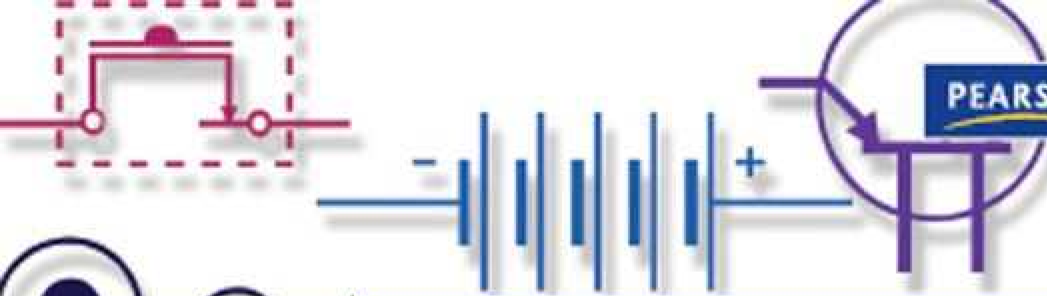
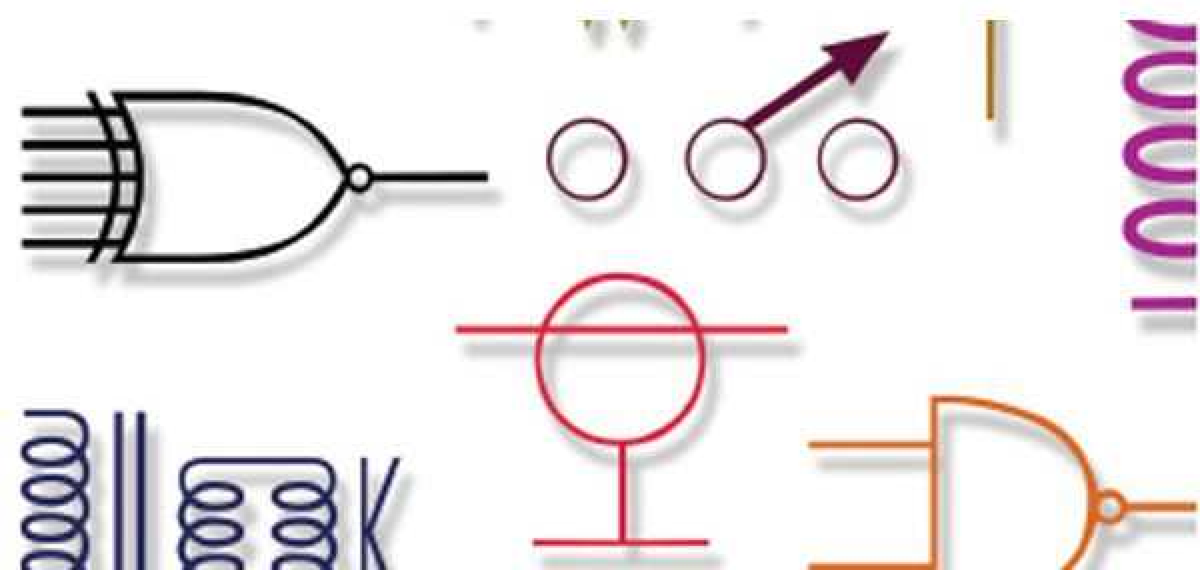


Diode Circuits

Basic Electronics



3

Diode Circuits

Outline

Objectives

This chapter analyses diode circuits and load line with the *Q*-point concept. The formulation of the diode as a voltage regulator, half-wave rectifier, and full-wave rectifier along with bridge rectification and performance analysis of rectifier circuits will be dealt with in detail. This is followed by a derivation of peak inverse voltage, dc voltage and current, ripple factor, and efficiency. Clipper and clamper circuits, comparators, and additional diode circuits will be analysed at the end of the chapter.

3-1 INTRODUCTION

In the field of electronics, the simplest and the most fundamental non-linear circuit element is the diode. The *p–n* junction diode is considered to be a circuit element. For easy and lucid evaluation of the diode element, the concept of load line is extremely important. Among the many applications of diodes, their use in the design of rectifiers, which convert ac to dc, is the most common. The piecewise linear model is used in certain applications of diodes, namely clippers, rectifiers and comparators. Many more such circuits are possible with one or more diodes being implemented in them.

3-2 ANALYSIS OF DIODE CIRCUITS

The basic diode circuit consists of a voltage source in series with a resistor and a diode. The circuit might be analysed properly to obtain the instantaneous current and diode voltage. For such an analysis to be done, the concept of load line and its effective use in various circuits has to be thoroughly understood. The concept of load line is absolutely essential.

3-3 LOAD LINE AND *Q*-POINT

The applied load will normally have an impact on the region (or point) of operation of a device. If the analysis is performed in a graphical manner, a line can be drawn on the characteristics of the device to represent the applied load. The intersection of the load line with the characteristics will determine the point of operation of the system. Physically, this point of operation mainly determines the conditions under which the device is to be operated in a circuit. This case takes care of the various intriguing attributes of the circuit. This kind of an analysis is known as the *load-line analysis*. We will discuss the concept of load line from all practical points of view. An example has been shown in Fig. 3-1(a) and Fig. 3-1(b).

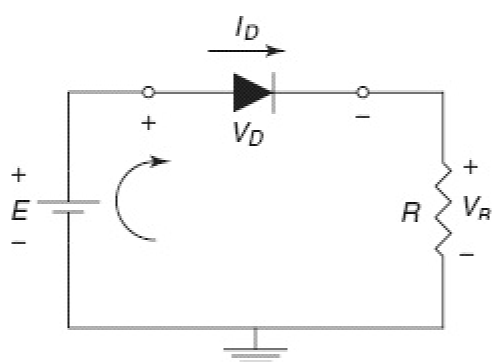


Figure 3-1(a) Analysis of a basic diode circuit

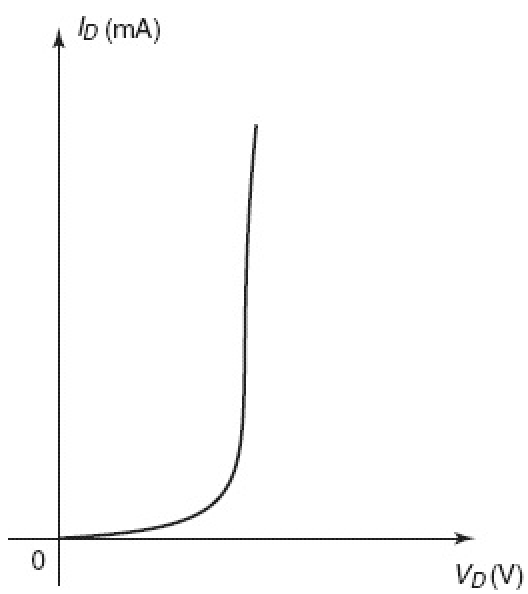


Figure 3-1(b) I-V characteristics of the diode

Let us consider the network and its characteristics as given in Fig. 3-1(a). The voltage established by the battery E is to generate a current through the series resistor R of the circuit in the clockwise direction. The fact that this current and the defined direction of conduction of the diode are the same reveals that the diode is in the ON state, i.e., the diode is forward-biased and consequently, the forward resistance of the diode is very low. Under normal conditions, this resistance is approximately 10 Ω. Applying Kirchoff's voltage law (KVL) of circuit theory, to the series circuit of Fig. 3-1(a), we obtain:

$$E - V_D - V_R = 0 \tag{3-1}$$

$$E = V_D + I_D R \tag{3-2}$$

The intersection of the load line with the curve of current–voltage characteristics under forward-biased conditions easily implicates the conditions of operation of the device in the circuit.

If $V_D = 0$ V, we can calculate I_D and plot the magnitude of I_D on the vertical axis.

As $V_D = 0$ V, Eq. (3-2) is modified as:

$$\begin{aligned} E &= V_D + I_D R \\ &= 0\text{ V} + I_D R \end{aligned}$$

$$I_D = \left.\frac{E}{R}\right|_{V_D = 0\text{V}} \tag{3-3}$$

If $I_D = 0$ A, we can calculate V_D and plot the magnitude of V_D on the horizontal axis.

As $I_D = 0$ A, Eq. (3-2) is modified as:

$$\begin{aligned} E &= V_D + I_D R \\ &= V_D + (0\text{ A})\,R \end{aligned}$$

$$V_D = E\,\big|_{I_D = 0\text{A}} \tag{3-4}$$

A straight line drawn between two points will define the load line, as shown in Fig. 3-2(a).

