$$v_1 = v_a + v_i = v_a \qquad \text{and} \qquad v_a = \frac{R_1}{R_1 + R_F} v_o \tag{3-23}$$

where $R_1$ and $R_F$ constitute a voltage divider across the output voltage. The gain of the *noninverting amplifier* circuit is

$$A_F = \frac{v_o}{v_1} = \frac{R_1 + R_F}{R_1} \tag{3-24}$$

Here again the gain is determined by the feedback network elements $R_1$ and $R_F$. For the noninverting circuit, however, the gain is positive and equal to or greater than unity.

**Example 8**

An op amp is used in the circuit of Fig. 3.23, where input signal $v_s$ is a function of time (a sinusoid or a combination of sinusoids). Derive an expression for $i_o(t)$.

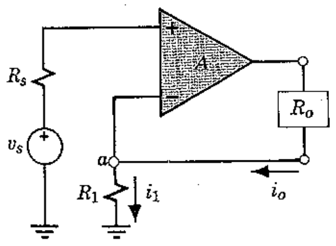


**Figure 3.23** Voltage-current converter

Because no current flows into an ideal op amp, there is no drop across $R_s$, and voltage $v_s(t)$ appears between the + terminal and ground.

Because there is no input voltage across the input terminals of an ideal op amp, $v_a = v_s = i_1 R_1$. But current $i_1$ must be supplied by the feedback current $i_o$. Hence

$$i_o(t) = i_1(t) = \frac{1}{R_1} v_s(t)$$

This noninverting circuit is serving as a voltage-to-current converter. The output current is proportional to the input voltage and independent of $R_s$ and $R_o$.

**Exercise 3-9**

An ideal amplifier is used in the circuit of Fig. 3-22 with $R_1 = 5$ kΩ and $R_F = 500$ kΩ.

(a) For an input voltage $v_1 = 0.01$ V, what is $v_a$? What is $i_i$?

(b) Considering the voltage divider $R_1$-$R_F$, what must $v_o$ be?

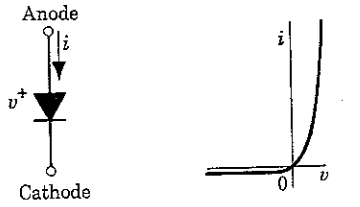
(c) Calculate the voltage gain $v_o/v_i$ by Eq. 3-24.

*Answers*: (a) 0.01 V, 0; (b) 1.01 V; (c) 101.

## 3-7

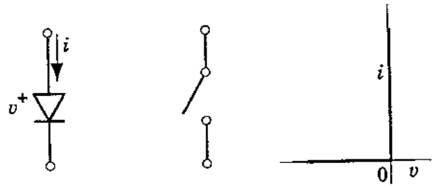
## IDEAL DIODES

A useful addition to our repertoire of electronic circuit elements is the *diode* or *rectifier*. A diode is a two-terminal device that acts as a switch; it permits current to flow readily in one direction but it tends to prevent the flow of current in the



(a) Symbol (b) $i$–$v$ characteristic

Figure 3.24 A real diode



(a) Symbol (b) $i$–$v$ characteristic

Figure 3.25 An ideal diode

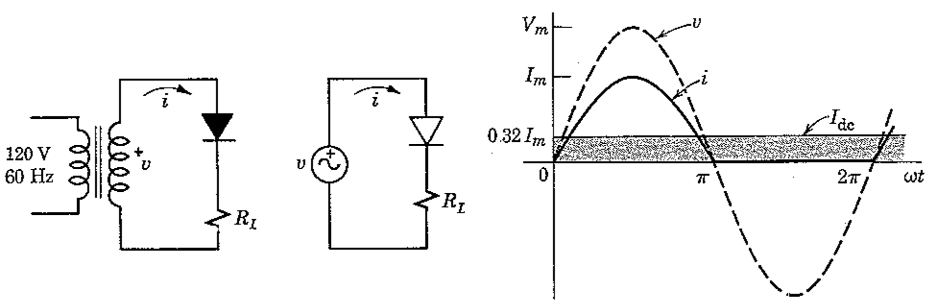
other direction. The direction of easy current flow is indicated by the arrowhead in the symbol of Fig. 3.24a. This is a nonlinear circuit element, and it is useful because it is *not* linear. However, the analysis of circuits containing diodes may be complicated because network theorems based on linearity cannot be used. Figure 3.24b shows the $i$–$v$ characteristic of a semiconductor diode consisting of a junction of dissimilar materials that we will study later. Just as we use ideal models to represent real $R$, $L$, and $C$ components, so we can approximate a real diode by the ideal characteristics shown in Fig. 3.25b. When the anode is positive with respect to the cathode, that is, when voltage $v$ is positive, the "switch" is closed and unlimited current $i$ can flow with no voltage drop. In contrast, when the cathode is positive with respect to the anode, the "switch" is open and no current flows even for large negative values of voltage $v$.

