Diode Applications

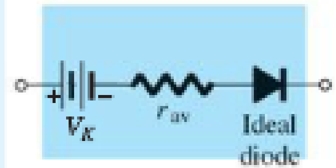
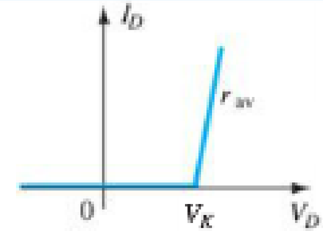
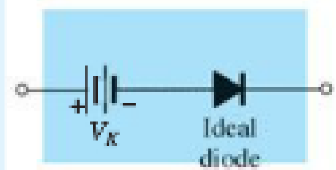
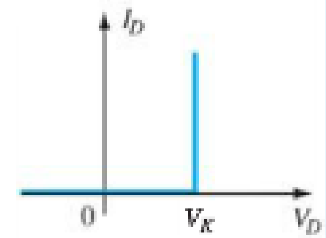
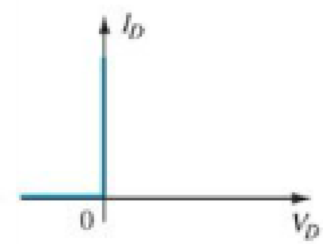
Topic 2 (Chapter 2)

Agenda

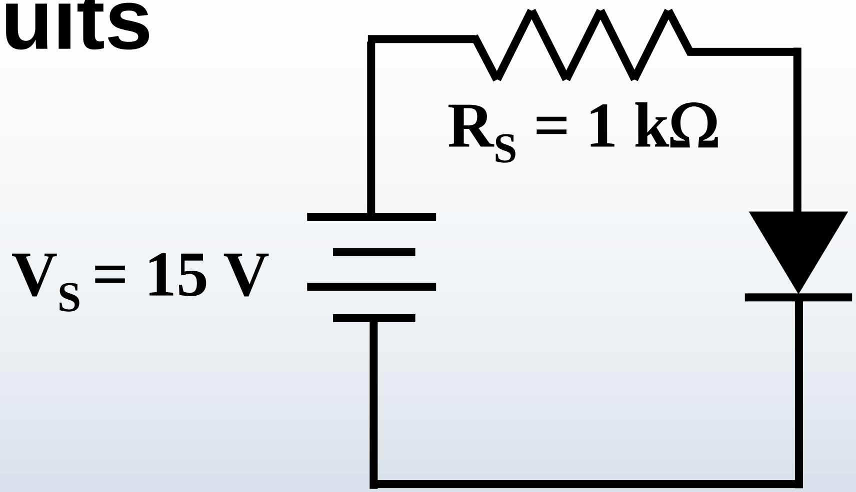
- Techniques for solving diode circuits
- Load-line analysis
- Series, parallel, and series-parallel diode networks
- Rectification
- Clipper and clamper

Summary Table

Diode Equivalent Circuits (Models)

Type	Conditions	Model	Characteristics
Piecewise-linear model 3rd Approximation			
Simplified model 2nd Approximation or Constant Voltage Drop Model	$R_{network} \gg r_{av}$		
Ideal device 1st Approximation	$R_{network} \gg r_{av}$ $E_{network} \gg V_K$		

Solving Diode Circuits



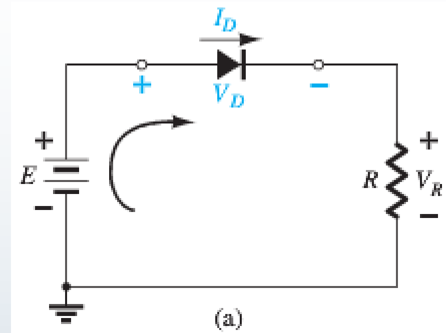
A circuit like this can be solved in several ways:

1. Use the <u>first</u> approximation or ideal equivalent circuit
2. Use the <u>second</u> approximation or simplified equivalent circuit or constant voltage drop model
3. Use the <u>third</u> approximation or piecewise linear equivalent circuit
4. Use a circuit simulator like Pspice or MultiSim
5. Use the diode's characteristic curve (load line analysis)

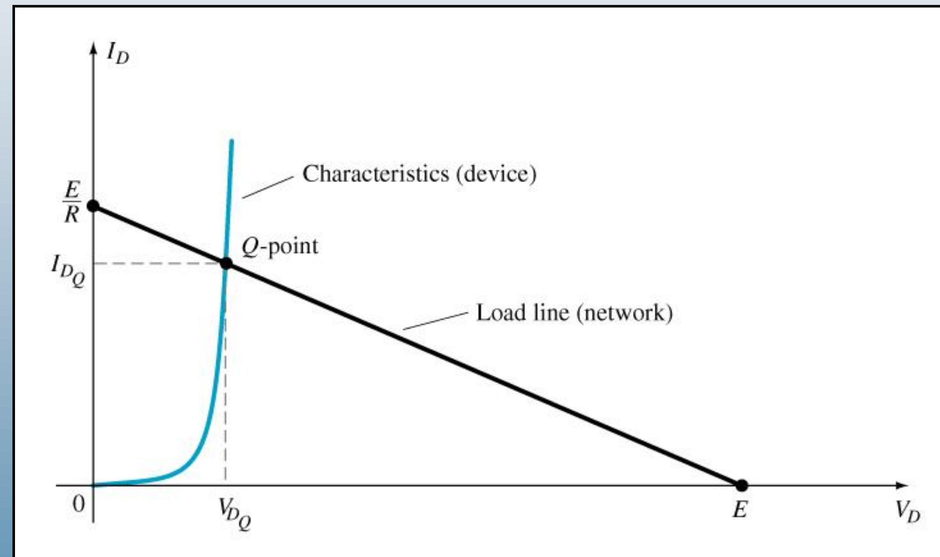
Load-Line Analysis

$$+E - V_D - V_R = 0$$

$$\boxed{E = V_D + I_D R}$$



The load line plots all possible combinations of diode current (I_D) and voltage (V_D) for a given circuit. The maximum I_D equals E/R, and the maximum V_D equals E.



The point where the load line and the characteristic curve intersect is the Q-point, which identifies I_D and V_D for a particular diode in a given circuit.

Load-Line Analysis

- The solution found by load-line analysis is similar to that obtained by a simultaneous solution of

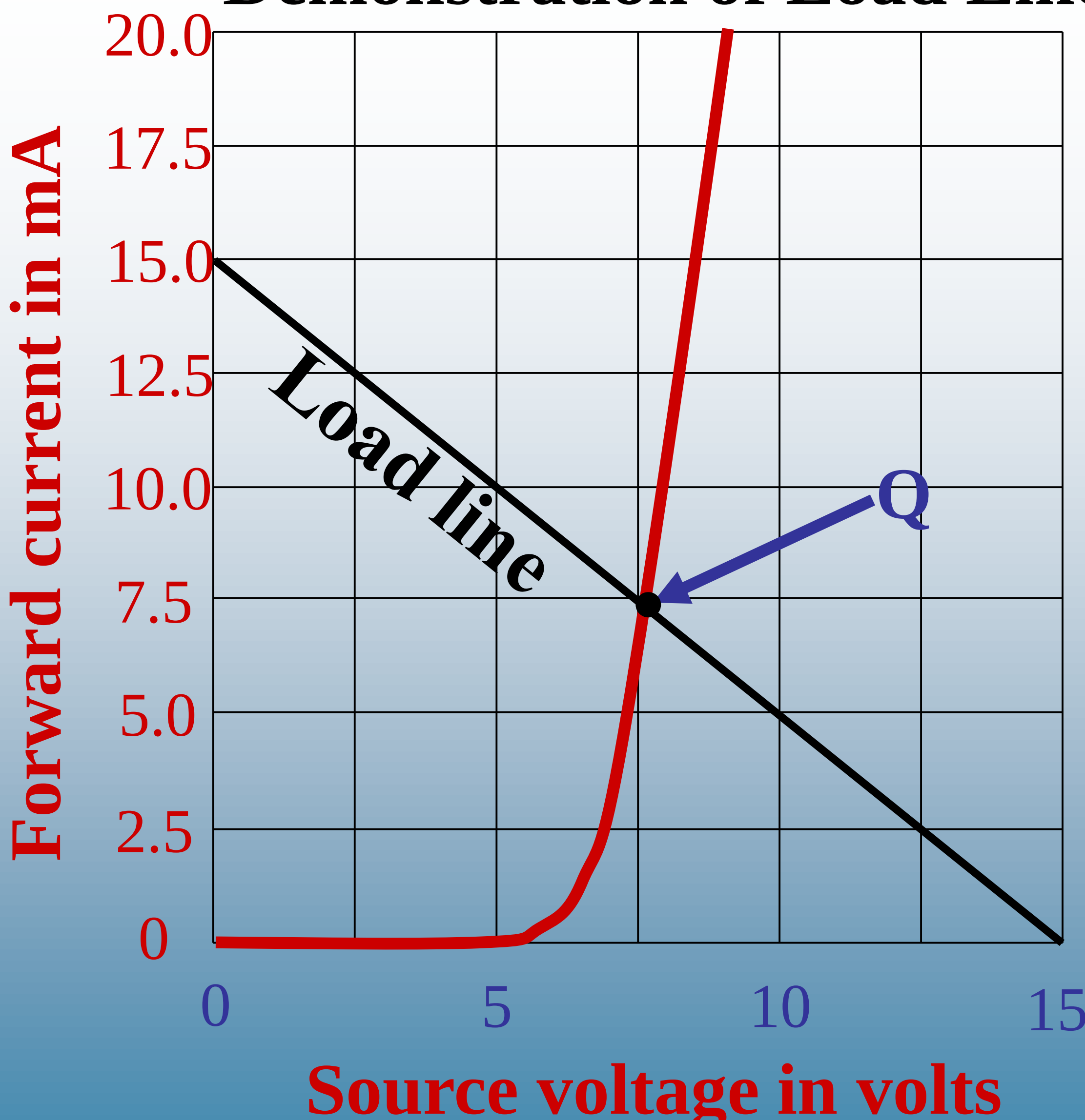
$$I_D = \frac{E}{R} - \frac{V_D}{R}$$

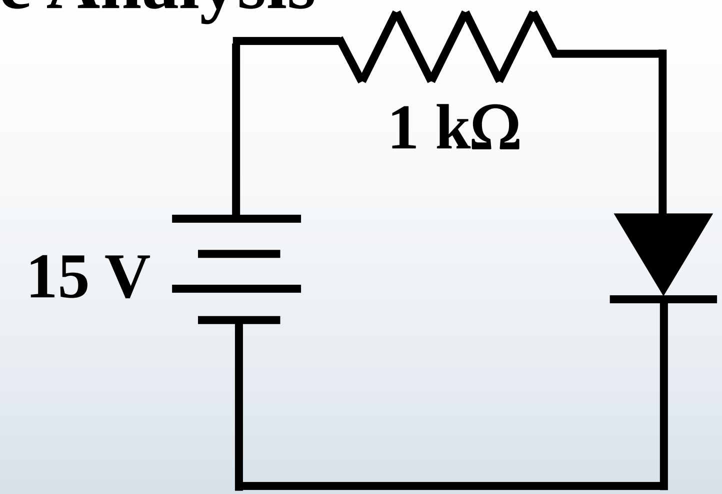
$$I_D = I_s(e^{V_D/nV_T} - 1)$$

(assuming this theoretical diode curve is very close to the actual curve.)

- The mathematics involved would require the use of nonlinear techniques that are beyond the needs and scope of this course.

Demonstration of Load Line Analysis





$$I_{SAT} = \frac{15\ \text{V}}{1\ \text{k}\Omega} = 15\ \text{mA}$$

$$V_{CUTOFF} = 15\ \text{V}$$

Q is the operating point or quiescent point

Series Diode Configurations

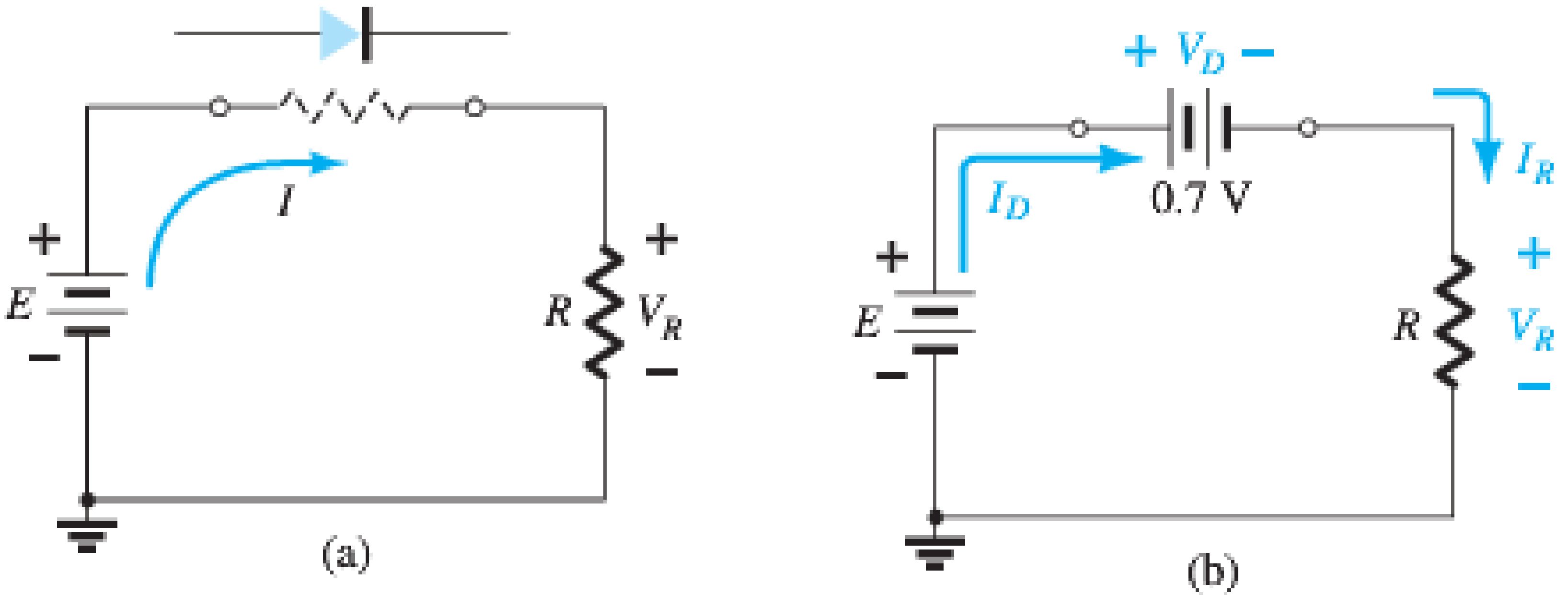


FIG. 2.9

(a) Determining the state of the diode of Fig. 2.8; (b) substituting the equivalent model for the "on" diode of Fig. 2.9a.

$$\boxed{V_D = V_K}$$

$$\boxed{V_R = E - V_K}$$

$$\boxed{I_D = I_R = \frac{V_R}{R}}$$

Reversing the diode

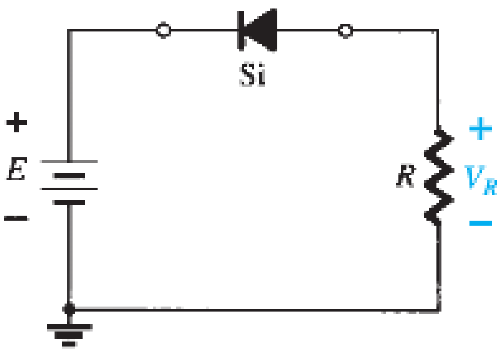


FIG. 2.10
Reversing the diode of Fig. 2.8.

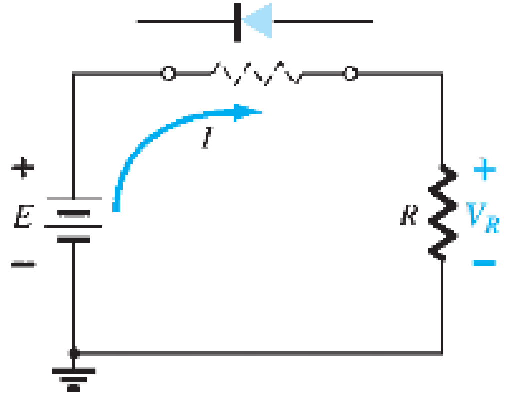


FIG. 2.11
Determining the state of the diode of Fig. 2.10.

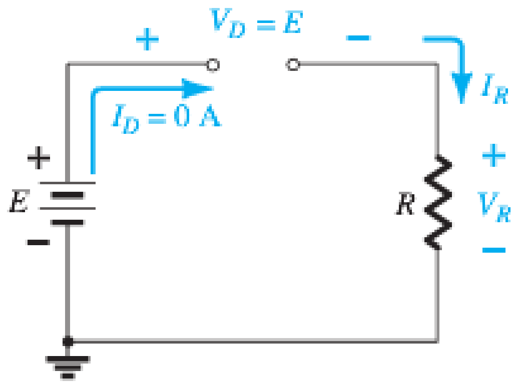


FIG. 2.12
Substituting the equivalent model for the "off" diode of Fig. 2.10.

$$V_R = I_R R = I_D R = (0\ \mathrm{A})R = \mathbf{0\ V}$$

EXAMPLE 2.4 For the series diode configuration of Fig. 2.13, determine V_D, V_R, and I_D.

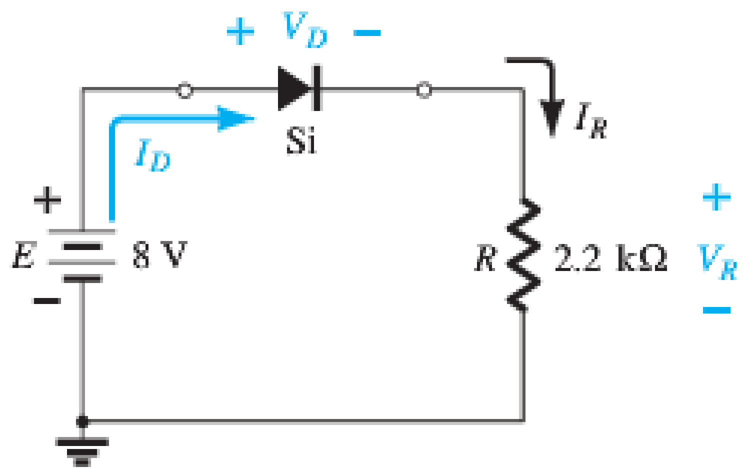


FIG. 2.13
Circuit for Example 2.4.

Solution: Since the applied voltage establishes a current in the clockwise direction to match the arrow of the symbol and the diode is in the "on" state,

$$V_D = \mathbf{0.7\ V}$$

$$V_R = E - V_D = 8\text{ V} - 0.7\text{ V} = \mathbf{7.3\ V}$$

$$I_D = I_R = \frac{V_R}{R} = \frac{7.3\text{ V}}{2.2\text{ k}\Omega} \cong \mathbf{3.32\ mA}$$

EXAMPLE 2.5 Repeat Example 2.4 with the diode reversed.

Solution: Removing the diode, we find that the direction of I is opposite to the arrow in the diode symbol and the diode equivalent is the open circuit no matter which model is employed. The result is the network of Fig. 2.14, where $I_D = \mathbf{0\ A}$ due to the open circuit. Since $V_R = I_R R$, we have $V_R = (0)R = \mathbf{0\ V}$. Applying Kirchhoff's voltage law around the closed loop yields

$$E - V_D - V_R = 0$$

and

$$V_D = E - V_R = E - 0 = E = 8\ \text{V}$$

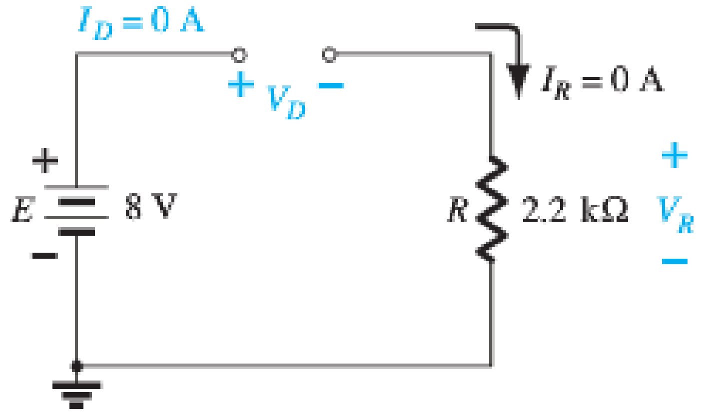


FIG. 2.14
Determining the unknown quantities for Example 2.5.

EXAMPLE 2.6 For the series diode configuration of Fig. 2.16, determine V_D, V_R, and I_D.

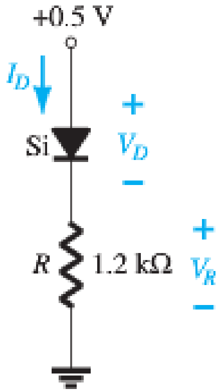


FIG. 2.16
Series diode circuit for Example 2.6.

Solution: Although the "pressure" establishes a current with the same direction as the arrow symbol, the level of applied voltage is insufficient to turn the silicon diode "on." The point of operation on the characteristics is shown in Fig. 2.17, establishing the open-circuit equivalent as the appropriate approximation, as shown in Fig. 2.18. The resulting voltage and current levels are therefore the following:

$$I_D = \mathbf{0\ A}$$

$$V_R = I_R R = I_D R = (0\ \text{A})\, 1.2\ \text{k}\Omega = \mathbf{0\ V}$$

and

$$V_D = E = \mathbf{0.5\ V}$$

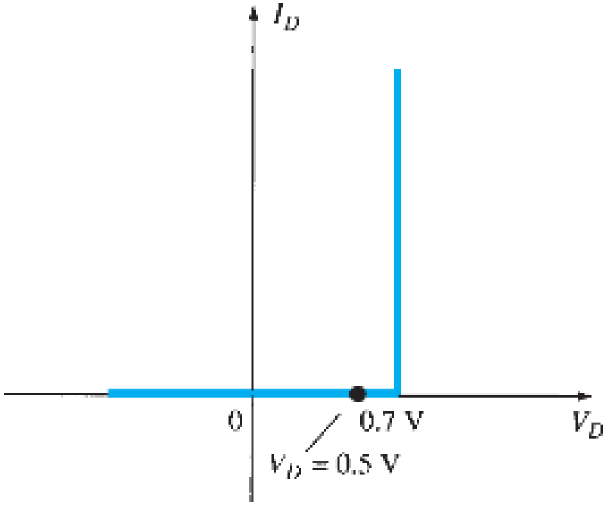


FIG. 2.17
Operating point with $E = 0.5$ V.

