(b) Ideal model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{10\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Practical model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{10\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Complete model:

$$I_R = \mathbf{1\ \mu A}$$
$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu A)(1.0\ k\Omega) = \mathbf{1\ mV}$$
$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 10\ V - 1\ mV = \mathbf{9.999\ V}$$

*Related Problem** Assume that the diode in Figure 2–18(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

***Answers can be found at www.pearsonhighered.com/floyd.**

Open the Multisim file E02-01 in the Examples folder on the companion website. Measure the voltages across the diode and the resistor in both circuits and compare with the calculated results in this example.

SECTION 2–3 CHECKUP

1. What are the two conditions under which a diode is operated?
2. Under what condition is a diode never intentionally operated?
3. What is the simplest way to visualize a diode?
4. To more accurately represent a diode, what factors must be included?
5. Which diode model represents the most accurate approximation?

2–4 HALF-WAVE RECTIFIERS

Because of their ability to conduct current in one direction and block current in the other direction, diodes are used in circuits called rectifiers that convert ac voltage into dc voltage. Rectifiers are found in all dc power supplies that operate from an ac voltage source. A power supply is an essential part of each electronic system from the simplest to the most complex.

After completing this section, you should be able to

- **Explain and analyze the operation of half-wave rectifiers**
- Describe a basic dc power supply
- Discuss half-wave rectification
  - Determine the average value of a half-wave voltage
- Explain how the barrier potential affects a half-wave rectifier output
  - Calculate the output voltage
- Define *peak inverse voltage*
- Explain the operation of a transformer-coupled rectifier

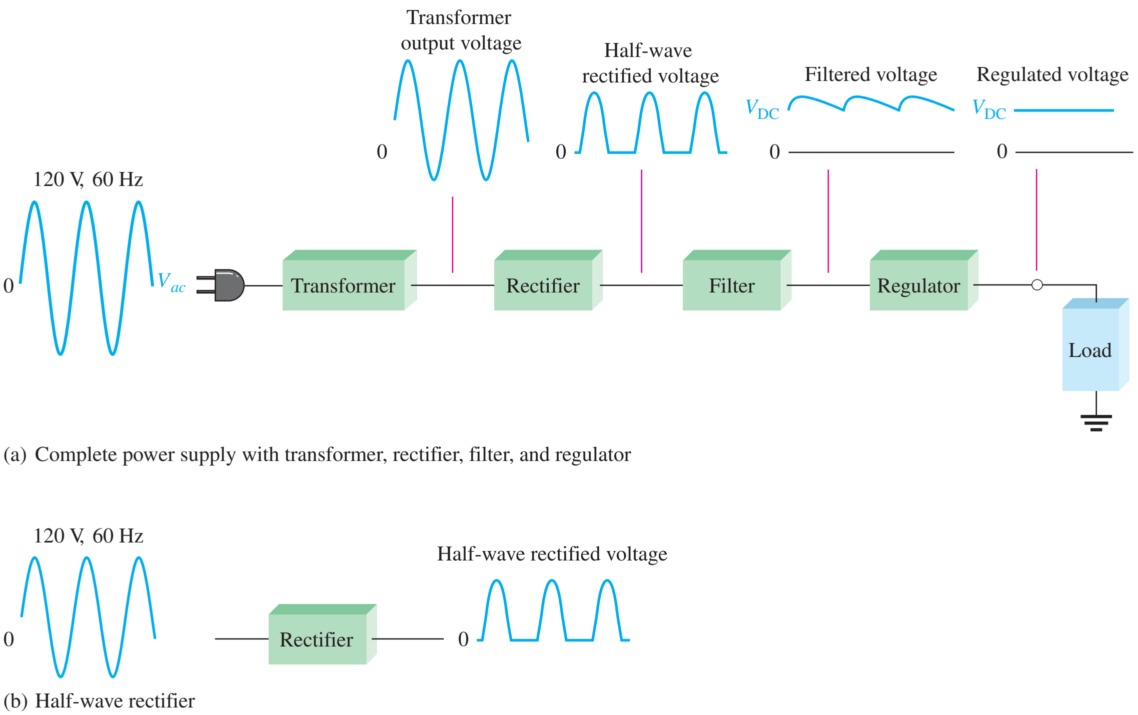
The Basic DC Power Supply

All active electronic devices require a source of constant dc that can be supplied by a battery or a dc power supply. The **dc power supply** converts the standard 120 V, 60 Hz ac voltage available at wall outlets into a constant dc voltage. The dc power supply is one of the most common circuits you will find, so it is important to understand how it works. The voltage produced is used to power all types of electronic circuits including consumer electronics (televisions, DVDs, etc.), computers, industrial controllers, and most laboratory instrumentation systems and equipment. The dc voltage level required depends on the application, but most applications require relatively low voltages.