## RECTIFIERS

The nonlinear characteristic of a diode is used to convert alternating current into unidirectional, but pulsating, current in the process called *rectification*. The pulsations are removed in a frequency-selective circuit called a *filter*. Rectifier circuits employ one, two, or four diodes to provide various degrees of rectifying effectiveness. Filter circuits use the energy-storage capabilities of inductors and capacitors to smooth out the pulsations and to provide a steady output current. A combination of ac source, rectifier, and filter is called a *power supply*.

HALF-WAVE RECTIFIER Ideally, a diode should conduct current freely in the forward direction and prevent current flow in the reverse direction. Practical diodes only approach the ideal. Semiconductor diodes, for example, present a small but appreciable voltage drop in the forward direction and permit a finite current to flow in the reverse direction. For most calculations, the reverse current flow is negligibly small and the forward voltage drop can be neglected with little error.

A practical circuit for *half-wave rectification* is shown in Fig. 3.26a. A *transformer* supplied from 120-V, 60-Hz house current provides the desired operating voltage, which is applied to a series combination of diode and load resistance $R_L$. (The transformer, consisting of two multiturn coils wound on a common iron core, provides a voltage "step-down" in direct proportion to the turn ratio.) For approximate analysis, the actual diode is represented by an ideal diode; the internal



(a) Wiring diagram (b) Circuit model (c) Output waveform

Figure 3.26 A half-wave rectifier

resistance of the transformer is neglected For $V = V_m \sin \omega t$, the resulting current is

$$\begin{cases} i = \dfrac{v}{R_L} = \dfrac{V_m \sin \omega t}{R_L} & \text{for } 0 \le \omega t \le \pi \\ i = 0 & \text{for } \pi \le \omega t \le 2\pi \end{cases} \tag{3-25}$$

as shown in Fig. 3.26c.

$$\begin{aligned} I_{dc} &= \frac{1}{2\pi}\int_0^{2\pi} i \, d(\omega t) = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin \omega t}{R_L}\, d(\omega t) + 0 \\ &= \frac{1}{2\pi}\frac{V_m}{R_L}\Big[-\cos \omega t\Big]_0^{\pi} = \frac{V_m}{\pi R_L} = \frac{I_m}{\pi} \end{aligned} \tag{3-26}$$

The current through the load resistance consists of half-sinewaves, and the dc component is approximately 30% of the maximum value.

**Example 9**

An ideal diode is connected in the circuit of Fig. 3.27. For $v = 170 \sin \omega t$ V, predict the current through $R = 5$ kΩ.

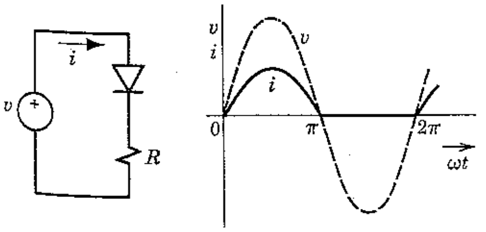


Figure 3.27 Application of diode.

For $0 < \omega t < \pi$, $v$ is positive, the diode switch is closed, and

$$i(t) = \frac{v}{R} = \frac{170 \sin \omega t}{5000} = 34 \sin \omega t \text{ mA}$$

For $\pi < \omega t < 2\pi$, $v$ is negative, the diode switch is open, and current $i = 0$. The resulting current is shown by the solid line. The sinusoidal voltage wave has been *rectified*.

