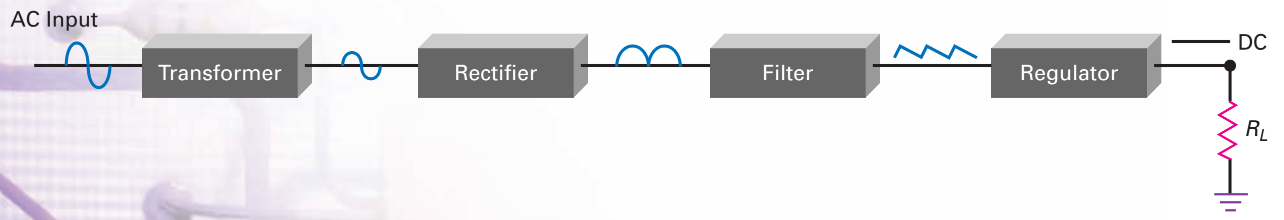
chapter

# 4

# Diode Circuits

Most electronic systems, like HDTVs, audio power amplifiers, and computers, need a dc voltage to work properly. Since the power-line voltage is alternating and normally too high of a value, we need to reduce the ac line voltage and then convert it to a relatively constant dc output voltage. The section of the electronic system that produces this dc voltage is called the power supply. Within the power supply are circuits that allow current to flow in only one direction. These circuits are called rectifiers. Other circuits will filter and regulate the dc output. This chapter discusses rectifier circuits, filters, an introduction to voltage regulators, clippers, clampers, and voltage multipliers.



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## Objectives

*After studying this chapter, you should be able to:*

- Draw a diagram of a half-wave rectifier and explain how it works.
- Describe the role of the input transformer in power supplies.
- Draw a diagram of a full-wave rectifier and explain how it works.
- Draw a diagram of a bridge rectifier and explain how it works.
- Analyze a capacitor input filter and its surge current.
- List three important specifications found on a rectifier data sheet.
- Explain how a clipper works and draw waveforms.
- Explain how a clamper works and draw waveforms.
- Describe the action of voltage multipliers.

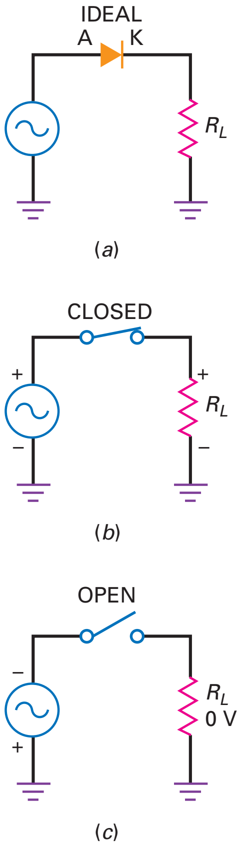
## Chapter Outline

**4-1** The Half-Wave Rectifier
**4-2** The Transformer
**4-3** The Full-Wave Rectifier
**4-4** The Bridge Rectifier
**4-5** The Choke-Input Filter
**4-6** The Capacitor-Input Filter
**4-7** Peak Inverse Voltage and Surge Current
**4-8** Other Power-Supply Topics
**4-9** Troubleshooting
**4-10** Clippers and Limiters
**4-11** Clampers
**4-12** Voltage Multipliers

## Vocabulary

bridge rectifier
capacitor-input filter
choke-input filter
clamper
clipper
dc value of a signal
filter
full-wave rectifier
half-wave rectifier
IC voltage regulator
integrated circuit
passive filter
peak detector
peak inverse voltage
polarized capacitor
power supply
rectifiers
ripple
surge current
surge resistor
switching regulator
unidirectional load current
voltage multiplier

**Figure 4-1** (*a*) Ideal half-wave rectifier; (*b*) on positive half-cycle; (*c*) on negative half-cycle.



# 4-1 The Half-Wave Rectifier

Figure 4-1*a* shows a **half-wave rectifier** circuit. The ac source produces a sinusoidal voltage. Assuming an ideal diode, the positive half-cycle of source voltage will forward-bias the diode. Since the switch is closed, as shown in Fig. 4-1*b*, the positive half-cycle of source voltage will appear across the load resistor. On the negative half-cycle, the diode is reverse biased. In this case, the ideal diode will appear as an open switch, as shown in Fig. 4-1*c*, and no voltage appears across the load resistor.

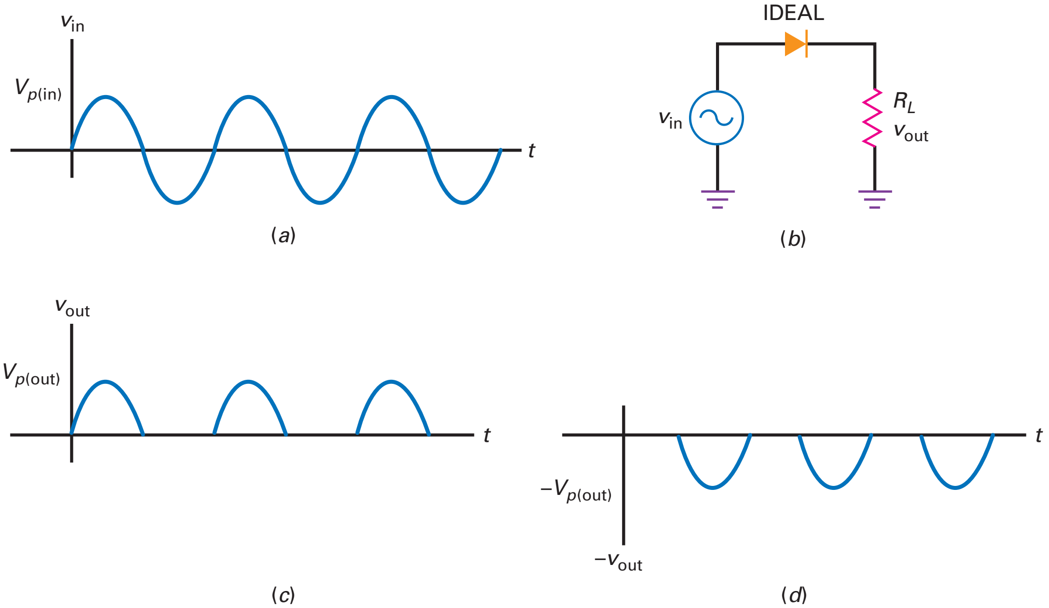
## Ideal Waveforms

Figure 4-2*a* shows a graphical representation of the input voltage waveform. It is a sine wave with an instantaneous value of $v_{\text{in}}$ and a peak value of $V_{p(\text{in})}$. A pure sinusoid like this has an average value of zero over one cycle because each instantaneous voltage has an equal and opposite voltage half a cycle later. If you measure this voltage with a dc voltmeter, you will get a reading of zero because a dc voltmeter indicates the average value.

In the half-wave rectifier of Fig. 4-2*b*, the diode is conducting during the positive half-cycles but is nonconducting during the negative half-cycles. Because of this, the circuit clips off the negative half-cycles, as shown in Fig. 4-2*c*. We call a waveform like this a *half-wave signal.* This half-wave voltage produces a **unidirectional load current.** This means that it flows in only one direction. If the diode were reversed, it would become forward biased when the input voltage was negative. As a result, the output pulses would be negative. This is shown in Fig. 4-2*d*. Notice how the negative peaks are offset from the positive peaks and follow the negative alternations of the input voltage.

A half-wave signal like the one in Fig. 4-2*c* is a pulsating dc voltage that increases to a maximum, decreases to zero, and then remains at zero during the negative half-cycle. This is not the kind of dc voltage we need for electronics equipment. What we need is a constant voltage, the same as you get from a

**Figure 4-2** (*a*) Input to half-wave rectifier; (*b*) circuit; (*c*) output of positive half-wave rectifier; (*d*) output of negative half-wave rectifier.



### GOOD TO KNOW

The rms value of a half-wave signal can be determined with the following formula:

$$V_{\text{rms}} = 1.57\ V_{\text{avg}}$$

where $V_{\text{avg}} = V_{\text{dc}} = 0.318V_p$

Another formula that works is:

$$V_{\text{rms}} = \frac{V_p}{\sqrt{2}}$$

For any waveform, the rms value corresponds to the equivalent dc value that will produce the same heating effect.

battery. To get this kind of voltage, we need to **filter** the half-wave signal (discussed later in this chapter).

When you are troubleshooting, you can use the ideal diode to analyze a half-wave rectifier. It's useful to remember that the peak output voltage equals the peak input voltage:

$$\textbf{Ideal half wave: } V_{p(\text{out})} = V_{p(\text{in})} \qquad \textbf{(4-1)}$$

## DC Value of Half-Wave Signal

The **dc value of a signal** is the same as the average value. If you measure a signal with a dc voltmeter, the reading will equal the average value. In basic courses, the dc value of a half-wave signal is derived. The formula is:

$$\textbf{Half wave: } V_{\text{dc}} = \frac{V_p}{\pi} \qquad \textbf{(4-2)}$$

The proof of this derivation requires calculus because we have to work out the average value over one cycle.

Since $1/\pi \approx 0.318$, you may see Eq. (4-2) written as:

$$V_{\text{dc}} \approx 0.318V_p$$

When the equation is written in this form, you can see that the dc or average value equals 31.8 percent of the peak value. For instance, if the peak voltage of the half-wave signal is 100 V, the dc voltage or average value is 31.8 V.

## Output Frequency

The output frequency is the same as the input frequency. This makes sense when you compare Fig. 4-2*c* with Fig. 4-2*a*. Each cycle of input voltage produces one cycle of output voltage. Therefore, we can write:

$$\textbf{Half wave: } f_{\text{out}} = f_{\text{in}} \qquad \textbf{(4-3)}$$

We will use this derivation later with filters.

## Second Approximation

We don't get a perfect half-wave voltage across the load resistor. Because of the barrier potential, the diode does not turn on until the ac source voltage reaches approximately 0.7 V. When the peak source voltage is much greater than 0.7 V, the load voltage will resemble a half-wave signal. For instance, if the peak source voltage is 100 V, the load voltage will be close to a perfect half-wave voltage. If the peak source voltage is only 5 V, the load voltage will have a peak of only 4.3 V. When you need to get a better answer, use this derivation:

$$\textbf{2d half wave: } V_{p(\text{out})} = V_{p(\text{in})} - 0.7\text{ V} \qquad \textbf{(4-4)}$$

## Higher Approximations

Most designers will make sure that the bulk resistance is much smaller than the Thevenin resistance facing the diode. Because of this, we can ignore bulk resistance in almost every case. If you must have better accuracy than you can get with the second approximation, you should use a computer and a circuit simulator like Multisim.

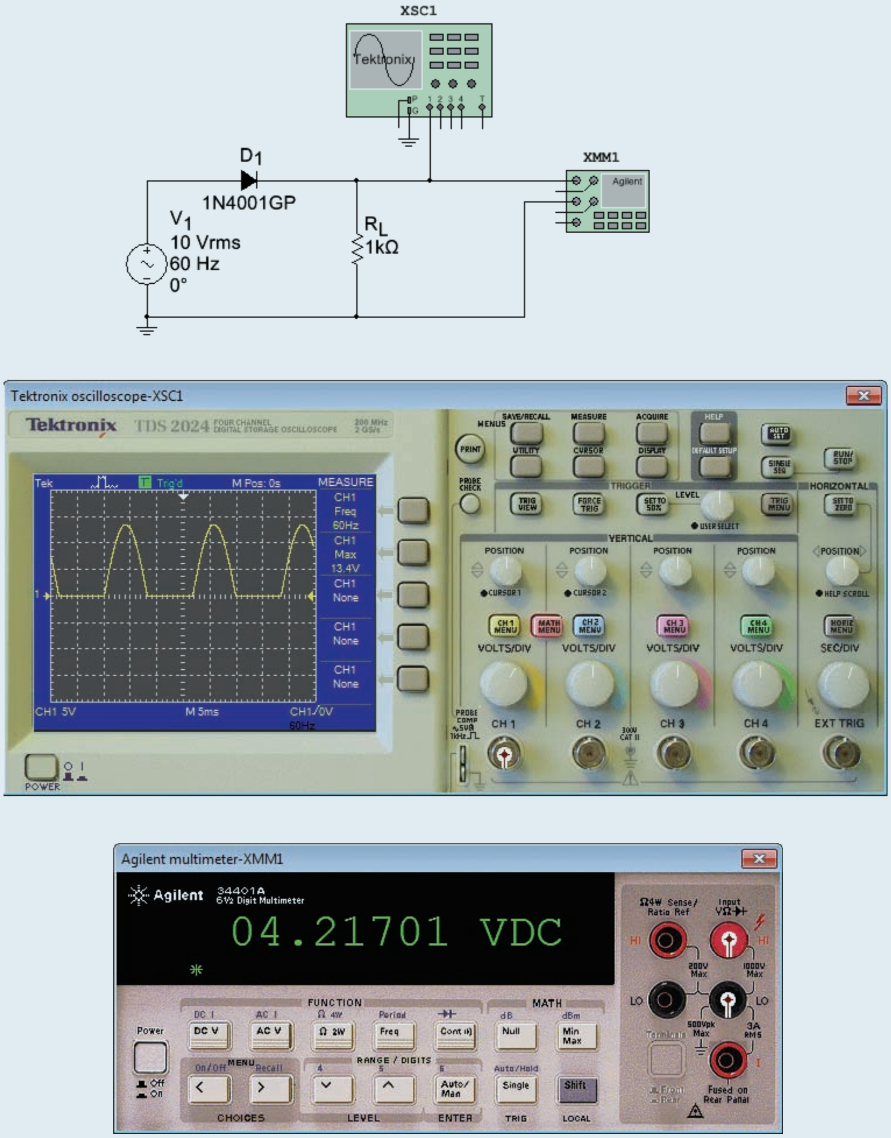
## Application Example 4-1

Multisim

Figure 4-3 shows a half-wave rectifier that you can build on the lab bench or on a computer screen with Multisim. An oscilloscope is across the 1 kΩ. Set the oscilloscope's vertical input coupling switch or setting to dc. This will show us the half-wave load voltage. Also, a multimeter is across the 1 kΩ to read the dc load voltage. Calculate the theoretical values of peak load voltage and the dc load voltage. Then, compare these values to the readings on the oscilloscope and the multimeter.

**SOLUTION** Figure 4-3 shows an ac source of 10 V and 60 Hz. Schematic diagrams usually show ac source voltages as effective or rms values. Recall that the *effective value* is the value of a dc voltage that produces the same heating effect as the ac voltage.

**Figure 4-3** Lab example of half-wave rectifier.



Tek Trig'd M Pos: 0s MEASURE
CH1 Freq 60Hz
CH1 Max 13.4V
CH1 None
CH1 None
CH1 None
CH1 5V M 5ms CH1 / 0V 60Hz

04.21701 VDC

Since the source voltage is 10 $\mathrm{V_{rms}}$, the first thing to do is calculate the peak value of the ac source. You know from earlier courses that the rms value of a sine wave equals:

$$V_{\text{rms}} = 0.707V_p$$

Therefore, the peak source voltage in Fig. 4-3 is:

$$V_p = \frac{V_{\text{rms}}}{0.707} = \frac{10\text{ V}}{0.707} = 14.1\text{ V}$$

With an ideal diode, the peak load voltage is:

$$V_{p(\text{out})} = V_{p(\text{in})} = 14.1\text{ V}$$

The dc load voltage is:

$$V_{\text{dc}} = \frac{V_p}{\pi} = \frac{14.1\text{ V}}{\pi} = 4.49\text{ V}$$

With the second approximation, we get a peak load voltage of:

$$V_{p(\text{out})} = V_{p(\text{in})} - 0.7\text{ V} = 14.1\text{ V} - 0.7\text{ V} = 13.4\text{ V}$$

and a dc load voltage of:

$$V_{\text{dc}} = \frac{V_p}{\pi} = \frac{13.4\text{ V}}{\pi} = 4.27\text{ V}$$

Figure 4-3 shows you the values that an oscilloscope and a multimeter will read. Channel 1 of the oscilloscope is set at 5 V per major division (5 V/Div). The half-wave signal has a peak value between 13 and 14 V, which agrees with the result from our second approximation. The multimeter also gives good agreement with theoretical values because it reads approximately 4.22 V.