A basic block diagram of the complete power supply is shown in Figure 2–19(a). Generally the ac input line voltage is stepped down to a lower ac voltage with a transformer (although it may be stepped up when higher voltages are needed or there may be no transformer at all in rare instances). As you learned in your dc/ac course, a **transformer** changes ac voltages based on the turns ratio between the primary and secondary. If the secondary has more turns than the primary, the output voltage across the secondary will be higher and the current will be smaller. If the secondary has fewer turns than the primary, the output voltage across the secondary will be lower and the current will be higher. The rectifier can be either a half-wave rectifier or a full-wave rectifier (covered in Section 2–5). The **rectifier** converts the ac input voltage to a pulsating dc voltage, called a half-wave rectified voltage, as shown in Figure 2–19(b). The **filter** eliminates the fluctuations in the rectified voltage and produces a relatively smooth dc voltage. The power supply filter is covered in Section 2–6. The **regulator** is a circuit that maintains a constant dc voltage for variations in the input line voltage or in the load. Regulators vary from a single semiconductor device to more complex integrated circuits. The load is a circuit or device connected to the output of the power supply and operates from the power supply voltage and current.

FYI

The standard line voltage in North America is 120 V/240 V at 60 Hz. Most small appliances operate on 120 V and larger appliances such as dryers, ranges, and heaters operate on 240 V. Occasionally, you will see references to 110 V or 115 V, but the standard is 120 V. Some foreign countries do use 110 V or 115 V at either 60 Hz or 50 Hz.



▲ **FIGURE 2–19**

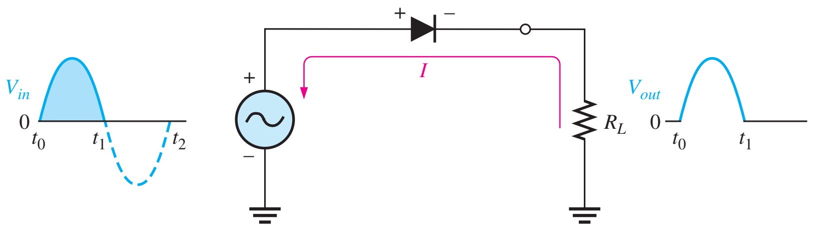
Block diagram of a dc power supply with a load and a rectifier.

GREENTECH NOTE

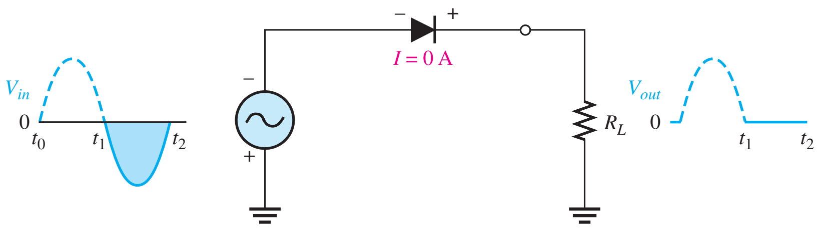
The *Energy Star* program was originally established by the EPA as a voluntary labeling program designed to indicate energy-efficient products. In order for power supplies to comply with the Energy Star requirements, they must have a minimum 80% efficiency rating for all rated power output. Try to choose a power supply that carries as 80 PLUS logo on it. This means that the power supply efficiency has been tested and approved to meet the Energy Star guidelines. Not all power supplies that claim to be high efficiency meet the Energy Star requirements.

Half-Wave Rectifier Operation

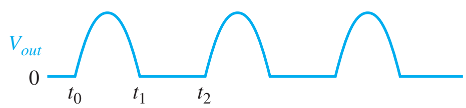
Figure 2–20 illustrates the process called *half-wave rectification.* A diode is connected to an ac source and to a load resistor, R_L, forming a **half-wave rectifier**. Keep in mind that all ground symbols represent the same point electrically. Let's examine what happens during one cycle of the input voltage using the ideal model for the diode. When the sinusoidal input voltage (V_{in}) goes positive, the diode is forward-biased and conducts current through the load resistor, as shown in part (a). The current produces an output voltage across the load R_L, which has the same shape as the positive half-cycle of the input voltage.



