. If you don't remember how to analyze a negative rectifier, refer back to Section 3.2.

Peak Inverse Voltage

When one of the diodes in a full-wave rectifier is reverse biased, the voltage across that diode will be approximately equal to V_2. This point is illustrated in Figure 3.19. The 24 V_{pk} across the primary develops peak voltages of +12 V and −12 V across the secondary (when measured from end to center tap). Note that $V_{2(pk)}$ equals the difference between these two voltages: 24 V. With the polarities shown, D_1 is conducting, and D_2 is reverse biased. If we assume D_1 to be ideal, the voltage drop across the component will equal 0 V. Thus, the cathode of D_1 will also be at +12 V. Since this point is connected directly to the cathode of D_2, its cathode is also at +12 V. With −12 V applied to the anode of D_2, the total voltage across the diode is 24 V.

The peak load voltage supplied by the full-wave rectifier is equal to one-half the secondary voltage, V_2. Therefore, the reverse voltage across either diode will be twice the peak load voltage. By formula,

$$\text{PIV} = 2\,V_{L(pk)} \qquad (3.20)$$

FIGURE 3.18

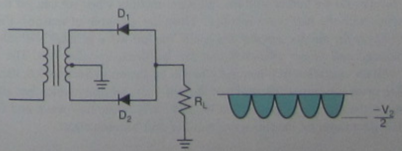
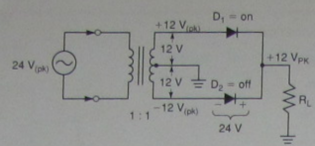


FIGURE 3.19 **Full-wave rectifier PIV.**



Since the peak load voltage is half the secondary voltage, we can also find the value of PIV as

$$\text{PIV} = V_{2(\text{pk})} \tag{3.21}$$

You may recall that equation (3.21) is the same as the equation we used for the half-wave rectifier, equation (3.15).

A Practical Consideration: It may seem confusing to have three different equations for PIV. However, you should keep two points in mind:

1. Equations (3.20) and (3.21) are actually saying the same thing.
2. The 0.7 V drop included in equation (3.22) may become important when you are dealing with low-voltage rectifiers, like those typically found in personal computers.

When calculating the PIV in a practical diode circuit, the 0.7 V drop across the conducting diode should be taken into consideration. In Figure 3.19, D_1 is on and will have a voltage drop of 0.7 V. Because D_1 is in series with D_2, the PIV across D_2 will be reduced by the voltage drop across D_1. The equation

$$\text{PIV} = V_{2(\text{pk})} - 0.7\text{ V} \tag{3.22}$$

gives a more accurate PIV voltage, but in most applications the 0.7 V will not make a difference in the choice of a diode.

Full-Wave Versus Half-Wave Rectifiers

There are quite a few similarities between full-wave and half-wave rectifiers. Figure 3.20 summarizes the relationships that you have been shown for the half-wave and full-wave rectifiers.

It would seem (at first) that the only similarity between the half-wave and the full-wave rectifiers is the method of finding the PIV values for the two circuits. However, there is another similarity that may not be as obvious. Let's assume for a moment that both of the rectifiers shown in Figure 3.20 are fed by 24 V_{ac} transformers. If you were to calculate the dc output voltages for the two circuits, you would get the following values:

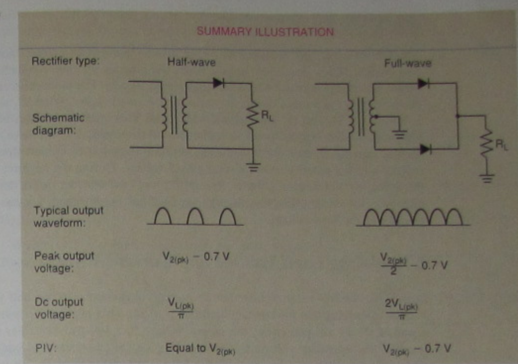
$V_{ave} = 10.58\ V_{dc}$ (for the half-wave rectifier)

$V_{ave} = 10.36\ V_{dc}$ (for the full-wave rectifier)

As you can see, the two circuits will produce nearly identical dc output voltages *for identical values of transformer secondary voltage*. In fact, if the values of R_L for the two circuits are equal, the dc output current values for the circuits will also be nearly identical.