**PRACTICE PROBLEM 4-1** Using Fig. 4-3, change the ac source voltage to 15 V. Calculate the second approximation dc load voltage $V_{dc}$.

## 4-2 The Transformer

Power companies in the United States supply a nominal line voltage of 120 $\mathrm{V_{rms}}$ and a frequency of 60 Hz. The actual voltage coming out of a power outlet may vary from 105 to 125 $\mathrm{V_{rms}}$, depending on the time of day, the locality, and other factors. Line voltage is too high for most of the circuits used in electronics equipment. This is why a transformer is commonly used in the power-supply section of almost all electronics equipment. The transformer steps the line voltage down to safer and lower levels that are more suitable for use with diodes, transistors, and other semiconductor devices.

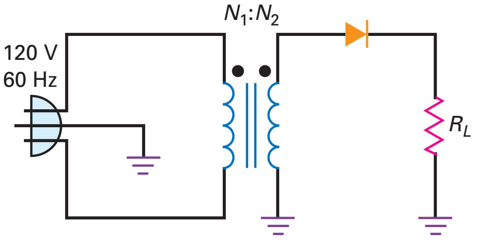
### Basic Idea

Earlier courses discussed the transformer in detail. All we need in this chapter is a brief review. Figure 4-4 shows a transformer. Here, you see line voltage applied to the primary winding of a transformer. Usually, the power plug has a third prong to ground the equipment. Because of the turns ratio $N_1/N_2$, the secondary voltage is stepped down when $N_1$ is greater than $N_2$.

### Phasing Dots

Recall the meaning of the phasing dots shown at the upper ends of the windings. Dotted ends have the same instantaneous phase. In other words, when a positive half-cycle appears across the primary, a positive half-cycle appears across the

**Figure 4-4** Half-wave rectifier with transformer.



secondary. If the secondary dot were on the ground end, the secondary voltage would be 180° out of phase with the primary voltage.

On the positive half-cycle of primary voltage, the secondary winding has a positive half sine wave across it and the diode is forward biased. On the negative half-cycle of primary voltage, the secondary winding has a negative half-cycle and the diode is reverse biased. Assuming an ideal diode, we will get a half-wave load voltage.

## Turns Ratio

Recall from your earlier course work the following derivation:

$$\boldsymbol{V_2 = \frac{V_1}{N_1/N_2}} \tag{4-5}$$

This says that the secondary voltage equals the primary voltage divided by the turns ratio. Sometimes you will see this equivalent form:

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

This says that the secondary voltage equals the inverse turns ratio times the primary voltage.

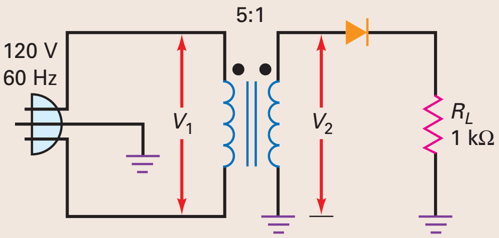
You can use either formula for rms, peak values, and instantaneous voltages. Most of the time, we will use Eq. (4-5) with rms values because ac source voltages are almost always specified as rms values.

The terms *step up* and *step down* are also encountered when dealing with transformers. These terms always relate the secondary voltage to the primary voltage. This means that a step-up transformer will produce a secondary voltage that is larger than the primary, and a step-down transformer will produce a secondary voltage that is smaller than the primary.

## Example 4-2

What are the peak load voltage and dc load voltage in Fig. 4-5?

**Figure 4-5** Transformer example.



**SOLUTION** The transformer has a turns ratio of 5 : 1. This means that the rms secondary voltage is one-fifth of the primary voltage:

$$V_2 = \frac{120\text{ V}}{5} = 24\text{ V}$$

and the peak secondary voltage is:

$$V_p = \frac{24\text{ V}}{0.707} = 34\text{ V}$$

With an ideal diode, the peak load voltage is:

$$V_{p(\text{out})} = 34\text{ V}$$

The dc load voltage is:

$$V_{\text{dc}} = \frac{V_p}{\pi} = \frac{34\text{ V}}{\pi} = 10.8\text{ V}$$

With the second approximation, the peak load voltage is:

$$V_{p(\text{out})} = 34\text{ V} - 0.7\text{ V} = 33.3\text{ V}$$

and the dc load voltage is:

$$V_{\text{dc}} = \frac{V_p}{\pi} = \frac{33.3\text{ V}}{\pi} = 10.6\text{ V}$$

**PRACTICE PROBLEM 4-2** Using Fig. 4-5, change the transformer's turns ratio to 2 : 1 and solve for the ideal dc load voltage.

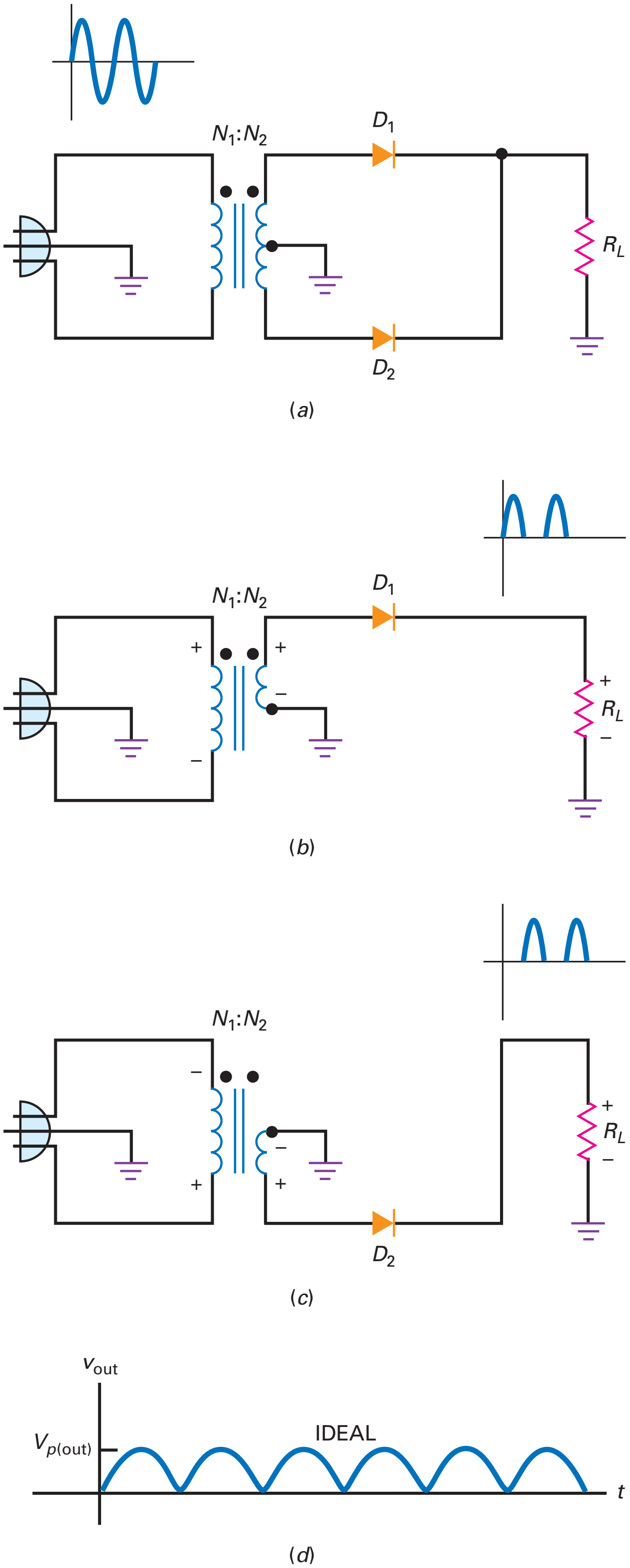
## 4-3 The Full-Wave Rectifier

Figure 4-6*a* shows a **full-wave rectifier** circuit. Notice the grounded center tap on the secondary winding. The full-wave rectifier is equivalent to two half-wave rectifiers. Because of the center tap, each of these rectifiers has an input voltage equal to half the secondary voltage. Diode $D_1$ conducts on the positive half-cycle, and diode $D_2$ conducts on the negative half-cycle. As a result, the rectified load current flows during both half-cycles. The full-wave rectifier acts the same as two back-to-back half-wave rectifiers.

Figure 4-6*b* shows the equivalent circuit for the positive half-cycle. As you see, $D_1$ is forward biased. This produces a positive load voltage as indicated by the plus-minus polarity across the load resistor. Figure 4-6*c* shows the equivalent circuit for the negative half-cycle. This time, $D_2$ is forward biased. As you can see, this also produces a positive load voltage.

During both half-cycles, the load voltage has the same polarity and the load current is in the same direction. The circuit is called a *full-wave rectifier* because it has changed the ac input voltage to the pulsating dc output voltage shown in Fig. 4-6*d*. This waveform has some interesting properties that we will now discuss.

**Figure 4-6** (*a*) Full-wave rectifier; (*b*) equivalent circuit for positive half-cycle; (*c*) equivalent circuit for negative half-cycle; (*d*) full-wave output.



## GOOD TO KNOW

The rms value of a full-wave signal is $V_{\text{rms}} = 0.707V_p$, which is the same as $V_{\text{rms}}$ for a full sine wave.

## DC or Average Value

Since the full-wave signal has twice as many positive cycles as the half-wave signal, the dc or average value is twice as much, given by:

$$\textbf{Full wave: } V_{\text{dc}} = \frac{2V_p}{\pi} \qquad \textbf{(4-6)}$$

Since $2/\pi = 0.636$, you may see Eq. (4-6) written as:

$$V_{\text{dc}} \approx 0.636V_p$$

In this form, you can see that the dc or average value equals 63.6 percent of the peak value. For instance, if the peak voltage of the full-wave signal is 100 V, the dc voltage or average value is 63.6 V.

## Output Frequency

With a half-wave rectifier, the output frequency equals the input frequency. But with a full-wave rectifier, something unusual happens to the output frequency. The ac line voltage has a frequency of 60 Hz. Therefore, the input period equals:

$$T_{\text{in}} = \frac{1}{f} = \frac{1}{60\text{ Hz}} = 16.7\text{ ms}$$

Because of the full-wave rectification, the period of the full-wave signal is half the input period:

$$T_{\text{out}} = 0.5(16.7\text{ ms}) = 8.33\text{ ms}$$

(If there is any doubt in your mind, compare Fig. 4-6*d* to Fig. 4-2*c*.) When we calculate the output frequency, we get:

$$f_{\text{out}} = \frac{1}{T_{\text{out}}} = \frac{1}{8.33\text{ ms}} = 120\text{ Hz}$$

The frequency of the full-wave signal is double the input frequency. This makes sense. A full-wave output has twice as many cycles as the sine-wave input has. The full-wave rectifier inverts each negative half-cycle so that we get double the number of positive half-cycles. The effect is to double the frequency. As a derivation:

$$\textbf{Full wave: } f_{\text{out}} = 2f_{\text{in}} \qquad \textbf{(4-7)}$$

## Second Approximation

Since the full-wave rectifier is like two back-to-back half-wave rectifiers, we can use the second approximation given earlier. The idea is to subtract 0.7 V from the ideal peak output voltage. The following example will illustrate the idea.

## Application Example 4-3

**Multisim**

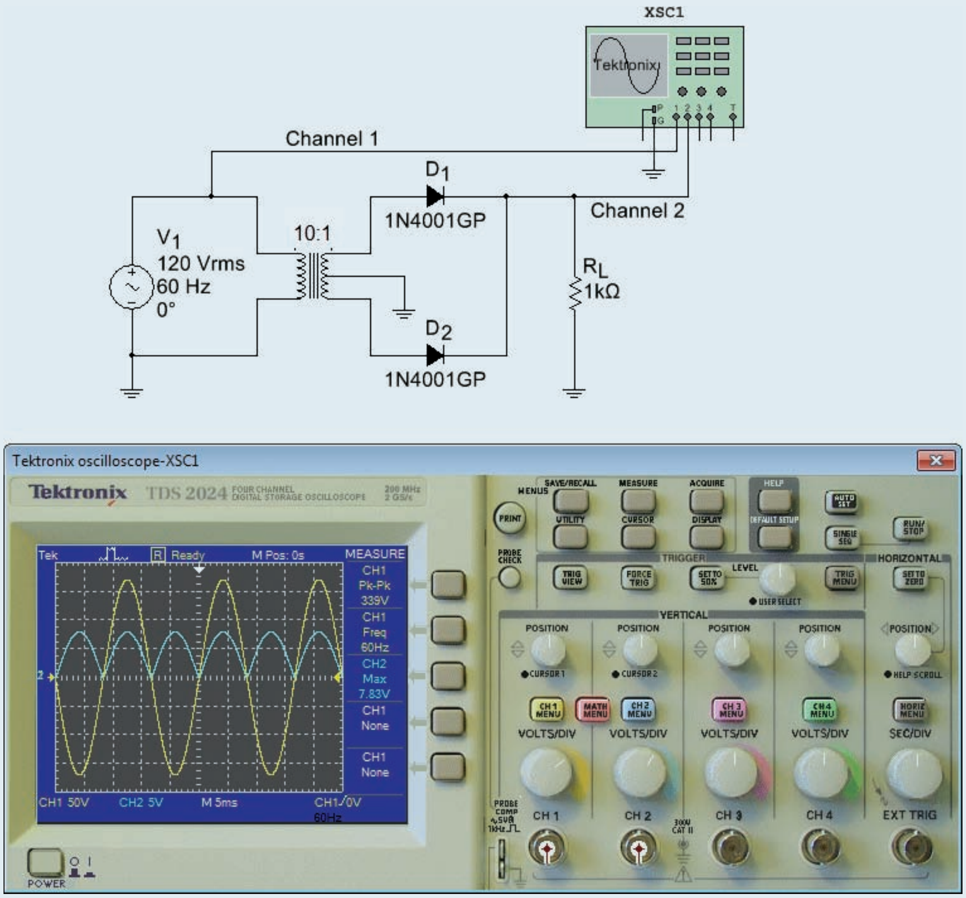
Figure 4-7 shows a full-wave rectifier that you can build on a lab bench or on a computer screen with Multisim. Channel 1 of the oscilloscope displays the primary voltage (the sine wave), and channel 2 displays the load voltage (the full-wave signal). Set Channel 1 as your positive input trigger point. Most oscilloscopes will need a 10× probe to measure the higher input voltage level. Calculate the peak input and output voltages. Then compare the theoretical values to the measured values.

### SOLUTION

The peak primary voltage is:

$$V_{p(1)} = \frac{V_{\text{rms}}}{0.707} = \frac{120\text{ V}}{0.707} = 170\text{ V}$$

**Figure 4-7** Lab example of full-wave rectifier.



Because of the 10 : 1 step-down transformer, the peak secondary voltage is:

$$V_{p(2)} = \frac{V_{p(1)}}{N_1/N_2} = \frac{170\text{ V}}{10} = 17\text{ V}$$

The full-wave rectifier acts like two back-to-back half-wave rectifiers. Because of the center tap, the input voltage to each half-wave rectifier is only half the secondary voltage:

$$V_{p(\text{in})} = 0.5(17\text{ V}) = 8.5\text{ V}$$

Ideally, the output voltage is:

$$V_{p(\text{out})} = 8.5\text{ V}$$

Using the second approximation:

$$V_{p(\text{out})} = 8.5\text{ V} - 0.7\text{ V} = 7.8\text{ V}$$

Now, let's compare the theoretical values with the measured values. The sensitivity of channel 1 is 50 V/Div. Since the sine-wave input reads approximately 3.4 divisions, its peak value is approximately 170 V. Channel 2 has a sensitivity of 5 V/Div. Since the full-wave output reads approximately 1.4 Div, its peak value is approximately 7 V. Both input and output readings are in reasonable agreement with theoretical values.

Once again, notice that the second approximation improves the answer only slightly. If you were troubleshooting, the improvement would not be of much value. If something was wrong with the circuit, the chances are that the full-wave output would be drastically different from the ideal value of 8.5 V.

**PRACTICE PROBLEM 4-3** Using Fig. 4-7, change the transformer's turns ratio to 5:1 and calculate the $V_{p(\text{in})}$ and $V_{p(\text{out})}$ second approximation values.

## Application Example 4-4

Multisim

If one of the diodes in Fig. 4-7 were open, what would happen to the different voltages?