If the value of R is changed, the intersection on the vertical axis will change. This affects the slope of the load line, and gives a different point of intersection between the load line and the device characteristics. The point of intersection between the device characteristics and the load line (V_{D0}, I_{D0}) is called the point of operation or the quiescent point (Q-point) as defined by a dc network.

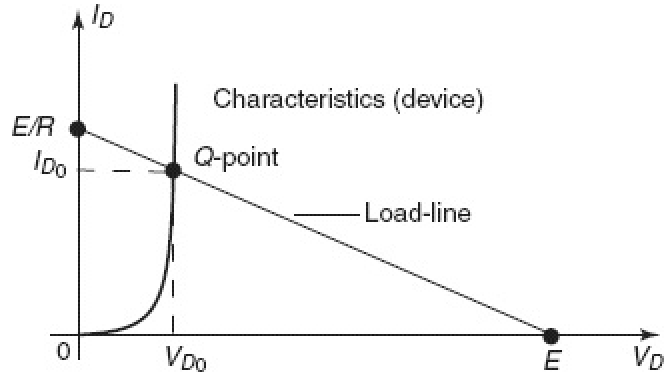


Figure 3-2(a) The load line on the characteristics of the diode

From the circuit diagram given in Fig. 3-1(a) it can be seen that the voltage drop across the diode is given by:

$$V_D = E - V_L$$

or

$$V_D = E - i_D R_L \qquad (3\text{-}5)$$

where, V is the supply voltage, V_L is the voltage across the load, and I_a is the current flowing through the diode.

Equation (3-5) gives a relation between the voltage across the diode and the current flowing through it. It can be seen that this equation is an equation of a straight line. The load line and the static characteristic curve of the diode intersect at the quiescent point. The co-ordinates of the Q-point are v_Q, i_Q The point is as shown in Fig. 3-3(a). Again, if the value of the voltage source is changed, another point on the static characteristic of the diode is obtained. The co-ordinates of the new point are Q' (v_Q', i_Q').

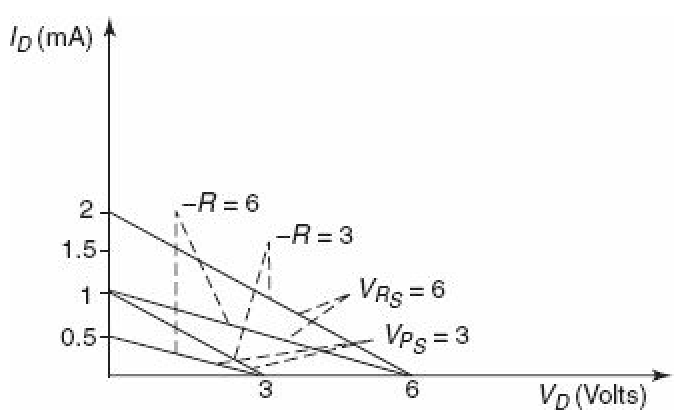


Figure 3-2(b) Illustration of a load line when: (1) voltage is constant and resistance varies (2) voltage varies and the resistance is constant

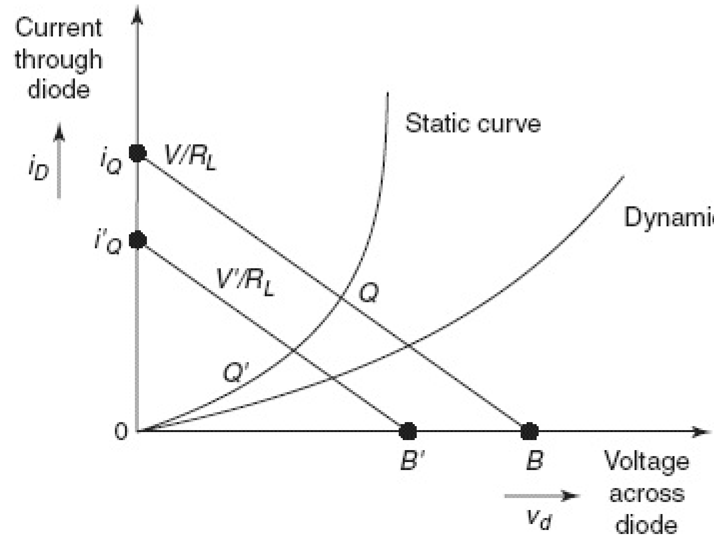


Figure 3-3(a) Change of Q-point with changes in supply voltage and load

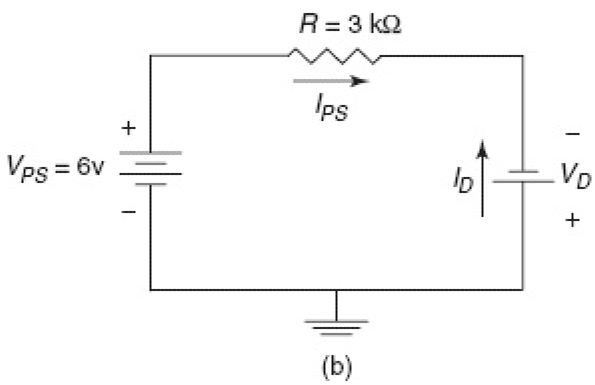


Figure 3-3(b) Reverse-biased diode circuit

If the diode currents i_Q and i_Q' are plotted vertically above the corresponding supply voltages, two distinct points are obtained—*B* and *B′*. The curve passing through these two points is known as the *dynamic load line*. Dynamic load line can be obtained for different load resistances. This dynamic load line is important, because with the help of this, for any given input voltage, the diode current can be obtained directly from the graph. The load-line concept is important in reverse biasing.

Figure 3-3(b) depicts the diode circuit under the reversed condition. The forward-biased parameters over here are I_D (diode current) and V_D (voltage). It can be written with the application of Kirchoff's voltage law, $V_{PS} = I_{PS}R - V_D = -I_DR - V_D$ (where, $I_D = -I_{PS}$).

The equation, $V_{PS} = I_{PS}R - V_D = -I_DR - V_D$, characterizes the load line.

For the first end point, putting $I_D = 0$:

$$V_D = -V_{PS} = -6\text{ V}$$

For the second end point, putting $I_D = 0$:

$$I_D = \frac{-V_{PS}}{R} = -\frac{6}{3} = -2\text{ mA}$$

Figure 3-3(c) depicts the plot of diode characteristics and load line. The reverse-biased condition of the diode is demonstrated by the fact that the load intersects the diode characteristics curve in the third quadrant at $V_D = -6$ V and $I_D = 0$.

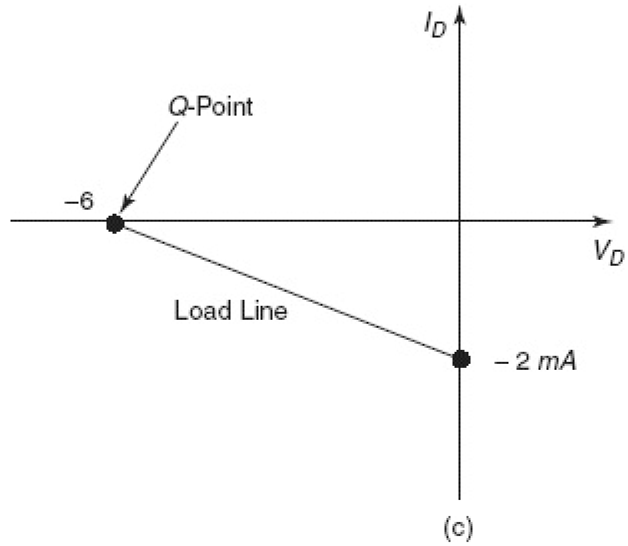


Figure 3-3(c) Load line

3-4 ZENER DIODE AS VOLTAGE REGULATOR

A Zener diode can be used as a voltage regulator because it maintains a constant output voltage even though the current passing through it changes. It is generally used at the output of an unregulated power supply to provide a constant output voltage free of ripple components.

The circuit diagram of a voltage regulator is shown in Fig. 3-4. The circuit consists of a current limiting resistor R_S and a Zener diode connected in parallel with the load resistance R_L. The diode is selected in such a way that its breakdown voltage is equal to the desired regulating output.

For proper voltage regulation, the voltage of an unregulated power supply must be greater than the Zener voltage of the diode selected. The diode does not conduct current when the input voltage is less than the Zener voltage. The value of R_S is chosen to ensure that the diode initially operates in the breakdown region under the Zener voltage across it. The function of the regulator is to keep the output voltage nearly constant with changes in V_{in} or I_L.