So why do we bother with the full-wave rectifier when we can get the same dc output values with the half-wave rectifier? There are a couple of reasons. First, *if the peak load voltages for the two circuits are equal, the full-wave rectifier will have twice the dc load voltage and power efficiency that the half-wave rectifier has*. The second reason deals with the operation of filters. As you will be shown in Section 3.6, the full-wave rectifier has twice the output frequency of the half-wave rectifier, which has an impact on the filtering of the rectifier output. When we add filters to the half-wave and full-wave rectifiers, the advantages of the full-wave rectifier will become clear.

FIGURE 3.20



Section Review

1. Briefly explain the operation of a full-wave rectifier.
2. How do you determine the PIV across each diode in a full-wave rectifier?
3. Briefly discuss the similarities and differences between the half-wave rectifier and the full-wave rectifier.

3.4 FULL-WAVE BRIDGE RECTIFIERS

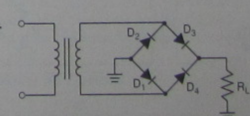
Why bridge rectifiers are preferred.

The bridge rectifier is the most commonly used full-wave rectifier circuit for several reasons:

1. It does not require the use of a center-tapped transformer, and therefore can be coupled directly to the ac power line, if desired.
2. Using a transformer with the same secondary voltage produces a peak output voltage that is nearly double the voltage of the full-wave center-tapped rectifier. This results in a higher dc voltage from the supply.

The bridge rectifier is shown in Figure 3.21. As you can see, the circuit consists of *four diodes* and a *resistor*.

FIGURE 3.21 **Bridge rectifier.**



Basic Circuit Operation

OBJECTIVE 5 ► The full-wave rectifier produces its output by alternating circuit conduction between the two diodes. When one is *on* (conducting), the other is *off* (not conducting), and vice versa. The bridge rectifier works basically the same way. The main difference is that the bridge rectifier alternates conduction between two diode *pairs*. When D_1 and D_3 (Figure 3.21) are on, D_2 and D_4 are off, and vice versa. This circuit operation is illustrated in Figure 3.22. During the positive half-cycle of the input, V_2 will have the polarities shown, causing D_1 and D_3 to conduct. Note the direction of current through the load resistor and the polarity of the resulting load voltage. During the negative half-cycle of the input, V_2 will reverse polarity. D_2 and D_4 will now conduct rather than D_1 and D_3. However, the current direction through the load has not changed, nor has the resulting polarity of the load voltage.

Calculating Load Voltage and Current Values

OBJECTIVE 6 ► Recall that the full-wave rectifier has an output voltage equal to one-half the secondary voltage (assuming that the conducting diode is ideal). This relationship was expressed in equation (3.17). As you know, the output voltage in a full-wave rectifier is reduced to one-half the secondary voltage by the center tap on the transformer secondary. The center-tapped transformer is essential for the full-wave rectifier to work, but it cuts the output voltage in half.

The bridge rectifier does not require the use of a center-tapped transformer. Assuming the diodes in the bridge to be ideal, the rectifier will have a peak output voltage of

$$V_{L(pk)} = V_{2(pk)} \quad \text{(ideal)} \tag{3.23}$$

Refer to Figure 3.22. If you consider the diodes to be ideal, the cathode and anode voltage will be equal for each diode. If you view the conducting diodes as being shorted connections to the transformer secondary, you can see that the voltage across the load resistor is equal to the voltage across the secondary.

Lab Reference: Bridge rectifier operation is demonstrated in Exercise 4.

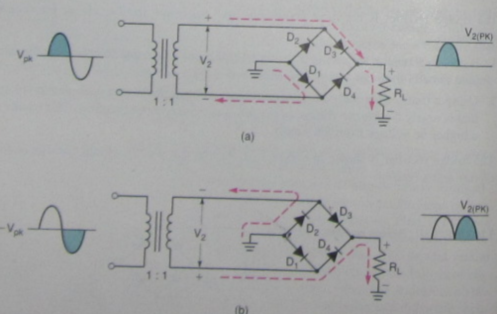


FIGURE 3.22 Bridge rectifier operation.

When calculating circuit output values, you will get more accurate results if you take the voltage drops across the two conducting diodes into account. To include these values, use the following equation when calculating peak load voltage:

$$V_{L(pk)} = V_{2(pk)} - 1.4\text{ V} \tag{3.24}$$

The 1.4 V value represents the sum of the diode voltage drops.