**SOLUTION** If one of the diodes is open, the circuit reverts to a half-wave rectifier. In this case, half the secondary voltage is still 8.5 V, but the load voltage will be a half-wave signal rather than a full-wave signal. This half-wave voltage will still have a peak of 8.5 V (ideally) or 7.8 V (second approximation).

## 4-4 The Bridge Rectifier

Figure 4-8*a* shows a **bridge rectifier** circuit. The bridge rectifier is similar to a full-wave rectifier because it produces a full-wave output voltage. Diodes $D_1$ and $D_2$ conduct on the positive half-cycle, and $D_3$ and $D_4$ conduct on the negative half-cycle. As a result, the rectified load current flows during both half-cycles.

Figure 4-8*b* shows the equivalent circuit for the positive half-cycle. As you can see, $D_1$ and $D_2$ are forward biased. This produces a positive load voltage as indicated by the plus-minus polarity across the load resistor. As a memory aid, visualize $D_2$ shorted. Then, the circuit that remains is a half-wave rectifier, which we are already familiar with.

Figure 4-8*c* shows the equivalent circuit for the negative half-cycle. This time, $D_3$ and $D_4$ are forward biased. This also produces a positive load voltage. If you visualize $D_3$ shorted, the circuit looks like a half-wave rectifier. So the bridge rectifier acts like two back-to-back half-wave rectifiers.

During both half-cycles, the load voltage has the same polarity and the load current is in the same direction. The circuit has changed the ac input voltage to the pulsating dc output voltage shown in Fig. 4-8*d*. Note the advantage of this type of full-wave rectification over the center-tapped version in the previous section: *The entire secondary voltage can be used.*

Figure 4-8*e* shows bridge rectifier packages that contain all four diodes.

### Average Value and Output Frequency

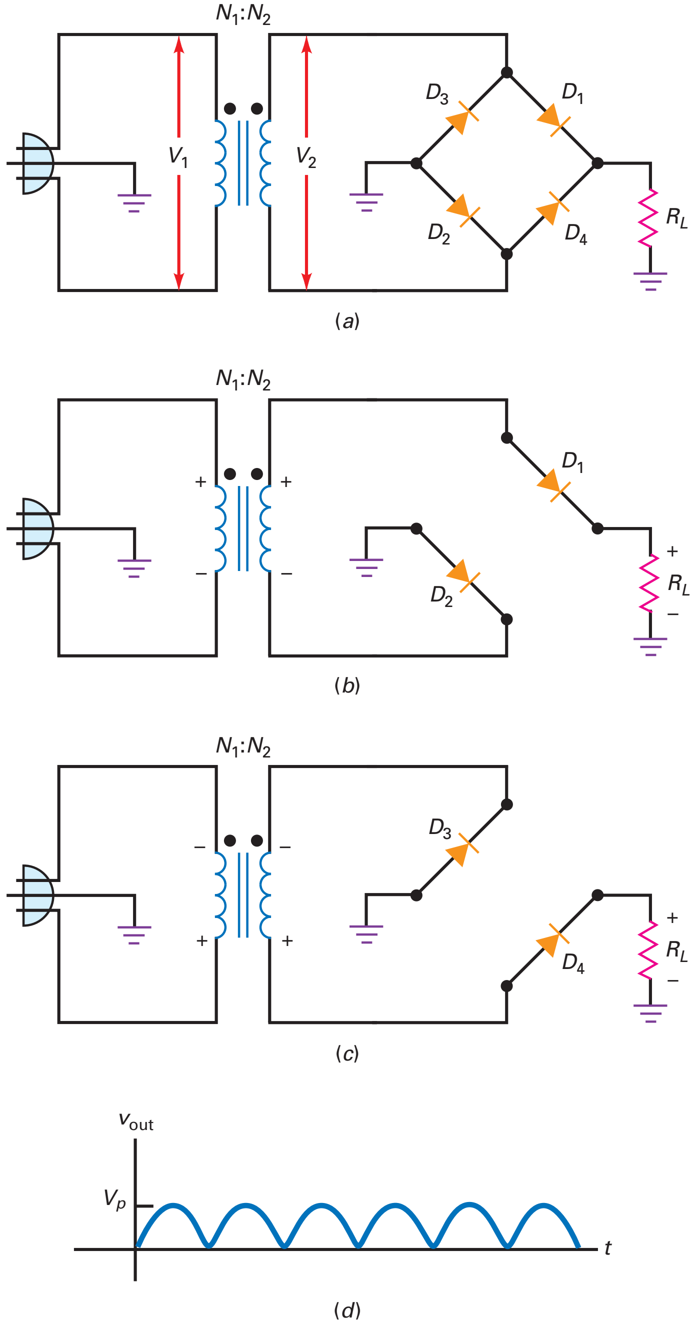
Because a bridge rectifier produces a full-wave output, the equations for average value and output frequency are the same as those given for a full-wave rectifier:

$$V_{\text{dc}} = \frac{2V_p}{\pi}$$

## GOOD TO KNOW

When a bridge rectifier, as opposed to a two-diode full-wave rectifier, is used, the same dc output voltage can be obtained with a transformer that has a higher turns ratio $N_1/N_2$. This means that with a bridge rectifier, fewer turns of wire are needed in the transformer. Therefore, the transformer used with a bridge rectifier versus a two-diode full-wave rectifier will be small and lighter and will cost less. This benefit alone outweighs using four diodes instead of two in a conventional two-diode full-wave rectifier.

**Figure 4-8** (*a*) Bridge rectifier; (*b*) equivalent circuit for positive half-cycle; (*c*) equivalent circuit for negative half-cycle; (*d*) full-wave output; (*e*) bridge rectifier packages.



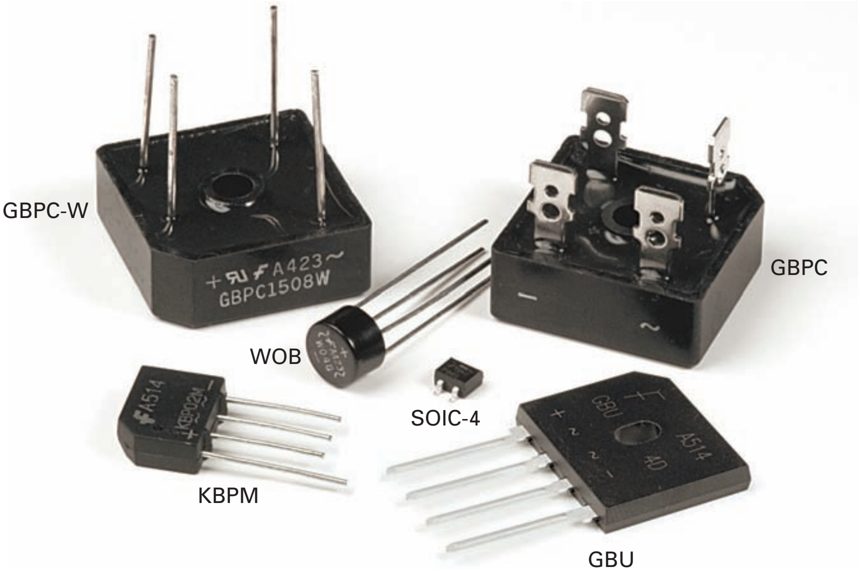
and

$$f_{out} = 2f_{in}$$

The average value is 63.6 percent of the peak value, and the output frequency is 120 Hz, given a line frequency of 60 Hz.

One advantage of a bridge rectifier is that all the secondary voltage is used as the input to the rectifier. Given the same transformer, we get twice as much peak voltage and twice as much dc voltage with a bridge rectifier as with a full-wave rectifier. Doubling the dc output voltage compensates for having to use two extra diodes. As a rule, you will see *the bridge rectifier used a lot more than the full-wave rectifier.*

**Figure 4-8** (continued)



(*e*)

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Incidentally, the full-wave rectifier was in use for many years before the bridge rectifier was used. For this reason, it has retained the name *full-wave rectifier* even though a bridge rectifier also has a full-wave output. To distinguish the full-wave rectifier from the bridge rectifier, some literature may refer to a full-wave rectifier as a *conventional full-wave rectifier,* a *two-diode full-wave rectifier,* or a *center-tapped full-wave rectifier.*

## Second Approximation and Other Losses

Since the bridge rectifier has two diodes in the conducting path, the peak output voltage is given by:

$$\textbf{2d bridge: } V_{p(\text{out})} = V_{p(\text{in})} - 1.4\text{ V} \qquad \textbf{(4-8)}$$

As you can see, we have to subtract two diode drops from the peak to get a more accurate value of peak load voltage. Summary Table 4-1 compares the three rectifiers and their properties.

**Summary Table 4-1 Unfiltered Rectifiers***

| | Half-wave | Full-wave | Bridge |
|---|---|---|---|
| Number of diodes | 1 | 2 | 4 |
| Rectifier input | $V_{p(2)}$ | $0.5V_{p(2)}$ | $V_{p(2)}$ |
| Peak output (ideal) | $V_{p(2)}$ | $0.5V_{p(2)}$ | $V_{p(2)}$ |
| Peak output (2d) | $V_{p(2)} - 0.7$ V | $0.5V_{p(2)} - 0.7$ V | $V_{p(2)} - 1.4$ V |
| DC output | $V_{p(\text{out})}/\pi$ | $2V_{p(\text{out})}/\pi$ | $2V_{p(\text{out})}/\pi$ |
| Ripple frequency | $f_{\text{in}}$ | $2f_{\text{in}}$ | $2f_{\text{in}}$ |

*$V_{p(2)}$ = peak secondary voltage; $V_{p(\text{out})}$ = peak output voltage.

## Application Example 4-5

Multisim

Calculate the peak input and output voltages in Fig. 4-9. Then compare the theoretical values to the measured values. Notice the circuit uses a bridge rectifier package.

**SOLUTION** The peak primary and secondary voltages are the same as in Application Example 4-3:

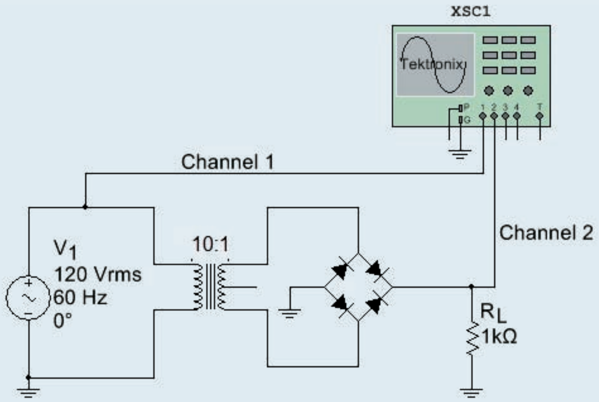
$$V_{p(1)} = 170 \text{ V}$$

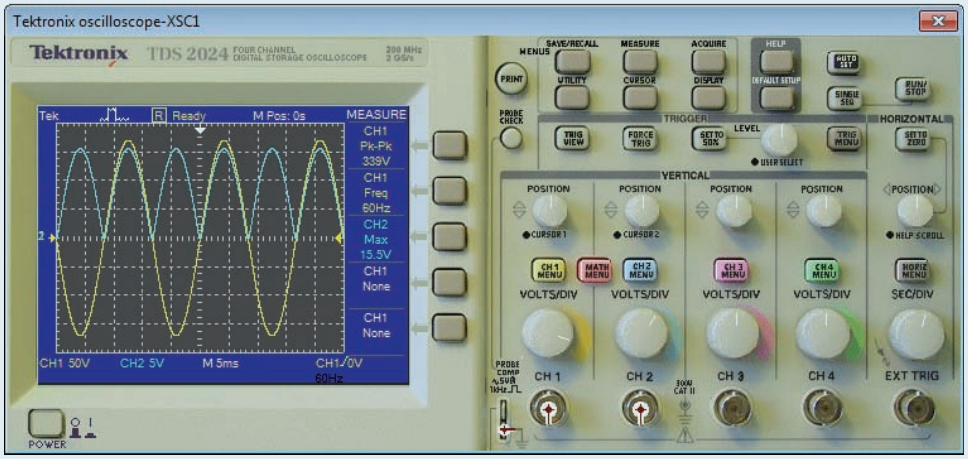
$$V_{p(2)} = 17 \text{ V}$$

With a bridge rectifier, all of the secondary voltage is used as the input to the rectifier. Ideally, the peak output voltage is:

$$V_{p(\text{out})} = 17 \text{ V}$$

**Figure 4-9** Lab example of bridge rectifier.




Tektronix oscilloscope-XSC1

Tek Ready M Pos: 0s

MEASURE
CH1 Pk-Pk 339V
CH1 Freq 60Hz
CH2 Max 15.5V
CH1 None
CH1 None

CH1 50V CH2 5V M 5ms CH1 ∕ 0V 60Hz

To a second approximation:

$$V_{p(\text{out})} = 17\text{ V} - 1.4\text{ V} = 15.6\text{ V}$$

Now, let's compare the theoretical values with the measured values. The sensitivity of channel 1 is 50 V/Div. Since the sine-wave input reads approximately 3.4 Div, its peak value is approximately 170 V. Channel 2 has a sensitivity of 5 V/Div. Since the half-wave output reads approximately 3.2 Div, its peak value is approximately 16 V. Both input and output readings are approximately the same as the theoretical values.

**PRACTICE PROBLEM 4-5** As in Application Example 4-5, calculate the ideal and second approximation $V_{p(\text{out})}$ values using a 5:1 transformer turns ratio.

## 4-5 The Choke-Input Filter

At one time, the choke-input filter was widely used to filter the output of a rectifier. Although not used much anymore because of its cost, bulk, and weight, this type of filter has instructional value and helps make it easier to understand other filters.

### Basic Idea

Look at Fig. 4-10*a*. This type of filter is called a **choke-input filter.** The ac source produces a current in the inductor, capacitor, and resistor. The ac current in each component depends on the inductive reactance, capacitive reactance, and the resistance. The inductor has a reactance given by:

$$X_L = 2\pi fL$$

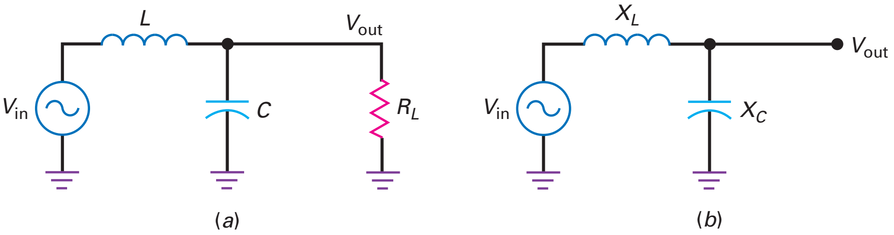
The capacitor has a reactance given by:

$$X_C = \frac{1}{2\pi fC}$$

As you learned in previous courses, the choke (or inductor) has the primary characteristic of opposing a change in current. Because of this, a choke-input filter ideally reduces the ac current in the load resistor to zero. To a second approximation, it reduces the ac load current to a very small value. Let us find out why.

The first requirement of a well-designed choke-input filter is to have $X_C$ at the input frequency be much smaller than $R_L$. When this condition is satisfied, we can ignore the load resistance and use the equivalent circuit of Fig. 4-10*b*. The second requirement of a well-designed choke-input filter is to have $X_L$ be much greater than $X_C$ at the input frequency. When this condition is satisfied, the ac output voltage approaches zero. On the other hand, since the choke approximates a short circuit at 0 Hz and the capacitor approximates an open at 0 Hz, the dc current can be passed to the load resistance with minimum loss.