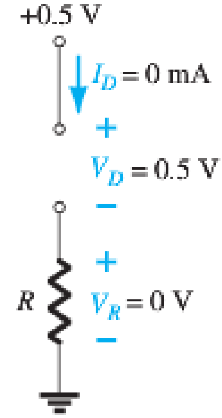


FIG. 2.18
Determining I_D, V_R, and V_D for the circuit of Fig. 2.16.

EXAMPLE 2.7 Determine V_o and I_D for the series circuit of Fig. 2.19.

Assume 1.8V forward voltage drop for the red LED.

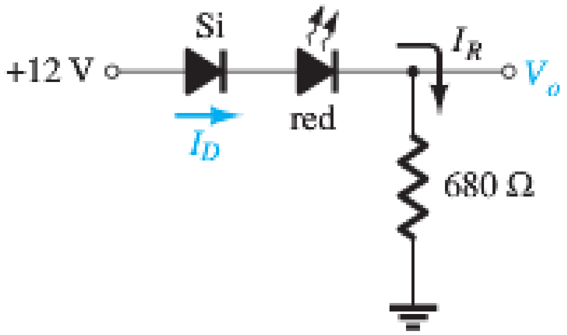


FIG. 2.19
Circuit for Example 2.7.

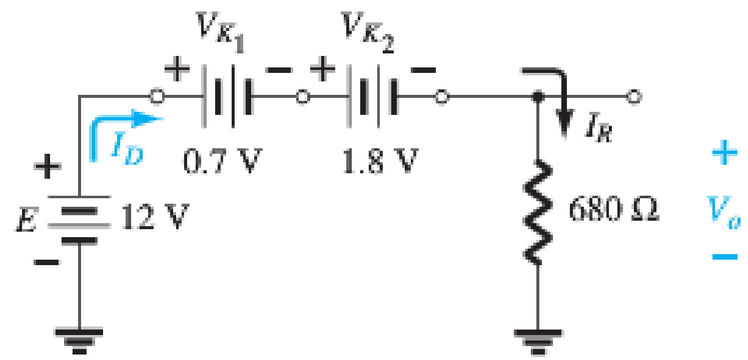


FIG. 2.20
Determining the unknown quantities for Example 2.7.

Solution: An attack similar to that applied in Example 2.4 will reveal that the resulting current has the same direction as the arrowheads of the symbols of both diodes, and the network of Fig. 2.20 results because $E = 12\text{ V} > (0.7\text{ V} + 1.8\text{ V}$ [Table 1.8]$) = 2.5\text{ V}$. Note the redrawn supply of 12 V and the polarity of V_o across the 680-Ω resistor. The resulting voltage is

$$V_o = E - V_{K_1} - V_{K_2} = 12\text{ V} - 2.5\text{ V} = \mathbf{9.5\text{ V}}$$

and

$$I_D = I_R = \frac{V_R}{R} = \frac{V_o}{R} = \frac{9.5\text{ V}}{680\ \Omega} = \mathbf{13.97\text{ mA}}$$

EXAMPLE 2.8 Determine I_D, V_{D_2}, and V_o for the circuit of Fig. 2.21.

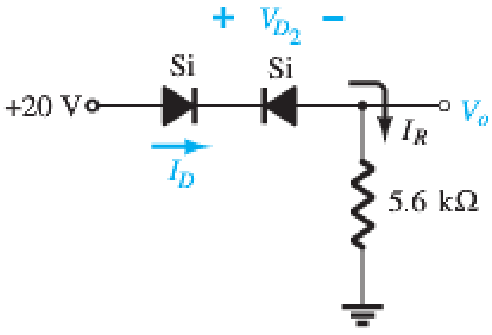


FIG. 2.21
Circuit for Example 2.8.

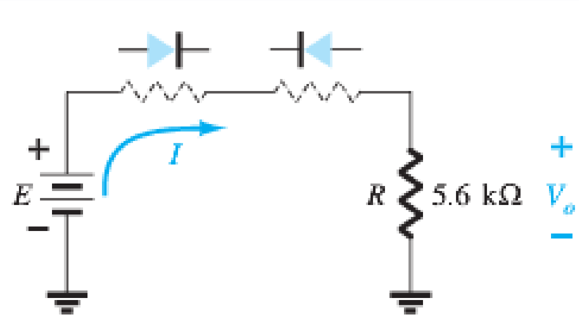


FIG. 2.22
Determining the state of the diodes of Fig. 2.21.

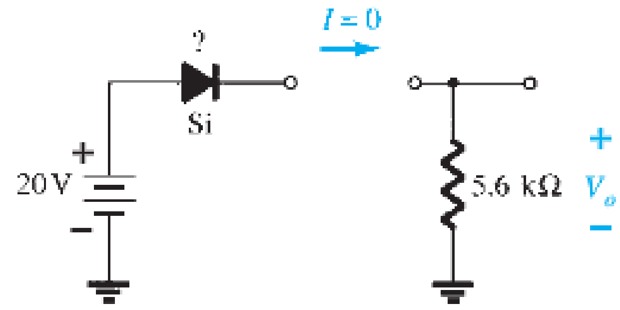


FIG. 2.23
Substituting the equivalent state for the open diode.

For an actual practical diode, when
$I_D = 0$ A, $V_D = 0$ V (and vice versa)

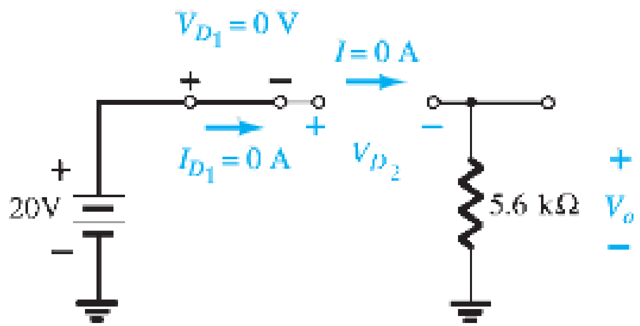


FIG. 2.24
Determining the unknown quantities for the circuit of Example 2.8.

$$V_o = I_R R = I_D R = (0\text{ A})R = \mathbf{0\ V}$$

and
$$V_{D_2} = V_{\text{open circuit}} = E = \mathbf{20\ V}$$

Applying Kirchhoff's voltage law in a clockwise direction gives

$$E - V_{D_1} - V_{D_2} - V_o = 0$$

and
$$V_{D_2} = E - V_{D_1} - V_o = 20\text{ V} - 0 - 0 = \mathbf{20\ V}$$

with
$$V_o = \mathbf{0\ V}$$

EXAMPLE 2.9 Determine I, V_1, V_2, and V_o for the series dc configuration of Fig. 2.25.

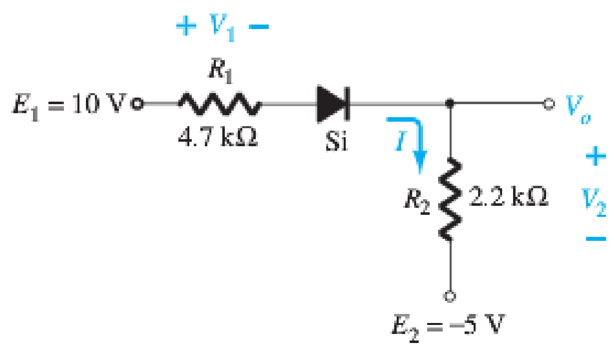


FIG. 2.25
Circuit for Example 2.9.

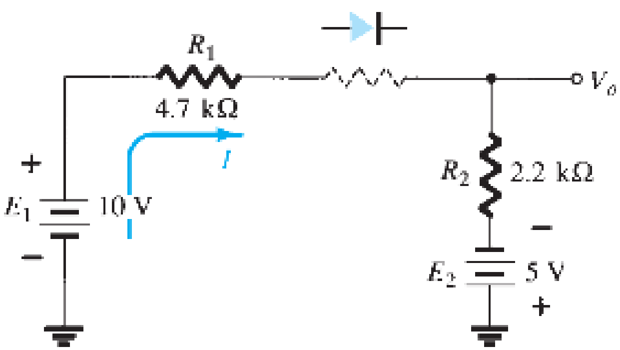


FIG. 2.26
Determining the state of the diode for the network of Fig. 2.25.

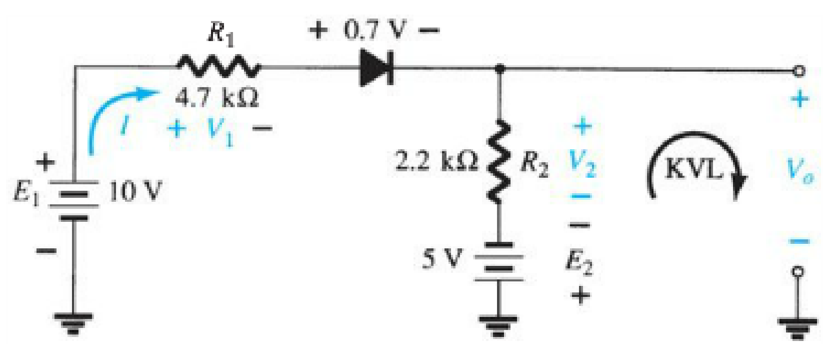


FIG. 2.27
Determining the unknown quantities for the network of Fig. 2.25. KVL, Kirchhoff voltage loop.

The resulting current through the circuit is

$$I = \frac{E_1 + E_2 - V_D}{R_1 + R_2} = \frac{10\text{ V} + 5\text{ V} - 0.7\text{ V}}{4.7\text{ k}\Omega + 2.2\text{ k}\Omega} = \frac{14.3\text{ V}}{6.9\text{ k}\Omega}$$
$$\cong \mathbf{2.07\ mA}$$

$$V_1 = IR_1 = (2.07\text{ mA})(4.7\text{ k}\Omega) = \mathbf{9.73\ V}$$
$$V_2 = IR_2 = (2.07\text{ mA})(2.2\text{ k}\Omega) = \mathbf{4.55\ V}$$

$$-E_2 + V_2 - V_o = 0$$
$$V_o = V_2 - E_2 = 4.55\text{ V} - 5\text{ V} = \mathbf{-0.45\ V}$$

PARALLEL AND SERIES–PARALLEL CONFIGURATIONS

- The methods applied for series diode configurations can be extended to the analysis of parallel and series–parallel configurations.
- For each area of application, simply match the sequential series of steps applied to series diode configurations.

EXAMPLE 2.10 Determine V_o, I_1, I_{D_1}, and I_{D_2} for the parallel diode configuration of Fig. 2.28.

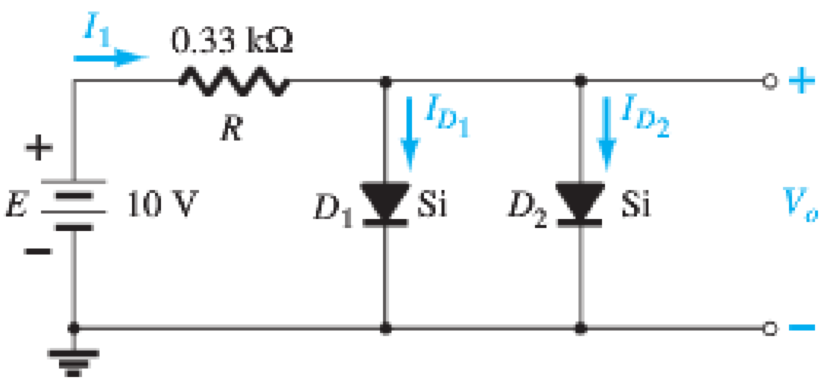


FIG. 2.28
Network for Example 2.10.

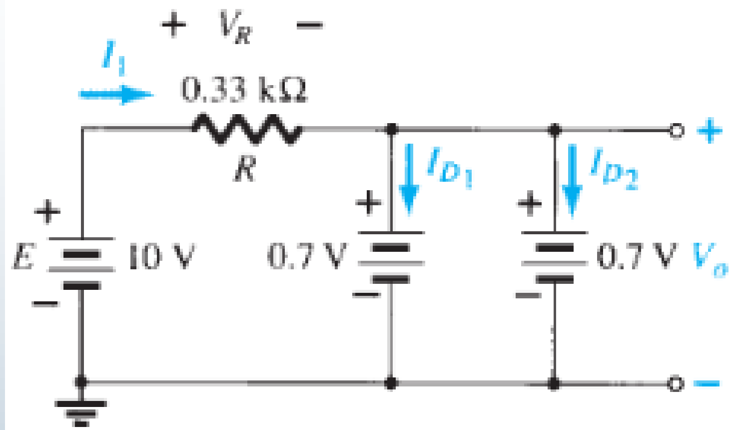


FIG. 2.29
Determining the unknown quantities for the network of Example 2.10.

$$V_o = \mathbf{0.7\ V}$$

The current is

$$I_1 = \frac{V_R}{R} = \frac{E - V_D}{R} = \frac{10\text{ V} - 0.7\text{ V}}{0.33\text{ k}\Omega} = \mathbf{28.18\ mA}$$

Assuming diodes of similar characteristics, we have

$$I_{D_1} = I_{D_2} = \frac{I_1}{2} = \frac{28.18\text{ mA}}{2} = \mathbf{14.09\ mA}$$

EXAMPLE 2.11 In this example there are two LEDs that can be used as a polarity detector. Apply a positive source voltage and a green light results. Negative supplies result in a red light. Packages of such combinations are commercially available.

Find the resistor R to ensure a current of 20 mA through the "on" diode for the configuration of Fig. 2.30. Both diodes have a reverse breakdown voltage of 3 V and an average turn-on voltage of 2 V.

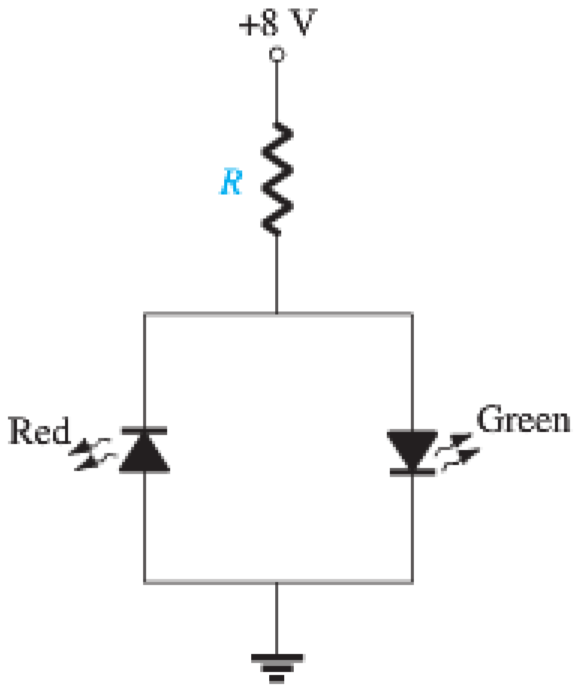


FIG. 2.30
Network for Example 2.11.

$$I = 20\text{ mA} = \frac{E - V_{\text{LED}}}{R} = \frac{8\text{ V} - 2\text{ V}}{R}$$

$$R = \frac{6\text{ V}}{20\text{ mA}} = \mathbf{300\ \Omega}$$

Home Reading Assignment from the Textbook:
Understand the situation what happens if the green LED is replaced with a blue LED and how to remedy the situation.

EXAMPLE 2.12 Determine the voltage V_o for the network of Fig. 2.35.

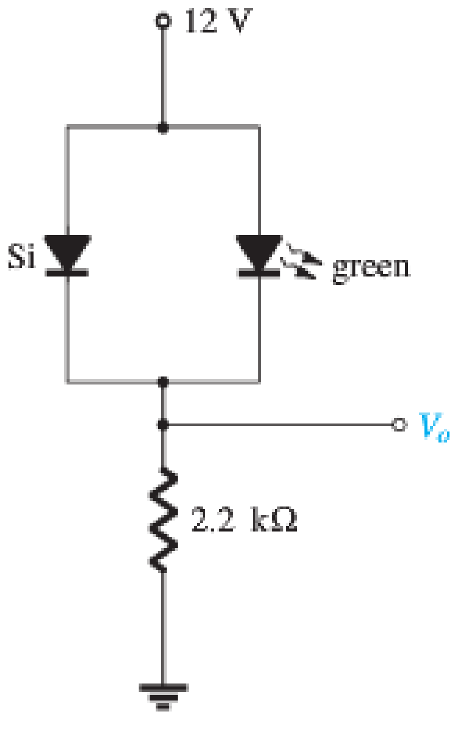


FIG. 2.35
Network for Example 2.12.

$$V_o = 12\text{ V} - 0.7\text{ V} = \mathbf{11.3\text{ V}}$$

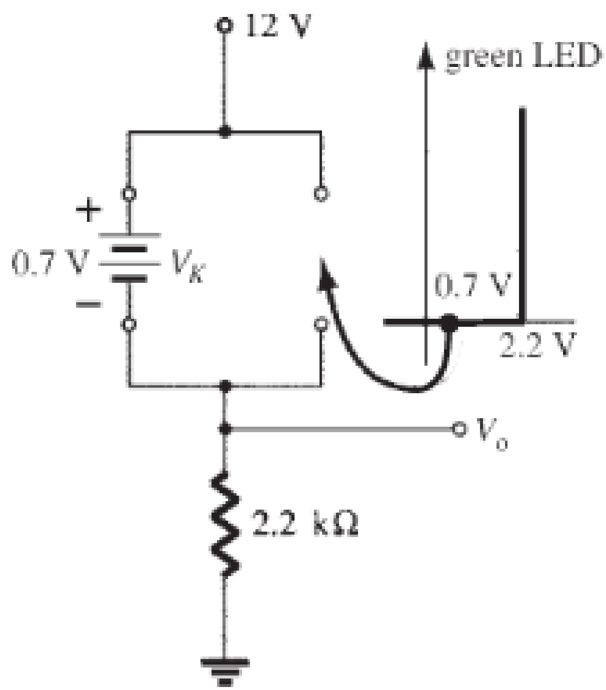


FIG. 2.36
Determining V_o for the network of Fig. 2.35.

EXAMPLE 2.13 Determine the currents I_1, I_2, and I_{D_2} for the network of Fig. 2.37.

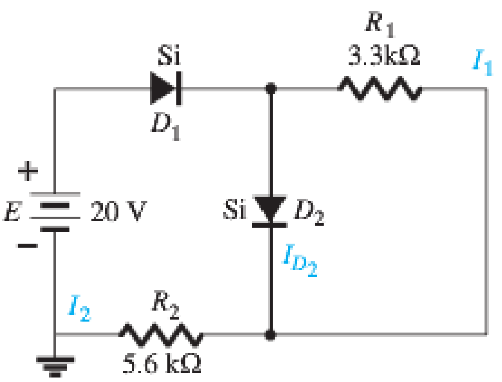


FIG. 2.37
Network for Example 2.13.

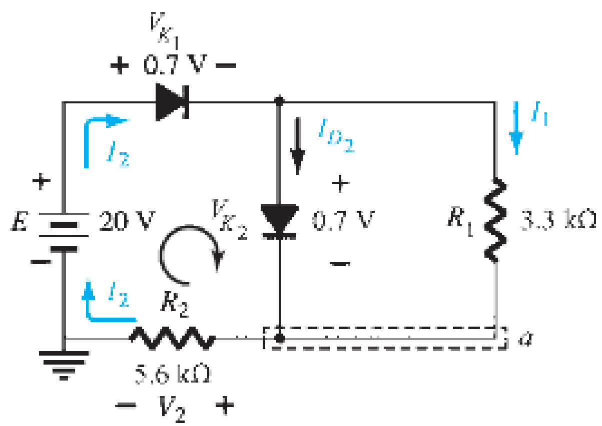


FIG. 2.38
Determining the unknown quantities for Example 2.13.

$$I_1 = \frac{V_{K_2}}{R_1} = \frac{0.7\text{ V}}{3.3\text{ k}\Omega} = \mathbf{0.212\text{ mA}}$$

Applying Kirchhoff's voltage law around the indicated loop in the clockwise direction yields

$$-V_2 + E - V_{K_1} - V_{K_2} = 0$$

and $$V_2 = E - V_{K_1} - V_{K_2} = 20\text{ V} - 0.7\text{ V} - 0.7\text{ V} = \mathbf{18.6\text{ V}}$$

with $$I_2 = \frac{V_2}{R_2} = \frac{18.6\text{ V}}{5.6\text{ k}\Omega} = \mathbf{3.32\text{ mA}}$$

At the bottom node *a*,

$$I_{D_2} + I_1 = I_2$$

and $$I_{D_2} = I_2 - I_1 = 3.32\text{ mA} - 0.212\text{ mA} \cong \mathbf{3.11\text{ mA}}$$

AND/OR GATES

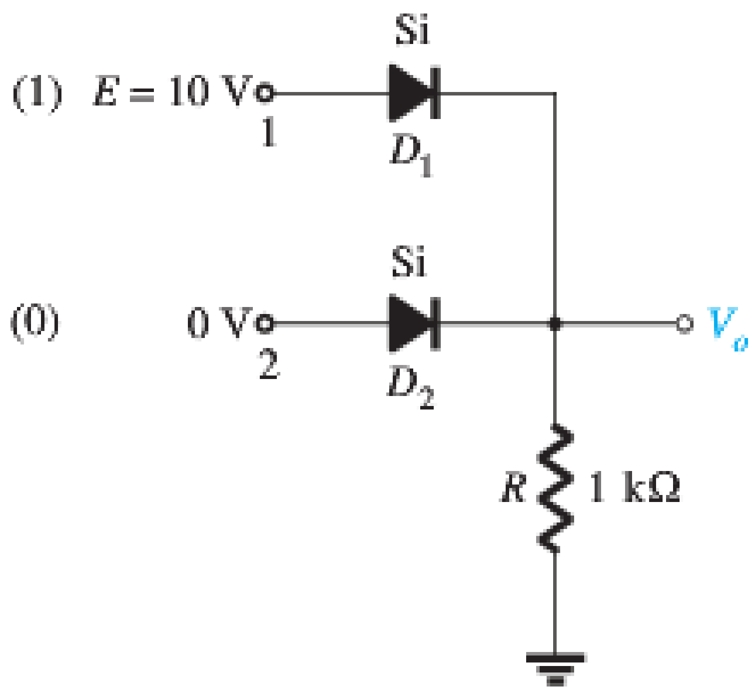


FIG. 2.39
Positive logic OR gate.