The rest of the load voltage and current values are found using the same equations as those used for the full-wave rectifier. This is illustrated in Example 3.11.

EXAMPLE 3.11

Determine the dc load voltage and current values for the circuit shown in Figure 3.23.

Solution: With the 12 V_{ac} rated transformer, the peak secondary voltage is found as

$$V_{2(pk)} = \frac{12\ V_{ac}}{0.707} = 16.97\ V_{pk}$$

The peak load voltage is now found as

$$V_{L(pk)} = V_{2(pk)} - 1.4\text{ V} = 15.57\ V_{pk}$$

The dc load voltage is found as

$$V_{ave} = \frac{2V_{L(pk)}}{\pi} = \frac{31.14\ V_{pk}}{\pi} = 9.91\ V_{dc}$$

Finally, the dc load current is found as

$$I_{ave} = \frac{V_{ave}}{R_L} = \frac{9.91\ V_{dc}}{12\text{ k}\Omega} = 825.8\ \mu A_{dc}$$

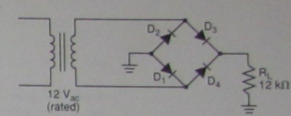


FIGURE 3.23

Lab Reference: These voltages are calculated and measured as part of Exercise 4.

PRACTICE PROBLEM 3.11

A bridge rectifier is fed by an 18 V_{ac} transformer. Determine the dc load voltage and current for the circuit when it has a 1.2 kΩ load.

It is easy to remember how the individual diodes are placed in a bridge rectifier circuit. All the diodes point toward the load. The corner opposite the load is the ground reference. The ac voltage is applied at the two remaining points of the square.

Bridge Versus Full-Wave Rectifiers

Let's analyze one more full-wave rectifier. This will give us some values for comparing the outputs from the full-wave and bridge rectifiers.

Example 3.12

A full-wave rectifier has a 12 V_{ac} transformer and a 12 kΩ load. Determine the dc load voltage and current values for the circuit.

Solution: The peak secondary voltage for the circuit is found as

$$V_{2(pk)} = \frac{12\ V_{ac}}{0.707} = 16.97\ V_{pk}$$

The peak load voltage is now found as

$$V_{L(pk)} = \frac{V_{2(pk)}}{2} - 0.7\ \text{V} = 7.79\ V_{pk}$$

The dc load voltage is found as

$$V_{ave} = \frac{2\,V_{L(pk)}}{\pi} = 4.96\ V_{dc}$$

Finally, the dc load current is found as

$$I_{ave} = \frac{V_{ave}}{R_L} = 413.3\ \mu\text{A}$$

Now let's compare the results from Examples 3.11 and 3.12. The only difference between these two circuits is that one is a full-wave rectifier and one is a bridge rectifier. For convenience, the results are summarized as follows:

Value	*Bridge Rectifier*	*Full-Wave Rectifier*
Peak load voltage	15.57 V_{pk}	7.79 V_{pk}
DC load voltage	9.91 V_{dc}	4.96 V_{dc}
DC load current	825.8 μA	413.3 μA

The primary advantages of using a bridge rectifier instead of a full-wave rectifier.

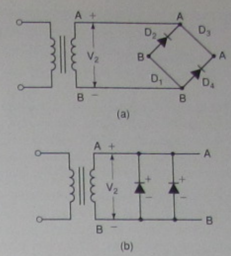
As you can see, the bridge rectifier has output values that are twice as high as a comparable full-wave rectifier. This higher output is the primary advantage of using a bridge rectifier instead of a full-wave rectifier. The power efficiency of the bridge rectifier is also higher than that of the full-wave rectifier.

Peak Inverse Voltage

Using the ideal diode model, the PIV of each diode in the bridge rectifier is equal to V_2. This is the same voltage that was applied to the diodes in the full-wave center-tapped rectifier. Figure 3.24 helps to illustrate this point. In Figure 3.24a, two things have been done:

1. The conducting diodes (D_1 and D_3) have been replaced by straight wires. Assuming that the diodes are ideal, they will have the same resistance as wire; therefore, the replacement is valid.
2. The positive side of the secondary has been labeled A and the negative side has been labeled B.