(a) During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source.



(b) During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.



(c) 60 Hz half-wave output voltage for three input cycles

▲ **FIGURE 2–20**

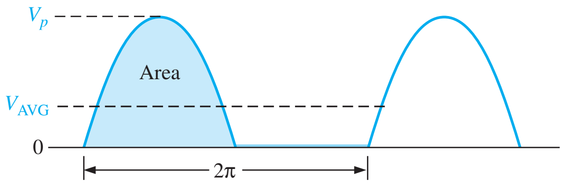
Half-wave rectifier operation. The diode is considered to be ideal.

When the input voltage goes negative during the second half of its cycle, the diode is reverse-biased. There is no current, so the voltage across the load resistor is 0 V, as shown in Figure 2–20(b). The net result is that only the positive half-cycles of the ac input voltage appear across the load. Since the output does not change polarity, it is a pulsating dc voltage with a frequency of 60 Hz, as shown in part (c).

Average Value of the Half-Wave Output Voltage The average value of the half-wave rectified output voltage is the value you would measure on a dc voltmeter. Mathematically, it is determined by finding the area under the curve over a full cycle, as illustrated in Figure 2–21, and then dividing by 2π, the number of radians in a full cycle. The result of this is expressed in Equation 2–3, where V_p is the peak value of the voltage. This equation shows that V_{AVG} is approximately 31.8% of V_p for a half-wave rectified voltage. The derivation for this equation can be found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd.

Equation 2–3

$$V_{AVG} = \frac{V_p}{\pi}$$

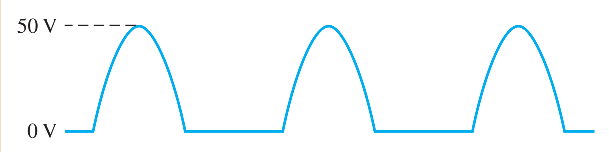


◀ FIGURE 2–21

Average value of the half-wave rectified signal.

EXAMPLE 2–2 What is the average value of the half-wave rectified voltage in Figure 2–22?

▶ FIGURE 2–22



Solution

$$V_{AVG} = \frac{V_p}{\pi} = \frac{50\text{ V}}{\pi} = \mathbf{15.9\text{ V}}$$

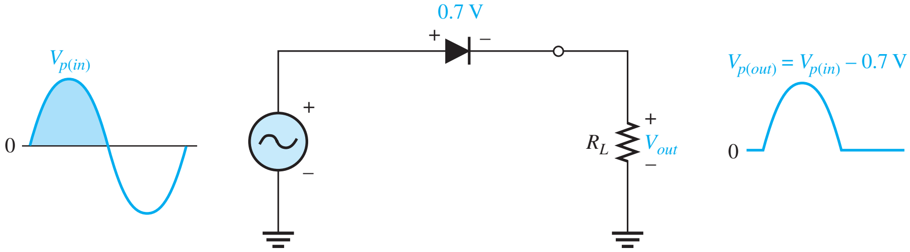
Notice that V_{AVG} is 31.8% of V_p.

Related Problem Determine the average value of the half-wave voltage if its peak amplitude is 12 V.

Effect of the Barrier Potential on the Half-Wave Rectifier Output

In the previous discussion, the diode was considered ideal. When the practical diode model is used with the barrier potential of 0.7 V taken into account, this is what happens. During the positive half-cycle, the input voltage must overcome the barrier potential before the diode becomes forward-biased. This results in a half-wave output with a peak value that is 0.7 V less than the peak value of the input, as shown in Figure 2–23. The expression for the peak output voltage is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V}$$ Equation 2–4