**Figure 4-10** (*a*) Choke-input filter; (*b*) ac-equivalent circuit.



In Fig. 4-10*b*, the circuit acts like a reactive voltage divider. When $X_L$ is much greater than $X_C$, almost all the ac voltage is dropped across the choke. In this case, the ac output voltage equals:

$$\boldsymbol{V_{\text{out}} \approx \frac{X_C}{X_L} V_{\text{in}}} \tag{4-9}$$

For instance, if $X_L = 10\ \text{k}\Omega$, $X_C = 100\ \Omega$, and $V_{\text{in}} = 15\ \text{V}$, the ac output voltage is:

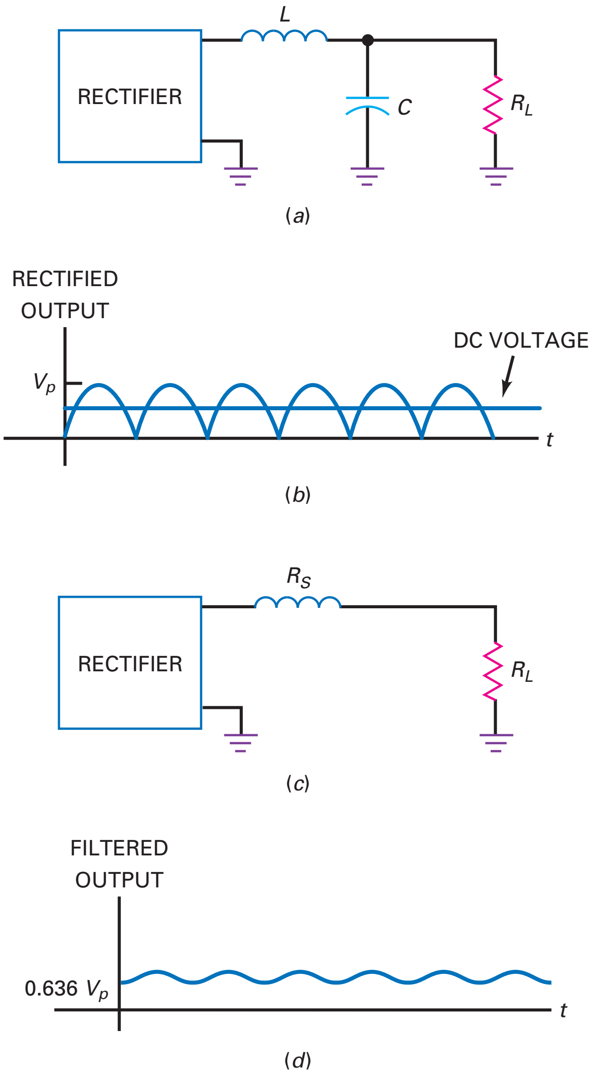
$$V_{\text{out}} \approx \frac{100\ \Omega}{10\ \text{k}\Omega} 15\ \text{V} = 0.15\ \text{V}$$

In this example, the choke-input filter reduces the ac voltage by a factor of 100.

## Filtering the Output of a Rectifier

Figure 4-11*a* shows a choke-input filter between a rectifier and a load. The rectifier can be a half-wave, full-wave, or bridge type. What effect does the choke-input filter have on the load voltage? The easiest way to solve this problem is to use the superposition theorem. Recall what this theorem says: If you have two or

**Figure 4-11** (*a*) Rectifier with choke-input filter; (*b*) rectifier output has dc and ac components; (*c*) dc-equivalent circuit; (*d*) filter output is a dc voltage with small ripple.



(*a*)

(*b*)

(*c*)

(*d*)

more sources, you can analyze the circuit for each source separately and then add the individual voltages to get the total voltage.

The rectifier output has two different components: a dc voltage (the average value) and an ac voltage (the fluctuating part), as shown in Fig. 4-11*b*. Each of these voltages acts like a separate source. As far as the ac voltage is concerned, $X_L$ is much greater than $X_C$, and this results in very little ac voltage across the load resistor. Even though the ac component is not a pure sine wave, Eq. (4-9) is still a close approximation for the ac load voltage.

The circuit acts like Fig. 4-11*c* as far as dc voltage is concerned. At 0 Hz, the inductive reactance is zero and the capacitive reactance is infinite. Only the series resistance of the inductor windings remains. Making $R_S$ much smaller than $R_L$ causes most of the dc component to appear across the load resistor.

That's how a choke-input filter works: Almost all of the dc component is passed on to the load resistor, and almost all of the ac component is blocked. In this way, we get an almost perfect dc voltage, one that is almost constant, like the voltage out of a battery. Figure 4-11*d* shows the filtered output for a full-wave signal. The only deviation from a perfect dc voltage is the small ac load voltage shown in Fig. 4-11*d*. This small ac load voltage is called **ripple.** With an oscilloscope, we can measure its peak-to-peak value. To measure the ripple value, set the oscilloscope's vertical input coupling switch or setting to ac instead of dc. This will allow you to see the ac component of the waveform while blocking the dc or average value.

### Main Disadvantage

A **power supply** is the circuit inside electronics equipment that converts the ac input voltage to an almost perfect dc output voltage. It includes a rectifier and a filter. The trend nowadays is toward low-voltage, high-current power supplies. Because line frequency is only 60 Hz, large inductances have to be used to get enough reactance for adequate filtering. But large inductors have large winding resistances, which create a serious design problem with large load currents. In other words, too much dc voltage is dropped across the choke resistance. Furthermore, bulky inductors are not suitable for modern semiconductor circuits, where the emphasis is on lightweight designs.

### Switching Regulators

One important application does exist for the choke-input filter. A **switching regulator** is a special kind of power supply used in computers, monitors, and an increasing variety of equipment. The frequency used in a switching regulator is much higher than 60 Hz. Typically, the frequency being filtered is above 20 kHz. At this much higher frequency, we can use much smaller inductors to design efficient choke-input filters. We will discuss the details in a later chapter.

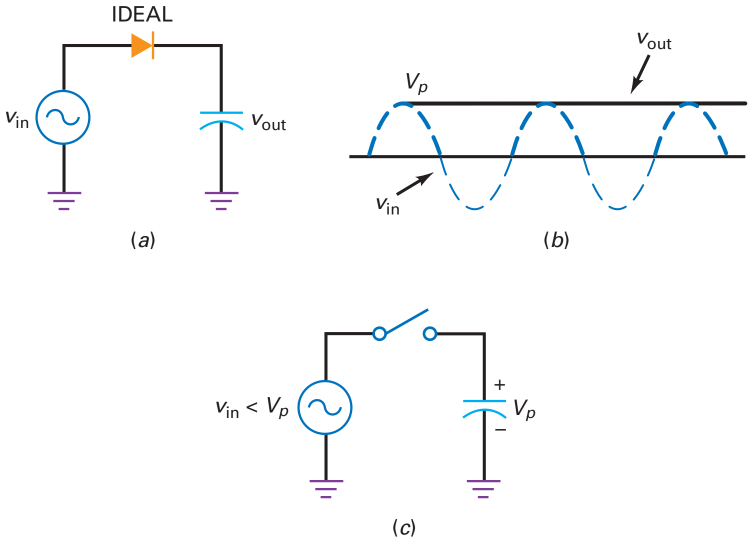
## 4-6 The Capacitor-Input Filter

The choke-input filter produces a dc output voltage equal to the average value of the rectified voltage. The **capacitor-input filter** produces a dc output voltage equal to the peak value of the rectified voltage. This type of filter is the most widely used in power supplies.

### Basic Idea

Figure 4-12*a* shows an ac source, a diode, and a capacitor. The key to understanding a capacitor-input filter is understanding what this simple circuit does during the first quarter-cycle.

**Figure 4-12** (*a*) Unloaded capacitor-input filter; (*b*) output is pure dc voltage; (*c*) capacitor remains charged when diode is off.



Initially, the capacitor is uncharged. During the first quarter-cycle of Fig. 4-12*b*, the diode is forward biased. Since it ideally acts like a closed switch, the capacitor charges, and its voltage equals the source voltage at each instant of the first quarter-cycle. The charging continues until the input reaches its maximum value. At this point, the capacitor voltage equals $V_p$.

After the input voltage reaches the peak, it starts to decrease. As soon as the input voltage is less than $V_p$, the diode turns off. In this case, it acts like the open switch of Fig. 4-12*c*. During the remaining cycles, the capacitor stays fully charged and the diode remains open. This is why the output voltage of Fig. 4-12*b* is constant and equal to $V_p$.

Ideally, all that the capacitor-input filter does is charge the capacitor to the peak voltage during the first quarter-cycle. This peak voltage is constant, the perfect dc voltage we need for electronics equipment. There's only one problem: There is no load resistor.

## Effect of Load Resistor

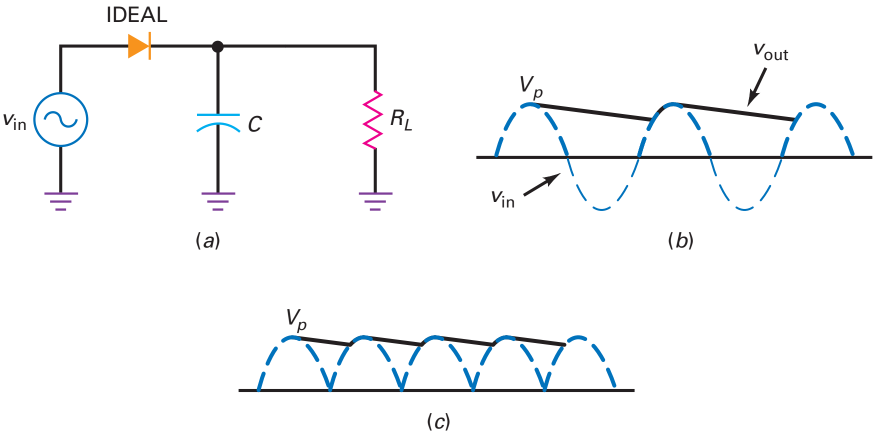
For the capacitor-input filter to be useful, we need to connect a load resistor across the capacitor, as shown in Fig. 4-13*a*. As long as the $R_LC$ time constant is much greater than the period, the capacitor remains almost fully charged and the load voltage is approximately $V_p$. The only deviation from a perfect dc voltage is the small ripple seen in Fig. 4-13*b*. The smaller the peak-to-peak value of this ripple, the more closely the output approaches a perfect dc voltage.

Between peaks, the diode is off and the capacitor discharges through the load resistor. In other words, the capacitor supplies the load current. Since the capacitor discharges only slightly between peaks, the peak-to-peak ripple is small. When the next peak arrives, the diode conducts briefly and recharges the capacitor to the peak value. A key question is: What size should the capacitor be for proper operation? Before discussing capacitor size, consider what happens with the other rectifier circuits.

## Full-Wave Filtering

If we connect a full-wave or bridge rectifier to a capacitor-input filter, the peak-to-peak ripple is cut in half. Figure 4-13*c* shows why. When a full-wave voltage is

**Figure 4-13** (*a*) Loaded capacitor-input filter; (*b*) output is a dc voltage with small ripple; (*c*) full-wave output has less ripple.



applied to the *RC* circuit, the capacitor discharges for only half as long. Therefore, the peak-to-peak ripple is half the size it would be with a half-wave rectifier.

## The Ripple Formula

Here is a derivation we will use to estimate the peak-to-peak ripple out of any capacitor-input filter:

$$V_R = \frac{I}{fC} \tag{4-10}$$

where $V_R$ = peak-to-peak ripple voltage
$I$ = dc load current
$f$ = ripple frequency
$C$ = capacitance

This is an approximation, not an exact derivation. We can use this formula to estimate the peak-to-peak ripple. When a more accurate answer is needed, one solution is to use a computer with a circuit simulator like Multisim.

For instance, if the dc load current is 10 mA and the capacitance is 200 $\mu$F, the ripple with a bridge rectifier and a capacitor-input filter is:

$$V_R = \frac{10\text{ mA}}{(120\text{ Hz})(200\ \mu\text{F})} = 0.417\text{ V}_{\text{p-p}}$$

When using this derivation, remember two things. First, the ripple is in peak-to-peak (p-p) voltage. This is useful because you normally measure ripple voltage with an oscilloscope. Second, the formula works with half-wave or full-wave voltages. Use 60 Hz for half wave, and 120 Hz for full wave.

You should use an oscilloscope for ripple measurements if one is available. If not, you can use an ac voltmeter, although there will be a significant error in the measurement. Most ac voltmeters are calibrated to read the rms value of a sine wave. Since the ripple is not a sine wave, you may get a measurement error of as much as 25 percent, depending on the design of the ac voltmeter. But this should be no problem when you are troubleshooting, since you will be looking for much larger changes in ripple.

### GOOD TO KNOW

Another, more accurate formula can be used to determine the ripple out of any capacitor input filter. It is

$$V_R = V_{p(\text{out})}\,(1 - \epsilon^{-t/R_LC})$$

Time *t* represents the length of time the filter capacitor *C* is allowed to discharge. For a half-wave rectifier, *t* can be approximated as 16.67 ms, whereas 8.33 ms can be used for a full-wave rectifier.

If you do use an ac voltmeter to measure the ripple, you can convert the peak-to-peak value given by Eq. (4-10) to an rms value using the following formula for a sine wave:

$$V_{\text{rms}} = \frac{V_{\text{p-p}}}{2\sqrt{2}}$$

Dividing by 2 converts the peak-to-peak value to a peak value, and dividing by $\sqrt{2}$ gives the rms value of a sine wave with the same peak-to-peak value as the ripple voltage.

## Exact DC Load Voltage

It is difficult to calculate the exact dc load voltage in a bridge rectifier with a capacitor-input filter. To begin with, we have the two diode drops that are subtracted from the peak voltage. Besides the diode drops, an additional voltage drop occurs, as follows: The diodes conduct heavily when recharging the capacitor because they are on for only a short time during each cycle. This brief but large current has to flow through the transformer windings and the bulk resistance of the diodes. In our examples, we will calculate either the ideal output or the output with the second approximation of a diode, remembering that the actual dc voltage is slightly lower.

## Example 4-6

What is the dc load voltage and ripple in Fig. 4-14?

**SOLUTION** The rms secondary voltage is:

$$V_2 = \frac{120\text{ V}}{5} = 24\text{ V}$$

The peak secondary voltage is:

$$V_p = \frac{24\text{ V}}{0.707} = 34\text{ V}$$

Assuming an ideal diode and small ripple, the dc load voltage is:

$$V_L = 34\text{ V}$$

To calculate the ripple, we first need to get the dc load current:

$$I_L = \frac{V_L}{R_L} = \frac{34\text{ V}}{5\text{ k}\Omega} = 6.8\text{ mA}$$

**Figure 4-14** Half-wave rectifier and capacitor-input filter.

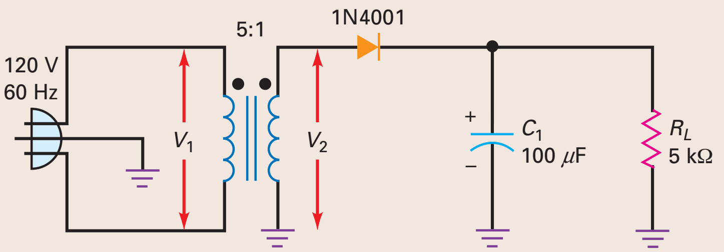
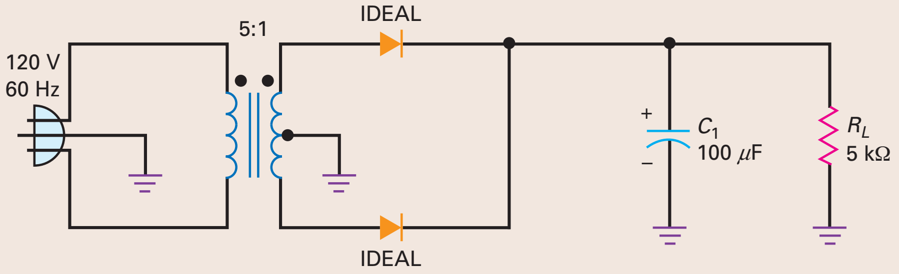


**Figure 4-15** Full-wave rectifier and capacitor-input filter.



Now we can use Eq. (4-10) to get:

$$V_R = \frac{6.8\text{ mA}}{(60\text{ Hz})(100\ \mu\text{F})} = 1.13\text{ V}_{\text{p-p}} \approx 1.1\text{ V}_{\text{p-p}}$$

We rounded the ripple to two significant digits because it is an approximation and cannot be accurately measured with an oscilloscope with greater precision.

Here is how to improve the answer slightly: There is about 0.7 V across a silicon diode when it is conducting. Therefore, the peak voltage across the load will be closer to 33.3 V than to 34 V. The ripple also lowers the dc voltage slightly. So the actual dc load voltage will be closer to 33 V than to 34 V. But these are minor deviations. Ideal answers are usually adequate for troubleshooting and preliminary analysis.