The dc component of the rectified current is (by Eq. 3-26)

$$I_{dc} = \frac{I_m}{\pi} = \frac{34}{\pi} = 10.8 \text{ mA}$$

Exercise 3-10

Find the output voltage, $v_o$, for the circuit of Fig. E3.10.

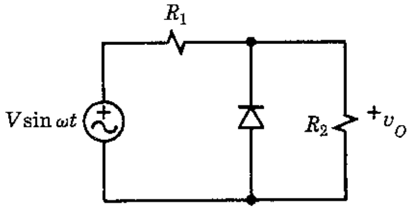
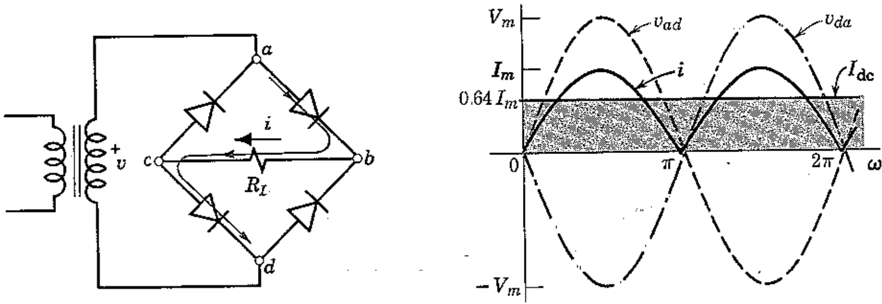


Figure E3.10

*Answer:*

$$v_o = \begin{cases} \dfrac{R_2}{R_1 + R_2} V \sin \omega t & \sin \omega t \geq 0 \\ 0 & \sin \omega t \leq 0 \end{cases}$$

FULL-WAVE RECTIFIER. The bridge rectifier circuit of Fig. 3.28 provides a greater dc value from the same transformer voltage. When the transformer voltage $v = v_{ad}$ is positive, the current flow is along path *abcd* as shown and a half-sinewave of current results. When the applied voltage reverses, the voltage $v_{da} = -v_{ad}$ is positive and the current flow is along path *dbca*. The current through the load resistance is always in the same direction, and the dc component is twice as large as in the half-wave rectifier or



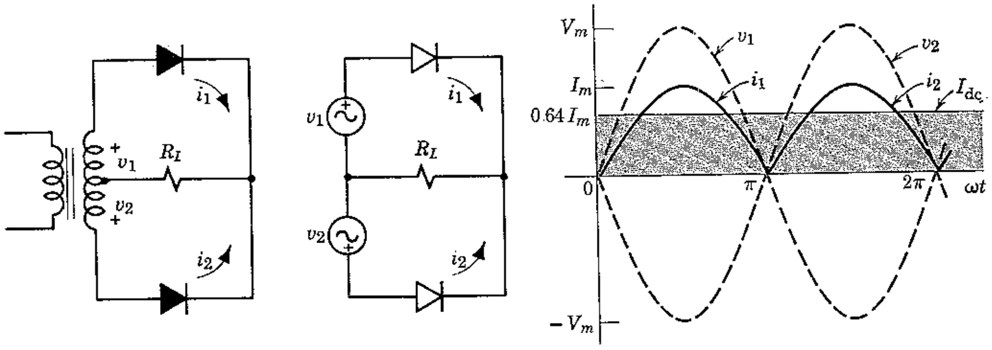
(a) Circuit

(b) Waveforms

Figure 3.28 A full-wave bridge rectifier

$$I_{dc} = \frac{2}{\pi}\frac{V_m}{R_L} = \frac{2I_m}{\pi} \tag{3-27}$$

The bridge circuit is disadvantageous because four diodes are required, and two diodes and their power-dissipating voltage drops are always in series with the load. The full-wave rectifier circuit of Fig. 3.29 uses a more expensive transformer to produce the same result with only two diodes and with higher operating efficiency. The second output winding on the transformer provides a voltage $v_2$ that is 180° out of phase with $v_1$; such a *center-tapped* winding serves as a *phase inverter*. While $v_1$ is positive, current $i_1$ is supplied through diode 1; while $v_1$ is negative, no