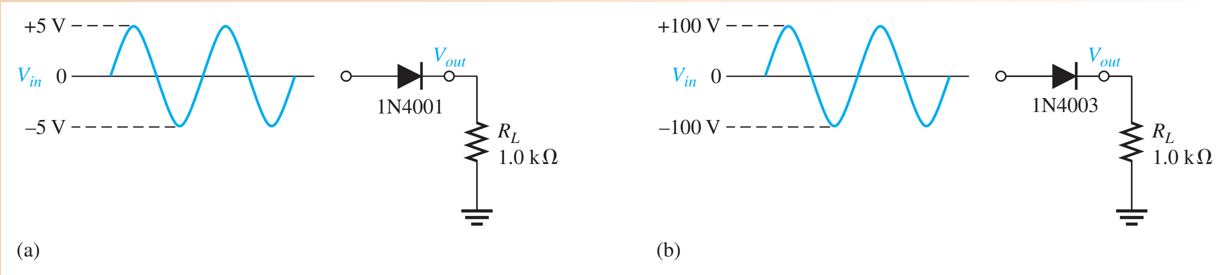
▲ FIGURE 2–23

The effect of the barrier potential on the half-wave rectified output voltage is to reduce the peak value of the input by about 0.7 V.

It is usually acceptable to use the ideal diode model, which neglects the effect of the barrier potential, when the peak value of the applied voltage is much greater than the barrier potential (at least 10 V, as a rule of thumb). However, we will use the practical model of a diode, taking the 0.7 V barrier potential into account unless stated otherwise.

EXAMPLE 2–3

Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2–24. The 1N4001 and 1N4003 are specific rectifier diodes.



▲ FIGURE 2–24

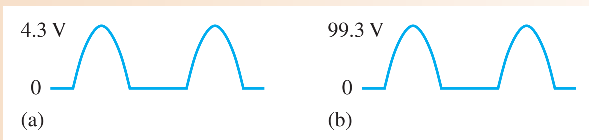
Solution The peak output voltage for circuit (a) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 5\text{ V} - 0.7\text{ V} = \mathbf{4.30\text{ V}}$$

The peak output voltage for circuit (b) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 100\text{ V} - 0.7\text{ V} = \mathbf{99.3\text{ V}}$$

The output voltage waveforms are shown in Figure 2–25. Note that the barrier potential could have been neglected in circuit (b) with very little error (0.7 percent); but, if it is neglected in circuit (a), a significant error results (14 percent).



▲ FIGURE 2–25

Output voltages for the circuits in Figure 2–24. They are not shown on the same scale.

Related Problem Determine the peak output voltages for the rectifiers in Figure 2–24 if the peak input in part (a) is 3 V and the peak input in part (b) is 50 V.

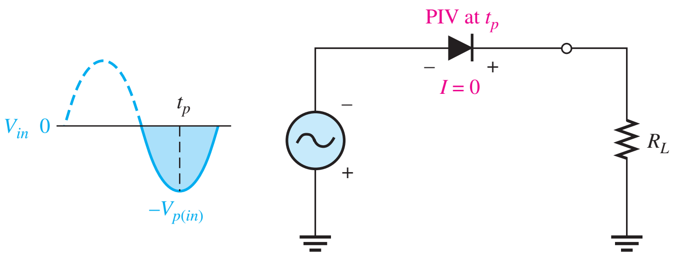
Open the Multisim file E02-03 in the Examples folder on the companion website. For the inputs specified in the example, measure the resulting output voltage waveforms. Compare your measured results with those shown in the example.

Peak Inverse Voltage (PIV)

The **peak inverse voltage (PIV)** equals the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage. For the diode in Figure 2–26, the maximum value of reverse voltage, designated as PIV, occurs at the peak of each negative alternation of the input voltage when the diode is reverse-biased. A diode should be rated at least 20% higher than the PIV.

Equation 2–5

$$\mathbf{PIV} = V_{p(in)}$$

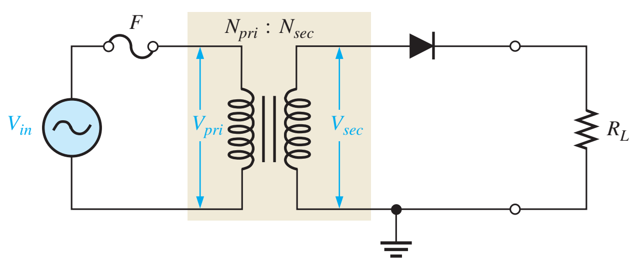


▲ FIGURE 2–26

The PIV occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased. In this circuit, the PIV occurs at the peak of each negative half-cycle.