A final point about the circuit. The plus and minus signs on the filter capacitor indicates a **polarized capacitor,** one whose plus side must be connected to the positive rectifier output. In Fig. 4-15, the plus sign on the capacitor case is correctly connected to the positive output voltage. You must look carefully at the capacitor case when you are building or troubleshooting a circuit to find out whether it is polarized or not. If you reverse the polarity of the rectifier diodes and build a negative power-supply circuit, be sure to connect the capacitor's negative side to the negative output voltage point and the positive capacitor side to circuit ground.

Power supplies often use polarized electrolytic capacitors because this type can provide high values of capacitance in small packages. As discussed in earlier courses, *electrolytic capacitors must be connected with the correct polarity* to produce the oxide film. If an electrolytic capacitor is connected in opposite polarity, *it becomes hot and may explode.*

## Example 4-7

Multisim

What is the dc load voltage and ripple in Fig. 4-15?

**SOLUTION** Since the transformer is 5:1 step-down like the preceding example, the peak secondary voltage is still 34 V. Half this voltage is the input to each half-wave section. Assuming an ideal diode and small ripple, the dc load voltage is:

$$V_L = 17\text{ V}$$

The dc load current is:

$$I_L = \frac{17\text{ V}}{5\text{ k}\Omega} = 3.4\text{ mA}$$

Now, Eq. (4-10) gives:

$$V_R = \frac{3.4\text{ mA}}{(120\text{ Hz})(100\ \mu\text{F})} = 0.283\text{ V}_{\text{p-p}} \approx 0.28\text{ V}_{\text{p-p}}$$

Because of the 0.7 V across the conducting diode, the actual dc load voltage will be closer to 16 V than to 17 V.

**PRACTICE PROBLEM 4-7** Using Fig. 4-15, change $R_L$ to 2 kΩ and calculate the new ideal dc load voltage and ripple.

---

## Example 4-8

Multisim

What is the dc load voltage and ripple in Fig. 4-16? Compare the answers with those in the two preceding examples.

**SOLUTION** Since the transformer is 5:1 step-down as in the preceding example, the peak secondary voltage is still 34 V. Assuming an ideal diode and small ripple, the dc load voltage is:

$$V_L = 34 \text{ V}$$

The dc load current is:

$$I_L = \frac{34 \text{ V}}{5 \text{ k}\Omega} = 6.8 \text{ mA}$$

Now, Eq. (4-10) gives:

$$V_R = \frac{6.8 \text{ mA}}{(120 \text{ Hz})(100\ \mu\text{F})} = 0.566 \text{ V}_{\text{p-p}} \approx 0.57 \text{ V}_{\text{p-p}}$$

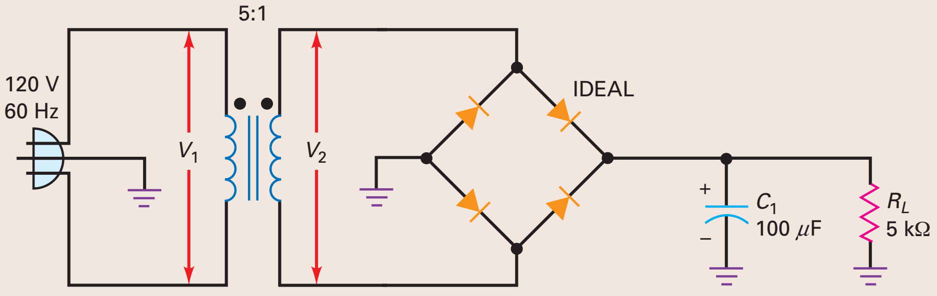
Because of the 1.4 V across two conducting diodes and the ripple, the actual dc load voltage will be closer to 32 V than to 34 V.

We have calculated the dc load voltage and ripple for the three different rectifiers. Here are the results:

Half-wave: 34 V and 1.13 V
Full-wave: 17 V and 0.288 V
Bridge: 34 V and 0.566 V

For a given transformer, the bridge rectifier is better than the half-wave rectifier because it has less ripple, and it's better than the full-wave rectifier because it produces twice as much output voltage. Of the three, *the bridge rectifier has emerged as the most popular.*

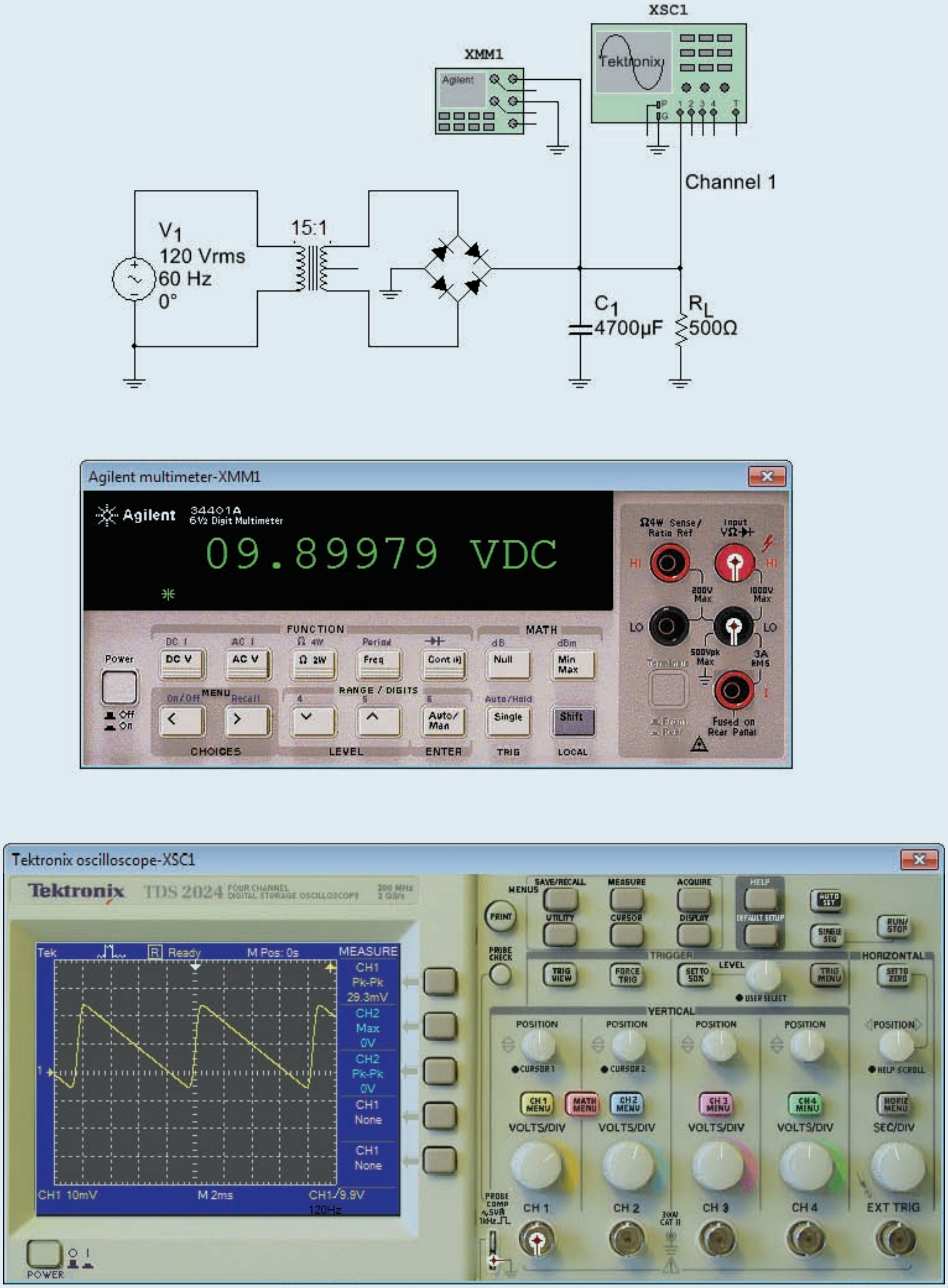
**Figure 4-16** Bridge rectifier and capacitor-input filter.



## Application Example 4-9

Figure 4-17 shows the values measured with Multisim. Calculate the theoretical load voltage and ripple and compare them to the measured values.

**Figure 4-17** Lab example of bridge rectifier and capacitor-input filter.



**SOLUTION** The transformer is a 15 : 1 step-down, so the rms secondary voltage is:

$$V_2 = \frac{120\text{ V}}{15} = 8\text{ V}$$

and the peak secondary voltage is:

$$V_p = \frac{8\text{ V}}{0.707} = 11.3\text{ V}$$

Let's use the second approximation of the diodes to get the dc load voltage:

$$V_L = 11.3\text{ V} - 1.4\text{ V} = 9.9\text{ V}$$

To calculate the ripple, we first need to get the dc load current:

$$I_L = \frac{9.9\text{ V}}{500\ \Omega} = 19.8\text{ mA}$$

Now, we can use Eq. (4-10) to get:

$$V_R = \frac{19.8\text{ mA}}{(120\text{ Hz})(4700\ \mu\text{F})} = 35\text{ mV}_{\text{p-p}}$$

In Fig. 4-17, a multimeter reads a dc load voltage of approximately 9.9 V.

Channel 1 of the oscilloscope is set to 10 mV/Div. The peak-to-peak ripple is approximately 2.9 Div, and the measured ripple is 29.3 mV. This is less than the theoretical value of 35 mV, which emphasizes the point made earlier. Equation (4-10) is to be used for *estimating* ripple. If you need more accuracy, use computer simulation software.

**PRACTICE PROBLEM 4-9** Change the capacitor value in Fig. 4-17 to 1000 μF. Calculate the new $V_R$ value.

## 4-7 Peak Inverse Voltage and Surge Current

The **peak inverse voltage (PIV)** is the maximum voltage across the nonconducting diode of a rectifier. *This voltage must be less than the breakdown voltage of the diode; otherwise, the diode will be destroyed.* The peak inverse voltage depends on the type of rectifier and filter. The worst case occurs with the capacitor-input filter.

As discussed earlier, data sheets from various manufacturers use many different symbols to indicate the maximum reverse voltage rating of a diode. Sometimes, these symbols indicate different conditions of measurement. Some of the data sheet symbols for the maximum reverse voltage rating are PIV, PRV, $V_B$, $V_{\text{BR}}$, $V_R$, $V_{\text{RRM}}$, $V_{\text{RWM}}$, and $V_{R(\text{max})}$.

### Half-Wave Rectifier with Capacitor-Input Filter

Figure 4-18*a* shows the critical part of a half-wave rectifier. This is the part of the circuit that determines how much reverse voltage is across the diode. The rest of the circuit has no effect and is omitted for the sake of clarity. In the worst case, the peak secondary voltage is on the negative peak and the capacitor is fully charged

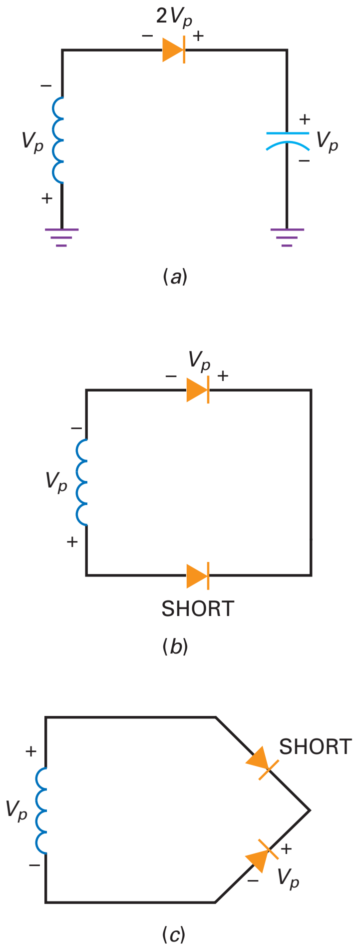


**Figure 4-18** (*a*) Peak inverse voltage in half-wave rectifier; (*b*) peak inverse voltage in full-wave rectifier; (*c*) peak inverse voltage in bridge-wave rectifier.

with a voltage of $V_p$. Apply Kirchhoff's voltage law, and you can see right away that the peak inverse voltage across the nonconducting diode is:

$$\textbf{PIV} = 2V_p \tag{4-11}$$

For instance, if the peak secondary voltage is 15 V, the peak inverse voltage is 30 V. As long as the breakdown voltage of the diode is greater than this, the diode will not be damaged.

## Full-Wave Rectifier with Capacitor-Input Filter

Figure 4-18*b* shows the essential part of a full-wave rectifier needed to calculate the peak inverse voltage. Again, the secondary voltage is at the negative peak. In this case, the lower diode acts like a short (closed switch) and the upper diode is open. Kirchhoff's law implies:

$$\textbf{PIV} = V_p \tag{4-12}$$

## Bridge Rectifier with Capacitor-Input Filter

Figure 4-18*c* shows part of a bridge rectifier. This is all you need to calculate the peak inverse voltage. Since the upper diode is shorted and the lower one is open, the peak inverse voltage across the lower diode is:

$$\textbf{PIV} = V_p \tag{4-13}$$

Another advantage of the bridge rectifier is that it has the lowest peak inverse voltage for a given load voltage. To produce the same load voltage, the full-wave rectifier would need twice as much secondary voltage.

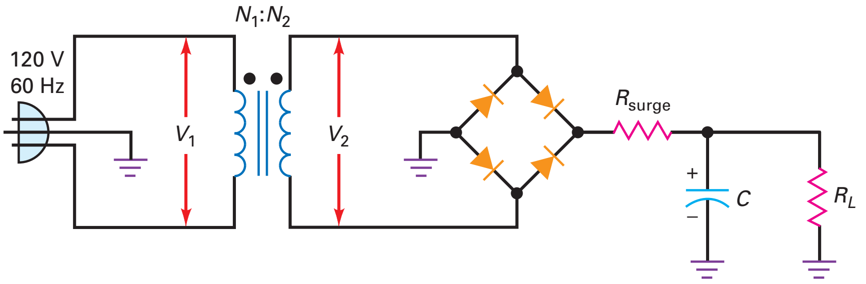
## Surge Resistor

Before the power is turned on, the filter capacitor is uncharged. At the first instant the power is applied, this capacitor looks like a short. Therefore, the initial charging current may be very large. All that exists in the charging path to impede the current is the resistance of the transformer windings and the bulk resistance of the diodes. The initial rush of current when the power is turned on is called the **surge current.**

Ordinarily, the designer of the power supply will select a diode with enough current rating to withstand the surge current. The key to the surge current is the size of the filter capacitor. Occasionally, a designer may decide to use a **surge resistor** rather than select another diode.

Figure 4-19 illustrates the idea. A small resistor is inserted between the bridge rectifier and the capacitor-input filter. Without the resistor, the surge current might destroy the diodes. By including the surge resistor, the designer reduces the surge current to a safe level. Surge resistors are not used very often and are mentioned just in case you see one used in a power supply.

**Figure 4-19** Surge resistor limits surge current.



## Example 4-10

What is the peak inverse voltage in Fig. 4-19 if the turns ratio is 8:1? A 1N4001 has a breakdown voltage of 50 V. Is it safe to use a 1N4001 in this circuit?

**SOLUTION** The rms secondary voltage is:

$$V_2 = \frac{120\text{ V}}{8} = 15\text{ V}$$

The peak secondary voltage is:

$$V_p = \frac{15\text{ V}}{0.707} = 21.2\text{ V}$$

The peak inverse voltage is:

$$\text{PIV} = 21.2\text{ V}$$

The 1N4001 is more than adequate, since the peak inverse voltage is much less than the breakdown voltage of 50 V.

**PRACTICE PROBLEM 4-10** Using Fig. 4-19, change the transformer's turns ratio to 2:1. Which 1N4000 series of diodes should you use?

## 4-8 Other Power-Supply Topics

You have a basic idea of how power-supply circuits work. In the preceding sections, you have seen how an ac input voltage is rectified and filtered to get a dc voltage. There are a few additional ideas you need to know about.

### Commercial Transformers

The use of turns ratios with transformers applies only to ideal transformers. Iron-core transformers are different. In other words, the transformers you buy from a parts supplier are not ideal because the windings have resistance, which produces power losses. Furthermore, the laminated core has eddy currents, which produce additional power losses. Because of these unwanted power losses, the turns ratio is only an approximation. In fact, the data sheets for transformers rarely list the turns ratio. Usually, all you get is the secondary voltage at a rated current.