The operation is based on the fact that in the Zener breakdown region small changes in the diode voltage are accompanied by large changes in the diode current. The large currents flowing through R_S produce voltages that compensate for the changes in V_{in} or I_L. The relation gives the input current:

$$I = \frac{V_{in} - V_Z}{R_S} = I_Z + I_L \tag{3-6}$$

There are two types of regulation:

i. Regulation with varying input voltage, also known as line regulation
ii. Regulation with varying load resistance, also known as load regulation

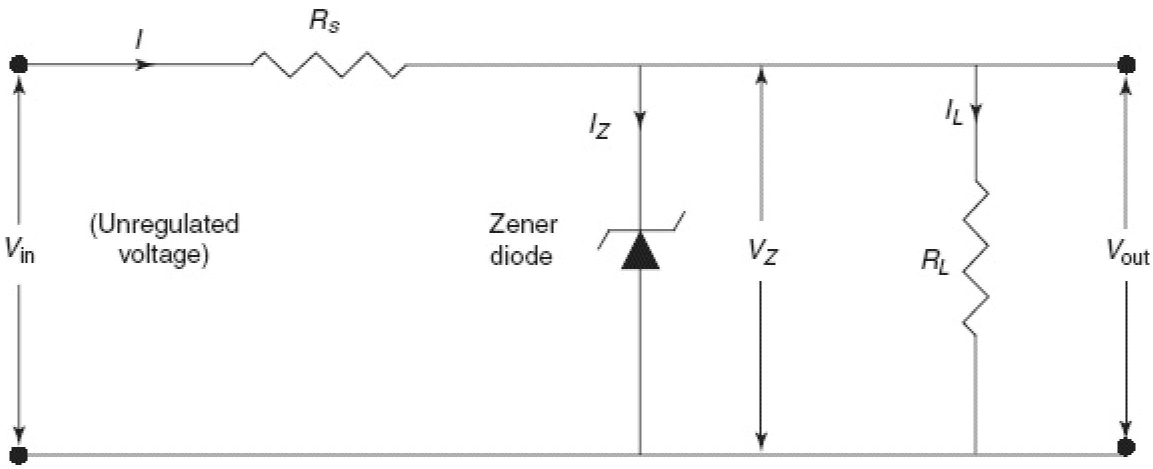


Figure 3-4 Zener regulation of a variable input voltage

3-4-1 Line Regulation

When the input voltage is more than V_Z, the Zener diode conducts. With a further increase in V_{in}, the input current I will also increase. This increases the current through the Zener diode without affecting the load current I_L. The limitations on the input-voltage variations are set by the minimum and maximum current values (I_{ZK} and I_{ZM}) within which the Zener diode can operate.

The increase in the input current I will also increase the voltage drop across series resistance R_S, thereby keeping the output voltage constant. If the input voltage decreases, the input current through the Zener diode will also decrease. Consequently, the voltage drop across the series resistance will be reduced. Thus, the output voltage and the load current remain constant.

For fixed values of R_L (see Fig. 3-4), the voltage V_i must be sufficiently large to turn the Zener diode on. The turn-on voltage is determined by V_L and $V_{i_{min}}$ as:

$$V_L = V_Z = \frac{R_L V_i}{R_L + R_S} \tag{3-7a}$$

$$V_{i_{\min}} = \frac{(R_L + R_S)V_Z}{R_L} \tag{3-7b}$$

The maximum value of V_i is limited by the maximum Zener current I_{ZM}

We have:

$$I_{ZM} = I_R - I_L \tag{3-8}$$

$$I_{R_{\max}} = I_{ZM} + I_L \tag{3-9}$$

As I_L is fixed at V_Z/R_L, and I_{ZM} is the maximum value of I_Z, the maximum V_i is given by:

$$V_{i_{\max}} = V_{R_{S_{\max}}} + V_Z \tag{3-10}$$

$$V_{i_{\max}} = I_{R_{\max}} R_S + V_Z \tag{3-11}$$

Figure 3-5(a) shows a plot of V_o versus V_i for line regulation. It is observed from the graph that the output voltage V_o remains constant when the diode is in the Zener region, i.e., when the stipulated current is flowing. This is called *input* or *line regulation*.

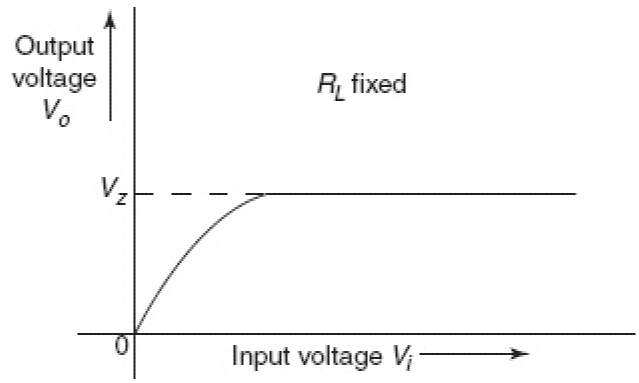


Figure 3-5(a) Output voltage vs. input voltage for line regulation

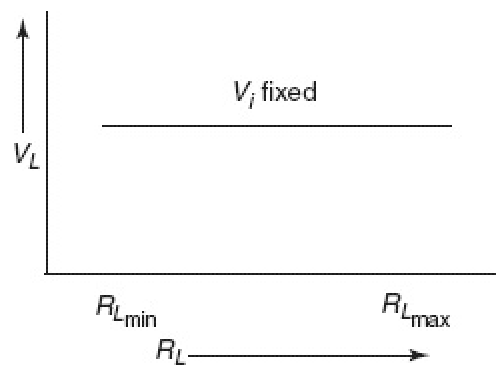


Figure 3-5(b) Load regulation showing the variation of load voltage V_L and R_L taking V_i as constant

3-4-2 Load Regulation: Regulation with Varying Load Resistance

In this case, the input voltage, $V_{in} > V_z$, is kept fixed and the load resistance, R_L, is varied. The variation of R_L changes the current I_L through it, thereby changing the output voltage. When the load resistance decreases, the current through it increases. This ultimately causes a decrease in the Zener current. As a result, the input current and the voltage drop across R_S remains constant. And the output voltage is also kept constant, as shown in Fig. 3-5(b). On the other hand, if the load resistance increases, the load current decreases. As a result, the Zener current I_Z increases. This again keeps the value of input current and voltage drop across the series resistance constant. Thus, the output voltage remains constant. This is called *load regulation*.

Due to the offset voltage V_Z, there is a specific range of resistor values, which will ensure that the

Zener is in the ON state. Too small a load resistance, R_L, will result in a voltage, V_L, across the load resistor to be less than V_Z, and the Zener device will be in the OFF state, which is usually not required in this kind of operation.

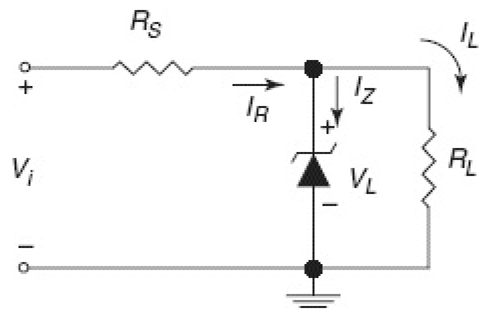


Figure 3-6 Diode as a voltage regulator

To determine the minimum load resistance which will turn the Zener diode on, simply remove the Zener diode, as shown in Fig. 3-6, and calculate the value of R_L that will result in a load voltage $V_L = V_z$

That is:

$$V_L = V_Z = \frac{R_L V_i}{R_L + R_S} \qquad (3\text{-}13)$$

From the voltage-divider rule and solving for R_L, we have:

$$R_{L_{\min}} = \frac{R_S V_Z}{V_i - V_Z} \qquad (3\text{-}14)$$

Any resistance with a value greater than the R_L will ensure that the Zener diode is in the ON state and the diode can be replaced by its V_Z source equivalent, as shown in Fig. 3-7.