Transformer Coupling

As you have seen, a transformer is often used to couple the ac input voltage from the source to the rectifier, as shown in Figure 2–27. Transformer coupling provides two advantages. First, it allows the source voltage to be stepped down as needed. Second, the ac source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.



◄ FIGURE 2–27

Half-wave rectifier with transformer-coupled input voltage.

The amount that the voltage is stepped down is determined by the **turns ratio** of the transformer. Unfortunately, the definition of turns ratio for transformers is not consistent between various sources and disciplines. In this text, we use the definition given by the IEEE for electronic power transformers, which is "the number of turns in the secondary (N_{sec}) divided by the number of turns in the primary (N_{pri})." Thus, a transformer with a turns ratio less than 1 is a step-down type and one with a turns ratio greater than 1 is a step-up type. To show the turns ratio on a schematic, it is common practice to show the numerical ratio directly above the windings.

The secondary voltage of a transformer equals the turns ratio, n, times the primary voltage.

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

If $n > 1$, the secondary voltage is greater than the primary voltage. If $n < 1$, the secondary voltage is less than the primary voltage. If $n = 1$, then $V_{sec} = V_{pri}$.

The peak secondary voltage, $V_{p(sec)}$, in a transformer-coupled half-wave rectifier is the same as $V_{p(in)}$ in Equation 2–4. Therefore, Equation 2–4 written in terms of $V_{p(sec)}$ is

$$V_{p(out)} = V_{p(sec)} - 0.7\text{ V}$$

and Equation 2–5 in terms of $V_{p(sec)}$ is

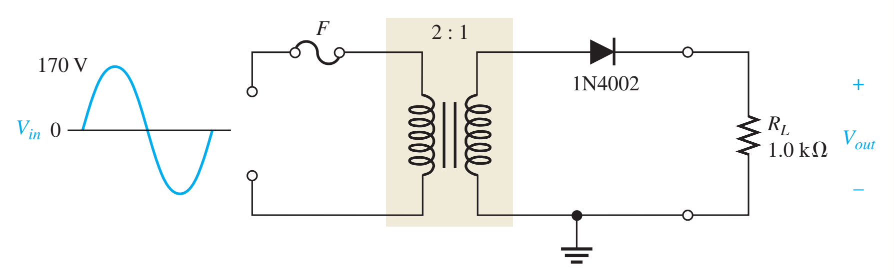
$$\text{PIV} = V_{p(sec)}$$

Turns ratio is useful for understanding the voltage transfer from primary to secondary. However, transformer datasheets rarely show the turns ratio. A transformer is generally specified based on the secondary voltage rather than the turns ratio.

EXAMPLE 2–4

Determine the peak value of the output voltage for Figure 2–28 if the turns ratio is 0.5.

▶ FIGURE 2–28



Solution

$$V_{p(pri)} = V_{p(in)} = 170\text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.5(170\text{ V}) = 85\text{ V}$$

The rectified peak output voltage is

$$V_{p(out)} = V_{p(sec)} - 0.7\text{ V} = 85\text{ V} - 0.7\text{ V} = \mathbf{84.3\text{ V}}$$

where $V_{p(sec)}$ is the input to the rectifier.

Related Problem

(a) Determine the peak value of the output voltage for Figure 2–28 if $n = 2$ and $V_{p(in)} = 312$ V.
(b) What is the PIV across the diode?
(c) Describe the output voltage if the diode is turned around.

Open the Multisim file E02-04 in the Examples folder on the companion website. For the specified input, measure the peak output voltage. Compare your measured result with the calculated value.

SECTION 2–4 CHECKUP

1. At what point on the input cycle does the PIV occur?
2. For a half-wave rectifier, there is current through the load for approximately what percentage of the input cycle?
3. What is the average of a half-wave rectified voltage with a peak value of 10 V?
4. What is the peak value of the output voltage of a half-wave rectifier with a peak sine wave input of 25 V?
5. What PIV rating must a diode have to be used in a rectifier with a peak output voltage of 50 V?

2–5 FULL-WAVE RECTIFIERS

Although half-wave rectifiers have some applications, the full-wave rectifier is the most commonly used type in dc power supplies. In this section, you will use what you learned about half-wave rectification and expand it to full-wave rectifiers. You will learn about two types of full-wave rectifiers: center-tapped and bridge.