(a) Circuit (b) Model (c) Waveforms

Figure 3.29 A full-wave rectifier with phase inverter

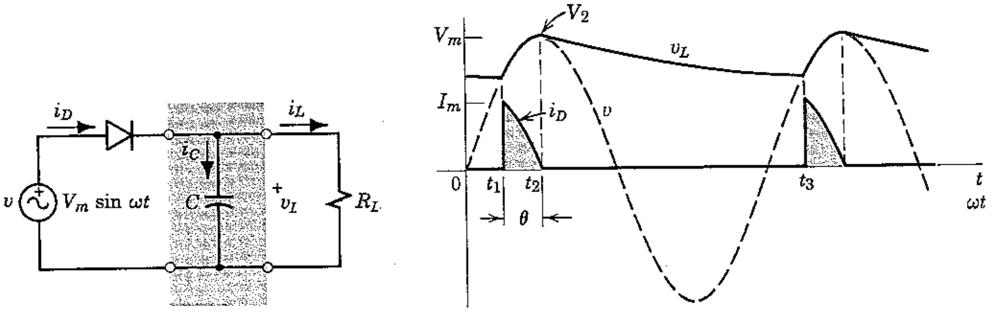
current flows through diode 1 but $v_2$ is positive and, therefore, current $i_2$ is supplied through diode 2. The current through the load resistance is $i_1 + i_2$ and $I_{dc} = 2I_m/\pi$ as in the bridge circuit.

## FILTERS

The desired result of rectification is direct current, but the output currents of the rectifier circuits described obviously contain large alternating components along with the dc component. Using full-wave instead of half-wave rectification reduces the ac component, but the remaining *ripple voltage* (voltage variation) across $R_L$ is still unsatisfactory for most electronic applications which require a nearly steady voltage. An *electrical filter* that passes the dc component while rejecting the ac component will provide the desired direct current.

CAPACITOR FILTER The ripple voltage can be greatly reduced by a filter consisting of a capacitor shunted across the load resistor. The capacitor can be thought of as a "tank" that stores charge during the period when the diode is conducting and releases charge to the load during the nonconducting period.

If the diode is nearly ideal and if the steady state has been reached, the operation is as shown in Fig. 3.30. At time $t = 0$, the source voltage $v$ is zero but



(a) Circuit (b) Voltage and current waveforms

Figure 3.30 A capacitor filter.

the load voltage $v_L = v_C$ is appreciable because the previously charged capacitor is discharging through the load. At $t = t_1$, the increasing supply voltage $v$ slightly exceeds $v_L$ and the diode conducts. The diode current $i_D$ rises abruptly to satisfy the relation $i_C = C\,dv/dt$ and then decreases to zero; the diode switches off when $v$ drops below $v_L$. During the charging period, $t_1 < t < t_2$,

$$v_L = V_m \sin \omega t \tag{3-28}$$

During the discharging period, $t_2 < t < t_3$, the capacitor voltage decays exponentially so that

$$v_L = V_2\, e^{-(t-t_2)/R_L C} \tag{3-29}$$

with a time constant defined by the $RC$ circuit. At time $t_3$, the supply voltage again exceeds the load voltage and the cycle repeats.

The load current $i_L$ is directly proportional to load voltage $v_L$. Because $i_L$ never goes to zero, the average value or dc component is relatively large as compared to the half-wave rectifier alone and the ac component is correspondingly lower. The ripple voltage is greatly reduced by the use of the capacitor.