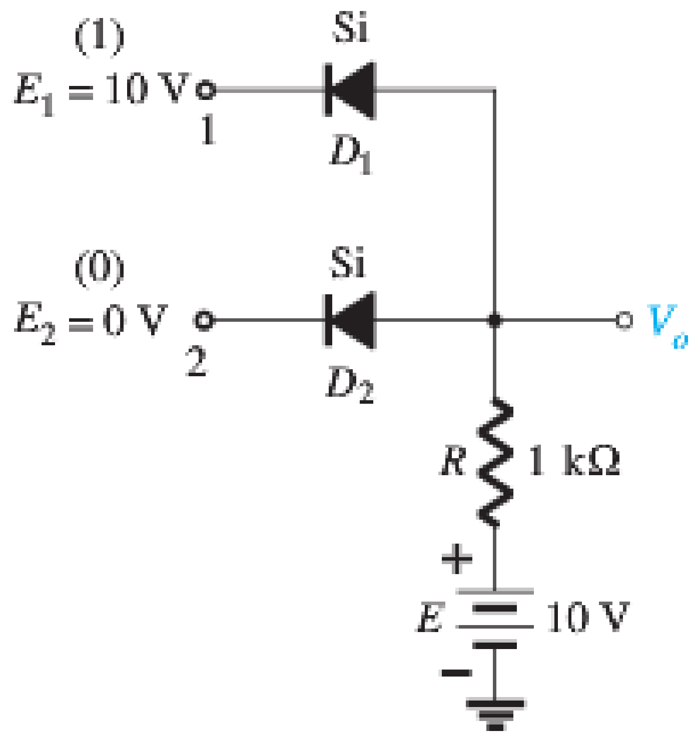


FIG. 2.42
Positive logic AND gate.

Rectifier Circuits

- One important application of diode is the **rectifier**
  - Converts AC to DC
  - Used to make dc power supplies

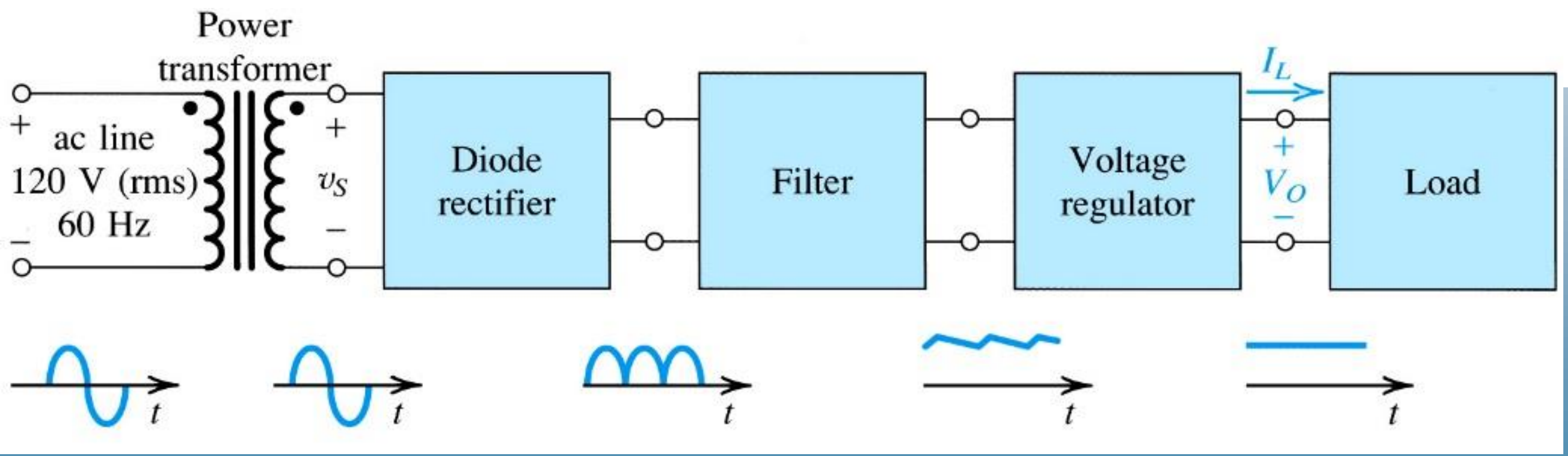


Figure: Block diagram of a dc power supply

Half-Wave Rectification

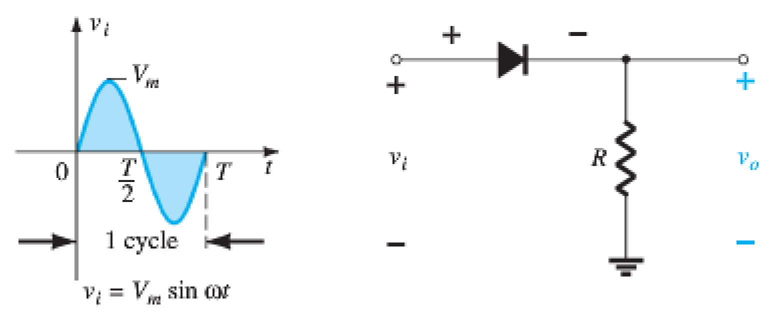


FIG. 2.44
Half-wave rectifier.

The process of removing one-half the input signal to establish a dc level is called half-wave rectification

Ideal Approximation

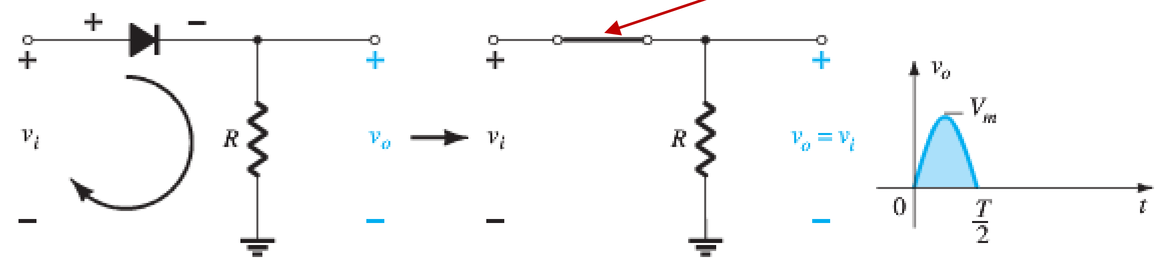


FIG. 2.45
Conduction region $(0 \rightarrow T/2)$.

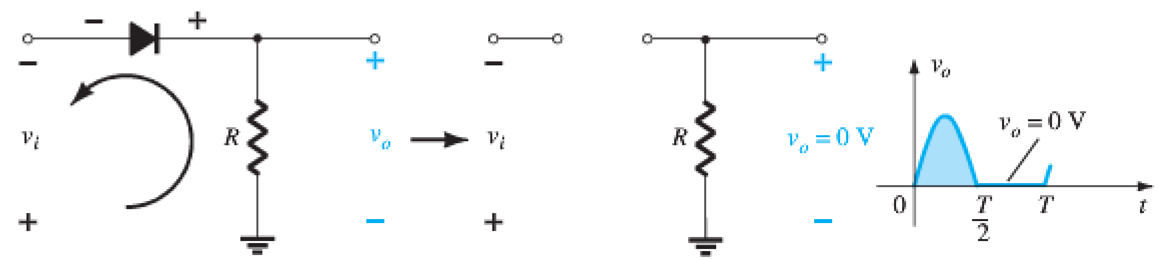


FIG. 2.46
Nonconduction region $(T/2 \rightarrow T)$.

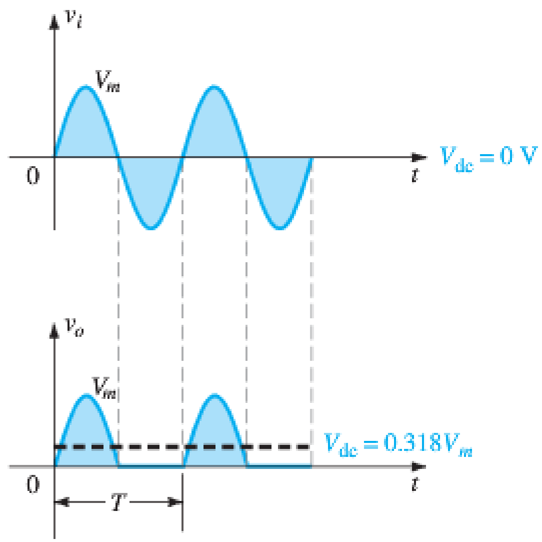


FIG. 2.47
Half-wave rectified signal.

$$\boxed{V_{dc} = 0.318\,V_m} \quad \text{half-wave}$$

The effect of using a real diode

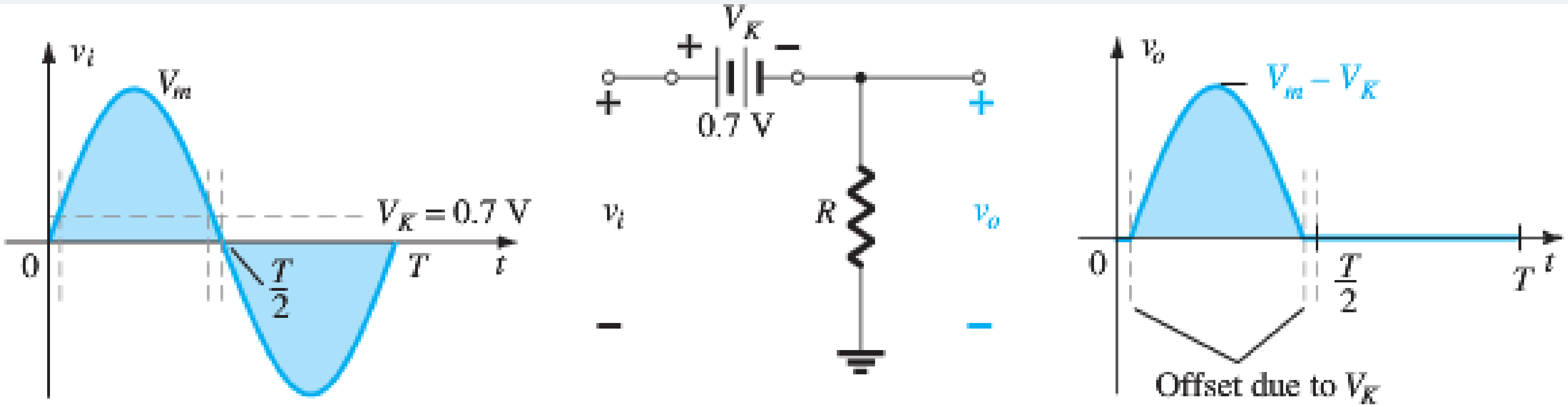


FIG. 2.48
Effect of V_K on half-wave rectified signal.

$$\boxed{V_{dc} \cong 0.318(V_m - V_K)}$$

The Half-Wave Rectifier

- Average Value (DC Component) of v_o, $V_o = \frac{Integration\ over\ one\ cycle}{Length\ of\ a\ Period} = \frac{\int_0^{2\pi} v_o d\theta}{2\pi}$

$$= \frac{\int_0^{\pi}(v_o - V_K)d\theta + \int_{\pi}^{2\pi} 0 d\theta}{2\pi}$$

$$= \frac{\int_0^{\pi}(V_m \sin\theta - V_K)d\theta}{2\pi}$$

$$= \frac{V_m}{2\pi}\int_0^{\pi} \sin\theta\, d\theta - \frac{V_K}{2\pi}\int_0^{\pi} d\theta$$

$$= \frac{V_m}{2\pi}[-\cos\theta]_0^{\pi} - \frac{V_K}{2\pi}[\theta]_0^{\pi}$$

$$= -\frac{V_m}{2\pi}[\cos\theta]_0^{\pi} - \frac{V_K}{2\pi}\pi$$

$$= -\frac{V_m}{2\pi}(-2) - \frac{V_K}{2} = \frac{V_m}{\pi} - \frac{V_K}{2}$$

$$V_o = \frac{V_m}{\pi} - \frac{V_K}{2} = 0.318\, V_m - 0.5\, V_K$$

- Peak diode current $= (V_s - V_D)/\mathrm{R}$

EXAMPLE 2.16

a. Sketch the output v_o and determine the dc level of the output for the network of Fig. 2.49.
b. Repeat part (a) if the ideal diode is replaced by a silicon diode.
c. Repeat parts (a) and (b) if V_m is increased to 200 V, and compare solutions using Eqs. (2.7) and (2.8).

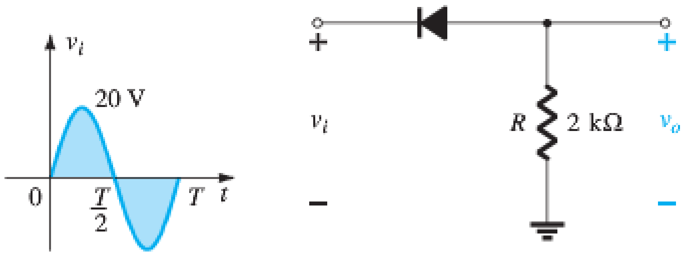


FIG. 2.49
Network for Example 2.16.

Solution:

a. In this situation the diode will conduct during the negative part of the input as shown in Fig. 2.50, and v_o will appear as shown in the same figure. For the full period, the dc level is

$$V_{dc} = -0.318V_m = -0.318(20\text{ V}) = \mathbf{-6.36\text{ V}}$$

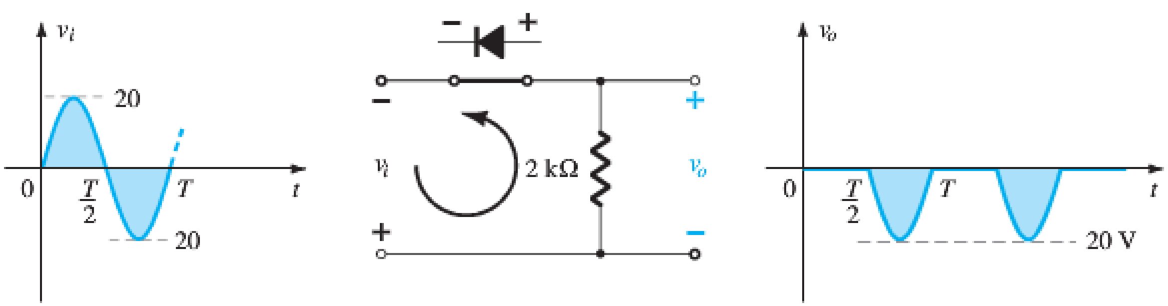


FIG. 2.50
Resulting v_o for the circuit of Example 2.16.

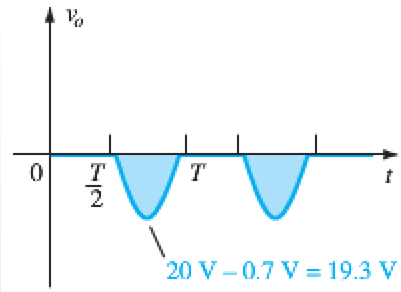


FIG. 2.51
Effect of V_K on output of Fig. 2.50.

$$V_{dc} \cong -0.318(V_m - 0.7\text{ V}) = -0.318(19.3\text{ V}) \cong \mathbf{-6.14\text{ V}}$$

The resulting drop in dc level is 0.22 V, or about 3.5%.

$$V_{dc} = -0.318\,V_m = -0.318(200\text{ V}) = \mathbf{-63.6\text{ V}}$$

$$V_{dc} = -0.318(V_m - V_K) = -0.318(200\text{ V} - 0.7\text{ V})$$
$$= -(0.318)(199.3\text{ V}) = \mathbf{-63.38\text{ V}}$$

which is a difference that can certainly be ignored for most applications.

PIV (PRV)

The diode is only forward biased for one-half of the AC cycle. It is also reverse biased for one-half cycle.

It is important that the reverse breakdown voltage rating of the diode be high enough to withstand the peak, reverse-biasing AC voltage.

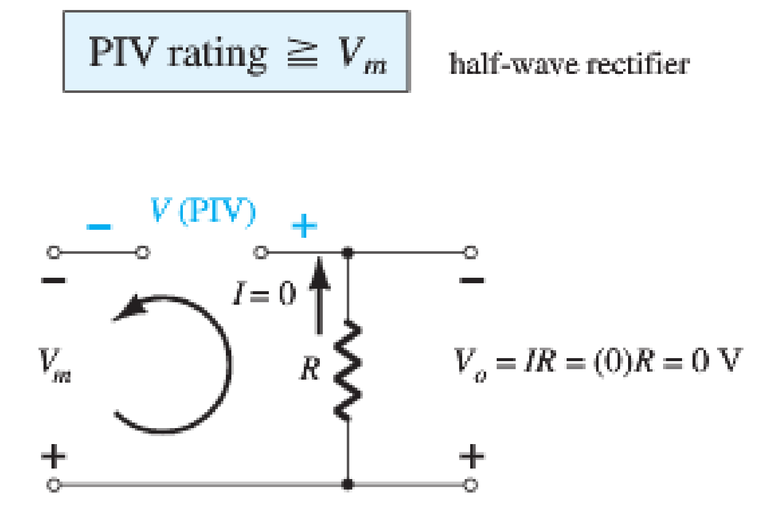


FIG. 2.52
Determining the required PIV rating for the half-wave rectifier.

PIV (or PRV) > V_m

Where **PIV** = Peak inverse voltage

PRV = Peak reverse voltage

V_m = Peak AC voltage

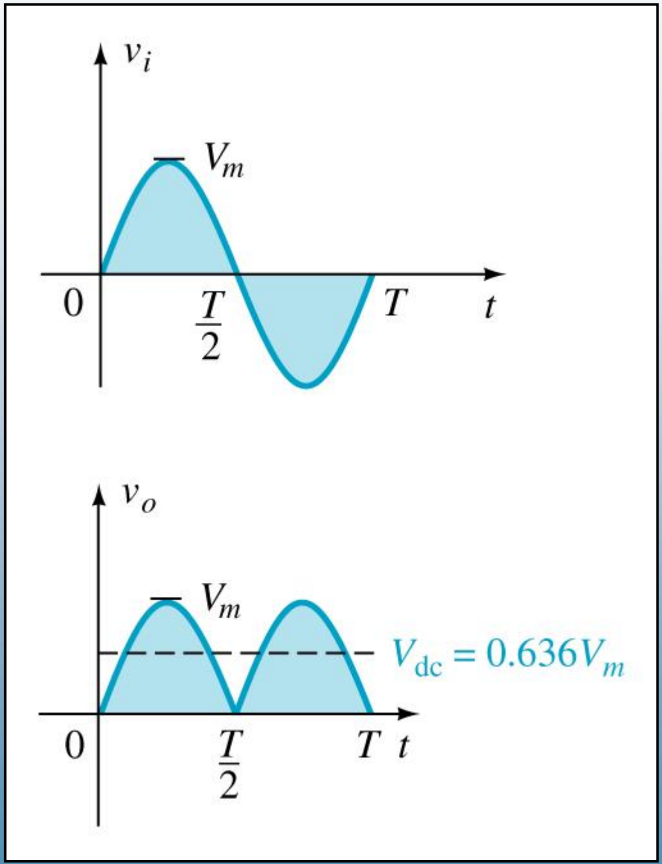
Full-Wave Rectification

The rectification process can be improved by using a full-wave rectifier circuit.