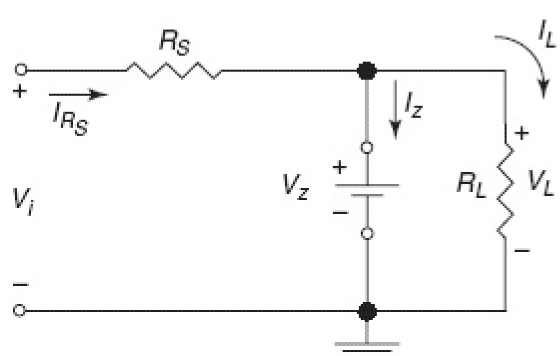


Figure 3-7 Analytical circuit of Zener diode being used as a regulator

The condition defined by Eq. (3-14) establishes the minimum R_L, but the maximum I_L is:

$$I_{L_{\max}} = \frac{V_L}{R_L} = \frac{V_Z}{R_{L_{\min}}} \qquad (3\text{-}15)$$

Once the diode is in the ON state, the voltage across R_S will remain fixed at:

$$V_{R_S} = V_i - V_Z \tag{3-16}$$

And I_R remains fixed at:

$$I_{R_S} = \frac{V_{R_S}}{R_S} \tag{3-17}$$

$$I_Z = I_R - I_L \tag{3-18}$$

This will result in a minimum I_Z when I_L is a maximum; and a maximum I_Z when I_L is a minimum value (I_R is constant). Since I_Z is limited to I_{ZM}, it does affect the range of R_L, and therefore, I_L.
Substituting I_{ZM} for I_Z establishes the minimum I_L as:

$$I_{L_{min}} = I_{R_S} - I_{ZM} \tag{3-19}$$

and the maximum load resistance as:

$$R_{L_{max}} = \frac{V_Z}{I_{L_{min}}} \tag{3-20}$$

Thus, load resistance can be calculated by using Eqs. (3-14) and (3-20).

Solved Examples

Example 3-1 A *p–n* germanium junction at room temperature has a reverse saturation current of 10 μA, negligible ohmic resistance, and a Zener breakdown voltage of 100 V. A 1.5 K resistor is in series with this diode, and a 45 V battery is impressed across this combination.

a. Find the current if the diode is forward-biased.
b. Find the current if the battery is inserted into the circuit with reverse polarity.
c. Repeat part (a) and (b) if the Zener breakdown voltage is 10 V with 1 K resistor and 30 V battery.

Solution:

a. The solution can be found graphically by plotting the diode characteristics and drawing the load line. Using the method of successive approximation, we have with us, diode drop equal to zero, in essence neglecting the diode threshold voltage.

$$I = \frac{45}{1.5\text{ K}} = 30\text{ mA}$$

For this current, V is given by:

$$30 \times 10^{-3} = 10 \times 10^{-6} (e^{38.4\text{ V}} - 1)$$

or,

$$e^{38.4\,V} = 3000 \quad \text{and} \quad V = 0.208\ \text{V}$$

Hence,

$$I = \frac{45 - 0.208}{1.5\ \text{K}} \approx 29.8\ \text{mA}$$

For this current, $V = 0.2$ V

∴

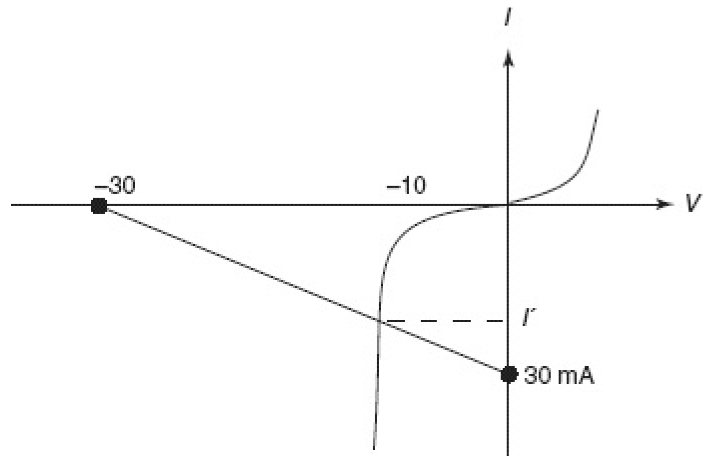
$$I = 29.8\ \text{mA}$$

b. The diode drop is −45 V and $I = -I_0 = -10\ \mu$A. The voltage drop across the 1.5 K resistors is only 15 mV and may be neglected.

c. In the forward direction, the answer is the same as in part (a), i.e., $I = 29.8$ mA.

In the reverse direction, we draw a load line from $V = -30$ V to $I = -30$ mA, as shown in the following figure. Then:

$$I' = -30 \times \frac{20}{30} = -20\ \text{mA}.$$

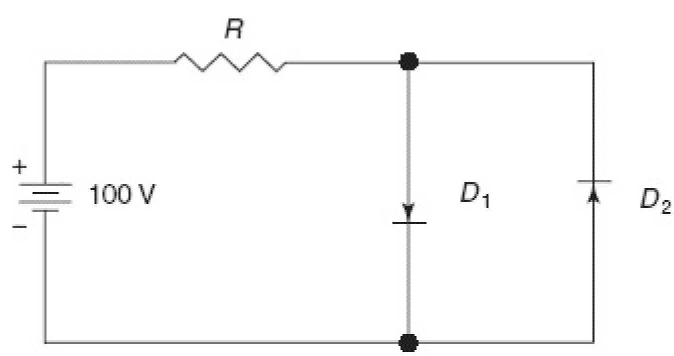


Alternatively, there is a 10 V across the diode, leaving 20 V across the 1 K resistor.

∴

Current = 20 mA, as there is a 10 V drop

Example 3-2 Each diode is described by a linearized volt–ampere characteristic with incremental resistance r and offset voltage V_γ. Diode D_1 is germanium with $V_\gamma = 0.2$ V and $r = 20\ \Omega$, whereas D_2 is silicon with $V_\gamma = 0.6$ V and $r = 15\ \Omega$. Find the diode currents if: (a) $R = 10$ K, (b) $R = 1.5$ K.

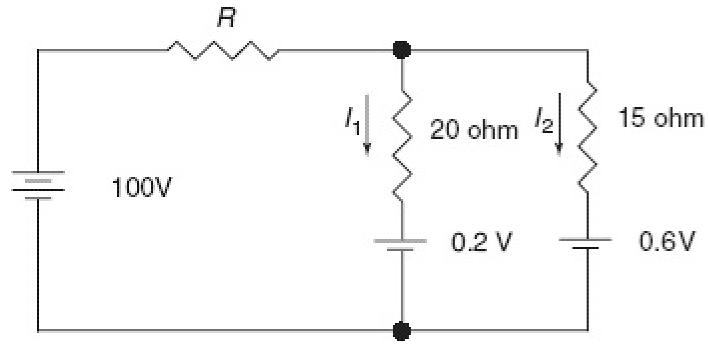


Solution:

a. $R = 10$ K. Assume both diodes are conducting. We have:

$$100 = 10.02I_1 + 10I_2 + 0.2$$

$$100 = 10.015I_2 + 10I_1 + 0.2$$



Solving for I_2 we find $I_2 < 0$. Thus our assumption that D is ON is not valid. Assume D_1 is ON and D_2 is OFF. Then:

$$I_1 = \frac{100 - 0.2}{10.02} = 9.97 \text{ mA} \quad \text{and} \quad I_2 = 0$$

b. $R = 1$ K. Assume both D_1 and D_2 are ON. We have:

$$100 = 1.52I_1 + 1.5I_2 + 0.2$$

$$100 = 1.515I_2 + 1.5I_1 + 0.6$$

Solving, we find $I_1 = 39.717$ mA and $I_2 = 26.287$ mA. Since both currents are positive, our assumption is valid.

Example 3-3 Calculate the break region over which the dynamic resistance of a diode is multiplied by a factor of 10,000.

Solution:

We have:

$$r = \eta \frac{V_T}{I_0} \varepsilon^{-V/\eta V_T}$$

Hence,

$$\frac{r_1}{r_2} = \varepsilon^{V_2 - V_1/\eta V_T}$$

But

$$\frac{r_1}{r_2} = 10^4$$

Hence,

$$\frac{\Delta V}{\eta V_T} = \frac{V_2 - V}{\eta V_T} = \ln 10^4$$

For silicon $\eta = 2$, and at room temperature $\Delta V = 2 \times 26 \times 4 \times 2.3 = 478$ mV.
For germanium, $\eta = 1$ and at room temperature $\Delta V = 1 \times 26 \times 4 \times 2.3 = 239$ mV.

3-5 RECTIFIERS

The process of rectification involves converting the alternating waveforms to the corresponding direct waveforms. Thus, it is one type of converter in which the direct waveforms must be filtered so that the resultant output waveforms become time invariant. Rectifiers can, in general, be classified into two categories.