FIGURE 3.24 **Bridge rectifier PIV.**



Connecting the common A points along a straight line and doing the same with the B points gives us the circuit shown in Figure 3.24b. With this equivalent circuit, you can see that the two reverse-biased diodes and the secondary of the transformer are all in *parallel*. Since parallel voltages are equal, the PIV across each diode is equal to V_2. The same situation will exist for D_1 and D_3 when they are reverse-biased.

Putting It All Together

The three commonly used rectifiers are the *half-wave rectifier*, *full-wave (center-tapped) rectifier*, and the *bridge rectifier*. The output characteristics of these circuits are summarized in Figure 3.25.

As you know, the *half-wave rectifier* is the simplest of the three circuits. For each input cycle, the half-wave rectifier produces a single half-cycle output. The polarity of the half-cycle output depends on the direction of the diode in the circuit. The half-wave rectifier is normally used in conjunction with a transformer. However, the circuit can be directly coupled to the ac line input.

The *full-wave (center-tapped) rectifier* uses two diodes in conjunction with a center-tapped transformer to convert an ac input to a pulsating dc output. For each input cycle, this rectifier produces two output half-cycles (as shown in Figure 3.25). As is the case with the half-wave rectifier, the output polarity of the full-wave rectifier is determined by the direction of the diodes in the circuit. Since a center-tapped transformer is required for this rectifier to operate, it *cannot* be directly coupled to the ac line input.

The *bridge rectifier* produces an output that is similar to that of a center-tapped full-wave rectifier. However, the diode configuration in this rectifier eliminates the need for a center-tapped transformer. As a result, the bridge rectifier has two distinct advantages over its full-wave counterpart:

1. The peak output (for a given peak input) is twice the value of the output produced by a center-tapped full-wave rectifier.
2. The bridge rectifier can be directly coupled to an ac line input, just like the half-wave rectifier.

Figure 3.25 summarizes the output relationships for the rectifiers we have discussed. Whenever you need to quickly review the relationships listed, you can refer to this illustration. For more detailed information, refer to the appropriate section of this chapter.

SUMMARY ILLUSTRATION

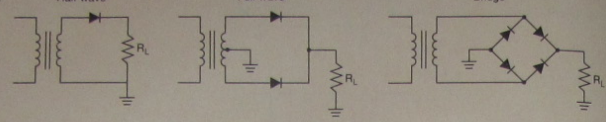
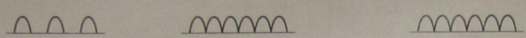
Rectifier type:	Half-wave	Full-wave	Bridge
Schematic diagram:			
Typical output waveform:			
Peak load voltage:	$V_{2(pk)} - 0.7$ V	$\frac{V_{2(pk)}}{2} - 0.7$ V	$V_{2(pk)} - 1.4$ V
dc load voltage:	$\frac{V_{L(pk)}}{\pi}$	$\frac{2V_{L(pk)}}{\pi}$	$\frac{2V_{L(pk)}}{\pi}$
dc load current:	$\frac{V_{ave}}{R_L}$	$\frac{V_{ave}}{R_L}$	$\frac{V_{ave}}{R_L}$
PIV:	Equal to $V_{2(pk)}$	$V_{2(PK)} - 0.7$ V	$V_{2(PK)} - 0.7$ V

FIGURE 3.25

Section Review

1. Describe the operation of the bridge rectifier.
2. List the advantages that the bridge rectifier has over the full-wave rectifier.
3. Describe the method for determining the PIV for a diode in a bridge rectifier.

3.5 WORKING WITH RECTIFIERS

Several practical factors involving rectifiers have been ignored up to this point. Most of these factors explain the differences between *theory* and *practice*.

Effects of Bulk Resistance and Reverse Current on Circuit Measurements

In Chapter 2, we discussed the effects of bulk resistance and reverse current on circuit voltage measurements. In that chapter, the following points were made:

1. The current through the bulk resistance of a diode can affect the actual value of V_F for the device.
2. When a diode is in series with a resistor, reverse current can cause a voltage to be developed across the resistor while the diode is biased *off*.

While the effects of bulk resistance and reverse current are not normally very drastic, they do serve to explain a few things:

1. Rectifiers tend to be very high current circuits. Thus, the effects of $I_F R_B$ on the value of V_F can be fairly significant. Many rectifier diodes will have a value of V_F that is closer to 1 V than to 0.7 V.
2. It is fairly common for *rectifier diodes* (those with high current capabilities) to have high reverse current ratings. For example, the MBR320-360 series of high-power rectifier diodes has a reverse current rating of 20 mA (maximum) at $T = 100°C$. This value of I_R could have a major impact on the operation of a power supply. To keep the amount of reverse current to a minimum, power supplies must be kept as cool as possible.