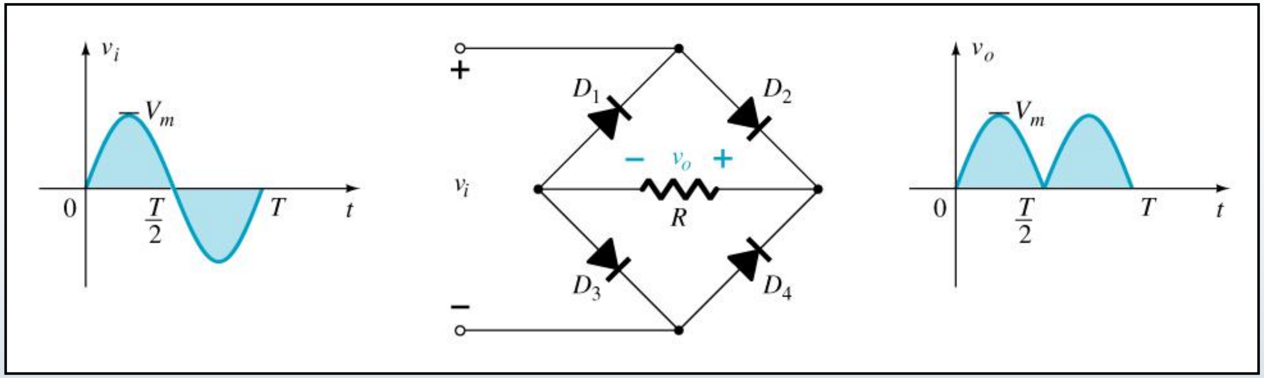
Full-wave rectification produces a greater DC output:

Half-wave: $V_{dc} = 0.318V_m$

Full-wave: $V_{dc} = 0.636V_m$

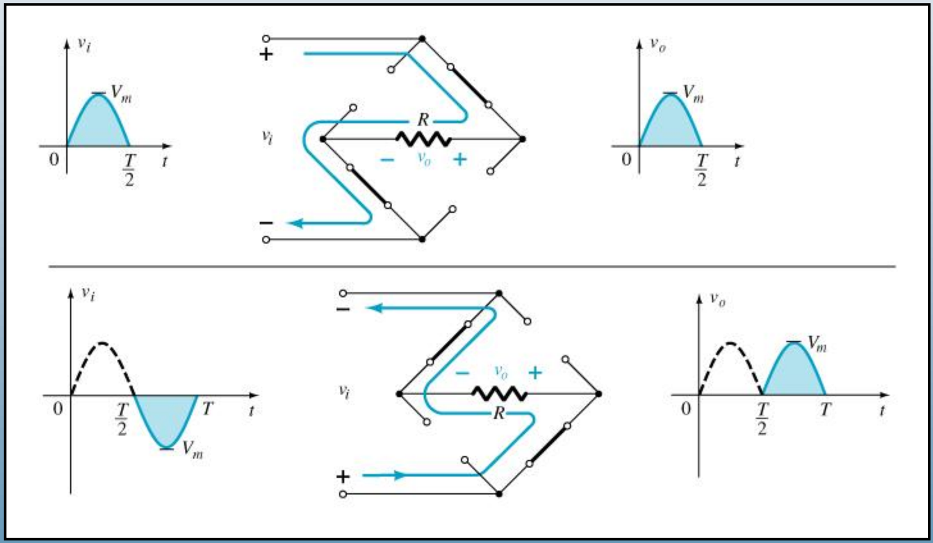


Full-Wave Rectification



Bridge Rectifier

A full-wave rectifier with four diodes that are connected in a bridge configuration



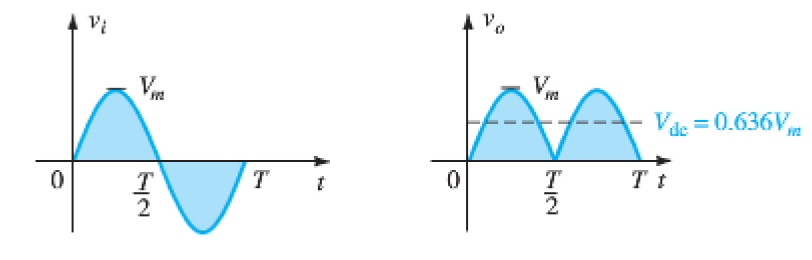


FIG. 2.57
Input and output waveforms for a full-wave rectifier.

$$V_{dc} = 2[\text{Eq. } (2.7)] = 2(0.318V_m)$$

$$\boxed{V_{dc} = 0.636\,V_m} \quad \text{full-wave}$$

The effect of using a real diode

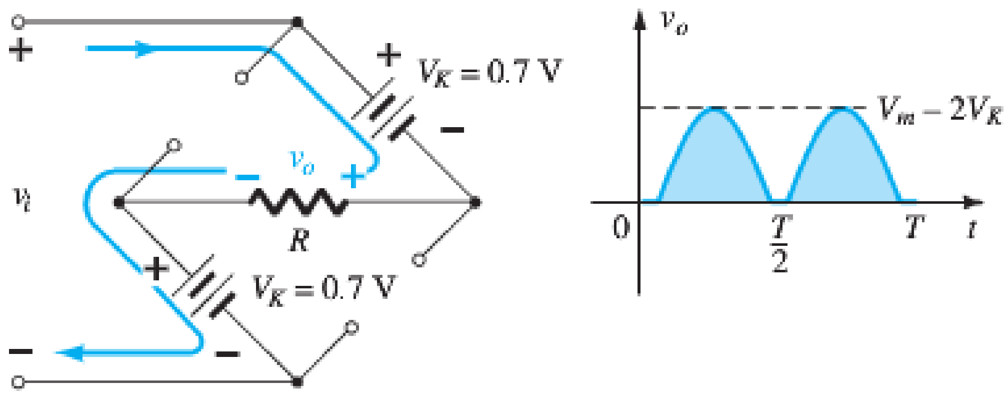


FIG. 2.58
Determining $V_{o_{max}}$ for silicon diodes in the bridge configuration.

$$v_i - V_K - v_o - V_K = 0$$
$$v_o = v_i - 2V_K$$

The peak value of the output voltage v_o is therefore

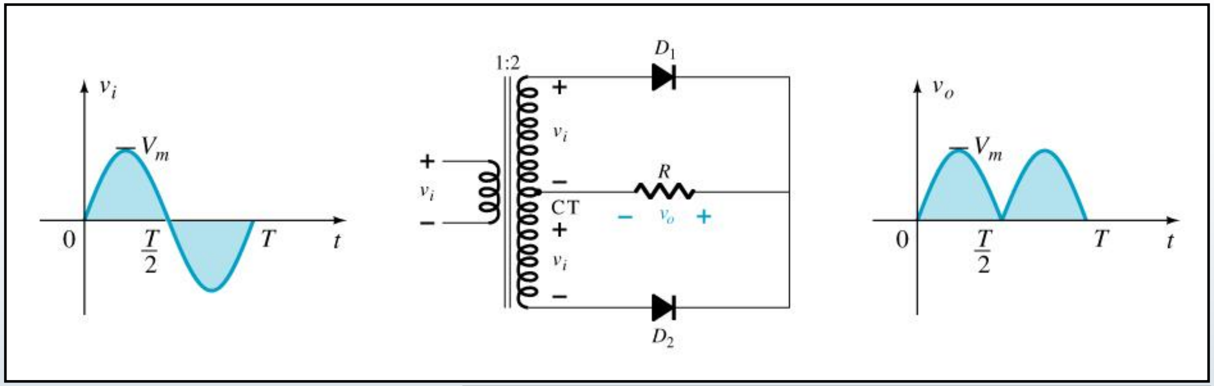
$$V_{o_{max}} = V_m - 2V_K$$

For situations where $V_m \gg 2V_K$, the following equation can be applied for the average value with a relatively high level of accuracy:

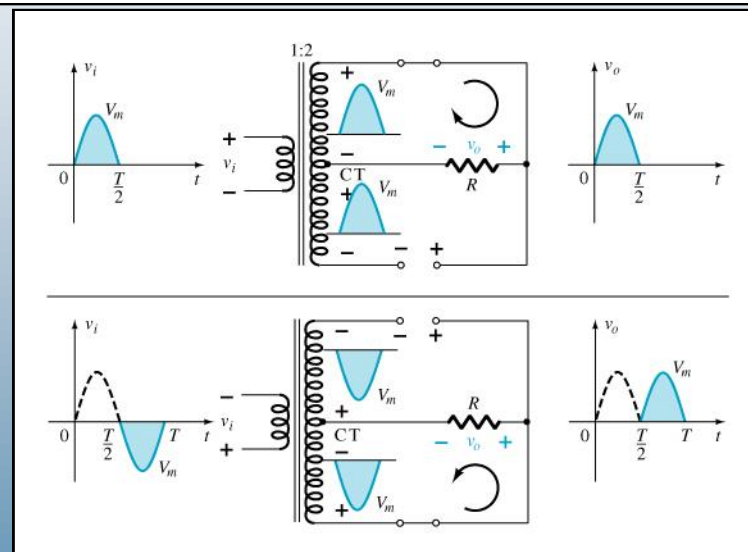
$$\boxed{V_{dc} \cong 0.636(V_m - 2V_K)} \qquad \textbf{(2.11)}$$

Then again, if V_m is sufficiently greater than $2V_K$, then Eq. (2.10) is often applied as a first approximation for V_{dc}.

Full-Wave Rectification



Center-Tapped Transformer Rectifier



Needs a bigger transformer, because the peak is only half the secondary voltage.

Requires two diodes and a center-tapped transformer

$$V_{DC} = 0.636V_m$$

PIV

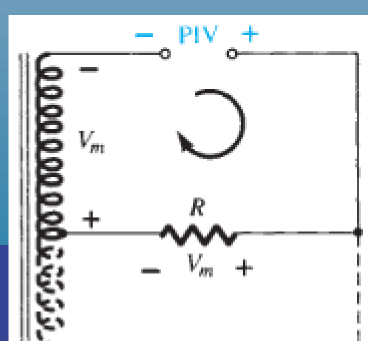


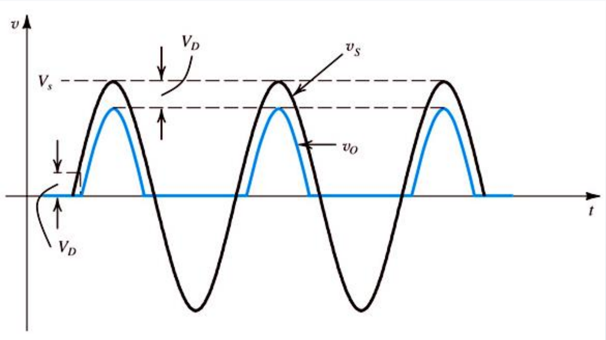
FIG. 2.63
Determining the PIV level for the diodes of the CT transformer full-wave rectifier.

$$\begin{aligned} \text{PIV} &= V_{\text{secondary}} + V_R \\ &= V_m + V_m \end{aligned}$$

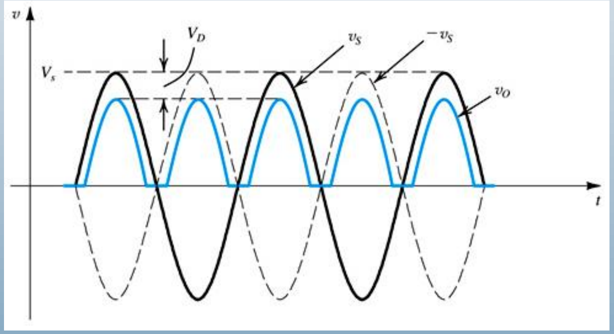
$$\boxed{\text{PIV} \geqq 2V_m}$$ CT transformer, full-wave rectifier

Summary of Rectifier Waveforms

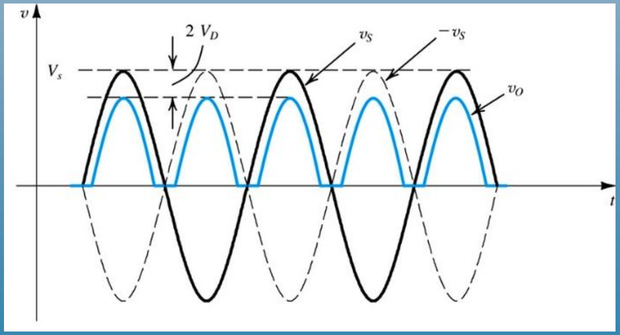
Half-Wave Rectifier



Full-Wave Rectifier



Bridge Rectifier



Summary of Rectifier Circuits

In the center tapped transformer rectifier circuit, the peak AC voltage is the transformer secondary voltage to the tap.

Rectifier	Ideal V_{DC}	Realistic V_{DC}
Half Wave Rectifier	$V_{DC} = 0.318V_m$	$V_{DC} = 0.318V_m - 0.7$
Bridge Rectifier	$V_{DC} = 0.636V_m$	$V_{DC} = 0.636V_m - 2(0.7\ V)$
Center-Tapped Transformer Rectifier	$V_{DC} = 0.636V_m$	$V_{DC} = 0.636V_m - 0.7\ V$

V_m = the peak AC voltage

EXAMPLE 2.17 Determine the output waveform for the network of Fig. 2.64 and calculate the output dc level and the required PIV of each diode.

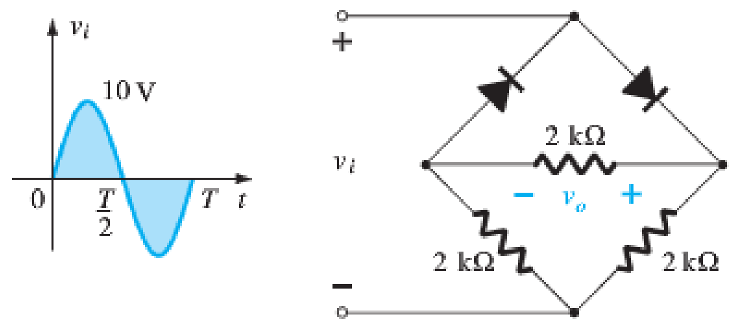


FIG. 2.64
Bridge network for Example 2.17.

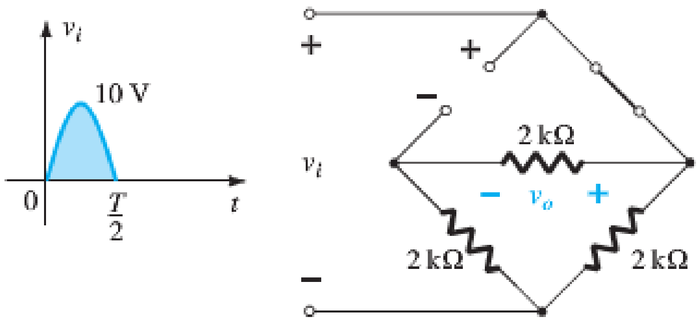


FIG. 2.65
Network of Fig. 2.64 for the positive region of v_i.

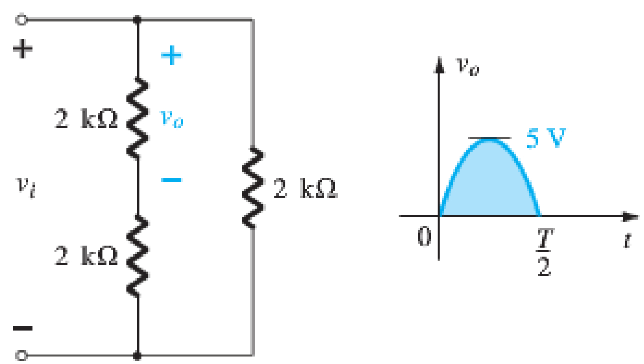


FIG. 2.66
Redrawn network of Fig. 2.65.

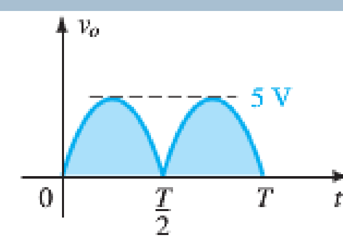


FIG. 2.67
Resulting output for Example 2.17.

$$V_{o_{max}} = \tfrac{1}{2}V_{i_{max}} = \tfrac{1}{2}(10\text{ V}) = 5\text{ V}$$

The effect of removing two diodes from the bridge configuration is therefore to reduce the available dc level to the following:

$$V_{dc} = 0.636(5\text{ V}) = \mathbf{3.18\text{ V}}$$

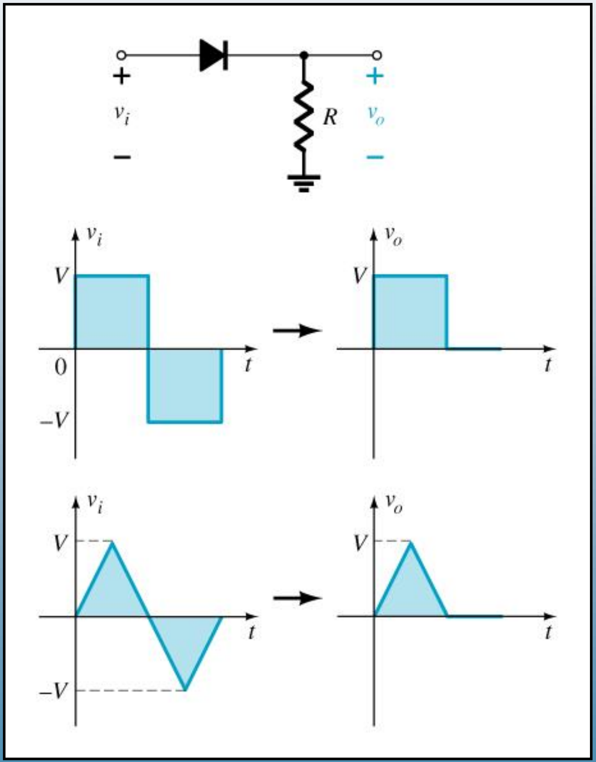
Diode Clippers

- Clippers are networks that employ diodes to “clip” away a portion of an input signal without distorting the remaining part of the applied waveform.
- The half-wave rectifier is an example of the simplest form of diode clipper—one resistor and a diode.
- Depending on the orientation of the diode, the positive or negative region of the applied signal is “clipped” off.
- Two general categories of clippers: series and parallel.
  - Series clippers: The diode in series with the load
  - Parallel clippers: The diode in parallel to the load

Diode Series Clippers

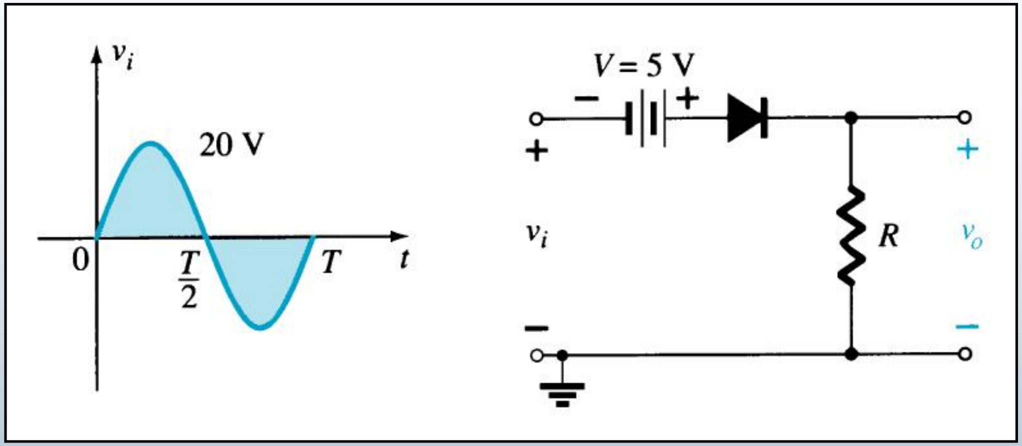
The diode in a series clipper "clips" any voltage that does not forward bias it:

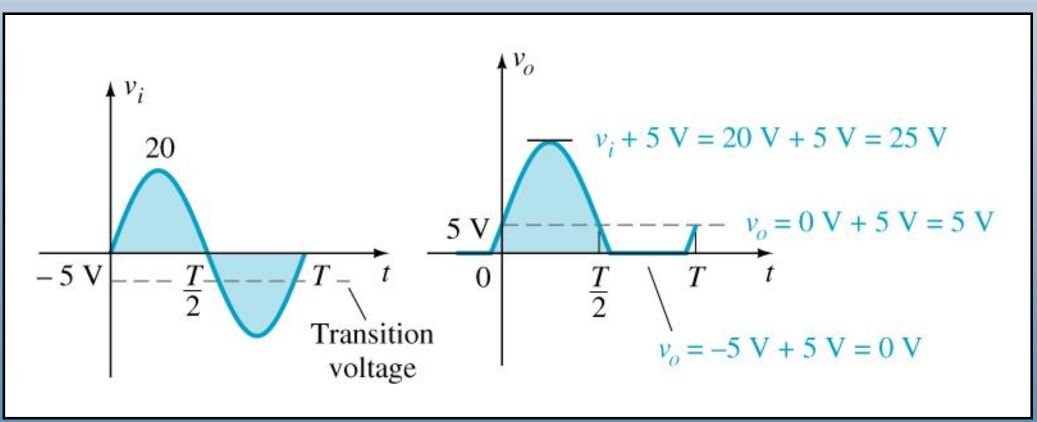
- A reverse-biasing polarity
- A forward-biasing polarity less than 0.7 V (for a silicon diode)



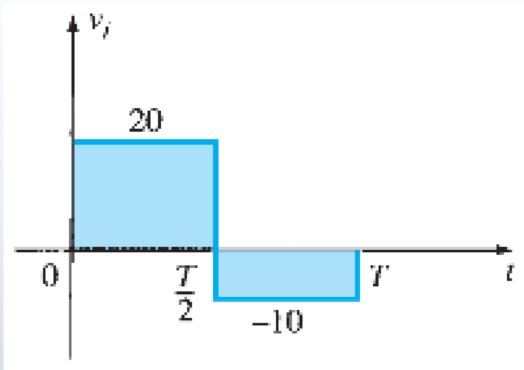
Biased Clippers

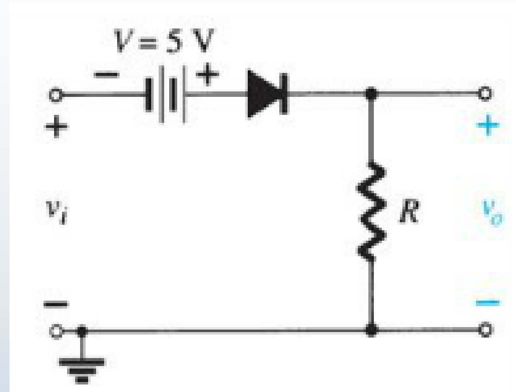
Adding a DC source in series with the clipping diode changes the effective forward bias of the diode.