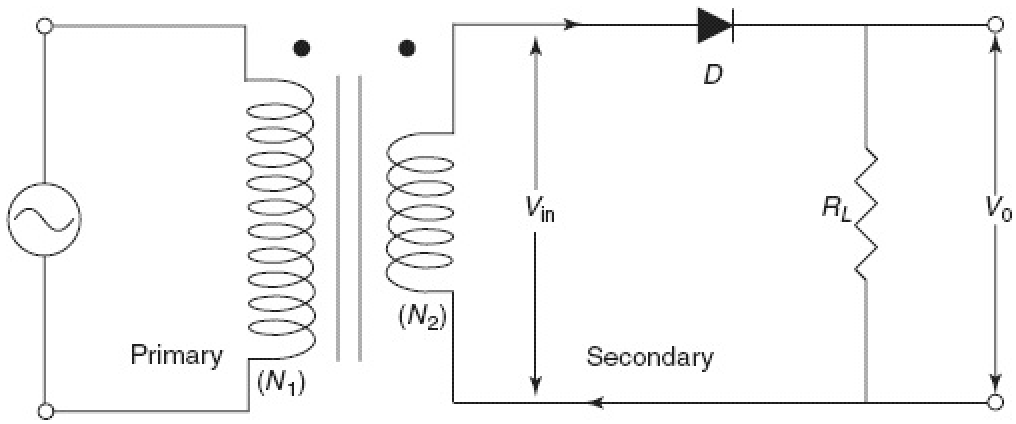


Figure 3-8 Half-wave rectifier

3-5-1 Half-Wave Rectifier

In a half-wave rectifier, the output waveform occurs after each alternate half-cycle of the input sinusoidal signal. Figure 3-8 shows a simple half-wave rectifier circuit.

The half-wave rectifier will generate an output waveform v_o. Between the time interval $t = 0$ to $T/2$, the polarity of the applied voltage v_i is such that it makes the diode forward-biased. As a result the diode is turned on, i.e., the forward voltage is more than the cut-in voltage of the diode. Substituting the short-circuit equivalence of the ideal diode will result in the equivalent circuit of Fig. 3-9 where it is obvious that the output signal is a replica of the applied signal.

For the period $T/2$ to T, the polarity of the input voltage (v_i) is reversed and the resulting polarity across the diode produces an OFF state with an open circuit equivalent, as shown in Fig. 3-10.

The result is the absence of a path for charge to flow and $v_o = i_R = 0$ V, $R = 0$ V for the period $T/2$ to T. The output signal v_o has the average value determined by:

$$V_{dc} = 0.318\ V_m$$

The input v_i and the output v_o are sketched together in Fig. 3-11. It is to be noted and clearly understood that when the diode is in the forward-biased mode, it consumes 0.7 V in the case of a silicon-based diode, and 0.3 V in the case of a germanium-based diode. Thus, in such a case, there must be a drop in the voltage across the diode. Consequently, the voltage across the resistance R in case of a half-wave rectifier is lowered to a value of $E - V_d$. If a sinusoidal source is kept in place of the battery, the sinusoidal voltage will represent the voltage across the resistance. The corresponding figure will then be as shown in Fig. 3-12.

In such a case, the peak of the voltage V_m gets lowered by an amount $V_m - V_d$. Thus, there is a finite time lag between turn-on and turn-off time of the diode in a complete time period.

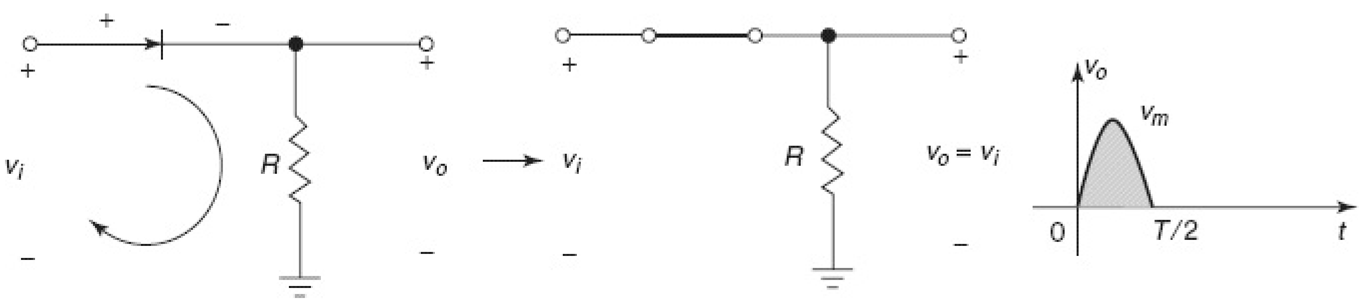


Figure 3-9 Conduction region (0 to *T*/2)

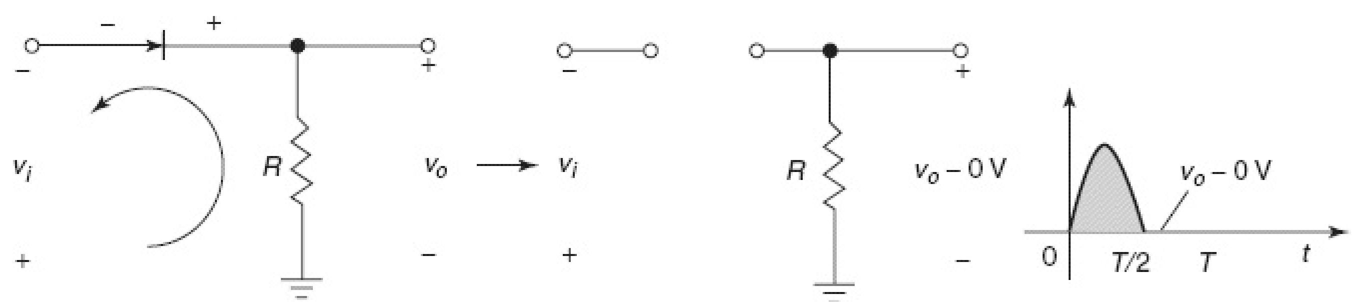


Figure 3-10 Non-conducting region (*T/2* to *T*)