CAPACITOR FILTER—APPROXIMATE ANALYSIS. If the time constant $R_L C$ is large compared to the period $T$ of the supply voltage, the decay in voltage $v_C = v_L$ will be small, and the ripple voltage $V_r = \Delta v_C$ will be small. The magnitude of the ripple can be estimated by assuming that $V_r$ is small, the charging interval $t_2 - t_1$ is small, and $v_C$ is nearly constant. Under this assumption, all the load current is supplied by the capacitor, and the charge transferred to the load is

$$\Delta q = I_{\text{dc}} T = C \Delta v_C = C V_r \tag{3-30}$$

Solving for the ripple voltage,

$$V_r = \frac{I_{\text{dc}} T}{C} = \frac{I_{\text{dc}}}{fC} = \frac{V_{\text{dc}}}{f R_L C} \tag{3-31}$$

This relation holds for a half-wave rectifier; a similar equation can be derived for a full-wave rectifier. By using this approximation, the performance of an existing filter can be predicted or a filter can be designed to meet specifications as in Example 10.

**Example 10**

A load ($R_L = 3330\ \Omega$) is to be supplied with 50 V at 15 mA with a ripple voltage no more than 1% of the dc voltage. Design a rectifier–filter to meet these specifications.

Assuming a 120-V, 60-Hz supply and the half-wave rectifier with capacitor filter of Fig. 3.30a, Eq. 3-31 is applicable. Solving for $C$,

$$C = \frac{V_{\text{dc}}/V_r}{f R_L} = \frac{100}{60 \times 3330} = 500\ \mu\text{F}$$

For a peak value of 50 V, the rms value of transformer secondary voltage should be $50/\sqrt{2} = 35.4$ V. The transformer turn ratio should be

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{120}{35.4} = 3.39$$

### Exercise 3-11

Redraw Fig. 3.30b to show the load voltage $V_L$ and the diode current $i_D$ for a full-wave rectifier-capacitor filter supply. For a full-wave rectifier:

(a) How many current pulses are there per second?
(b) Derive the equation for $V_r$ for this case.
(c) What size capacitor is needed to meet the specifications of Example 10?

*Answers*: (a) $2f$; (b) $V_r = V_{dc}/2fR_LC$; (c) 250 $\mu$F

## 3-8
## WAVESHAPING CIRCUITS

A major virtue of electronic circuits is the ease, speed, and precision with which voltage and current waveforms can be controlled. Some of the basic waveshaping functions are illustrated by a radar pulse-train generator. The word *radar* stands

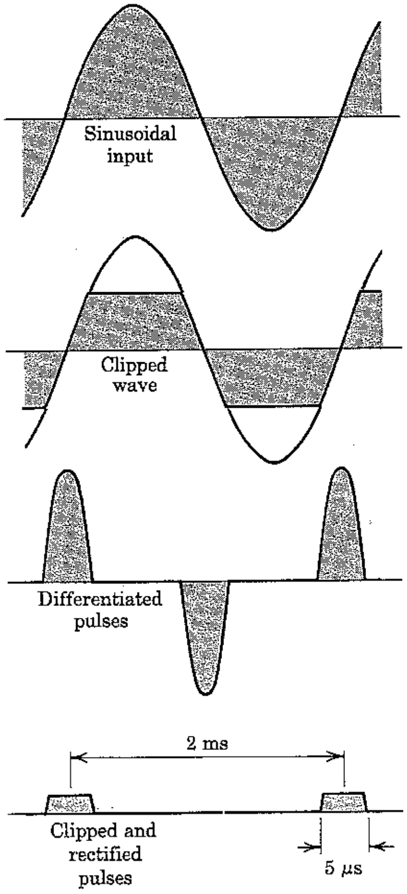


Figure 3.31 Generation of a train of timing pulses.

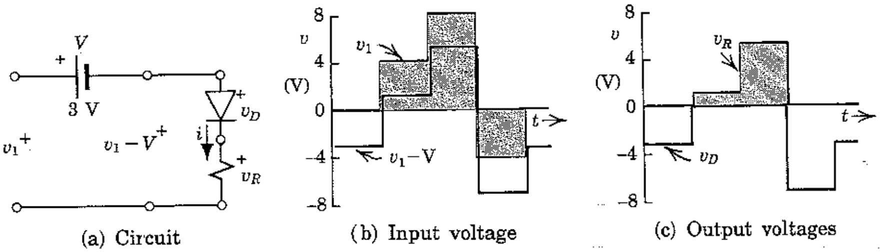
for *ra*dio *d*etection *a*nd *r*anging. A very short burst of high-intensity radiation is transmitted in a given direction; a return echo indicates the presence, distance, direction, and speed of a reflecting object. The operation of a radar system requires a precisely formed series of timing pulses. Typically, these may be of 5 μs duration with a repetition rate of 500 pulses per second. Starting with a 500-Hz sinusoidal generator, the pulse train could be developed as shown in Fig. 3.31. Can you visualize some relatively simple electronic circuits that would perform the indicated functions?