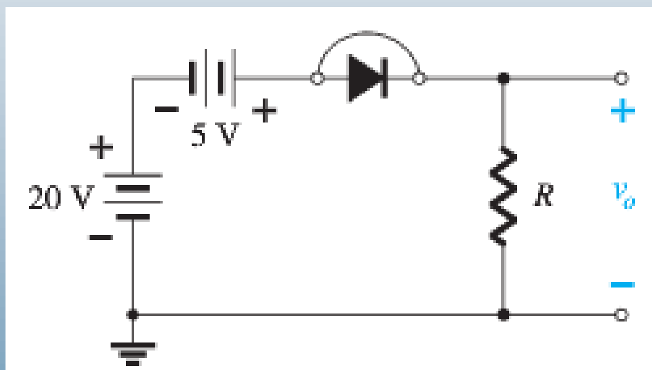


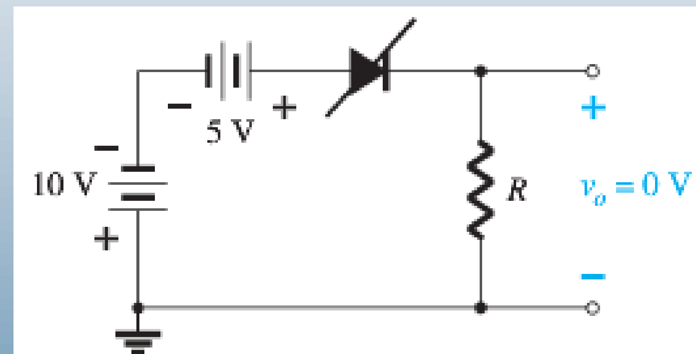


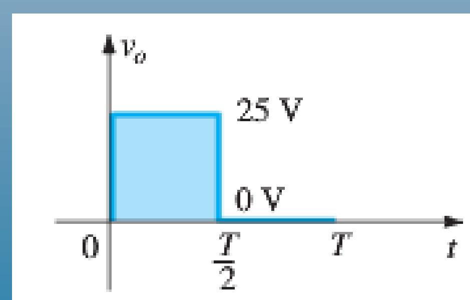
EXAMPLE 2.19 Find the output voltage for the network examined in Example 2.18 if the applied signal is the square wave of Fig. 2.77.







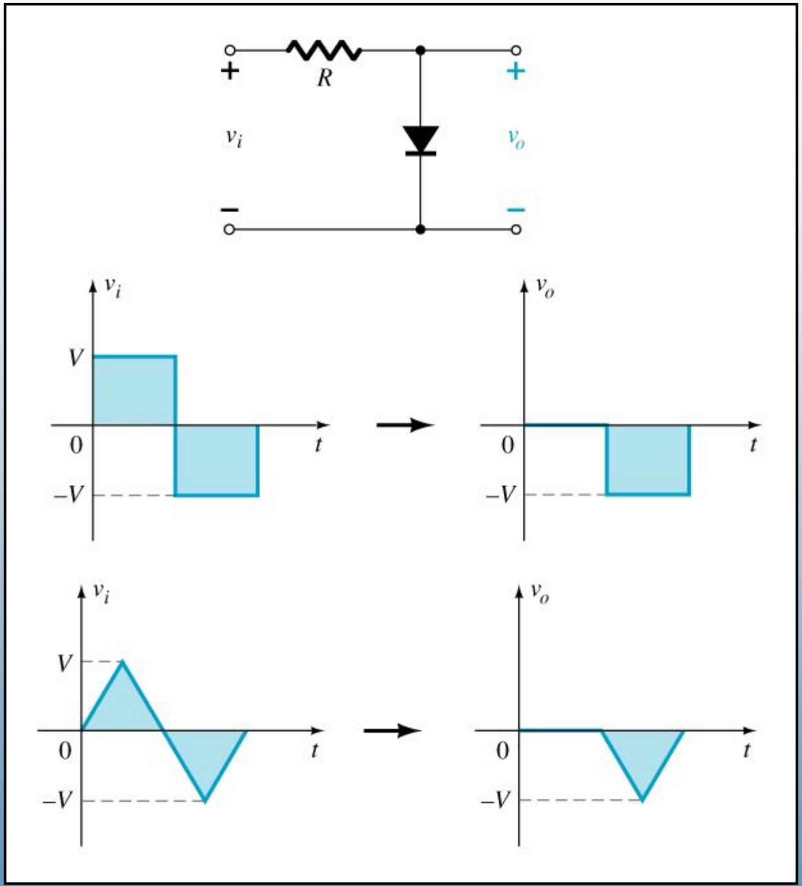




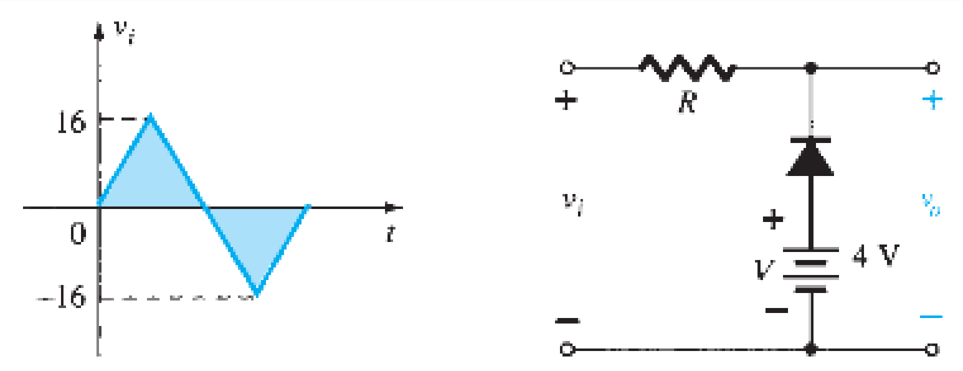
Parallel Clippers

The diode in a parallel clipper circuit "clips" any voltage that forward biases it.

DC biasing can be added in series with the diode to change the clipping level.



EXAMPLE 2.20 Determine v_o for the network of Fig. 2.82.



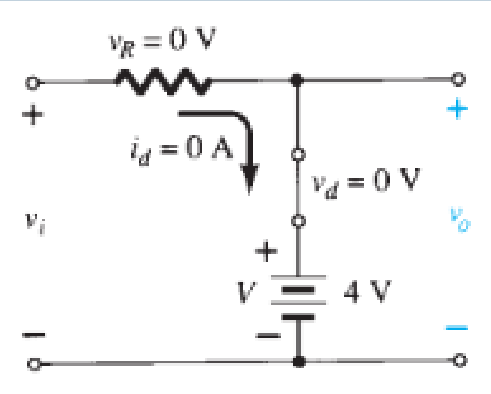
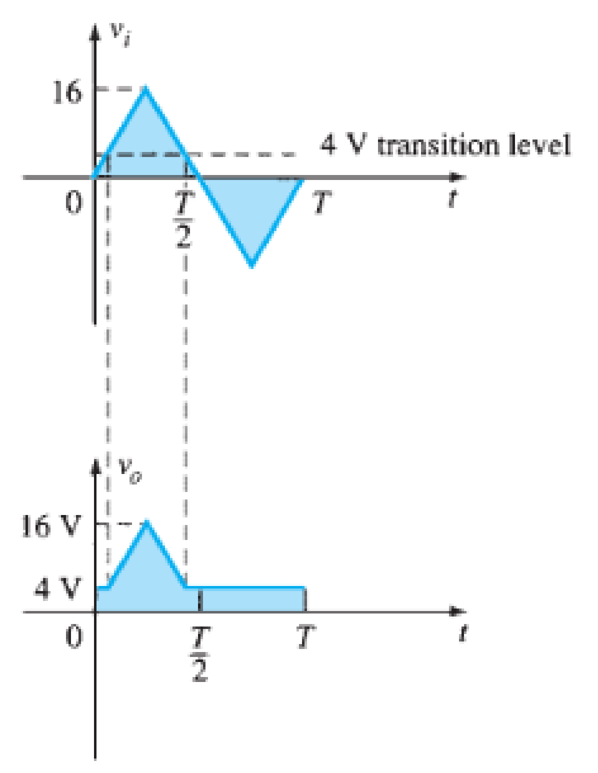
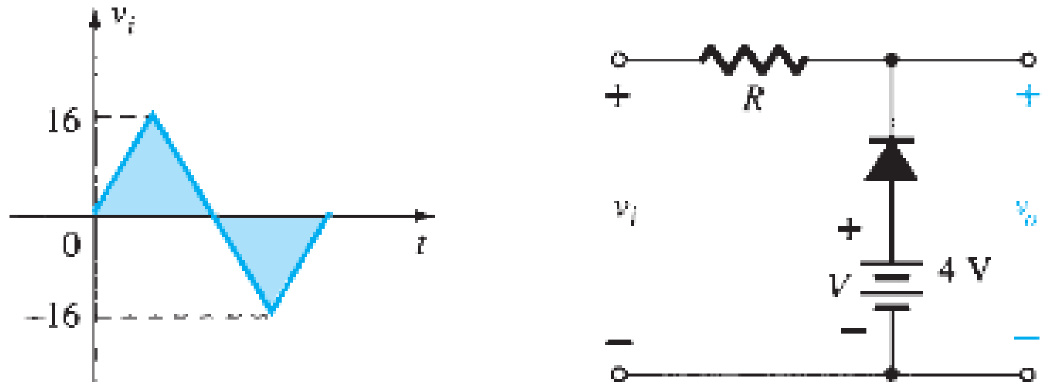


FIG. 2.83



EXAMPLE 2.21 Repeat Example 2.20 using a silicon diode with $V_K = 0.7$ V.



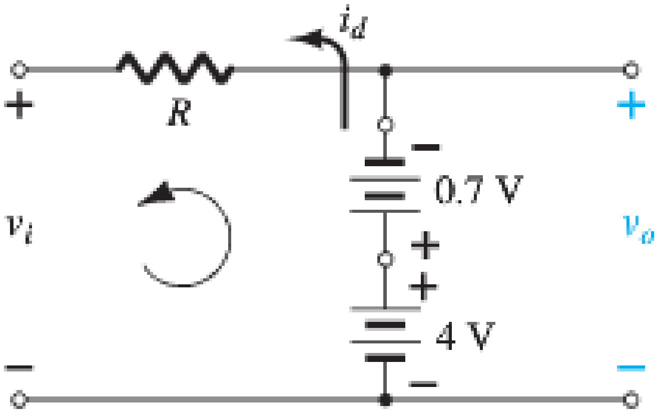


FIG. 2.86
Determining v_o for the diode of Fig. 2.82 in the "on" state.

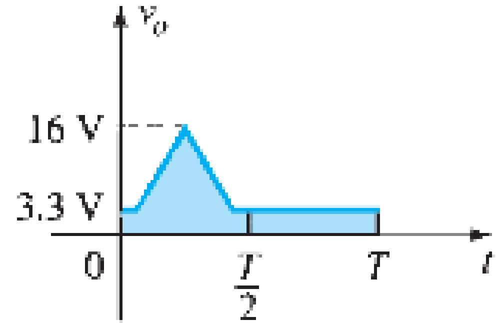
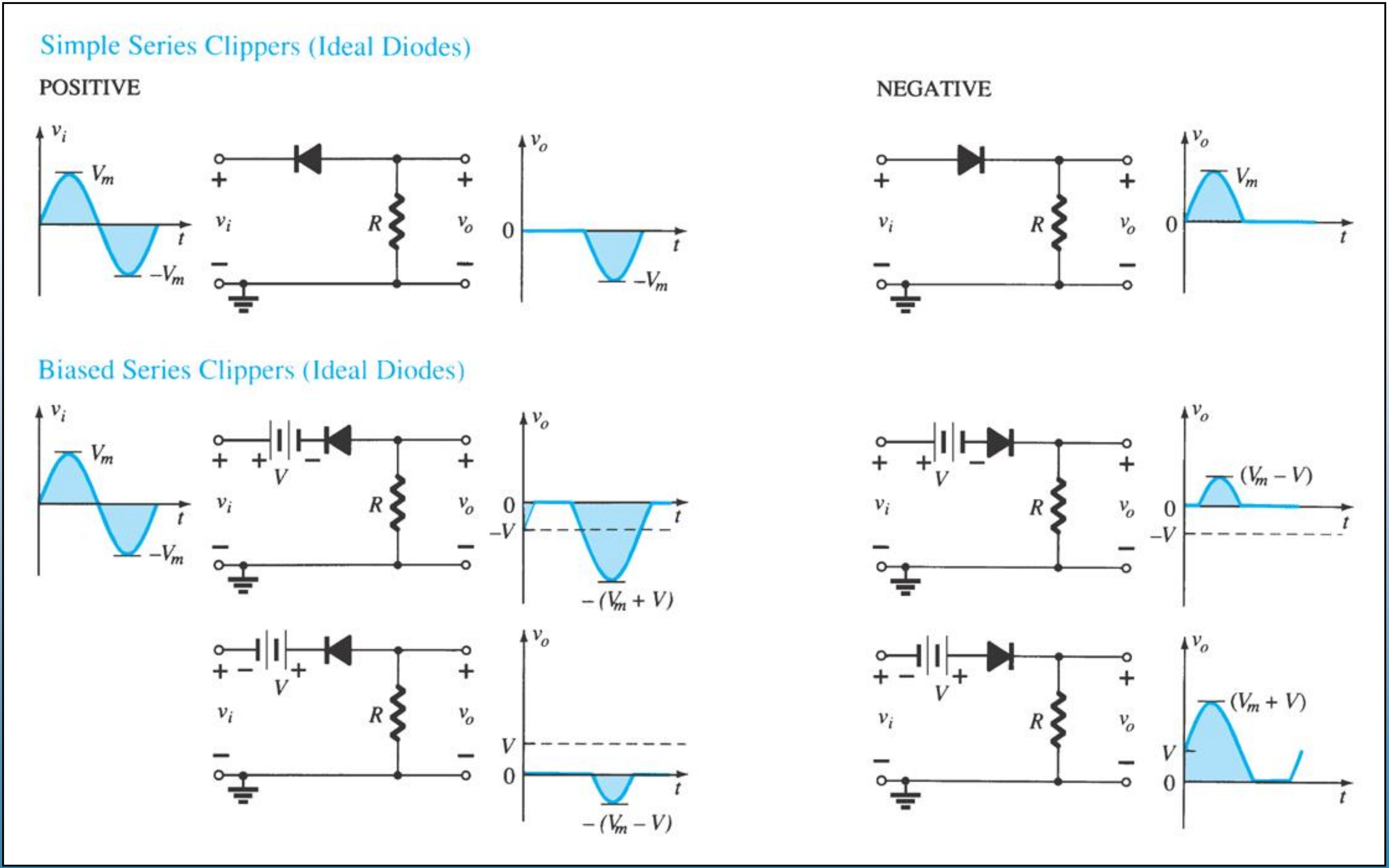
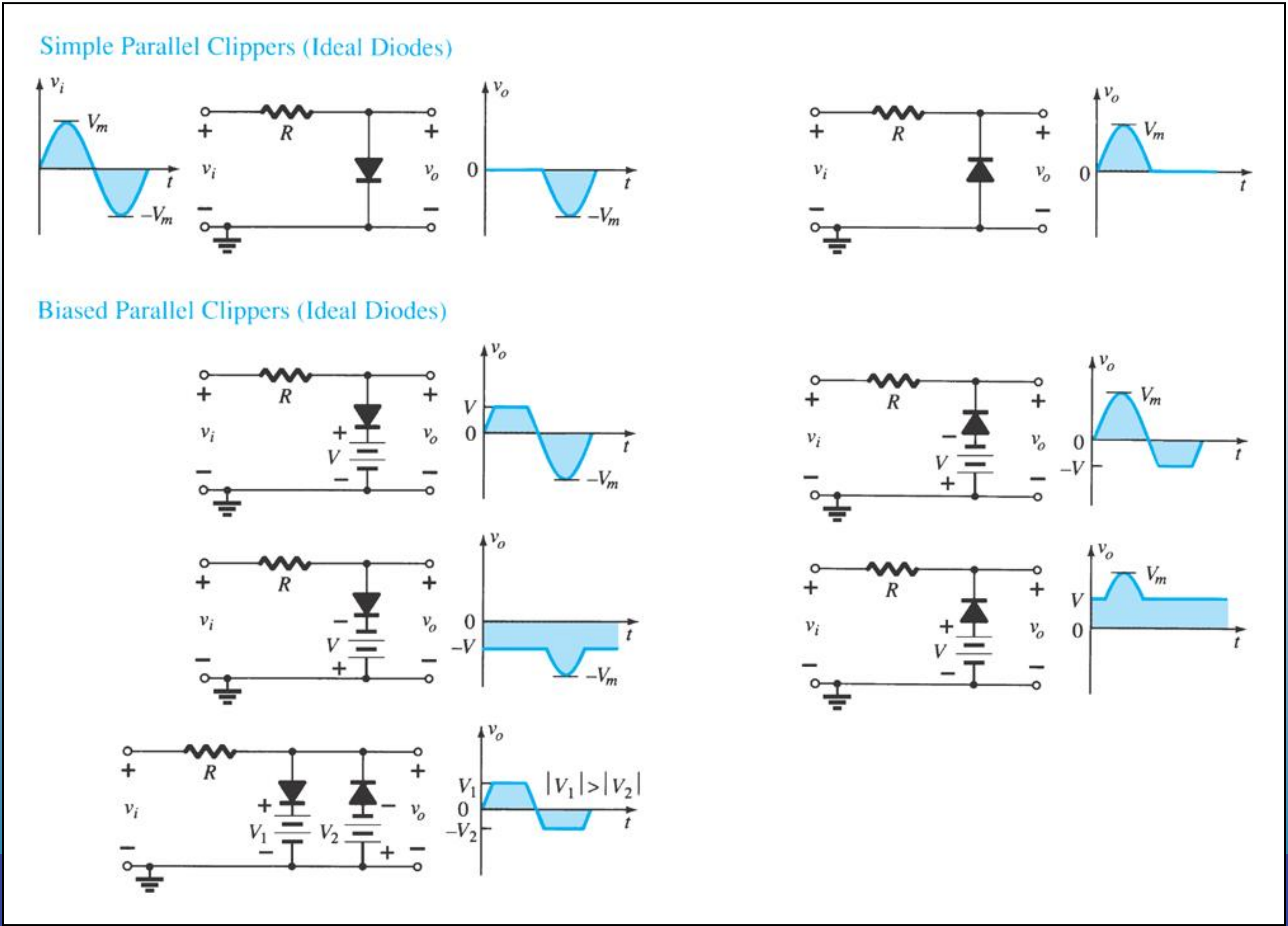


FIG. 2.87
Sketching v_o for Example 2.21.

Summary of Clipper Circuits

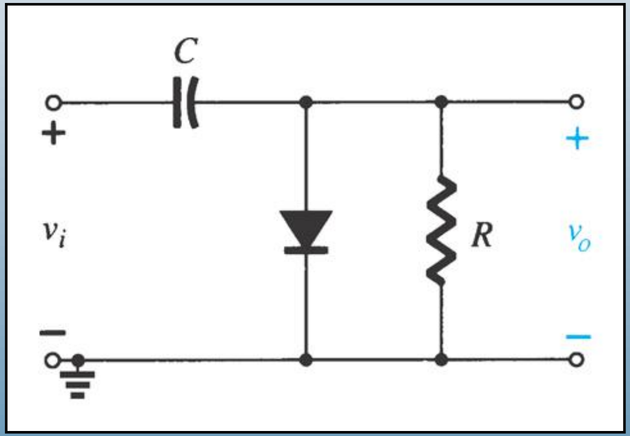


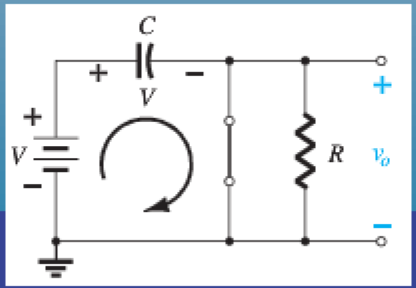
Summary of Clipper Circuits

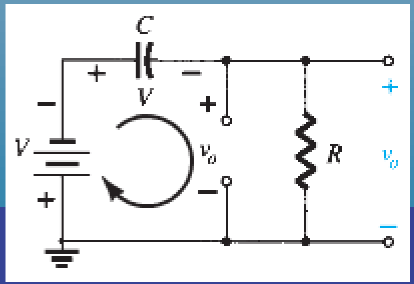


Clampers

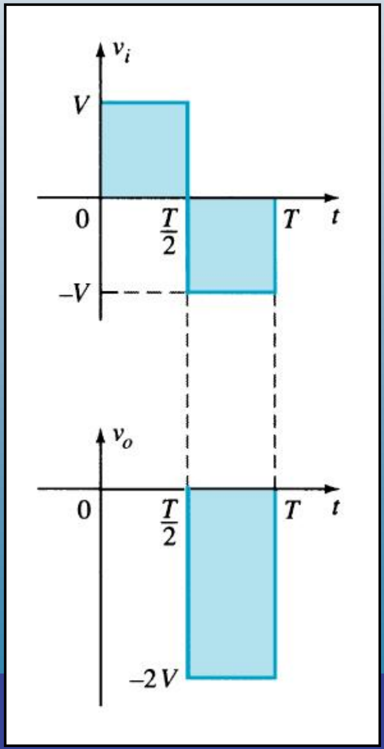
- A clamper is a network constructed of a diode, a resistor, and a capacitor that shifts a waveform to a different dc level without changing the appearance of the applied signal.
- Clamping networks have a capacitor connected directly from input to output with a resistive element in parallel with the output signal.
  - The diode is also in parallel with the output signal but may or may not have a series dc supply as an added element.