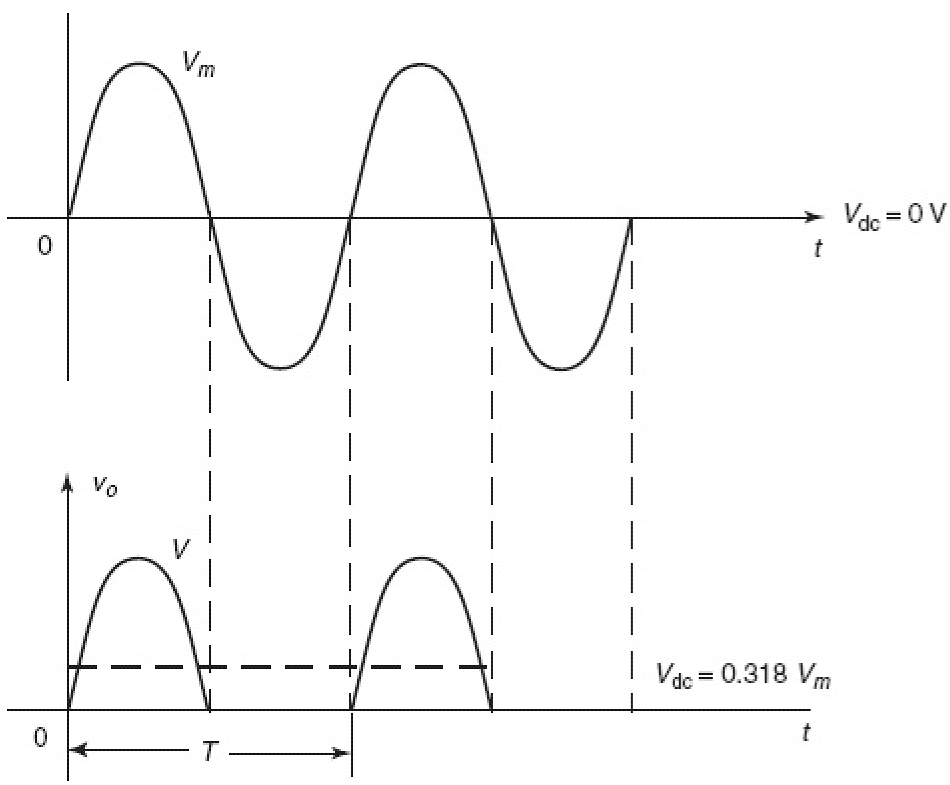


Figure 3-11 Half-wave rectified signal

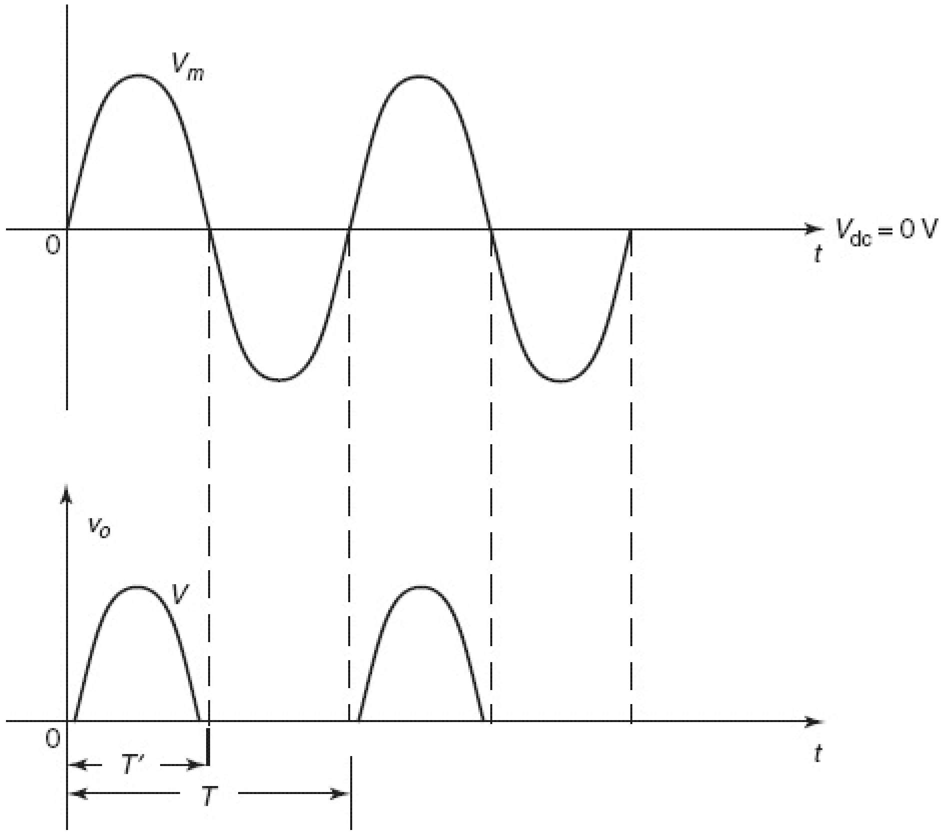


Figure 3-12 Output signal of the form $V_{in} - V_{diode}$

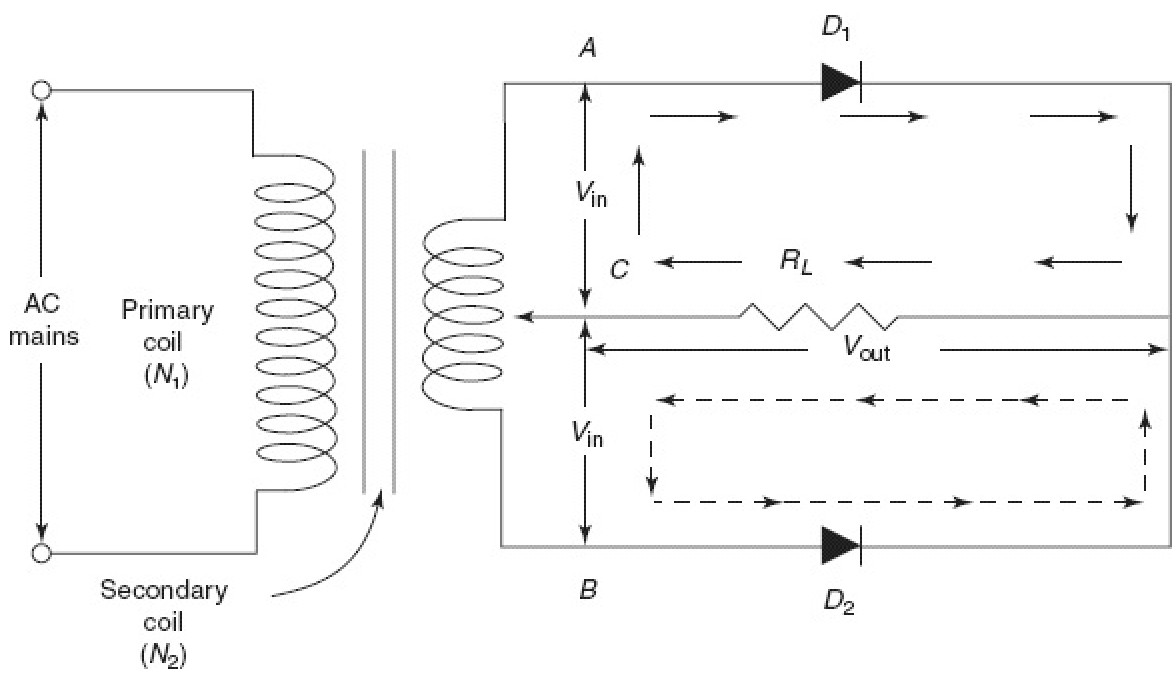


Figure 3-13 Full-wave rectifier

3-5-2 Full-Wave Rectifier

The circuit diagram for full-wave rectifier is shown in Fig. 3-13. The full-wave rectifier can be classified into two distinct types.

i. Centre-tapped transformer full-wave rectifier

ii. Bridge type full-wave rectifier

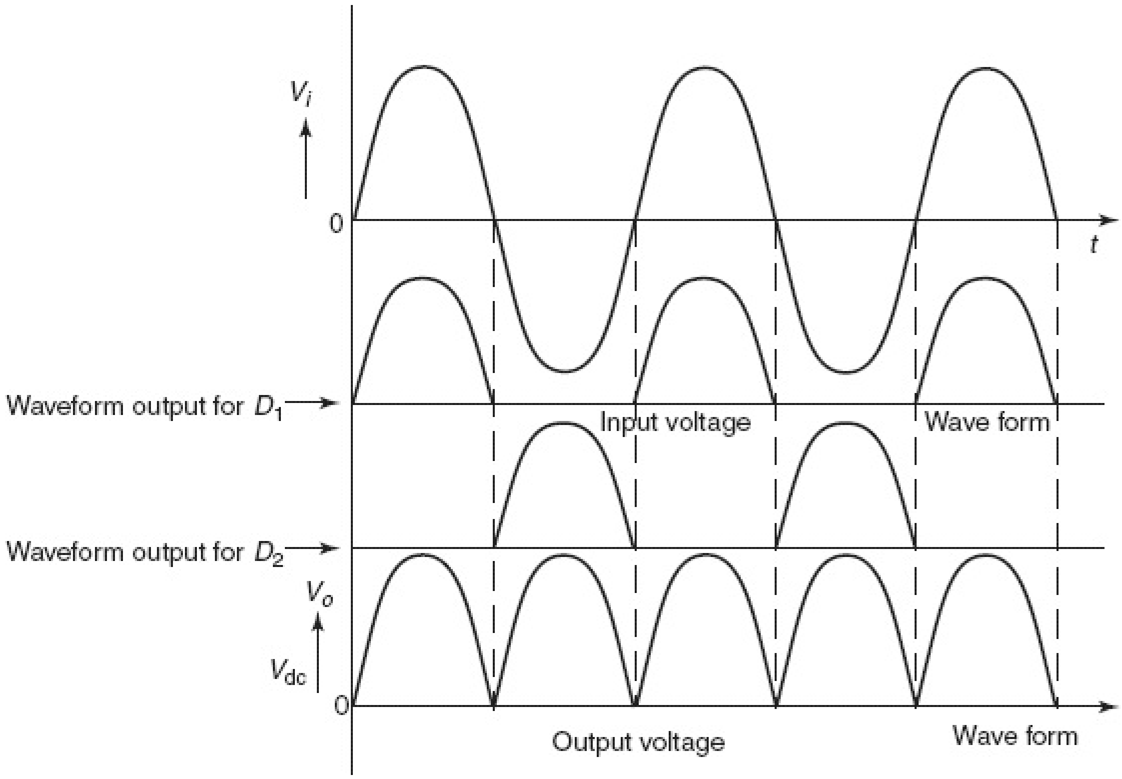


Figure 3-14 Waveform for full-wave rectifier

Centre-tapped transformer rectifier

It comprises of two half-wave circuits, connected in such a manner that conduction takes place through one diode during one half of the power cycle and through the other diode during the second half of the cycle.