A Practical Consideration: Forward voltage values in high-current rectifiers are typically as high as 1.4 V.

Many power rectifiers are mounted to a heat sink to keep the diodes cool when used in high-current circuits. The heat sink draws the heat away from the diode, keeping the *pn* junction cooler. There are many configurations for heat sinks, from flat aluminum stock, to those that have elaborate cooling fins. Many times, heat sinks have forced air flowing through and around them to keep them from becoming too hot. Many power diodes, such as the one shown in Figure 3.26, are threaded on one end. This allows the diode to be directly mounted onto a heat sink.

Reverse current is one of the reasons that many power supplies are fan cooled.

Integrated-circuit bridge rectifiers, like the one shown in Figure 3.27, are also designed to be mounted against a heat sink. There is a hole in the middle of the component to allow a mounting bolt to pass through. The bottom of the bridge may be aluminum, which is electrically isolated from all diode junctions and serves as an excellent thermal conductor to transfer the heat. (IC bridge rectifiers are discussed further at the end of this section.)

Transformer Rating Tolerance

The tolerance of a transformer's output rating can have a major effect on circuit voltage measurements. Depending on the quality of the transformer, the output voltage may (at times) be above or below the rated value by as much as 20 percent! This can have a major impact on any voltage measured in the circuit.

Later in this chapter, you will learn about *zener voltage regulators*. As you will be shown, voltage regulators provide varying degrees of **line regulation**; that is, *they are capable (up to a point) of maintaining a constant load voltage despite changes in the rectifier output voltage*. The bottom line here is simple: Voltage regulators make it possible to have a stable dc output voltage despite the variation in output voltage of the components in the rectifier. Thus, transformer rating tolerances may cause a measured rectifier voltage to be off by a considerable margin, but they will have little effect on dc load voltage when a voltage regulator is used. Again, the effect of voltage regulation on the operation of a power supply will be covered in detail later in this chapter.

Line regulation
The ability of a voltage regulator to maintain a stable dc output voltage despite variations in rectifier output voltage.

Power Rectifiers

Many power supplies require the use of rectifier diodes that have extremely high forward current and/or power dissipation ratings. The characteristics of these **power rectifiers** are illustrated in Figure 3.26, which contains the spec sheet for the MUR50 series of power rectifiers.

Power rectifiers
Diodes with extremely high forward current and/or power dissipation ratings.

The spec sheet shown illustrates the primary differences between power rectifiers and small-signal diodes. These differences are as follows:

1. Power rectifiers have extremely high forward current ratings. The MUR50 series diodes are capable of handling an average forward current of up to 50 A!
2. Power rectifiers (as stated earlier) tend to have values of V_F that are greater than 0.7 V. The typical values of V_F for the MUR50 diodes are between 0.8 V and 1.15 V.

Question and Answer: The spec sheet for the MUR50 series calls these components *ultrafast* power rectifiers. Ultrafast rectifiers can be switched on and off at a very high rate of speed. This is required when working with switching power supplies, which switch at a high frequency, typically from 20 to over 100 kHz.

Equation Summary

Equation Number	Equation	Section Number
(3.35)	$I_Z = I_T - I_L$	3.7
(3.36)	$R_{L(\min)} = \dfrac{V_Z}{I_{L(\max)}}$	3.7
(3.37)	$V_{r(\text{out})} = \dfrac{(Z_Z \parallel R_L)}{(Z_Z \parallel R_L) + R_S} V_r$	3.7