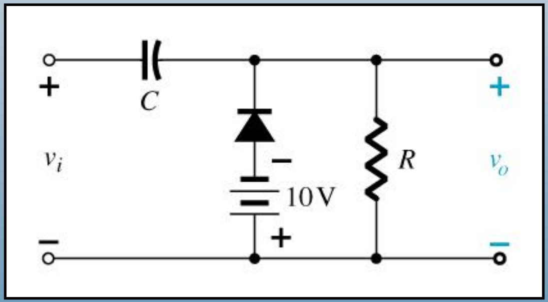


$$-V - V - v_o = 0$$
$$v_o = -2V$$

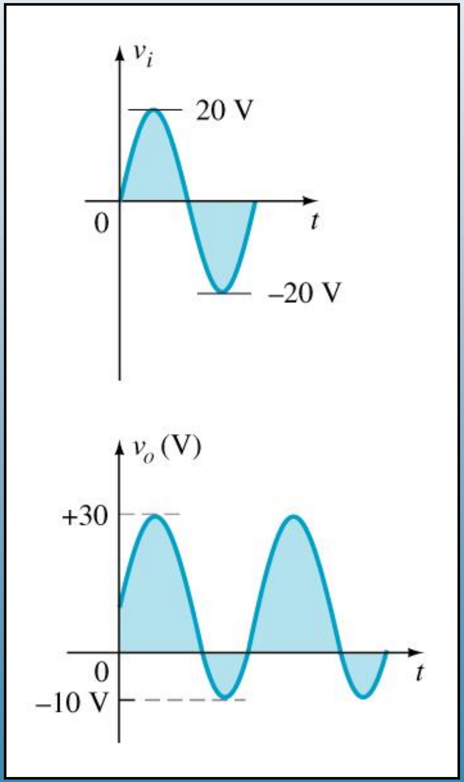


Biased Clamper Circuits

The input signal can be any type of waveform such as a sine, square, or triangle wave.



The DC source lets you adjust the DC camping level.



EXAMPLE 2.22 Determine v_o for the network of Fig. 2.93 for the input indicated.

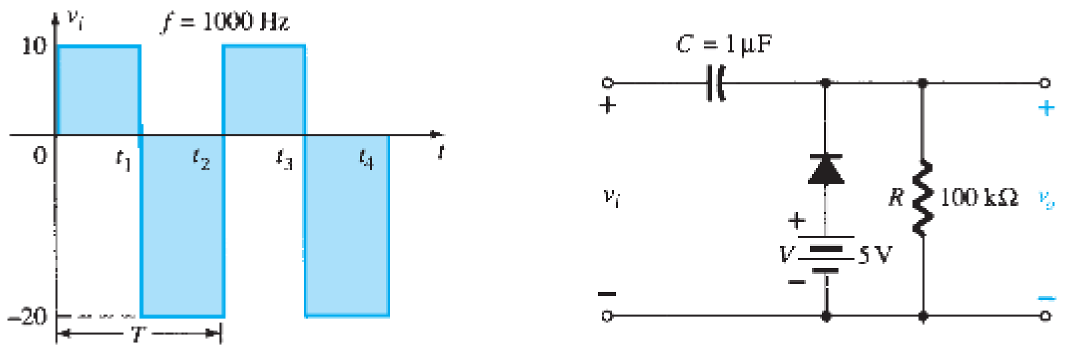


FIG. 2.93
Applied signal and network for Example 2.22.

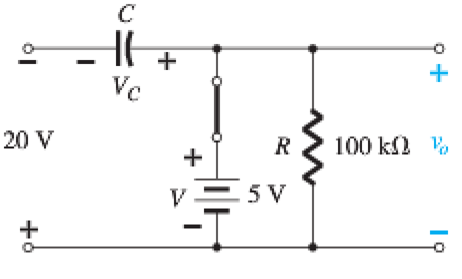


FIG. 2.94
Determining v_o and V_C with the diode in the "on" state.

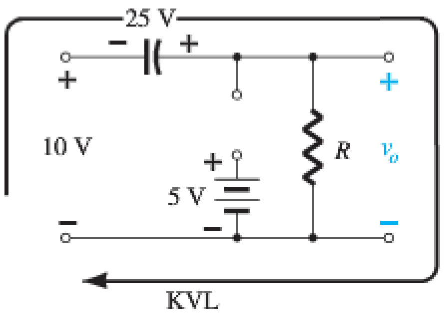


FIG. 2.95
Determining v_o with the diode in the "off" state.

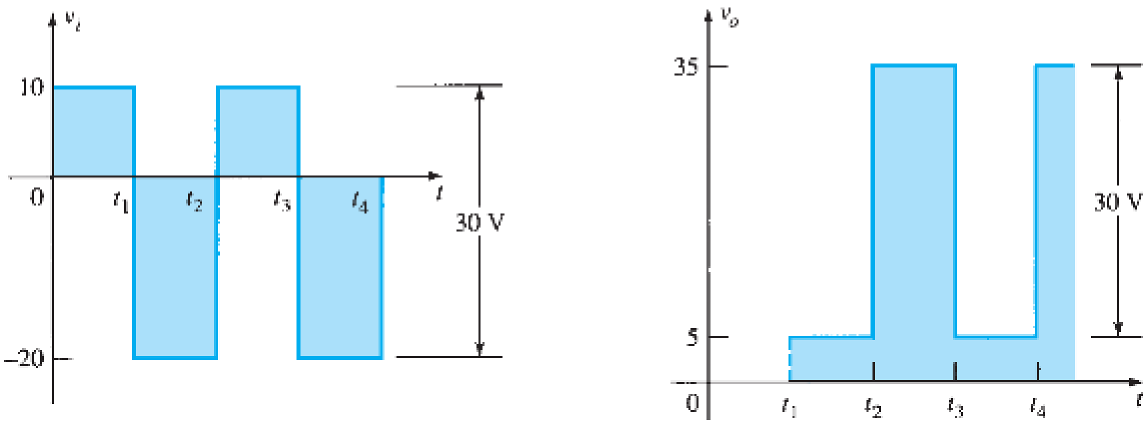
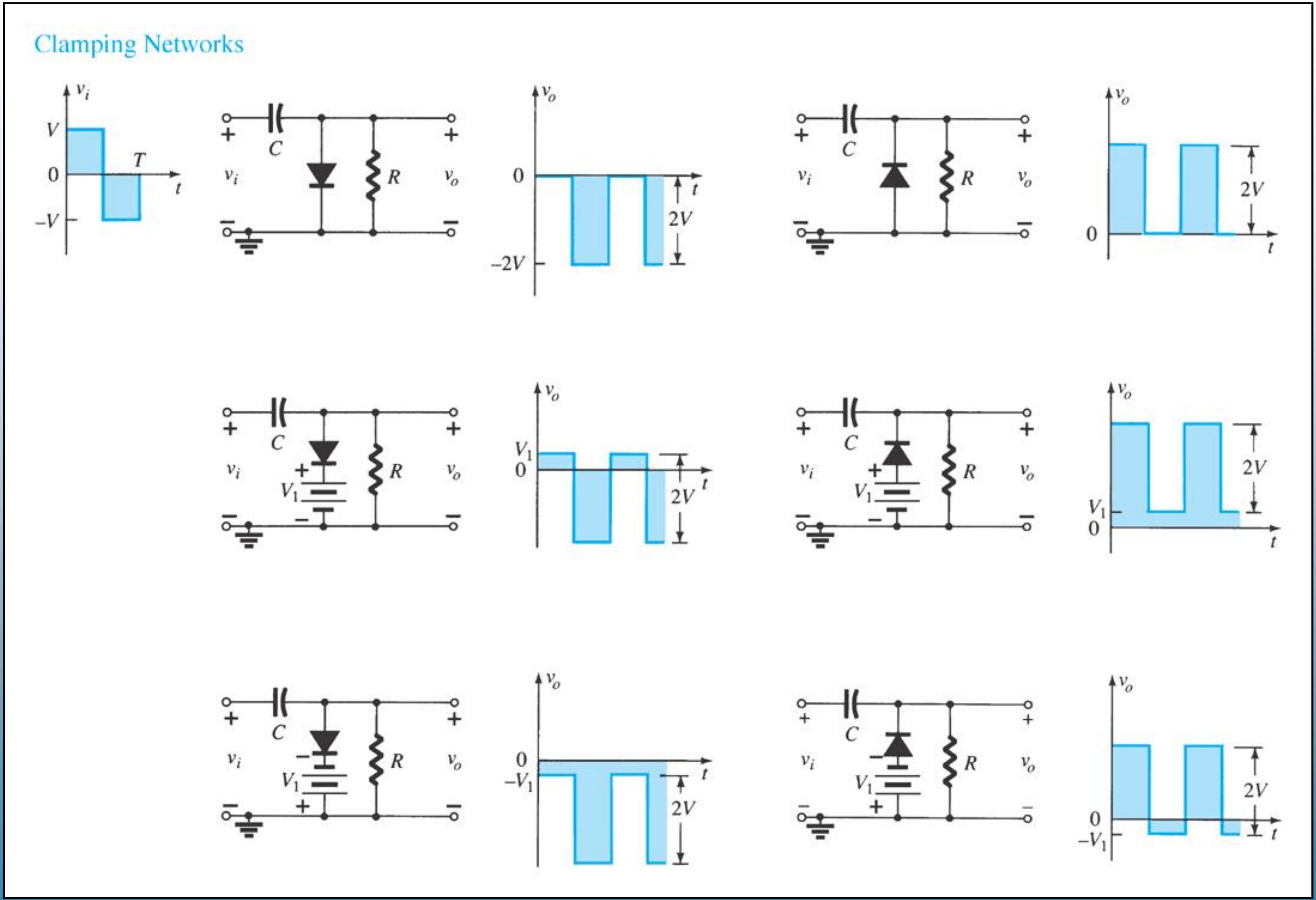
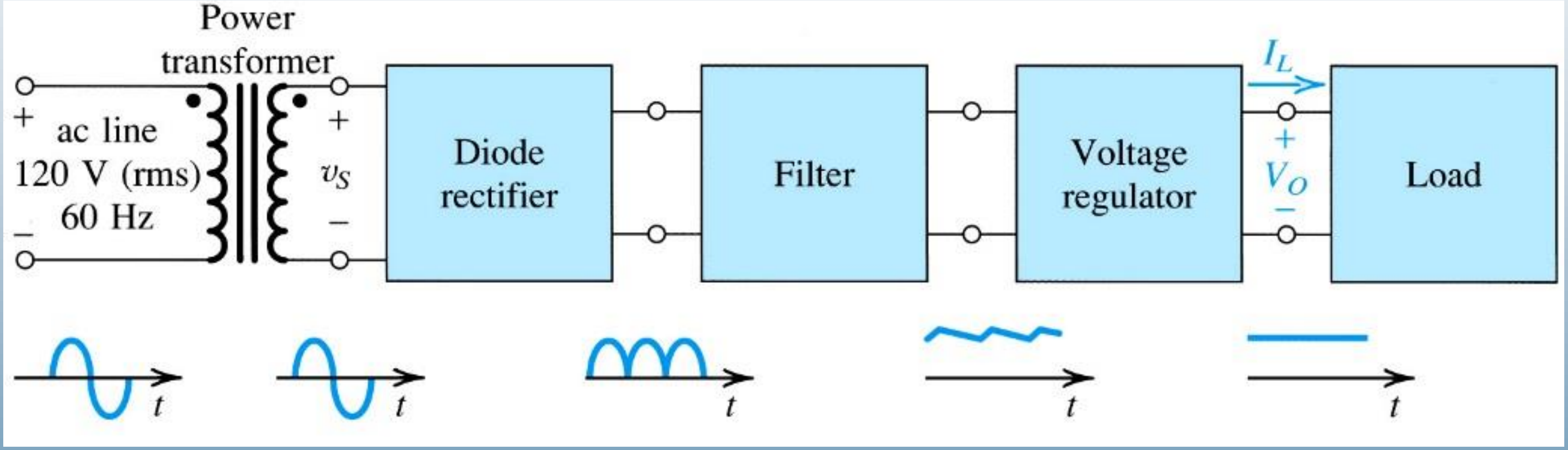


FIG. 2.96
v_i and v_o for the clamper of Fig. 2.93.