For instance, Fig. 4-20*a* shows an F-25X, an industrial transformer whose data sheet gives only the following specifications: for a primary voltage of 115 V ac, the secondary voltage is 12.6 V ac when the secondary current is 1.5 A. If the secondary current is less than 1.5 A in Fig. 4-20*a*, the secondary voltage will be more than 12.6 V ac because of lower power losses in the windings and laminated core.

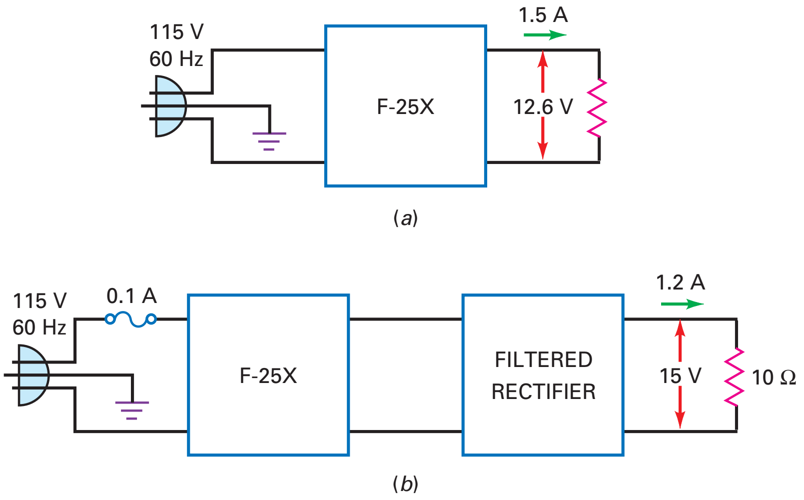
If it is necessary to know the primary current, you can estimate the turns ratio of a real transformer by using this definition:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \tag{4-14}$$

### GOOD TO KNOW

When a transformer is unloaded, the secondary voltage usually measures a value that is 5 to 10 percent higher than its rated value.

**Figure 4-20** (*a*) Rating on real transformer; (*b*) calculating fuse current.



For instance, the F25X has $V_1 = 115$ V and $V_2 = 12.6$ V. The turns ratio at the rated load current of 1.5 A is:

$$\frac{N_1}{N_2} = \frac{115}{12.6} = 9.13$$

This is an approximation because the calculated turns ratio decreases when the load current decreases.

## Calculating Fuse Current

When troubleshooting, you may need to calculate the primary current to determine whether a fuse is adequate or not. The easiest way to do this with a real transformer is to assume that the input power equals the output power: $P_{\text{in}} = P_{\text{out}}$. For instance, Fig. 4-20*b* shows a fused transformer driving a filtered rectifier. Is the 0.1-A fuse adequate?

Here is how to estimate the primary current when troubleshooting. The output power equals the dc load power:

$$P_{\text{out}} = VI = (15 \text{ V})(1.2 \text{ A}) = 18 \text{ W}$$

Ignore the power losses in the rectifier and the transformer. Since the input power must equal the output power:

$$P_{\text{in}} = 18 \text{ W}$$

Since $P_{\text{in}} = V_1 I_1$, we can solve for the primary current:

$$I_1 = \frac{18 \text{ W}}{115 \text{ V}} = 0.156 \text{ A}$$

This is only an estimate because we ignored the power losses in the transformer and rectifier. The actual primary current will be higher by about 5 to 20 percent because of these additional losses. In any case, the fuse is inadequate. It should be at least 0.25 A.

## Slow-Blow Fuses

Assume that a capacitor-input filter is used in Fig. 4-20*b*. If an ordinary 0.25-A fuse is used in Fig. 4-20*b*, it will blow out when you turn the power on. The reason is the surge current, described earlier. Most power supplies use a slow-blow fuse, one that can temporarily withstand overloads in current. For instance, a 0.25-A slow-blow fuse can withstand

2 A for 0.1 s
1.5 A for 1 s
1 A for 2 s

and so on. With a slow-blow fuse, the circuit has time to charge the capacitor. Then, the primary current drops down to its normal level with the fuse still intact.

## Calculating Diode Current

Whether a half-wave rectifier is filtered or not, the average current through the diode has to equal the dc load current because there is only one path for current. As a derivation:

$$\textbf{Half wave: } I_{\text{diode}} = I_{\text{dc}} \qquad \textbf{(4-15)}$$

On the other hand, the average current through a diode in the full-wave rectifier equals only half the dc load current because there are two diodes in the circuit, each sharing the load. Similarly, each diode in a bridge rectifier has to withstand an average current of half the dc load current. As a derivation:

$$\textbf{Full wave: } I_{\text{diode}} = 0.5 I_{\text{dc}} \qquad \textbf{(4-16)}$$

Summary Table 4-2 compares the properties of the three capacitor-input filtered rectifiers.

## Reading a Data Sheet

Refer to the data sheet of the 1N4001 in Chap. 3, Fig. 3-15. The maximum peak repetitive reverse voltage, $V_{\text{RRM}}$ on the data sheet, is the same as the peak inverse voltage discussed earlier. The data sheet says that the 1N4001 can withstand a voltage of 50 V in the reverse direction.

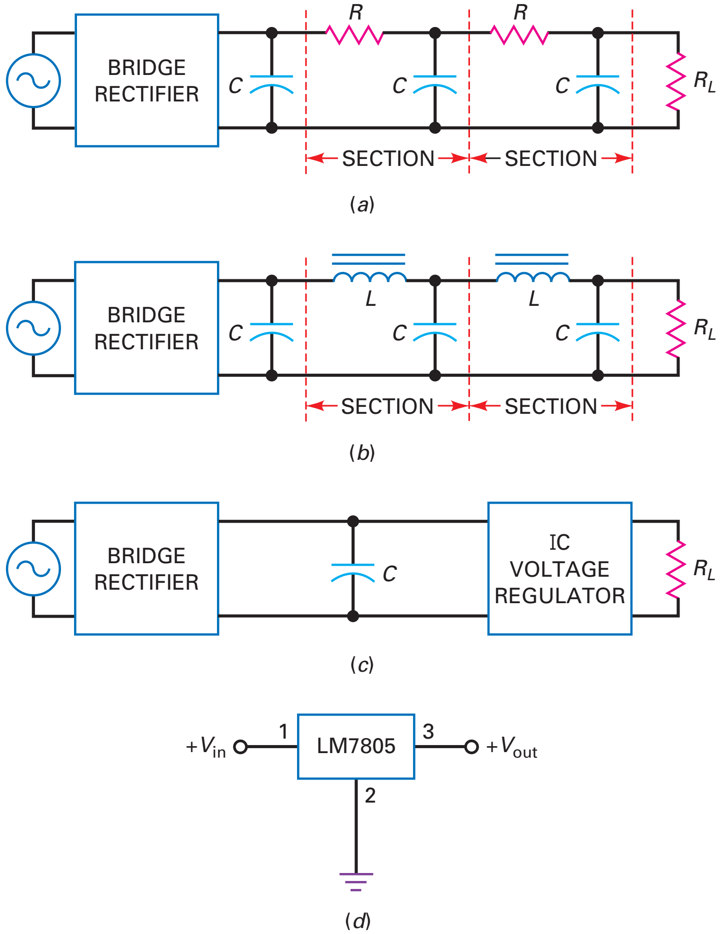
The average rectified forward current—$I_{F(\text{av})}$, $I_{(\text{max})}$, or $I_0$—is the dc or average current through the diode. For a half-wave rectifier, the diode current equals the dc load current. For a full-wave or bridge rectifier, it equals half the dc load current. The data sheet says that a 1N4001 can have a dc current of 1 A, which means that the dc load current can be as much as 2 A in a bridge rectifier. Notice also the surge-current rating $I_{FSM}$. The data sheet says that a 1N4001 can withstand 30 A during the first cycle when the power is turned on.

**Summary Table 4-2** **Capacitor-Input Filtered Rectifiers***

| | Half-wave | Full-wave | Bridge |
|---|---|---|---|
| Number of diodes | 1 | 2 | 4 |
| Rectifier input | $V_{p(2)}$ | $0.5V_{p(2)}$ | $V_{p(2)}$ |
| DC output (ideal) | $V_{p(2)}$ | $0.5V_{p(2)}$ | $V_{p(2)}$ |
| DC output (2d) | $V_{p(2)} - 0.7$ V | $0.5V_{p(2)} - 0.7$ V | $V_{p(2)} - 1.4$ V |
| Ripple frequency | $f_{\text{in}}$ | $2f_{\text{in}}$ | $2f_{\text{in}}$ |
| PIV | $2V_{p(2)}$ | $V_{p(2)}$ | $V_{p(2)}$ |
| Diode current | $I_{\text{dc}}$ | $0.5I_{\text{dc}}$ | $0.5I_{\text{dc}}$ |

*$V_{p(2)}$ = peak secondary voltage; $V_{p(\text{out})}$ = peak output voltage; $I_{\text{dc}}$ = dc load current.

**Figure 4-21** (*a*) *RC* filtering; (*b*) *LC* filtering; (*c*) voltage-regulator filtering; (*d*) three-terminal voltage regulator.



## RC Filters

Before the 1970s, **passive filters** ($R$, $L$, and $C$ components) were often connected between the rectifier and the load resistance. Nowadays, you rarely see passive filters used in semiconductor power supplies, but there might be special applications, such as audio power amplifiers, in which you might encounter them.

Figure 4-21*a* shows a bridge rectifier and a capacitor-input filter. Usually, a designer will settle for a peak-to-peak ripple of as much as 10 percent across the filter capacitor. The reason for not trying to get even lower ripple is because the filter capacitor would become too large. Additional filtering is then done by *RC* sections between the filter capacitor and the load resistor.

The *RC* sections are examples of a passive filter, one that uses only $R$, $L$, or $C$ components. By deliberate design, $R$ is much greater than $X_C$ at the ripple frequency. Therefore, the ripple is reduced before it reaches the load resistor. Typically, $R$ is at least 10 times greater than $X_C$. This means that each section attenuates (reduces) the ripple by a factor of at least 10. The disadvantage of an *RC* filter is the loss of dc voltage across each $R$. Because of this, the *RC* filter is suitable only for very light loads (small load current or large load resistance).

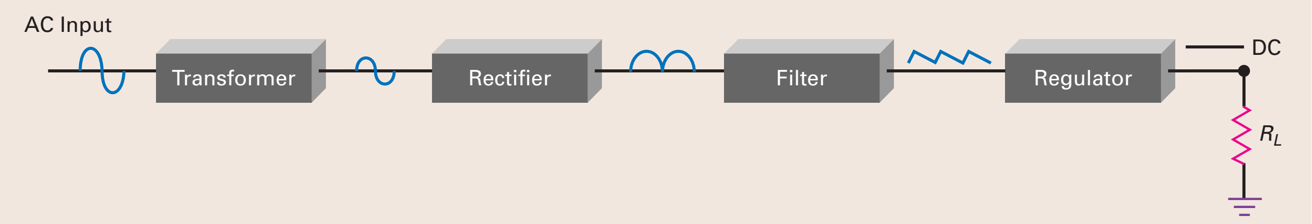
### GOOD TO KNOW

A filter made of an inductor placed in between two capacitors is often called a pi ($\pi$) filter.

## LC Filter

When the load current is large, the *LC* filters of Fig. 4-21*b* are an improvement over *RC* filters. Again, the idea is to drop the ripple across the series components, in this case, the inductors. By making $X_L$ much greater than $X_C$, we can reduce the ripple

**Summary Table 4-3** **Power Supply Block Diagram**



| | | | | |
|---|---|---|---|---|
| Purpose | Provides proper secondary ac voltage and ac ground isolation | Changes ac input to pulsating dc | Smooths out dc pulses | Provides a constant output voltage under varying loads and ac input voltage |
| Types | Step-up, step-down, isolation (1:1) | Half-wave, full-wave, full-wave bridge | Choke-input, capacitor-input | Discrete components, integrated circuit (IC) |

to a very low level. The dc voltage drop across the inductors is much smaller than it is across the resistors of *RC* sections because the winding resistance is smaller.

The *LC* filter was very popular at one time. Now, it's becoming obsolete in typical power supplies because of the size and cost of inductors. For low-voltage power supplies, the *LC* filter has been replaced by an **integrated circuit (IC).** This is a device that contains diodes, transistors, resistors, and other components in a miniaturized package to perform a specific function.

Figure 4-21*c* illustrates the idea. An **IC voltage regulator,** one type of integrated circuit, is between the filter capacitor and the load resistor. This device not only reduces the ripple, it also holds the output voltage constant. We will discuss specific details of IC voltage regulators in a later chapter. Figure 4-21*d* shows an example of a three-terminal voltage regulator. The LM7805 IC provides for a five-volt fixed positive output voltage, as long as the input voltage to the IC is at least 2 to 3 volts greater than the required output voltage. Other regulators in the 78XX series can regulate a range of output values, such as 9 V, 12 V, and 15 V. The 79XX series provides regulated negative output values. Because of their low cost, IC voltage regulators are now the standard method used for ripple reduction.

Summary Table 4-3 breaks the power supply down into functional blocks.

## 4-9 Troubleshooting

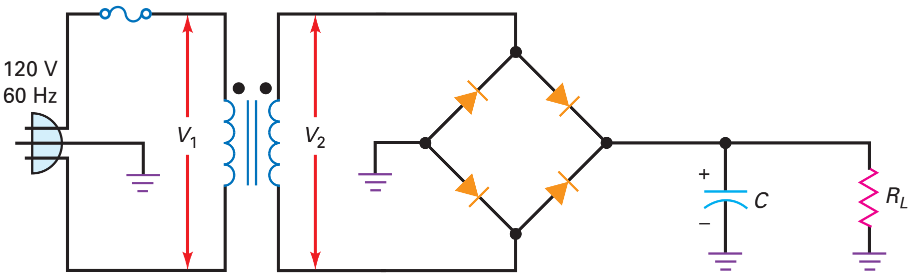
Almost every piece of electronics equipment has a power supply, typically a rectifier, driving a capacitor-input filter followed by a voltage regulator. This power supply produces the dc voltages needed by transistors and other devices. If a piece of electronics equipment is not working properly, start your troubleshooting with the power supply. More often than not, *equipment failure is caused by troubles in the power supply.*

### Procedure

Assume that you are troubleshooting the circuit of Fig. 4-22. You can start by measuring the dc load voltage. It should be approximately the same as the peak secondary voltage. If not, there are two possible courses of action.

First, if there is no load voltage, you can use a floating VOM or DMM to measure the secondary voltage (ac range). The reading is the rms voltage across the secondary winding. Convert this to peak value. You can estimate the peak value by adding 40 percent to the rms value. If this is normal, the diodes may be defective. If there is no secondary voltage, either the fuse is blown or the transformer is defective.

**Figure 4-22** Troubleshooting.



Second, if there is dc load voltage but it is lower than it should be, look at the dc load voltage with an oscilloscope and measure the ripple. A peak-to-peak ripple around 10 percent of the ideal load voltage is reasonable. The ripple may be somewhat more or less than this, depending on the design. Furthermore, the ripple frequency should be 120 Hz for a full-wave or bridge rectifier. If the ripple is 60 Hz, one of the diodes may be open.

## Common Troubles

Here are the most common troubles that arise in bridge rectifiers with capacitor-input filters:

1. If the fuse is open, there will be no voltages anywhere in the circuit.
2. If the filter capacitor is open, the dc load voltage will be low because the output will be an unfiltered full-wave signal.
3. If one of the diodes is open, the dc load voltage will be low because there will be only half-wave rectification. Also, the ripple frequency will be 60 Hz instead of 120 Hz. If all diodes are open, there will be no output.
4. If the load is shorted, the fuse will be blown. Possibly, one or more diodes may be ruined or the transformer may be damaged.
5. Sometimes, the filter capacitor becomes leaky with age, and this reduces the dc load voltage.
6. Occasionally, shorted windings in the transformer reduce the dc output voltage. In this case, the transformer often feels very warm to the touch.
7. Besides these troubles, you can have solder bridges, cold-solder joints, bad connections, and so on.

Summary Table 4-4 lists these troubles and their symptoms.