Answers to the Example Practice Problems

3.1. $I_2 = 20.83$ mA (maximum)
3.2. $V_{L(\text{pk})} = 17.3\ V_{\text{pk}}$
3.3. $V_{L(\text{pk})} = 33.25\ V_{\text{pk}}$
3.4. $I_{L(\text{pk})} = 2.07\ \text{mA}_{\text{pk}}$
3.5. $V_{\text{ave}} = 4.60\ V_{\text{dc}}$
3.6. $I_{\text{ave}} = 10.91$ mA
3.7. $I_{\text{ave}} = 1.78$ mA
3.8. $V_{2(\text{pk})} = -50.92$ V, $V_{L(\text{pk})} = -50.22\ V_{\text{pk}}$, $V_{\text{ave}} = -15.99\ V_{\text{dc}}$
3.9. $V_{\text{ave}} = 10.36\ V_{\text{dc}}$
3.10. $I_{L(\text{pk})} = 7.4$ mA, $I_{\text{ave}} = 4.71\ \text{mA}_{\text{dc}}$
3.11. $V_{\text{ave}} = 15.32\ V_{\text{dc}}$, $I_{\text{ave}} = 12.77$ mA
3.13. $I_{\text{surge}} = 10$A
3.15. $V_r = 274\ \text{mV}_{\text{pp}}$, $V_{\text{dc}} = 16.14$ V
3.16. $I_T = 2$ mA
3.17. $I_L = 1$ mA
3.18. $I_Z = 1$ mA
3.19. $R_{L(\min)} = 515.2\ \Omega$
3.20. $V_{r(\text{out})} = 236\ \text{mV}_{\text{pp}}$
3.21. $V_{\text{dc}} = 10$ V, $I_L = 1.96$ mA, $V_{r(\text{out})} = 30.73\ \text{mV}_{\text{pp}}$

Practice Problems

§3.1

1. Determine the transformer secondary V_{pk} in Figure 3.50.
2. Determine the transformer secondary V_{rms} in Figure 3.51.
3. If the transformer in Figure 3.57a has 250 mA of current in the primary, what will be the value of the secondary current?
4. What is V_{pk} across the transformer secondary in Figure 3.56 (page 132)?
5. What is the V_{rms} across the transformer secondary in Figure 3.57a (page 132)?
6. If a transformer has 40 V_{pk} across the primary and 320 V_{pk} across the secondary, what is the turns ratio?

§3.2

7. Determine the peak load voltage for the circuit shown in Figure 3.50.
8. Determine the peak load voltage for the circuit shown in Figure 3.51.
9. Determine the peak load voltage for the circuit shown in Figure 3.52.
10. Determine the peak load current for the circuit shown in Figure 3.52.

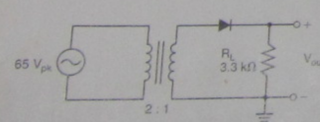


FIGURE 3.50

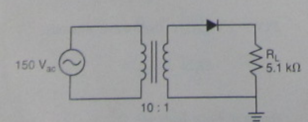


FIGURE 3.51

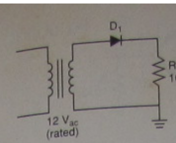


FIGURE 3.52

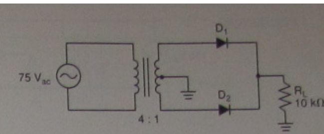


FIGURE 3.53

11. Determine the average (dc) load voltage for the circuit shown in Figure 3.50.
12. Determine the average (dc) load voltage for the circuit shown in Figure 3.51.
13. Determine the average (dc) load voltage for the circuit shown in Figure 3.52.
14. Assume that the diode in Figure 3.50 is reversed. Determine the new values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit.
15. Assume that the diode in Figure 3.51 is reversed. Determine the new values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit.
16. Assume that the diode in Figure 3.52 is reversed. Determine the new values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit.
17. Determine the PIV for the diode in Figure 3.51.
18. A negative half-wave rectifier with a 12 kΩ load is driven by a 20 V_{ac} transformer. Draw the schematic for the circuit and determine the following values: PIV, $V_{L(\text{pk})}$, V_{ave}, and I_{ave}.

§3.3

19. Determine the values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit shown in Figure 3.53.
20. Determine the values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit shown in Figure 3.54.
21. Determine the values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit shown in Figure 3.55.
22. Determine the PIV of the circuit shown in Figure 3.53.
23. Determine the PIV of the circuit shown in Figure 3.54.
24. Determine the PIV of the circuit shown in Figure 3.55.
25. Assume that the diodes in Figure 3.53 are both reversed. Determine the new values of $V_{L(\text{pk})}$, V_{ave}, and I_{ave} for the circuit.
26. A negative full-wave rectifier with a 910 Ω load is driven by a 16 V_{ac} transformer. Draw the schematic diagram of the circuit and determine the following values: $V_{L(\text{pk})}$, PIV, V_{ave}, and I_{ave}.