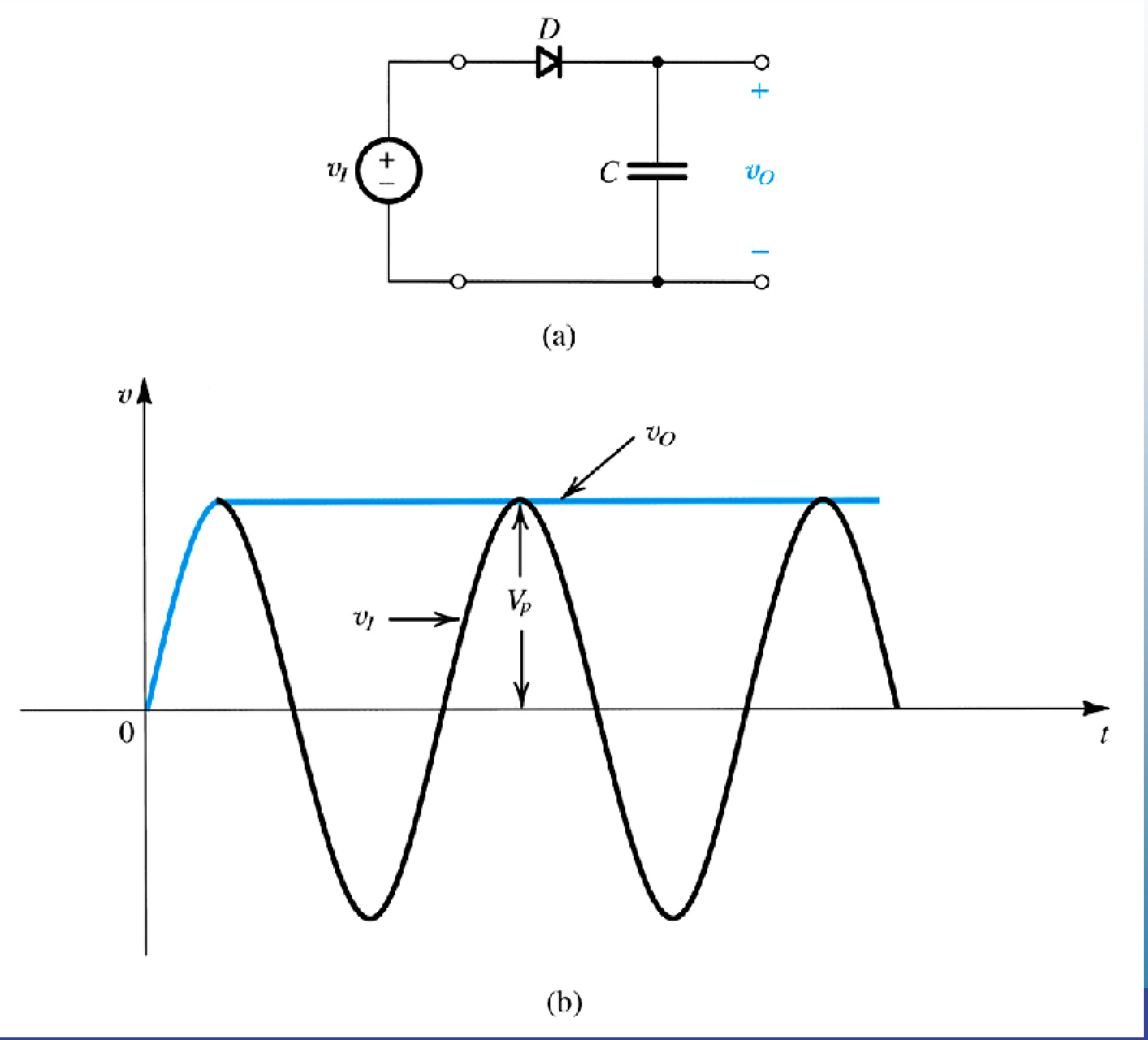
Summary of Clamper Circuits



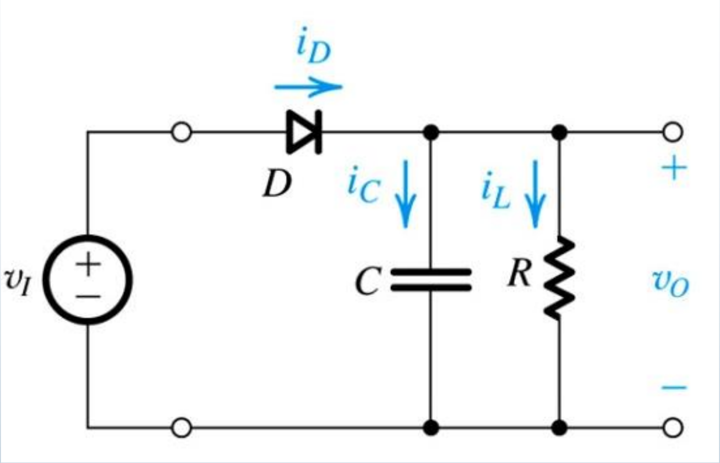
DC Power Supply Block Diagram

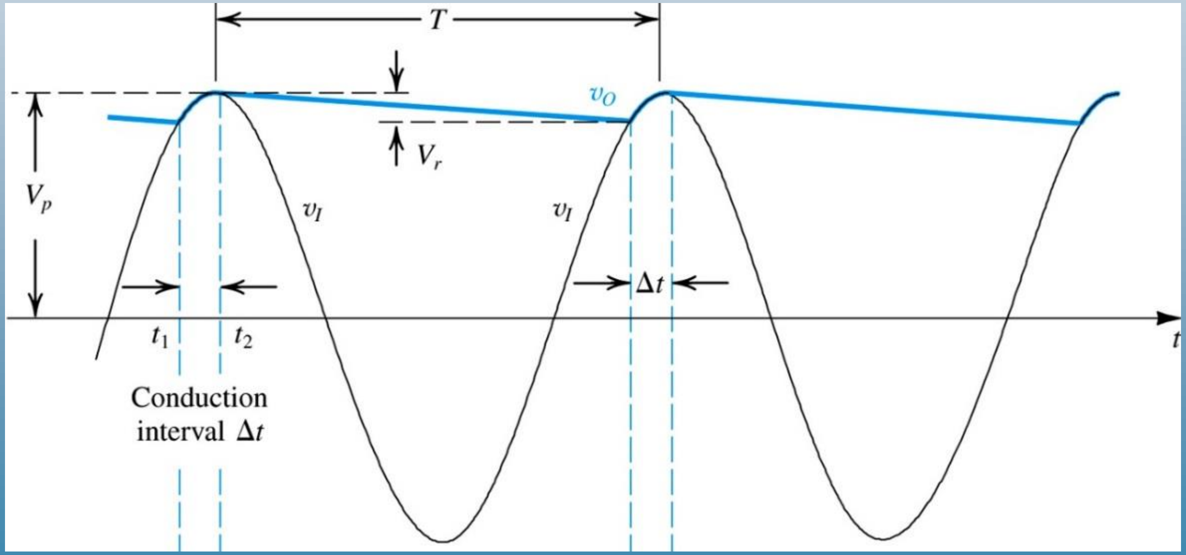


The Rectifier with a Filter Capacitor - The Peak Rectifier

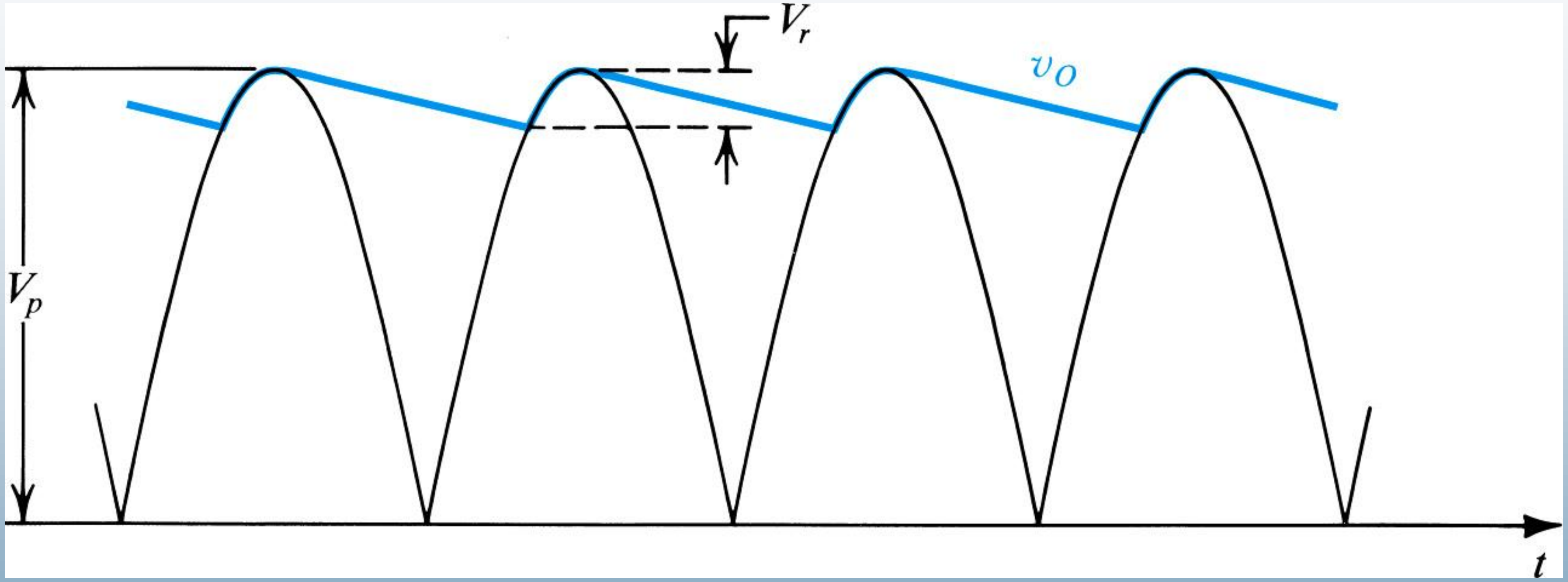


k Rectifier with a Load Resistor – A More Practic



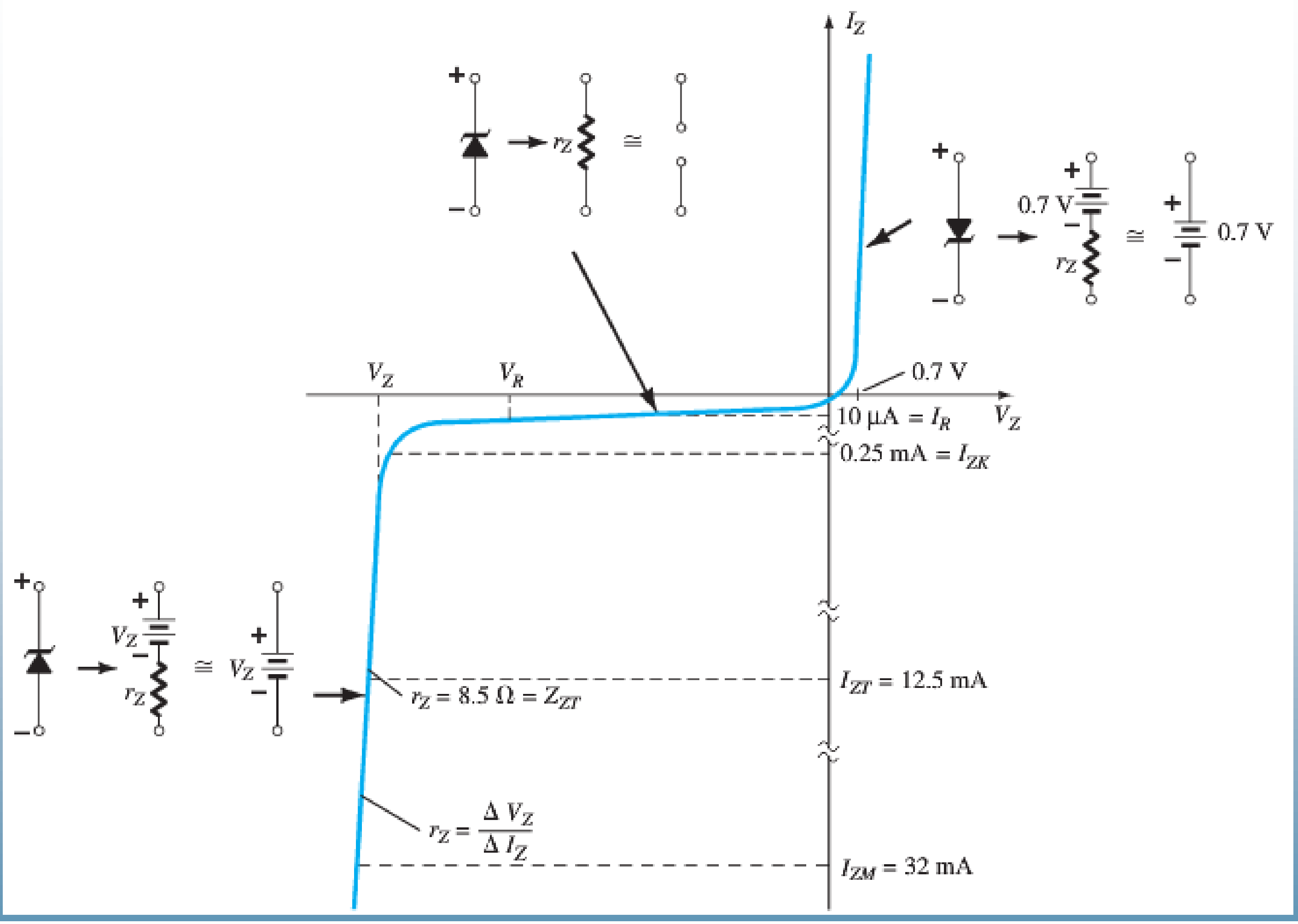


The full-wave peak rectifier



- The ripple is smaller
- The ripple frequency will be twice that of the input

Zener Diode Characteristics



Zener Voltage Nominal V_Z (V)	Test Current I_{ZT} (mA)	Maximum Dynamic Impedance Z_{ZT} at I_{ZT} (Ω)	Maximum Knee Impedance Z_{ZK} at I_{ZK} (Ω)	(mA)	Maximum Reverse Current I_R at V_R (µA)	Test Voltage V_R (V)	Maximum Regulator Current I_{ZM} (mA)	Typical Temperature Coefficient (%/°C)
10	12.5	8.5	700	0.25	10	7.2	32	+0.072

Zener Diodes

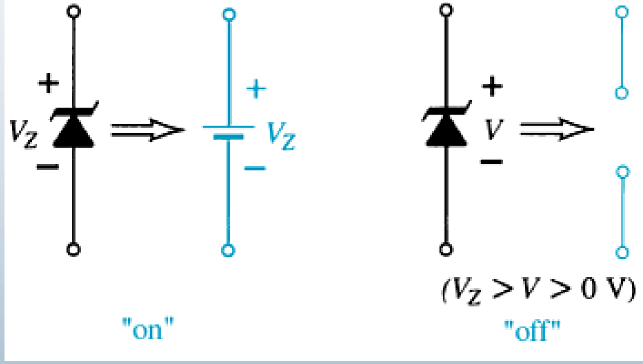
The Zener is a diode that is operated in reverse bias at the Zener Voltage (V_z).

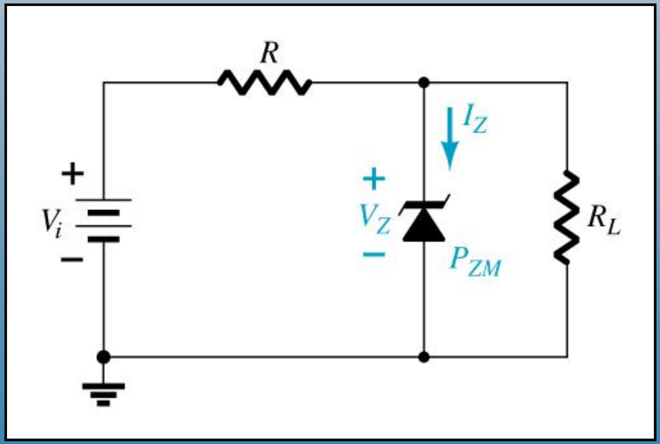
When $V_i \geq V_Z$

- The Zener is on
- Voltage across the Zener is V_Z
- Zener current: $I_Z = I_R - I_{RL}$
- The Zener Power: $P_Z = V_Z I_Z$

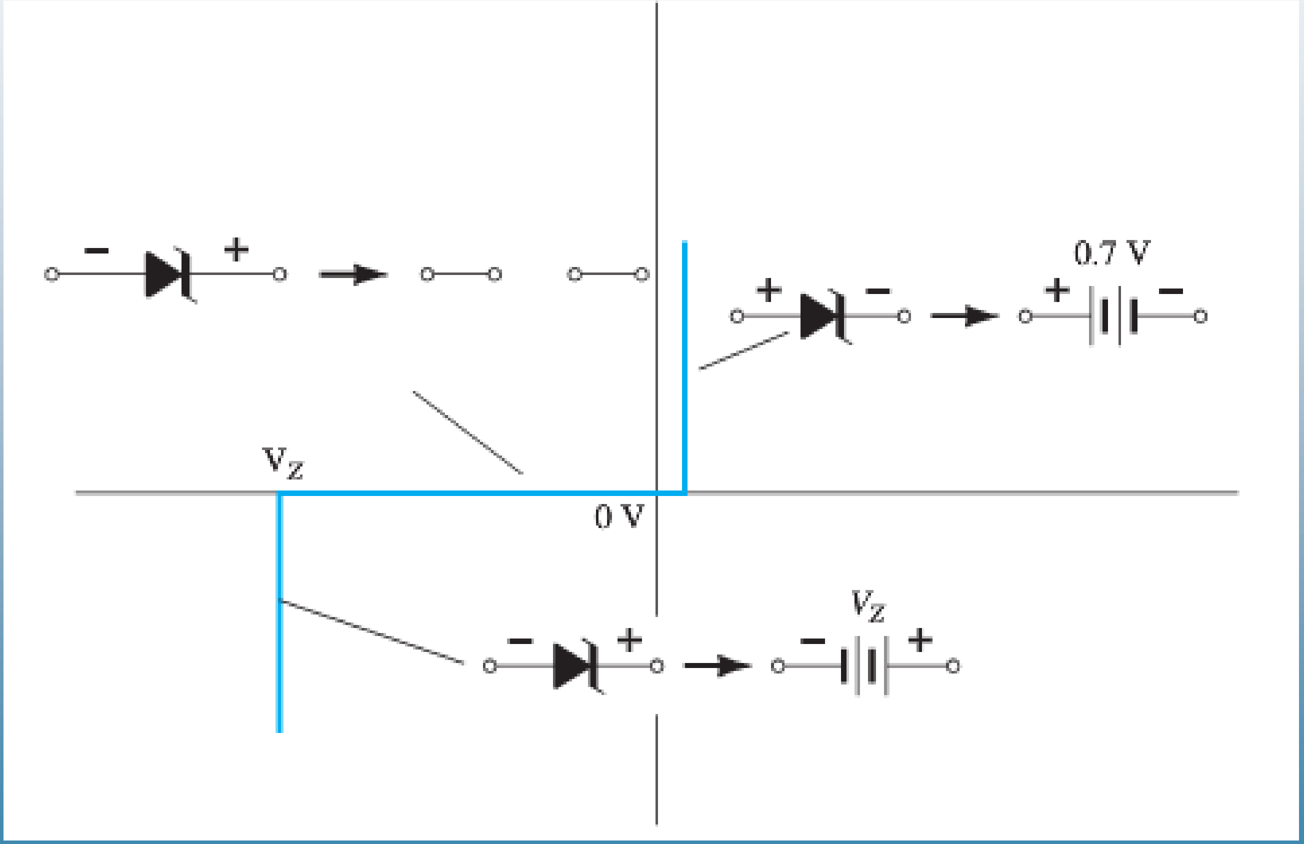
When $V_i < V_Z$

- The Zener is off
- The Zener acts as an open circuit





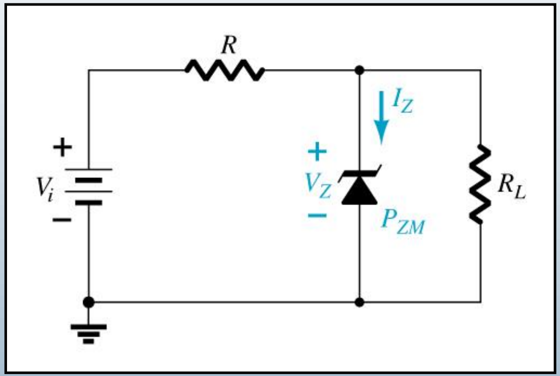
Approximate equivalent circuits for the Zener diode in the three possible regions of application



Zener Resistor Values

If R is too large, the Zener diode cannot conduct because $I_Z < I_{ZK}$. The minimum current is given by:

$$I_{Lmin} = I_R - I_{ZK}$$



The *maximum* value of resistance is:

$$R_{Lmax} = \frac{V_Z}{I_{Lmin}}$$

If R is too small, $I_Z > I_{ZM}$. The maximum allowable current for the circuit is given by:

$$I_{Lmax} = \frac{V_L}{R_L} = \frac{V_Z}{R_{Lmin}}$$

The *minimum* value of resistance is:

$$R_{Lmin} = \frac{RV_Z}{V_i - V_Z}$$

EXAMPLE 2.24 Determine the reference voltages provided by the network of Fig. 2.109, which uses a white LED to indicate that the power is on. What is the level of current through the LED and the power delivered by the supply? How does the power absorbed by the LED compare to that of the 6-V Zener diode?

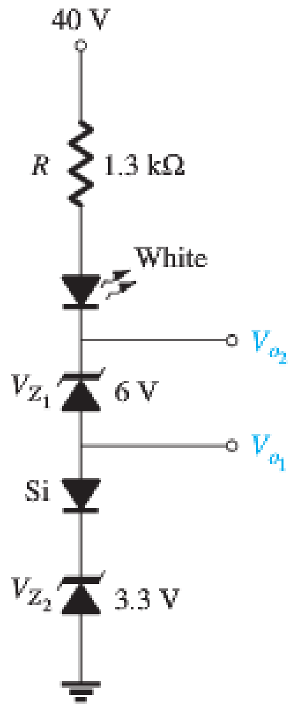


FIG. 2.109
Reference setting circuit for Example 2.24.

Note that the silicon diode was used to create a reference voltage of 4 V because

$$V_{o_1} = V_{Z_2} + V_K = 3.3\text{ V} + 0.7\text{ V} = \mathbf{4.0\text{ V}}$$

Combining the voltage of the 6-V Zener diode with the 4 V results in

$$V_{o_2} = V_{o_1} + V_{Z_1} = 4\text{ V} + 6\text{ V} = \mathbf{10\text{ V}}$$

Finally, the 4 V across the white LED will leave a voltage of 40 V – 14 V = 26 V across the resistor, and

$$I_R = I_{\text{LED}} = \frac{V_R}{R} = \frac{40\text{ V} - V_{o_2} - V_{\text{LED}}}{1.3\text{ k}\Omega} = \frac{40\text{ V} - 10\text{ V} - 4\text{ V}}{1.3\text{ k}\Omega} = \frac{26\text{ V}}{1.3\text{ k}\Omega} = \mathbf{20\text{ mA}}$$

which should establish the proper brightness for the LED.

The power delivered by the supply is simply the product of the supply voltage and current drain as follows:

$$P_s = EI_s = EI_R = (40\text{ V})(20\text{ mA}) = \mathbf{800\text{ mW}}$$

The power absorbed by the LED is

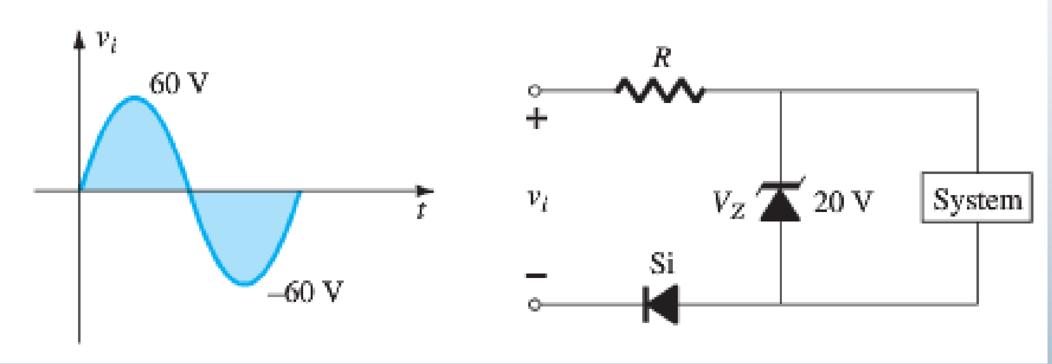
$$P_{\text{LED}} = V_{\text{LED}}I_{\text{LED}} = (4\text{ V})(20\text{ mA}) = \mathbf{80\text{ mW}}$$

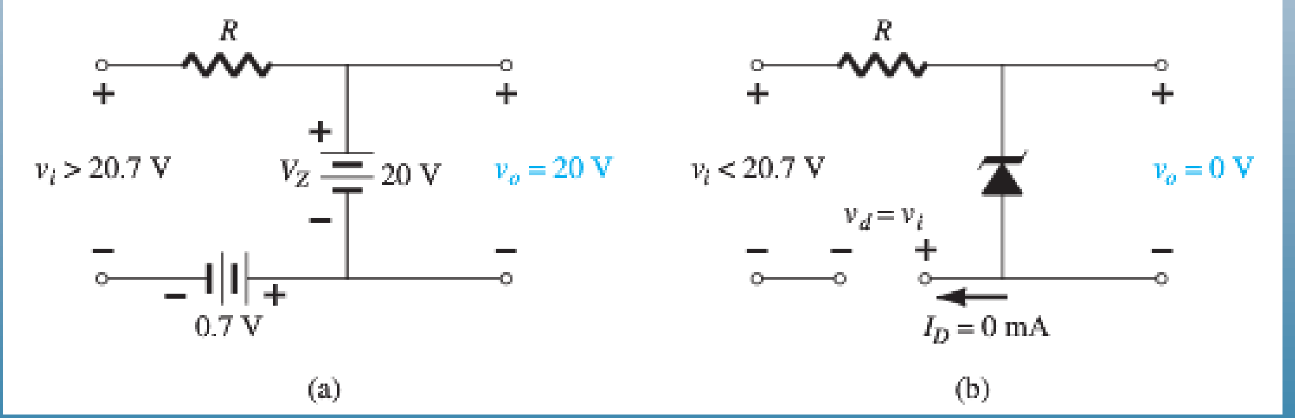
and the power absorbed by the 6-V Zener diode is

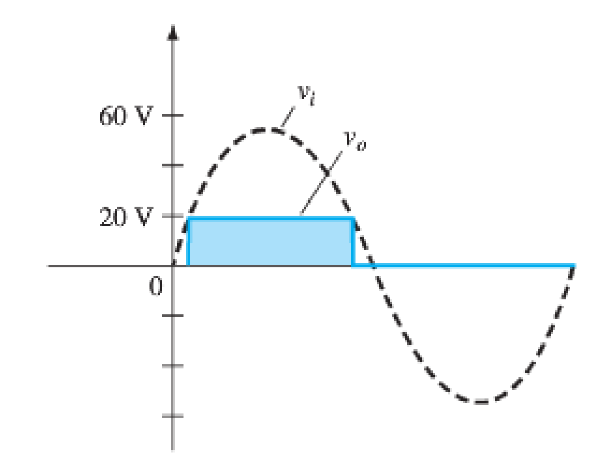
$$P_Z = V_Z I_Z = (6\text{ V})(20\text{ mA}) = \mathbf{120\text{ mW}}$$

The power absorbed by the Zener diode exceeds that of the LED by 40 mW.

EXAMPLE 2.25 The network of Fig. 2.110 is designed to limit the voltage to 20 V during the positive portion of the applied voltage and to 0 V for a negative excursion of the applied voltage. Check its operation and plot the waveform of the voltage across the system for the applied signal. Assume the system has a very high input resistance so it will not affect the behavior of the network.







EXAMPLE 2.26

a. For the Zener diode network of Fig. 2.115, determine V_L, V_R, I_Z, and P_Z.

b. Repeat part (a) with $R_L = 3\ \text{k}\Omega$.

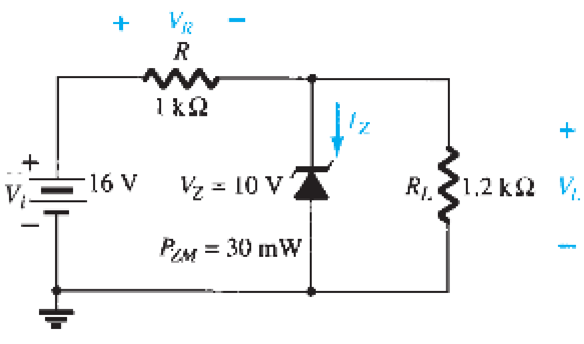
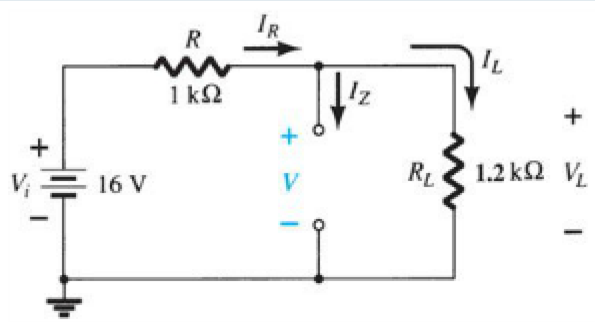


FIG. 2.115

Zener diode regulator for Example 2.26.



$$V = \frac{R_L V_i}{R + R_L} = \frac{1.2\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 1.2\ \text{k}\Omega} = 8.73\ \text{V}$$

$$V_L = V = \mathbf{8.73\ V}$$

$$V_R = V_i - V_L = 16\ \text{V} - 8.73\ \text{V} = \mathbf{7.27\ V}$$

$$I_Z = \mathbf{0\ A}$$

$$P_Z = V_Z I_Z = V_Z(0\ \text{A}) = \mathbf{0\ W}$$

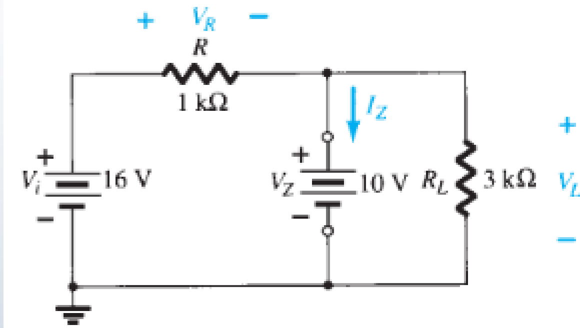


FIG. 2.118

Network of Fig. 2.115 in the "on" state.

$$V = \frac{R_L V_i}{R + R_L} = \frac{3\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 3\ \text{k}\Omega} = 12\ \text{V}$$

$$V_L = V_Z = \mathbf{10\ V}$$

$$V_R = V_i - V_L = 16\ \text{V} - 10\ \text{V} = \mathbf{6\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{10\ \text{V}}{3\ \text{k}\Omega} = 3.33\ \text{mA}$$

$$I_R = \frac{V_R}{R} = \frac{6\ \text{V}}{1\ \text{k}\Omega} = 6\ \text{mA}$$

$$I_Z = I_R - I_L\ [\text{Eq. (2.18)}]$$
$$= 6\ \text{mA} - 3.33\ \text{mA}$$
$$= \mathbf{2.67\ mA}$$

The power dissipated is

$$P_Z = V_Z I_Z = (10\ \text{V})(2.67\ \text{mA}) = \mathbf{26.7\ mW}$$

which is less than the specified $P_{ZM} = 30\ \text{mW}$.

EXAMPLE 2.27

a. For the network of Fig. 2.119, determine the range of R_L and I_L that will result in V_{RL} being maintained at 10 V.

b. Determine the maximum wattage rating of the diode.

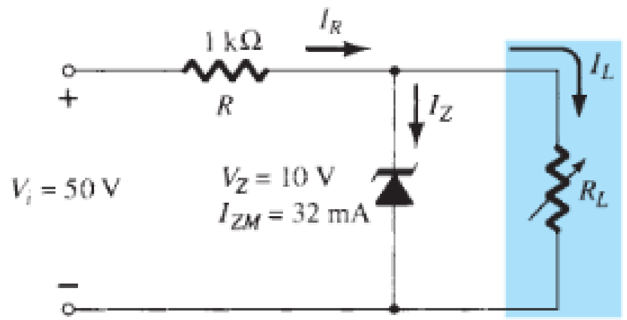


FIG. 2.119

Voltage regulator for Example 2.27.