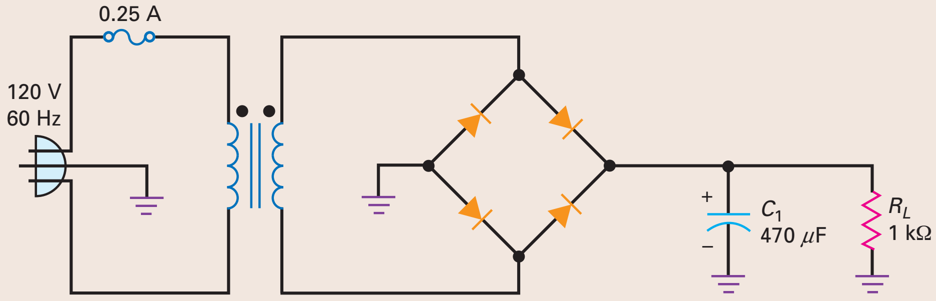
### Summary Table 4-4 Typical Troubles for Capacitor-Input Filtered Bridge Rectifier

| | $V_1$ | $V_2$ | $V_{L(dc)}$ | $V_R$ | $f_{ripple}$ | Scope on Output |
|---|---|---|---|---|---|---|
| Fuse blown | Zero | Zero | Zero | Zero | Zero | No output |
| Capacitor open | OK | OK | Low | High | 120 Hz | Full-wave signal |
| One diode open | OK | OK | Low | High | 60 Hz | Half-wave ripple |
| All diodes open | OK | OK | Zero | Zero | Zero | No output |
| Load shorted | Zero | Zero | Zero | Zero | Zero | No output |
| Leaky capacitor | OK | OK | Low | High | 120 Hz | Low output |
| Shorted windings | OK | Low | Low | OK | 120 Hz | Low output |

## Example 4-11

When the circuit of Fig. 4-23 is working normally, it has an rms secondary voltage of 12.7 V, a load voltage of 18 V, and a peak-to-peak ripple of 318 mV. If the filter capacitor is open, what happens to the dc load voltage?

**Figure 4-23**



**SOLUTION** With an open filter capacitor, the circuit reverts to a bridge rectifier with no filter capacitor. Because there is no filtering, an oscilloscope across the load will display a full-wave signal with a peak value of 18 V. The average value is 63.6 percent of 18 V, which is 11.4 V.

## Example 4-12

Suppose the load resistor of Fig. 4-23 is shorted. Describe the symptoms.

**SOLUTION** A short across the load resistor will increase the current to a very high value. This will blow out the fuse. Furthermore, it is possible that one or more diodes will be destroyed before the fuse blows. Often, when one diode shorts, it will cause the other rectifier diodes to also short. Because of the blown fuse, all voltages will measure zero. When you check the fuse visually or with an ohmmeter, you will see that it is open.

With the power off, you should check the diodes with an ohmmeter to see whether any of them have been destroyed. You should also measure the load resistance with an ohmmeter. If it measures zero or very low, you have more troubles to locate.

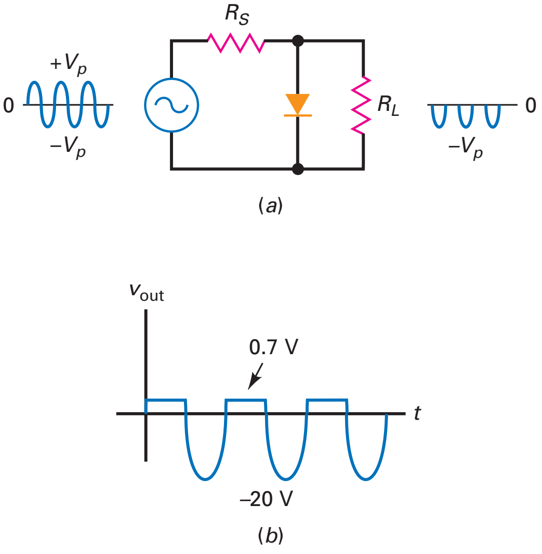
The trouble could be a solder bridge across the load resistor, incorrect wiring, or any number of possibilities. Fuses do occasionally blow out without a permanent short across the load. But the point is this: *When you get a blown fuse, check the diodes for possible damage and the load resistance for a possible short.*

A troubleshooting exercise at the end of the chapter has eight different troubles, including open diodes, filter capacitors, shorted loads, blown fuses, and open grounds.

## 4-10 Clippers and Limiters

The diodes used in low-frequency power supplies are *rectifier diodes.* These diodes are optimized for use at 60 Hz and have power ratings greater than 0.5 W. The typical rectifier diode has a forward current rating in amperes. Except for power supplies, rectifier diodes have little use because most circuits inside electronics equipment are running at much higher frequencies.

**Figure 4-24** (*a*) Positive clipper; (*b*) output waveform.



## Small-Signal Diodes

In this section, we will be using *small-signal diodes.* These diodes are optimized for use at high frequencies and have power ratings less than 0.5 W. The typical small-signal diode has a current rating in milliamperes. It is this smaller and lighter construction that allows the diode to work at higher frequencies.

## The Positive Clipper

A **clipper** is a circuit that removes either positive or negative parts of a waveform. This kind of processing is useful for signal shaping, circuit protection, and communications. Figure 4-24*a* shows a *positive clipper.* The circuit removes all the positive parts of the input signal. This is why the output signal has only negative half-cycles.

Here is how the circuit works: During the positive half-cycle, the diode turns on and looks like a short across the output terminals. Ideally, the output voltage is zero. On the negative half-cycle, the diode is open. In this case, a negative half-cycle appears across the output. By deliberate design, the series resistor is much smaller than the load resistor. This is why the negative output peak is shown as $-V_p$ in Fig. 4-24*a*.

To a second approximation, the diode voltage is 0.7 V when conducting. Therefore, the clipping level is not zero, but 0.7 V. For instance, if the input signal has a peak value of 20 V, the output of the clipper will look like Fig. 4-24*b*.

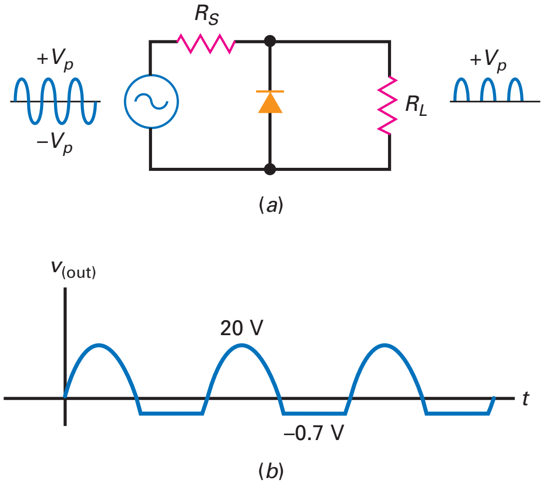
## Defining Conditions

Small-signal diodes have a smaller junction area than rectifier diodes because they are optimized to work at higher frequencies. As a result, they have more bulk resistance. The data sheet of a small-signal diode like the 1N914 lists a forward current of 10 mA at 1 V. Therefore, the bulk resistance is:

$$R_B = \frac{1\text{ V} - 0.7\text{ V}}{10\text{ mA}} = 30\ \Omega$$

Why is bulk resistance important? Because the clipper will not work properly unless the series resistance $R_S$ is much greater than the bulk resistance. Furthermore, the clipper won't work properly unless the series resistance $R_S$ is

**Figure 4-25** (*a*) Negative clipper; (*b*) output waveform.



much smaller than the load resistance. For a clipper to work properly, we will use this definition:

$$\textbf{Stiff clipper: } 100R_B < R_S < 0.01R_L \qquad \textbf{(4-17)}$$

This says that the series resistance must be 100 times greater than the bulk resistance and 100 times smaller than the load resistance. When a clipper satisfies these conditions, we call it a *stiff clipper.* For instance, if the diode has a bulk resistance of 30 Ω, the series resistance should be at least 3 kΩ and the load resistance should be at least 300 kΩ.

## The Negative Clipper

If we reverse the polarity of the diode as shown in Fig. 4-25*a*, we get a *negative clipper.* As you would expect, this removes the negative parts of the signal. Ideally, the output waveform has nothing but positive half-cycles.

The clipping is not perfect. Because of the diode *offset voltage* (another way of saying *barrier potential*), the clipping level is at −0.7 V. If the input signal has a peak of 20 V, the output signal will look like Fig. 4-25*b*.

## The Limiter or Diode Clamp

The clipper is useful for waveshaping, but the same circuit can be used in a totally different way. Take a look at Fig. 4-26*a*. The normal input to this circuit is a signal with a peak of only 15 mV. Therefore, the normal output is the same signal because neither diode is turned during the cycle.

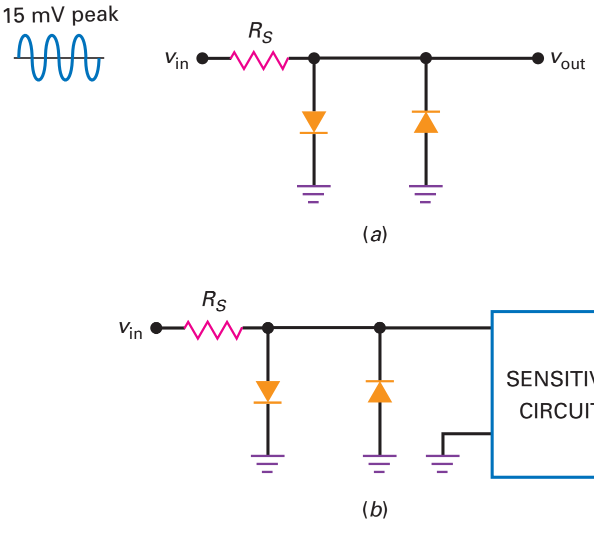
What good is the circuit if the diodes don't turn on? Whenever you have a sensitive circuit, one that cannot have too much input, you can use a positive-negative *limiter* to protect its input, as shown in Fig. 4-26*b*. If the input signal tries to rise above 0.7 V, the output is limited to 0.7 V. On the other hand, if the input signal tries to drop below −0.7 V, the output is limited to −0.7 V. In a circuit like this, normal operation means that the input signal is always smaller than 0.7 V in either polarity.

An example of a sensitive circuit is the *op amp,* an IC that will be discussed in later chapters. The typical input voltage to an op amp is less than 15 mV. Voltages greater than 15 mV are unusual, and voltages greater than 0.7 V are abnormal. A limiter on the input side of an op amp will prevent excessive input voltage from being accidentally applied.

### GOOD TO KNOW

Negative diode clamps are often used on the inputs of digital Transistor-Transistor Logic gates (TTL).

**Figure 4-26** (*a*) Diode clamp; (*b*) protecting a sensitive circuit.



A more familiar example of a sensitive circuit is a moving-coil meter. By including a limiter, we can protect the meter movement against excessive input voltage or current.

The limiter of Fig. 4-26*a* is also called a *diode clamp*. The term suggests clamping or limiting the voltage to a specified range. With a diode clamp, the diodes remain off during normal operation. The diodes conduct only when something is abnormal, when the signal is too large.

## Biased Clippers

The reference level (same as the clipping level) of a positive clipper is ideally zero, or 0.7 V to a second approximation. What can we do to change this reference level?

In electronics, *bias* means applying an external voltage to change the reference level of a circuit. Figure 4-27*a* is an example of using bias to change the reference level of a positive clipper. By adding a dc voltage source in series with the diode, we can change the clipping level. The new $V$ must be less than $V_p$ for normal operation. With an ideal diode, conduction starts as soon as the input

**Figure 4-27** (*a*) Biased positive clipper; (*b*) biased negative clipper.

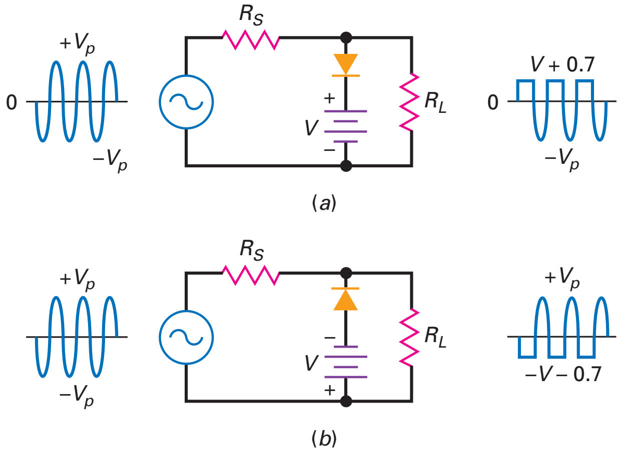
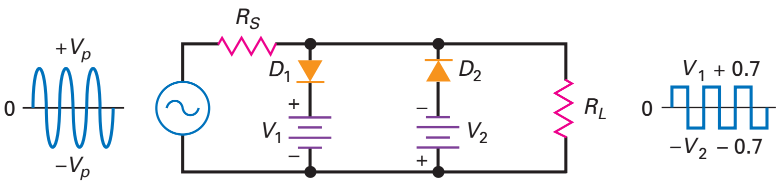


**Figure 4-28** Biased positive-negative clipper.



voltage is greater than $V$. To a second approximation, it starts when the input voltage is greater than $V + 0.7$ V.

Figure 4-27*b* shows how to bias a negative clipper. Notice that the diode and battery have been reversed. Because of this, the reference level changes to $-V - 0.7$ V. The output waveform is negatively clipped at the bias level.

## Combination Clipper

We can combine the two biased clippers as shown in Fig. 4-28. Diode $D_1$ clips off positive parts above the positive bias level, and diode $D_2$ clips off parts below the negative bias level. When the input voltage is very large compared to the bias levels, the output signal is a *square wave,* as shown in Fig. 4-28. This is another example of the signal shaping that is possible with clippers.

## Variations

Using batteries to set the clipping level is impractical. One approach is to add more silicon diodes because each produces a bias of 0.7 V. For instance, Fig. 4-29*a* shows three diodes in a positive clipper. Since each diode has an offset of around 0.7 V, the three diodes produce a clipping level of approximately +2.1 V. The application does not have to be a clipper (waveshaping). We can use the same circuit as a diode clamp (limiting) to protect a sensitive circuit that cannot tolerate more than a 2.1-V input.

Figure 4-29*b* shows another way to bias a clipper without batteries. This time, we are using a voltage divider ($R_1$ and $R_2$) to set the bias level. The bias level is given by:

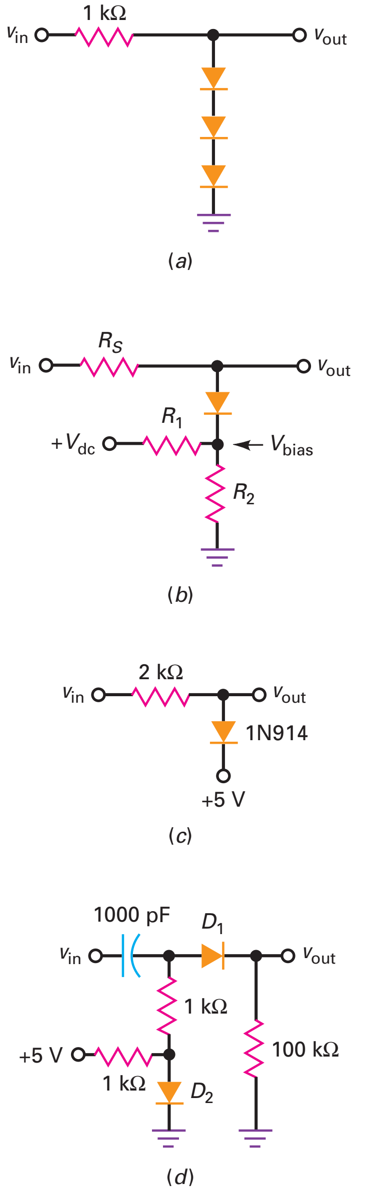
$$V_{\text{bias}} = \frac{R_2}{R_1 + R_2} V_{\text{dc}} \tag{4-18}$$

In this case, the output voltage is clipped or limited when the input is greater than $V_{\text{bias}} + 0.7$ V.

Figure 4-29*c* shows a biased diode clamp. It can be used to protect sensitive circuits from excessive input voltages. The bias level is shown as +5 V. It can be any bias level you want it to be. With a circuit like this, a destructively large voltage of +100 V never reaches the load because the diode limits the output voltage to a maximum value of +5.7 V.

Sometimes a variation like Fig. 4-29*d* is used to remove the offset of the limiting diode $D_1$. Here is the idea: Diode $D_2$ is biased slightly into forward conduction so that it has approximately 0.7 V across it. This 0.7 V is applied to 1 kΩ in series with $D_1$ and 100 kΩ. This means that diode $D_1$ is on the verge of conduction. Therefore, when a signal comes in, diode $D_1$ conducts near 0 V.