## CLIPPING

To remove an undesired portion of a signal, we can use a *clipping circuit* consisting of a diode, a resistance, and a voltage source. In Fig. 3.32, the input signal $v_1$ varies with time as shown; we are interested in output signals $v_R$ and $v_D$. The sum of the voltages around the loop is zero and the voltage relations are

$$v_D + v_R = v_1 - V \qquad v_R = v_1 - V - v_D \qquad v_D = v_1 - V - v_R \qquad (3\text{-}32)$$

The behavior of the circuit depends on the state of the diode switch; it is closed when $v_D + v_R = v_1 - V$ (plotted in Fig. 3.32b) is positive. With the diode switch closed, $v_D = 0$ and $v_1 - V$ appears across $R$. At all other times, $v_D$ is negative and the diode is open; no current flow in $R$ and $v_R = 0$; this part of the signal has been *clipped*. In other words, the battery shifts the signal down and the diode cuts it off.



(a) Circuit (b) Input voltage (c) Output voltages

Figure 3.32 A clipping circuit.

The waveshaping function performed by the circuit depends on how we arrange the circuit components.

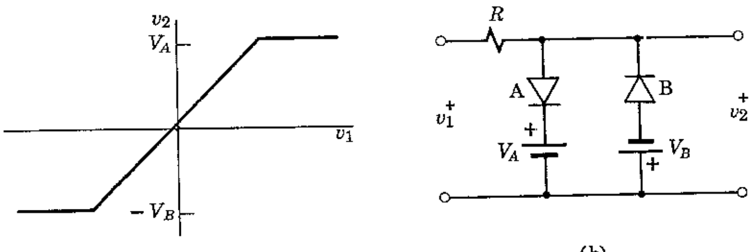
### Exercise 3-12

(a) In the circuit of Fig. 3.32a, $v_1 = 6 \sin \omega t$ V. Sketch $v_R$ for one cycle.

(b) Reverse the diode connections and repeat part (a).

*Answers:* (a) The signal below $v_1 = +3$ V is clipped; (b) $v_R = 0$ for $30° < \omega t < 150°$, $v_R = 6 \sin \omega t - 3$ V elsewhere.

One common type of *clipping* circuit provides an output voltage $v_2$ equal to (or proportional to) the input voltage $v_1$ up to a certain value $V$; above $V$ the wave



(a) (b)

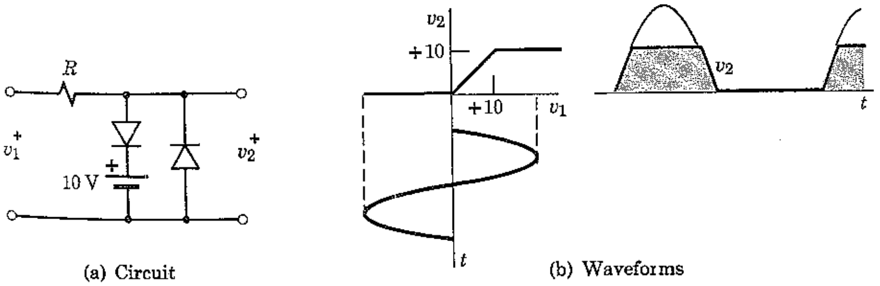
Figure 3.33 Clipping characteristic and circuit.

is clipped off. If both positive and negative peaks are to be clipped, the desired *transfer characteristic* $v_2$ versus $v_1$ is as shown in Fig. 3.33a. The diode circuit for this type of clipping is shown in Fig. 3.33b. The *bias* voltages are set so that diode A conducts whenever $v_1 > V_A$ and diode B conducts whenever $v_1 < -V_B$. When $-V_B < v_1 < V_A$, neither diode conducts and voltage $v_1$ appears across the output terminals. When either diode is conducting, the difference between $v_1$ and $v_2$ appears as a voltage drop across $R$. The effect of an asymmetric clipping circuit on a sinewave is illustrated in Example 11.