Solution:

a. To determine the value of R_L that will turn the Zener diode on, apply Eq. (2.2

$$R_{L_{\min}} = \frac{RV_Z}{V_i - V_Z} = \frac{(1\text{ k}\Omega)(10\text{ V})}{50\text{ V} - 10\text{ V}} = \frac{10\text{ k}\Omega}{40} = \mathbf{250\ \Omega}$$

The voltage across the resistor R is then determined by Eq. (2.22):

$$V_R = V_i - V_Z = 50\text{ V} - 10\text{ V} = \mathbf{40\ V}$$

and Eq. (2.23) provides the magnitude of I_R:

$$I_R = \frac{V_R}{R} = \frac{40\text{ V}}{1\text{ k}\Omega} = \mathbf{40\ mA}$$

The minimum level of I_L is then determined by Eq. (2.25):

$$I_{L_{\min}} = I_R - I_{ZM} = 40\text{ mA} - 32\text{ mA} = \mathbf{8\ mA}$$

with Eq. (2.26) determining the maximum value of R_L:

$$R_{L_{\max}} = \frac{V_Z}{I_{L_{\min}}} = \frac{10\text{ V}}{8\text{ mA}} = \mathbf{1.25\ k\Omega}$$

b. $P_{\max} = V_Z I_{ZM}$
$= (10\text{ V})(32\text{ mA}) = \mathbf{320\ mW}$

EXAMPLE 2.28 Determine the range of values of V_i that will maintain the Zener diode of Fig. 2.121 in the "on" state.

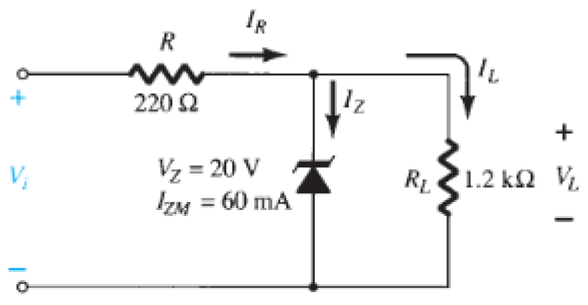


FIG. 2.121

Regulator for Example 2.28.

Solution:

Eq. (2.27): $$V_{i_{\min}} = \frac{(R_L + R)V_Z}{R_L} = \frac{(1200\ \Omega + 220\ \Omega)(20\ \text{V})}{1200\ \Omega} = \mathbf{23.67\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} = \frac{20\ \text{V}}{1.2\ \text{k}\Omega} = 16.67\ \text{mA}$$

Eq. (2.28): $$I_{R_{\max}} = I_{ZM} + I_L = 60\ \text{mA} + 16.67\ \text{mA}$$
$$= 76.67\ \text{mA}$$

Eq. (2.29): $$V_{i_{\max}} = I_{R_{\max}}R + V_Z$$
$$= (76.67\ \text{mA})(0.22\ \text{k}\Omega) + 20\ \text{V}$$
$$= 16.87\ \text{V} + 20\ \text{V}$$
$$= \mathbf{36.87\ V}$$

A plot of V_L versus V_i is provided in Fig. 2.122.

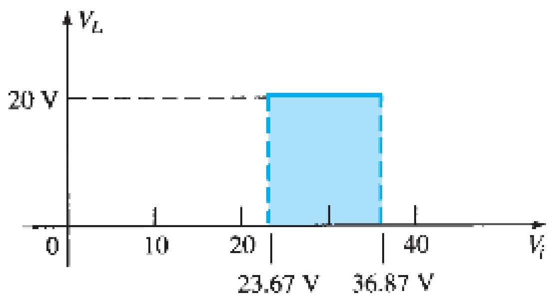
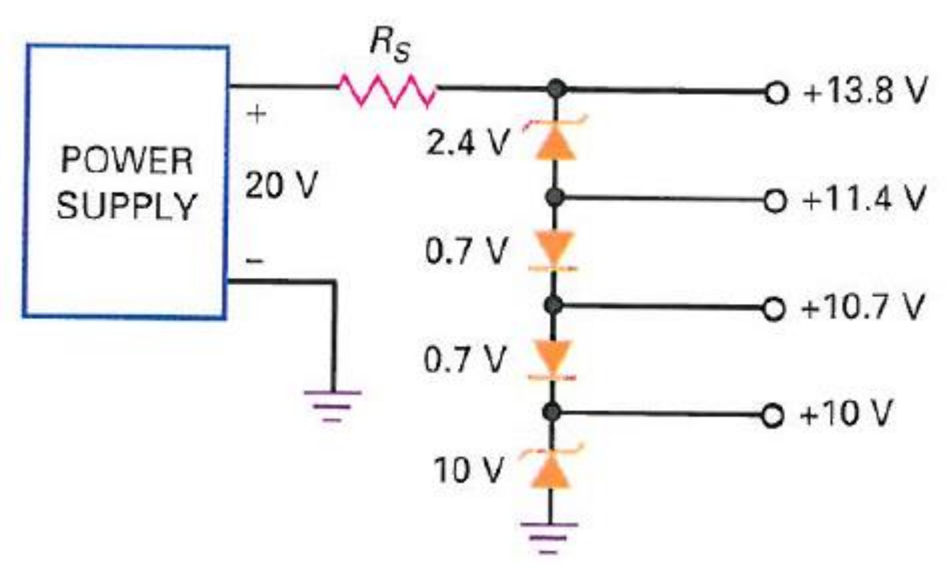


FIG. 2.122

V_L versus V_i for the regulator of Fig. 2.121.

Zener application

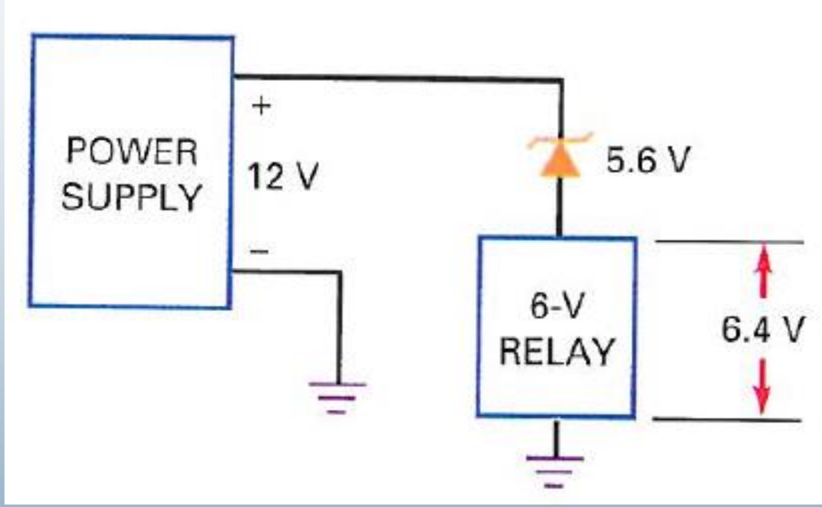
- **Producing nonstandard output voltages**



- **Each silicon diode is forward biased and zener diodes are operating in the breakdown region**
- **With other combinations of zener and silicon diodes, a circuit like this can produce different dc output voltages**

Zener application

- Using a 6-V relay in a 12-V system



- If you try to connect a 6-V relay to a 12-V system, you will probably damage the relay.
- With the zener in series, only 6.4 V appears across the relay, which is usually within the tolerance of the relay's voltage rating.

Voltage-Multiplier Circuits

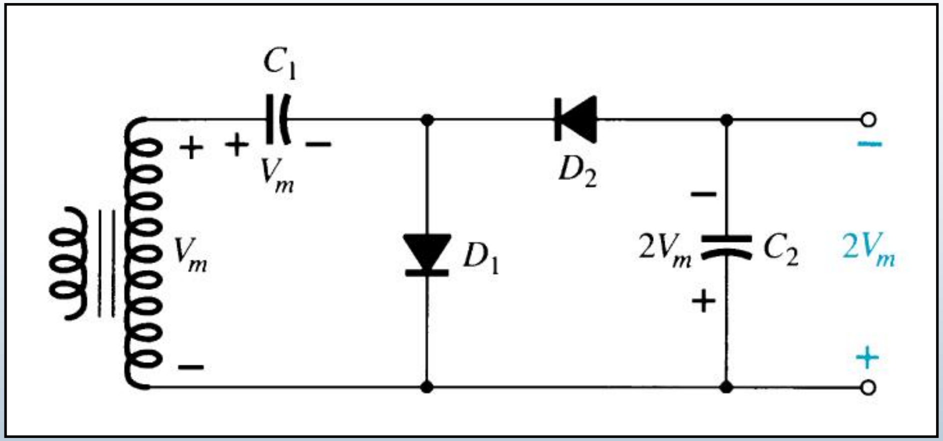
Voltage multiplier circuits use a combination of diodes and capacitors to step up the output voltage of rectifier circuits. Three common voltage multipliers are the:

Voltage Doubler

Voltage Tripler

Voltage Quadrupler

Voltage Doubler



This half-wave voltage doubler's output can be calculated using:

$$V_{out} = V_{C2} = 2V_m$$

where V_m = peak secondary voltage of the transformer

Voltage Doubler

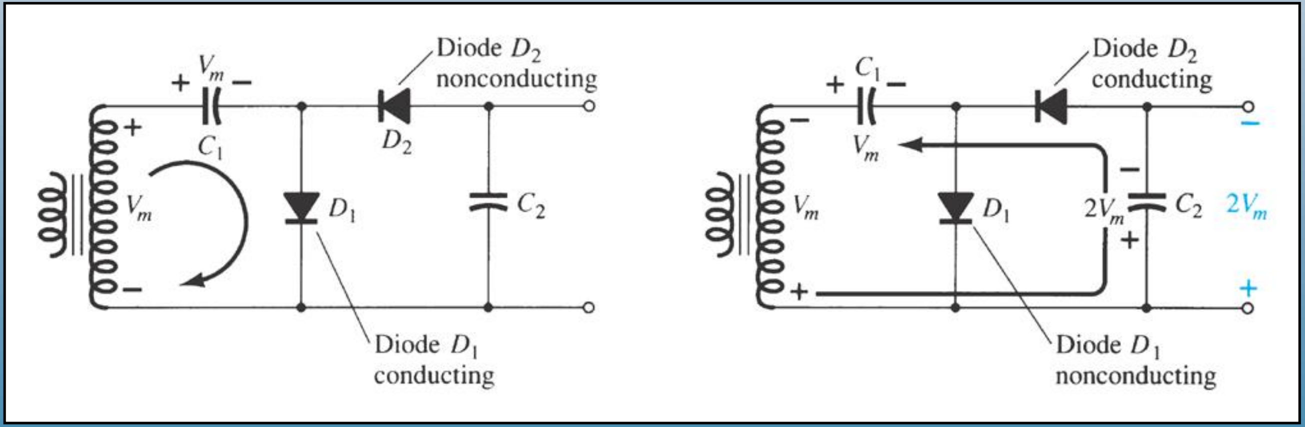
Positive Half-Cycle

D_1 conducts
D_2 is switched off
Capacitor C_1 charges to V_m

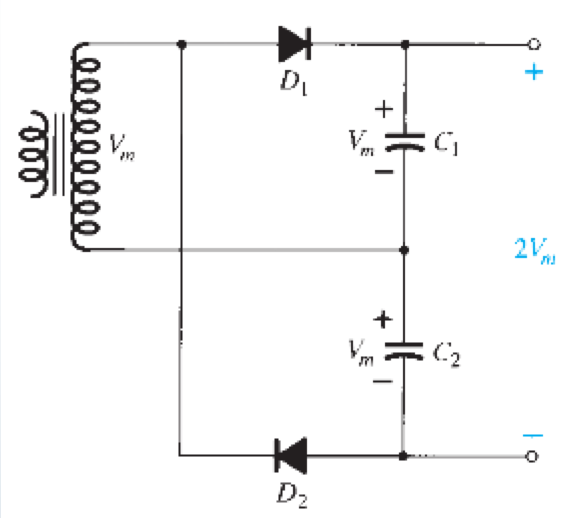
Negative Half-Cycle

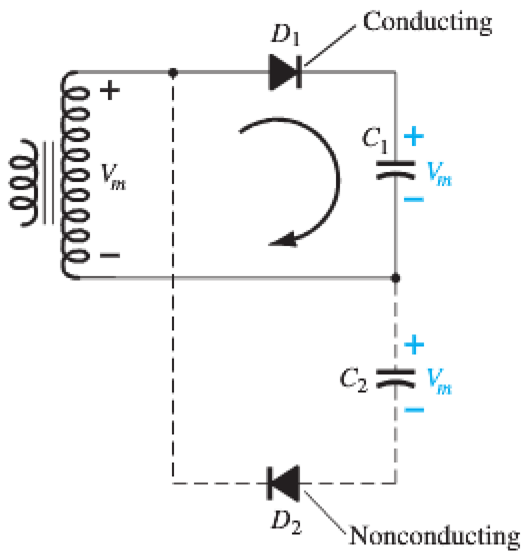
D_1 is switched off
D_2 conducts
Capacitor C_2 charges to V_m

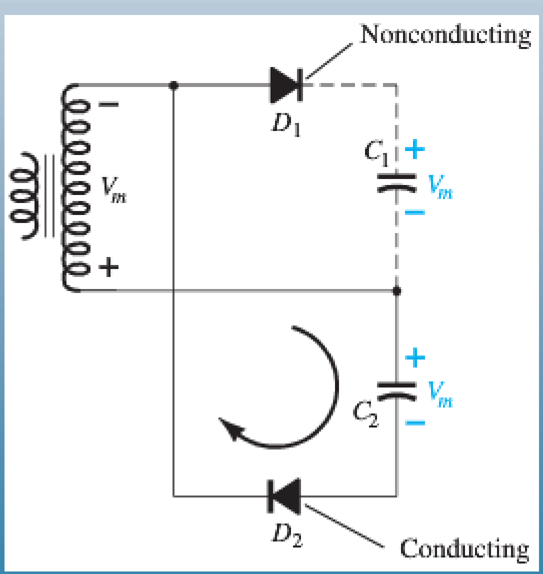
$V_{out} = V_{C2} = 2V_m$



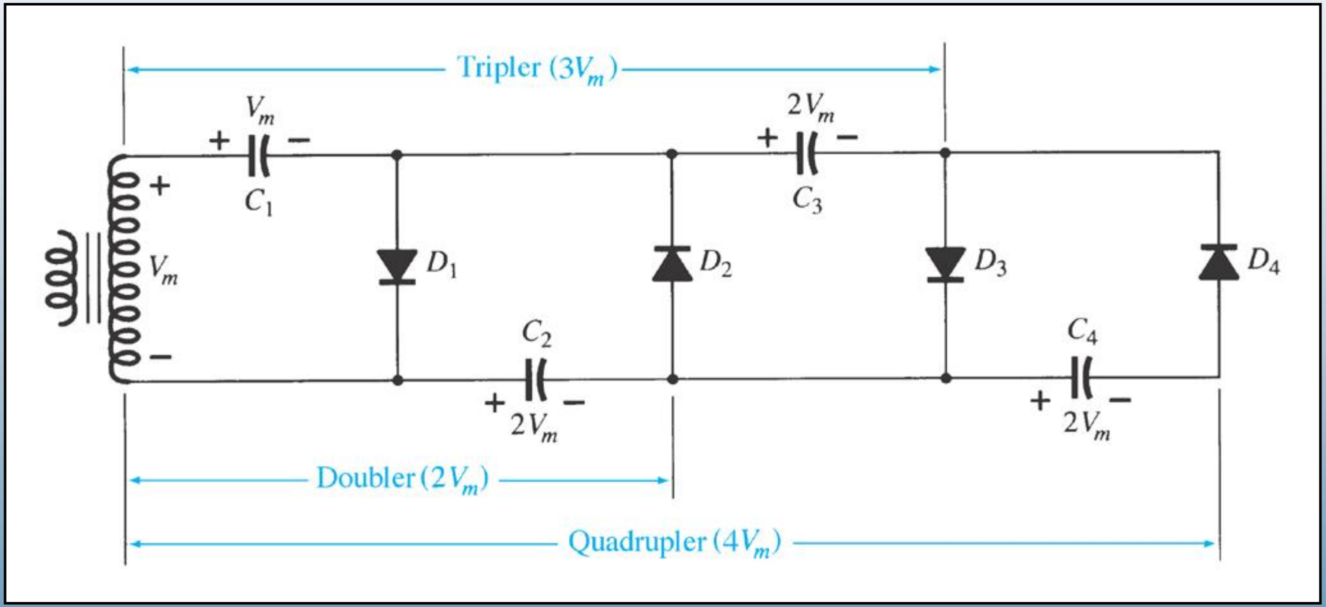
Full-Wave Voltage Doubler







Voltage Tripler and Quadrupler



Practical Applications

Rectifier Circuits

Conversions of AC to DC for DC operated circuits
Battery Charging Circuits

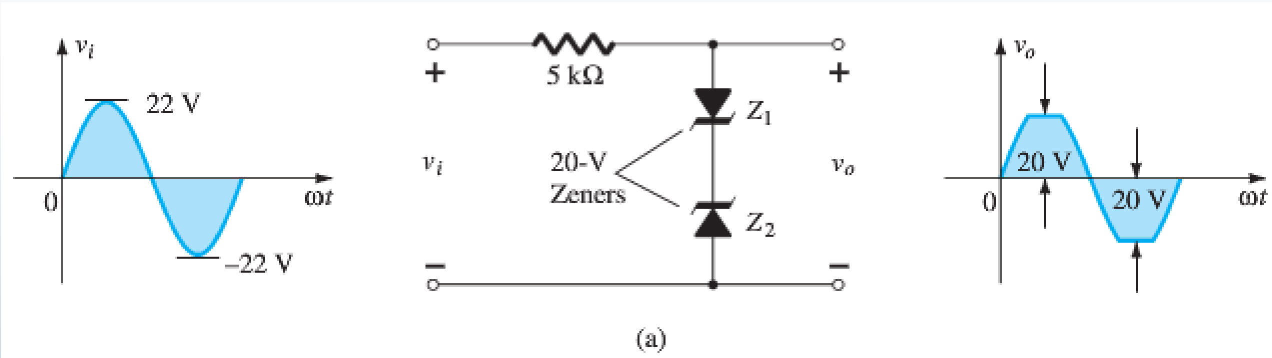
Simple Diode Circuits

Protective Circuits against
Overcurrent
Polarity Reversal
Currents caused by an inductive kick in a relay circuit

Zener Circuits

Overvoltage Protection
Setting Reference Voltages

An Application: AC Regulator and Square-Wave Generator



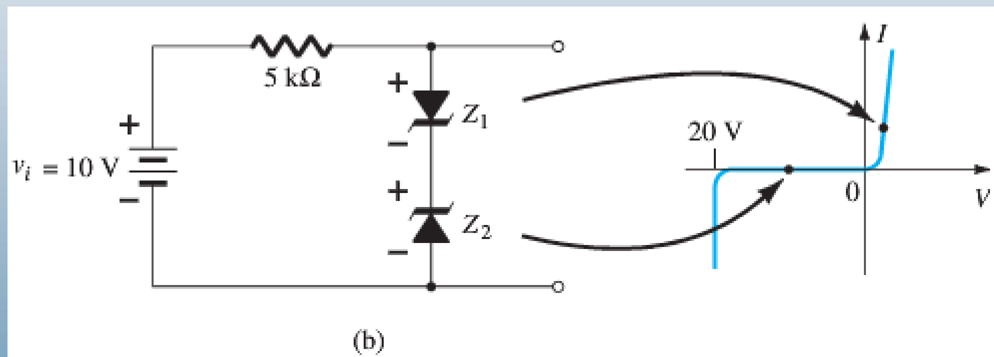


Figure: Sinusoidal ac regulation: (a) 40-V peak-to-peak sinusoidal ac regulator;
(b) circuit operation at v *i = 10 V*.

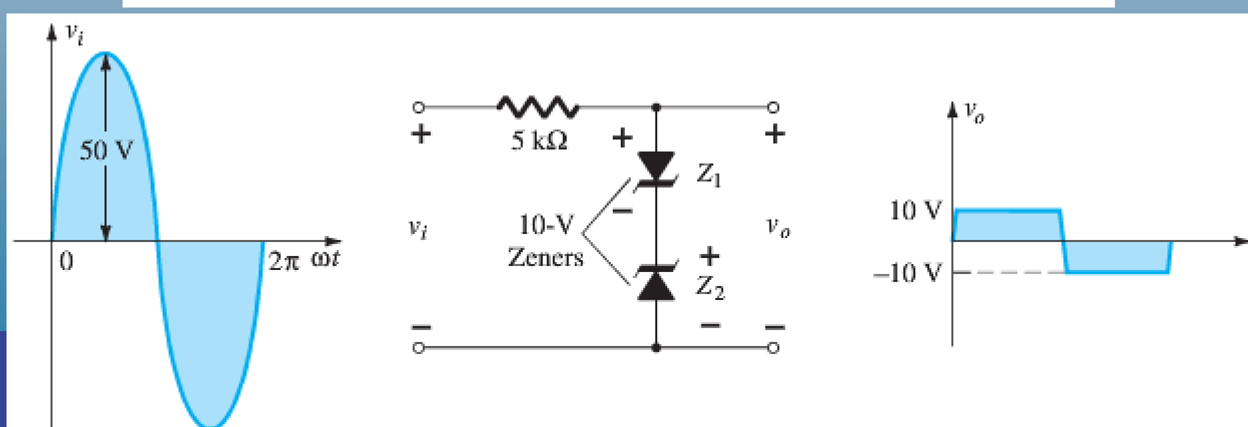


Figure: Simple square-wave generator.