**Figure 4-29** (*a*) Clipper using three-diode offset; (*b*) voltage divider biases clipper; (*c*) diode clamp protects above 5.7 V; (*d*) diode $D_2$ biases $D_1$ to remove offset voltage.



# 4-11 Clampers

The diode clamp, which was discussed in the preceding section, protects sensitive circuits. The **clamper** is different, so don't confuse the similar-sounding names. A clamper adds a dc voltage to the signal.

## Positive Clamper

Figure 4-30*a* shows the basic idea for a positive clamper. When a positive clamper has a sine-wave input, it adds a positive dc voltage to the sine wave. Stated another way, the positive clamper shifts the ac reference level (normally zero) up to a dc level. The effect is to have an ac voltage centered on a dc level. This means that each point on the sine wave is shifted upward, as shown on the output wave.

Figure 4-30*b* shows an equivalent way of visualizing the effect of a positive clamper. An ac source drives the input side of the clamper. The Thevenin voltage of the clamper output is the superposition of a dc source and an ac source. The ac signal has a dc voltage of $V_p$ added to it. This is why the entire sine wave of Fig. 4-30*a* has shifted upward so that it has a positive peak of $2V_p$ and a negative peak of zero.

**GOOD TO KNOW**

Clampers are commonly used in IC application circuits to shift the dc level of a signal in a positive or negative direction.

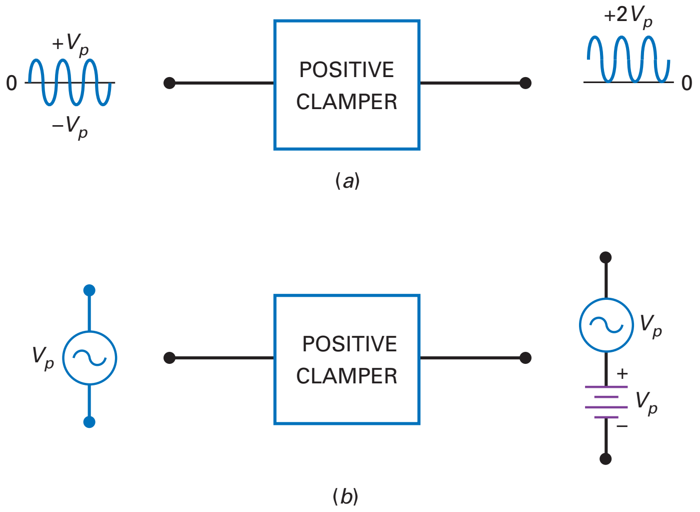
Figure 4-31*a* is a positive clamper. Ideally, here is how it works. The capacitor is initially uncharged. On the first negative half-cycle of input voltage, the diode turns on (Fig. 4-31*b*). At the negative peak of the ac source, the capacitor has fully charged and its voltage is $V_p$ with the polarity shown.

Slightly beyond the negative peak, the diode shuts off (Fig. 4-31*c*). The $R_LC$ time constant is deliberately made much larger than the period $T$ of the signal. We will define *much larger* as at least 100 times greater:

$$\textbf{Stiff clamper: } R_LC > 100T \qquad \textbf{(4-19)}$$

For this reason, the capacitor remains almost fully charged during the off time of the diode. To a first approximation, the capacitor acts like a battery of $V_p$ volts. This is why the output voltage in Fig. 4-31*a* is a positively clamped signal. Any clamper that satisfies Eq. (4-19) is called a *stiff clamper.*

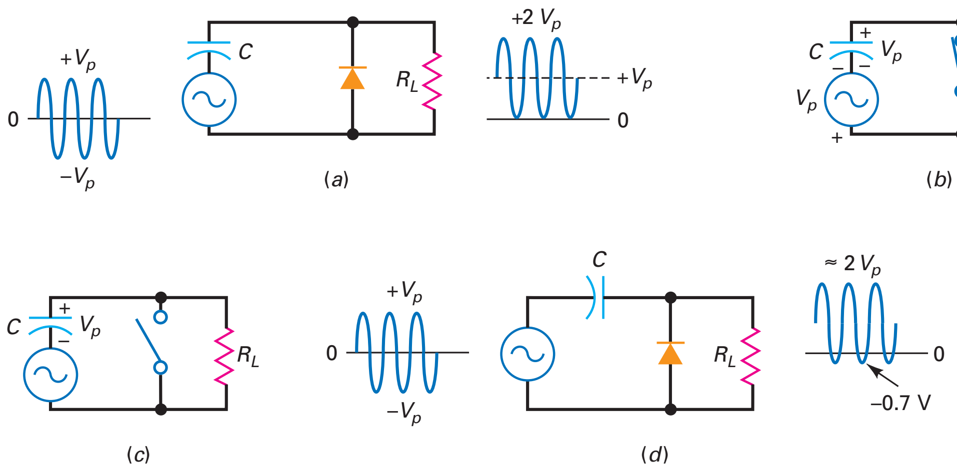
**Figure 4-30** (*a*) Positive clamper shifts waveform upward; (*b*) positive clamper adds a dc component to signal.



(*a*)

(*b*)

**Figure 4-31** (*a*) Ideal positive clamper; (*b*) at the positive peak; (*c*) beyond the positive peak; (*d*) clamper is not quite perfect.



The idea is similar to the way a half-wave rectifier with a capacitor-input filter works. The first quarter-cycle charges the capacitor fully. Then, the capacitor retains almost all of its charge during subsequent cycles. The small charge that is lost between cycles is replaced by diode conduction.

In Fig. 4-31*c*, the charged capacitor looks like a battery with a voltage of $V_p$. This is the dc voltage that is being added to the signal. After the first quarter-cycle, the output voltage is a positively clamped sine wave with a reference level of zero; that is, it sits on a level of 0 V.

Figure 4-31*d* shows the circuit as it is usually drawn. Since the diode drops 0.7 V when conducting, the capacitor voltage does not quite reach $V_p$. For this reason, the clamping is not perfect, and the negative peaks have a reference level of −0.7 V.

## Negative Clamper

What happens if we turn the diode in Fig. 4-31*d* around? We get the negative clamper of Fig. 4-32. As you can see, the capacitor voltage reverses, and the circuit becomes a negative clamper. Again, the clamping is less than perfect because the positive peaks have a reference level of 0.7 V instead of 0 V.

As a memory aid, notice that the diode points in the direction of shift. In Fig. 4-32, the diode points downward, the same direction as the shift of the sine wave. This tells you that it's a negative clamper. In Fig. 4-31*a*, the diode points up, the waveform shifts up, and you have positive clamper.

**Figure 4-32** Negative clamper.

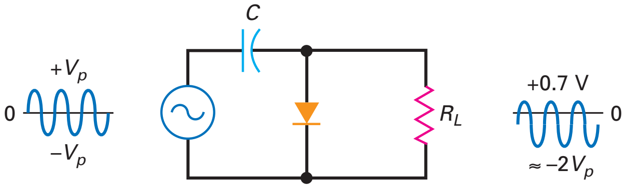
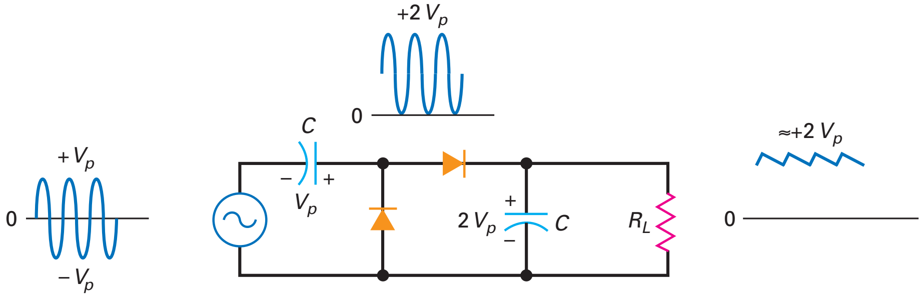


Figure 4-33 Peak-to-peak detector.



Both positive and negative clampers are widely used. For instance, television receivers use a clamper to change the reference level of video signals. Clampers are also used in radar and communication circuits.

A final point. The less-than-perfect clipping and clamping discussed so far are no problem. After we discuss op amps, we will look again at clippers and clampers. At that time, you will see how easy it is to eliminate the barrier-potential problem. In other words, we will look at circuits that are almost perfect.

### Peak-to-Peak Detector

A half-wave rectifier with a capacitor-input filter produces a dc output voltage approximately equal to the peak of the input signal. When the same circuit uses a small-signal diode, it is called a **peak detector.** Typically, peak detectors operate at frequencies that are much higher than 60 Hz. The output of a peak detector is useful in measurements, signal processing, and communications.

If you cascade a clamper and a peak detector, you get a *peak-to-peak detector* (see Fig. 4-33). As you can see, the output of a clamper is used as the input to a peak detector. Since the sine wave is positively clamped, the input to the peak detector has a peak value of $2V_p$. This is why the output of the peak detector is a dc voltage equal to $2V_p$.

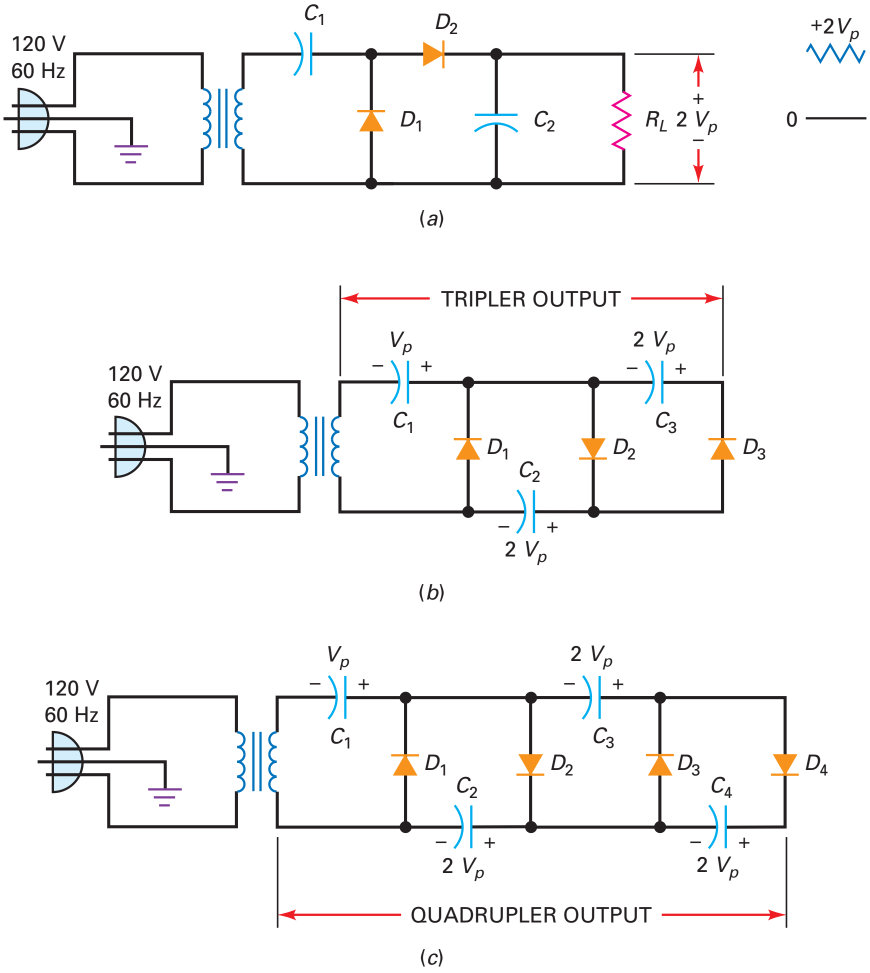
As usual, the *RC* time constant must be much greater than the period of the signal. By satisfying this condition, you get good clamping action and good peak detection. The output ripple will therefore be small.

One application is in measuring nonsinusoidal signals. An ordinary ac voltmeter is calibrated to read the rms value of an ac signal. If you try to measure a nonsinusoidal signal, you will get an incorrect reading with an ordinary ac voltmeter. However, if the output of a peak-to-peak detector is used as the input to a dc voltmeter, it will indicate the peak-to-peak voltage. If the nonsinusoidal signal swings from −20 to + 50 V, the reading is 70 V.

## 4-12 Voltage Multipliers

A peak-to-peak detector uses small-signal diodes and operates at high frequencies. By using rectifier diodes and operating at 60 Hz, we can produce a new kind of power supply called a *voltage doubler.*

**Figure 4-34** Voltage multipliers with floating loads. (*a*) Doubler; (*b*) tripler; (*c*) quadrupler.



## Voltage Doubler

Figure 4-34*a* is a *voltage doubler*. The configuration is the same as a peak-to-peak detector, except that we use rectifier diodes and operate at 60 Hz. The clamper section adds a dc component to the secondary voltage. The peak detector then produces a dc output voltage that is two times the secondary voltage.

Why bother using a voltage doubler when you can change the turns ratio to get more output voltage? The answer is that you don't need to use a voltage doubler at lower voltages. The only time you run into a problem is when you are trying to produce very high dc output voltages.

For instance, line voltage is 120 V rms, or 170 V peak. If you are trying to produce 3400 V dc, you will need to use a 1:20 step-up transformer. Here is where the problem comes in. Very high secondary voltages can be obtained only with bulky transformers. At some point, a designer may decide that it would be simpler to use a voltage doubler and a smaller transformer.

## Voltage Tripler

By connecting another section, we get the *voltage tripler* of Fig. 4-34*b*. The first two sections act like a doubler. At the peak of the negative half-cycle, $D_3$ is forward biased. This charges $C_3$ to $2V_p$ with the polarity shown in Fig. 4-34*b*. The tripler output appears across $C_1$ and $C_3$. The load resistance can be connected across the tripler output. As long as the time constant is long, the output equals approximately3 $V_p$.

## Voltage Quadrupler

Figure 4-34*c* is a *voltage quadrupler* with four sections in *cascade* (one after another). The first three sections are a tripler, and the fourth makes the overall circuit a quadrupler. The first capacitor charges to $V_p$. All others charge to $2V_p$. The quadrupler output is across the series connection of $C_2$ and $C_4$. We can connect a load resistance across the quadrupler output to get an output of $4V_p$.

Theoretically, we can add sections indefinitely, but the ripple gets much worse with each new section. Increased ripple is another reason why **voltage multipliers** (doublers, triplers, and quadruplers) are not used in low-voltage power supplies. As stated earlier, voltage multipliers are almost always used to produce high voltages, well into the hundreds or thousands of volts. Voltage multipliers are the natural choice for high-voltage and low-current devices like the cathode-ray tube (CRT) used in television receivers, oscilloscopes, and computer monitors.

## Variations

All of the voltage multipliers shown in Fig. 4-34 use load resistances that are *floating*. This means that neither end of the load is grounded. Figures 4-35*a*, *b*, and *c* show variations of the voltage multipliers. Figure 4-35*a* merely adds grounds to Fig. 4-34*a*. On the other hand, Figs. 4-35*b* and *c* are redesigns of the tripler (Fig. 4-34*b*) and quadrupler (Fig. 4-34*c*). In some applications, you may see floating-load designs used (such as in the CRT); in others, you may see the grounded-load designs used.

## Full-Wave Voltage Doubler

Figure 4-35*d* shows a full-wave voltage doubler. On the positive half-cycle of the source, the upper capacitor charges to the peak voltage with the polarity shown. On the next half-cycle, the lower capacitor charges to the peak voltage with the indicated polarity. For a light load, the final output voltage is approximately $2V_p$.

The voltage multipliers discussed earlier are half-wave designs; that is, the output ripple frequency is 60 Hz. On the other hand, the circuit of Fig. 4-35*d* is called a *full-wave voltage doubler* because one of the output capacitors is being charged during each half-cycle. Because of this, the output ripple is 120 Hz. This ripple frequency is an advantage because it is easier to filter. Another advantage of the full-wave doubler is that the PIV rating of the diodes need only be greater than $V_p$.

**Figure 4-35** Voltage multipliers with grounded loads, except full-wave doubler. (*a*) Doubler; (*b*) tripler; (*c*) quadrupler; (*d*) full-wave doubler.