**Example 11**

A sinewave $v_1 = 20 \sin \omega t$ V is applied to the circuit of Fig. 3.34a. Draw the transfer characteristic and predict the output voltage $v_2$.

In this circuit the first diode and the 10-V battery provide clipping for voltages greater than +10 V. With $V_B = 0$, the second diode provides clipping of all negative voltages or rectification. The transfer characteristic and the resulting output are as shown in Fig. 3.34b.

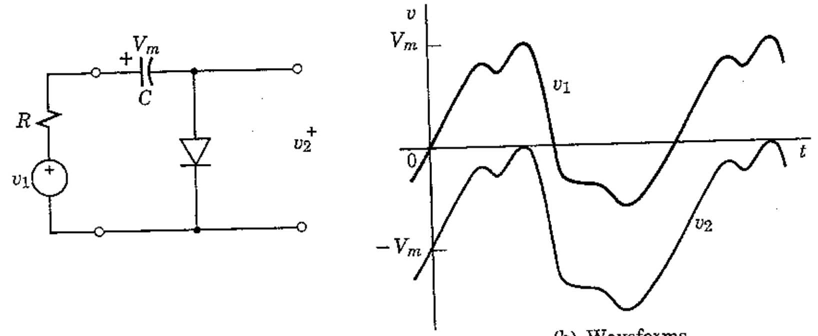


(a) Circuit (b) Waveforms

Figure 3.34 A clipping and rectifying circuit

## CLAMPING

To provide satisfactory pictures in television receivers, the peak values of certain variable signal voltages must be held or *clamped* at predetermined levels. In passing through ordinary amplifiers, the dc reference level is lost and a *clamper* or *dc restorer* is necessary to return the signal to its original form.



(a) Circuit (b) Waveforms

**Figure 3.35** A diode clamping circuit

In the circuit of Fig. 3.35a, if $R$ is small the capacitor tends to charge up to the positive peak value of the input wave, just as in the half-wave rectifier with capacitor. When the polarity of $v_1$ reverses, the capacitor voltage remains at $V_m$ because the diode prevents current flow in the opposite direction. Neglecting the small voltage across $R$, the output voltage across the diode is

$$v_2 = v_1 - V_m \tag{3-33}$$

The signal waveform is unaffected, but a dc value just equal to the peak value of the signal has been introduced. The positive peak is said to be clamped at zero

If the amplitude of the input signal changes, the dc voltage across $C$ also changes (after a few cycles) and the output voltage again just touches the axis. If the diode is reversed, the negative peaks are clamped at zero. If a battery is inserted in series with the diode, the reference level of the output may be maintained at voltage $V_B$.

Clamping and rectifying are related waveshaping functions performed by the same combination of diode and capacitor. In the rectifier the variable component is rejected and the dc value is transmitted; in the clamper the variable component is transmitted and the dc component is restored

## Example 12

Design a circuit that will clamp the minimum point of any periodic signal to $-5$ V.

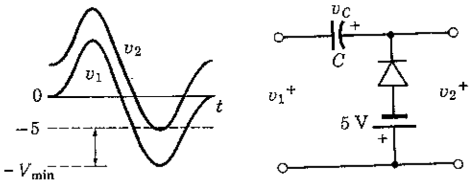


**Figure 3.36** Designing a clamping circuit.

In Fig 3.36, the output is to be

$$v_2 = v_1 + (V_{\min} - 5) = v_1 + v_C$$

Therefore, the capacitor must charge up to the voltage $v_C = V_{\min} - 5$ with the polarity shown.

When the input signal is negative with a magnitude greater than 5 V, current must flow through the diode, which must be connected as shown.