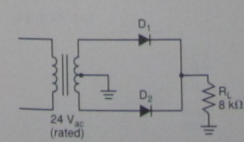


FIGURE 3.54

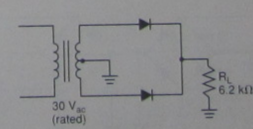
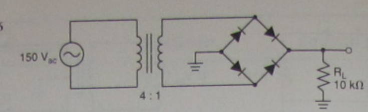


FIGURE 3.55

FIGURE 3.56



§3.4

27. Determine the peak and average output voltage and current values for the circuit shown in Figure 3.56.

28. Repeat Problem 27. Assume that the transformer is a 16 V_{ac} transformer.

29. What is the minimum allowable value of V_{RRM} for each of the diodes in Problem 28?

30. A bridge rectifier with a 1.2 kΩ load is driven by a 48 V_{ac} transformer. Draw the schematic diagram for the circuit and calculate the dc load voltage and current values. Also, determine the PIV for each diode in the circuit.

§3.6

31. The circuit in Figure 3.57a has values of $R_W = 1\ \Omega$ and $R_B = 6\ \Omega$. What is the value of surge current for the circuit?

32. A half-wave rectifier has values of $R_W = 2\Omega$, $R_B = 12\Omega$, and $V_2 = 36\ V_{ac}$. What is the value of surge current for the circuit?

33. What are the values of V_{dc} and V_r for the circuit shown in Figure 3.57a?

34. What are the values of V_{dc} and V_r for the circuit shown in Figure 3.57b?

35. The circuit shown in Figure 3.58 has the following values: $V_2 = 18\ V_{ac}$ (rated), $C = 470\ \mu F$, and $R_L = 820\ \Omega$. Determine the values of V_r, V_{dc}, and I_L for the circuit.

36. The circuit shown in Figure 3.58 has the following values: $V_2 = 24\ V_{ac}$ (rated), $C = 1200\ \mu F$, and $R_L = 200\ \Omega$. Determine the values of V_r, V_{dc}, and I_L for the circuit.

37. What is the PIV for the circuit described in problem 36?

38. What is the PIV for the circuit shown in Figure 3.57a?

FIGURE 3.57

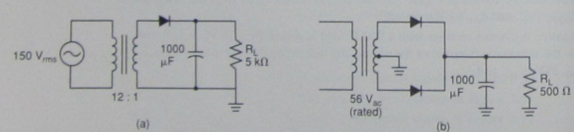


FIGURE 3.58

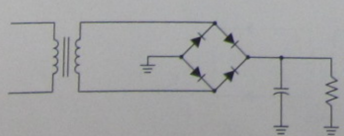


FIGURE 3.59

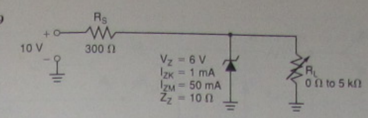
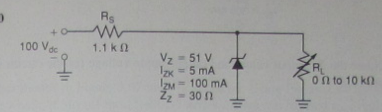


FIGURE 3.60



§3.7

39. For the circuit shown in Figure 3.59, determine the total circuit current.

40. For the circuit shown in Figure 3.59, determine the value of I_L for $R_L = 2\ k\Omega$.

41. For the circuit shown in Figure 3.59, determine the value of I_Z for $R_L = 2\ k\Omega$.

42. For the circuit shown in Figure 3.59, determine the value of I_Z for $R_L = 3\ k\Omega$.

43. For the circuit shown in Figure 3.59, determine the minimum allowable value of R_L.

44. For the circuit shown in Figure 3.60, determine the total circuit current.

45. For the circuit shown in Figure 3.60, determine the value of I_Z for $R_L = 5\ k\Omega$.

46. For the circuit shown in Figure 3.60, determine the minimum allowable value of R_L.

47. Determine the values of I_T, I_L, and I_Z for the circuit shown in Figure 3.61.

48. The 12-V input to Figure 3.61 has 770 mV_{pp} of ripple voltage. What is the output ripple voltage for the circuit?

§3.8

49. Calculate the dc output voltage and current values for the circuit shown in Figure 3.62.

50. Calculate the output ripple voltage for the circuit shown in Figure 3.62.

FIGURE 3.61

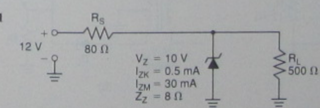


FIGURE 3.62