When the positive half-cycle is applied to the input, i.e., transformer primary, then the top of the transformer secondary is positive with reference to the centre tap, while the bottom of the transformer secondary is negative with reference to the centre tap. As a result, diode D_1 is forward-biased and diode D_2 is reverse-biased. So the current will flow through D_1, but not through D_2 during the positive half-cycle. During the negative half-cycle, the condition is reversed. Diode D_2 is now forward-biased and diode D_1 is reverse-biased. Current will flow through diode D_2 and not through D_1 for the negative half-cycle. So the load current is shared alternatively by the two diodes and is unidirectional in each half-cycle. As a result, for the full-wave rectifier, we get the output for both the half-cycles. The waveforms for the full-wave rectifier are shown in Fig. 3-14.

Bridge rectifier

The most important disadvantage of the centre-tapped rectifier is that it brings in the use of a heavy transformer with three terminals at its output, i.e., a centre-tapped transformer. The centre tapping may not be perfect in most cases. This problem can be solved by designing another circuit with four diodes and a simple transformer. This is called a *bridge rectifier.* The circuit of the bridge rectifier is shown in Fig. 3-15(a).

The circuit realizes a full-wave rectifier using four different diodes, connected in such a way that two of these diodes are forward-biased at a time and the other two are kept in OFF state. Consequently, the circuit is completed in both the half-cycles and a rectified output is obtained.

In the positive half-cycle of the input voltage, the current flows through the diode D_4, the resistor R and diode D_3. Meanwhile the diodes D_1 and D_2 are reverse-biased. Thus, we observe that two diodes D_3 and D_4 are in the ON state and two diodes D_1 and D_2 are in the OFF state. The disadvantage of the bridge rectifier is that it uses four diodes instead of two as used in the full-wave rectifier. This does not matter much because diodes are quite cheap.

In the negative half-cycle, the other two diodes (D_1 and D_2) are switched ON and the previous two (D_3 and D_4) are in the OFF state. An important point to be noted is that since the current in both the half-cycle flow in the same direction, the output voltage is positive.

The biggest advantage of such a rectifier is that it does not require the use of a centre-tapped transformer. Again the PIV of the diodes has to be greater than the maximum negative voltage of the input signal.

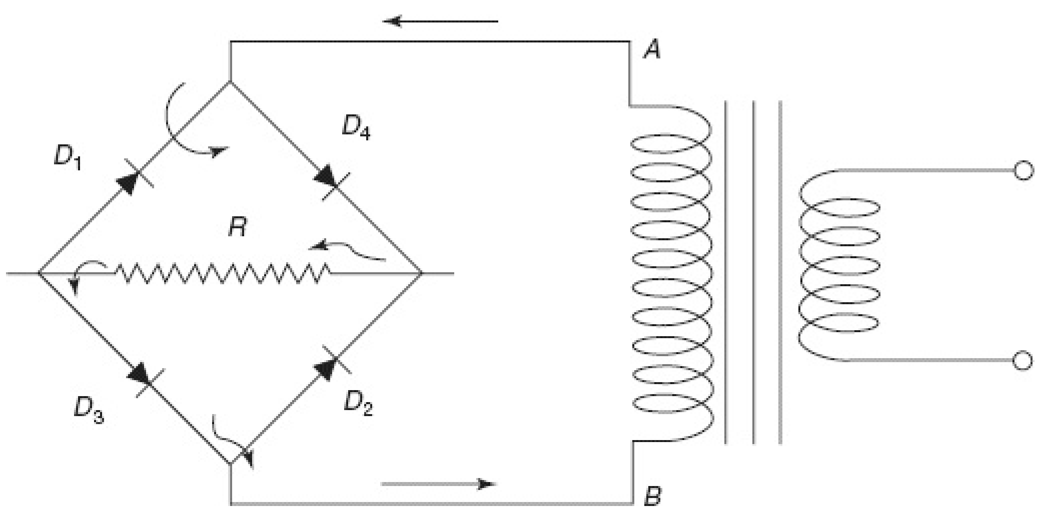


Figure 3-15(a) Bridge rectifier

Advantages of a bridge rectifier

i. In the bridge circuit a transformer without a centre tap is used.
ii. The bridge circuit requires a smaller transformer as compared to a full-wave rectifier giving the identical rectified dc output voltage.
iii. For the same dc output voltage, the PIV rating of a diode in a bridge rectifier is half of that for a full-wave circuit.
iv. The bridge circuit is more appropriate for high-voltage applications, thus, making the circuit compact.

Disadvantages of a bridge rectifier

i. Two or more diodes are required in case of a bridge rectifier, as a full-wave rectifier uses two diodes whereas a bridge rectifier uses four diodes.
ii. The amount of power dissipated in a bridge circuit is higher as compared to a full-wave rectifier. Hence, the bridge rectifier is not efficient as far as low voltages are concerned.

Comparison between half-wave and full-wave rectifier

i. In a half-wave rectifier, a single diode exists and the load current flows through it for only the positive half-cycle. On the other hand, in a full-wave rectifier, the current flows throughout the cycles of the input signals.
ii. Full-wave rectifiers require a centre-tapped transformer. For a half-wave rectifier, only a simple transformer is required.
iii. The PIV in a half-wave rectifier is the maximum voltage across the transformer secondary. Whereas, in the case of a full-wave rectifier, the PIV for each diode is two times the maximum voltage between the centre tap and at the either end of the transformer secondary.
iv. In a half-wave rectifier, the frequency of the load current is the same as that of the input signal and it is twice the frequency of the input supply for the full-wave rectifier.
v. The dc load current and conversion efficiency for a full-wave rectifier is twice that of a half-wave rectifier. Also, the ripple factor of the full-wave rectifier is less than that of the half-wave circuit. This indicates that the performance of the full-wave rectifier is better than the half-wave rectifier.
vi. In a full-wave rectifier, two diode currents flow through the two halves of the centre-tapped transformer secondary in opposite directions, so that there is no magnetization of the core. The transformer losses being smaller, a smaller transformer can be used for a full-wave rectifier.

3-5-3 Use of Filters in Rectification

A rectifier converts ac to dc Inadvertently, when the output voltage of the rectifier is passed through the load, fluctuating components of currents appear across the load; these are called *ripples.* Filters help in reducing these ripples considerably. The simplest filter in a rectifier can be understood by placing a capacitor across the load, as shown in Fig. 3-15(b).

In the filtered-rectified circuit, diodes D_1 and D_2 conduct in alternate half cycles at the secondary of the transformer. So, in the absence of the filtering capacitor C, the output voltage consists of a series of half sinusoids. This is shown in Fig. 3-16.

During the positive half-cycle the capacitor starts charging and gets charged to the maximum amplitude of the input signal. Beyond this maximum voltage the voltage across the diode D_1 is reversed and the diode D_1 consequently stops conducting. During this period, the capacitor discharges through the load with a time constant $\tau = CR$. As the capacitor reactance at the ripple frequency is much smaller than R, the time constant CR is much larger than the time period of the alternating voltage. The capacitor, thus, discharges very slowly and the output waveform during this interval is represented by the curve BD. In the following half-cycle also, the same thing is repeated with the diode D_2. Thus, due to the operation of the filter, it can be seen from Fig. 3-16 that the output curve is smoothened and consequently, the ripple factor also decreases. Also, the regulation increases. The capacitor voltage at any given time is:

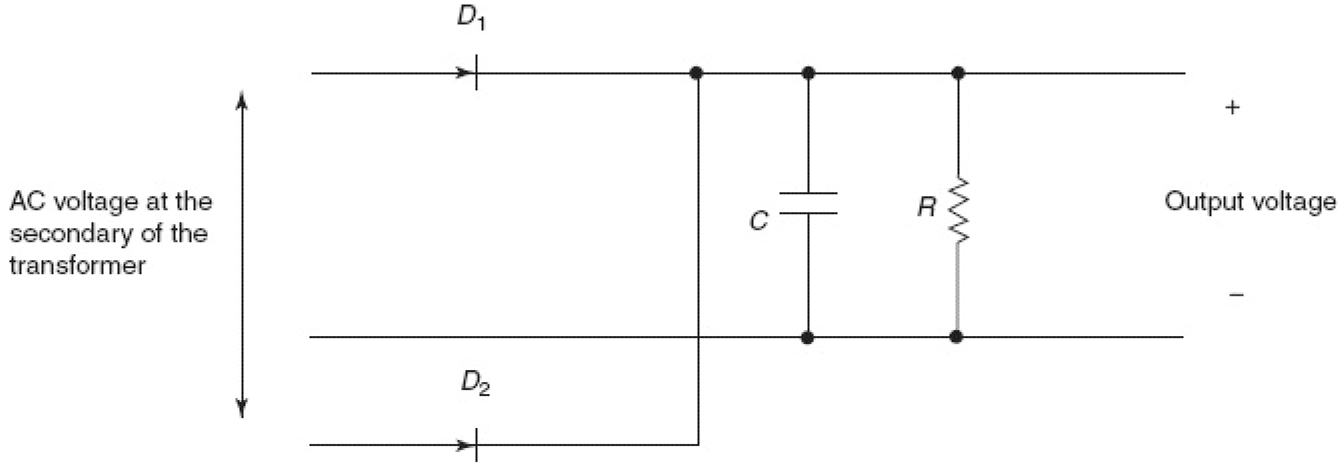


Figure 3-15(b) A full-wave capacitor-filtered rectifier

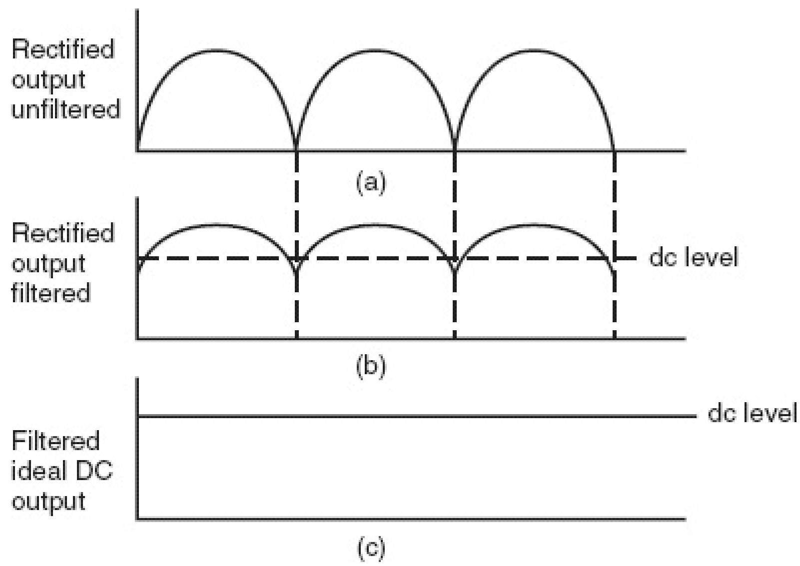


Figure 3-16 (a) Rectified output without filter
(b) Rectified output with filter
(c) Ideal dc filtered dc output with proper choice of capacitor in filter

$$\frac{V_{NL} - V_{RL}}{V_{RL}} \times 100 = \frac{V_M - I_{dc} R_L}{I_{dc} R_L} \times 100$$
$$= \frac{I_{dc} R_0}{I_{dc} R_L} \times 100 = \frac{100}{4 fCR_L}$$

$$\Delta V = \frac{I_{dc} T}{2C} \tag{3-21}$$

where, T is the time period of the input signal.
The average voltage across the capacitor is:

$$V_{dc} = V_m - \frac{\Delta V}{2} = V_m - \frac{I_{dc}}{4 fC} \tag{3-22}$$

The percentage regulation (discussed in detail in the next section) is:

$$\frac{V_{NL}-V_{RL}}{V_{RL}}\times 100=\frac{V_M-I_{dc}R_L}{I_{dc}R_L}\times 100$$

$$=\frac{I_{dc}R_0}{I_{dc}R_L}\times 100=\frac{100}{4fCR_L}\text{ percent} \qquad (3\text{-}23)$$

The fluctuation ΔV is a measure of the ripple voltage, we have:

$$V'^2_{rms}=\frac{2}{T}\int_0^{T/2}\left(\frac{\Delta V}{2}-\frac{\Delta V}{T/2}t\right)^2 dt$$

so that,

$$V'_{rms}=\Delta V/2\sqrt{3}=I_{dc}/\left(4\sqrt{3}fC\right) \qquad (3\text{-}24)$$

noting that $V_{dc}=I_{dc}\,R_L$, the ripple factor is written as:

$$\gamma=\frac{V'_{rms}}{V_{dc}}=\frac{1}{4\sqrt{3}fCR_L} \qquad (3\text{-}25)$$

3-5-4 Regulation

The average load current can be written as:

$$I_{dc}=KI_m=\frac{KV_s}{R_f+R_L} \qquad (3\text{-}26)$$

where, R_f is the forward resistance of the diode and R_L is the value of the load resistance.

Again, the value of K is:

$$\frac{V_{NL}-V_{RL}}{V_{RL}}\times 100\% \qquad (3\text{-}27)$$

The value of K is $1/\pi$ in case of a half-wave rectifier and $2/\pi$ in case of a full-wave rectifier. The dc load voltage is given by:

$$V_{dc}=I_{dc}R_L=KV_s-I_{dc}R_L \qquad (3\text{-}28)$$

A plot of V_{dc} against I_{dc} gives a linear variation of V_{dc} with I_{dc}.

The variation of V_{dc} with I_{dc} is called regulation and the plot of V_{dc} vs. I_{dc} is referred to as the voltage regulation characteristics of the rectifier. In an ideal rectifier, V_{dc} is independent of I_{dc}. In practice, the departure of the behaviour of an actual rectifier from that ideal rectifier is expressed by percentage voltage regulation. It is defined as:

Percentage voltage regulation:

$$\frac{V_{NL} - V_{RL}}{V_{RL}} \times 100\% \tag{3-29}$$

In an ideal case, $V_{NL} = V_{RL}$. So we get the percentage regulation of a rectifier as zero.

Solved Examples

Example 3-4 A diode, whose internal resistance is 30 Ω, is to supply power to a 990 Ω load from a 110 V (rms) source of supply. Calculate (a) the peak load current, (b) the dc load current, (c) the ac load current, (d) the dc diode voltage, (e) the total input power to the circuit, and (f) the percentage regulation from no load to the given load.

Solution:

a.

$$I_m = \frac{V_m}{R_f + R_L} = \frac{110/2}{1020} = 152.5 \text{ mA}$$

b.

$$I_{dc} = \frac{I_m}{\pi} = 152.5/\pi = 48.5 \text{ mA}$$

c.

$$I_{rms} = \frac{1}{2}(152.5) = 76.2 \text{ mA}$$

d.

$$V_{dc} = \frac{I_m R_L}{\pi} = -48.5 \times .990 = -48 \text{ mA}$$

e.

$$P_i = I^2_{rms}(R_f + R_L) = (76.2 \times 10^{-3})^2 (1020)$$
$$= 5800 \times 10^{-6} \times 1020 = 5.92 \text{ W}$$

f.

$$\text{Percentage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}}(100\%) = \frac{V_m/\pi - I_{dc}R_L}{I_{dc}R_L}(100\%)$$
$$= \frac{49.5 - 48}{48} = 3.125\%$$

3-5-5 Performance Analysis of Various Rectifier Circuits

Half-wave rectifier

Peak inverse voltage (PIV). It is the voltage that the diode must withstand, and it is equal to the peak input voltage, V_m.

DC voltage. The average output voltage

$$V_{o\,(\mathrm{dc})} = 0.318\, V_m \tag{3-30}$$

And the rms voltage:

$$V_{\mathrm{rms}} = 1.21\, V_{o\,(\mathrm{dc})} \tag{3-31}$$

DC value of load current. The load current of a rectifier is unidirectional but fluctuating. The current at the output of the diode is:

$$i_L = I_m \sin \omega t \text{ for } 0 \le \omega t \le \pi,$$

$$i_L = 0 \text{ for } \pi \le \omega t \le 2\pi$$

where, I_m is the amplitude of the input signal. If V_s is the amplitude of the transformer secondary voltage, the value of I_m is given by:

$$I_m = \frac{V_S}{R_f + R_L}$$

From the definition of the average value of the load current:

$$I_{\mathrm{dc}} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin \omega t d(\omega t) = \frac{I_m}{\pi} \tag{3-32}$$

The value of rms current can be obtained from the definition, that is:

$$\begin{aligned} I_{\mathrm{rms}}^2 &= \frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t d(\omega t) = \frac{I_m^2}{4} \\ I_{\mathrm{rms}} &= \frac{I_m}{2} \end{aligned} \tag{3-33}$$

Ripple factor. Periodically, fluctuating components—the ripples—are superimposed on I_{dc} to give the actual load current. Due to these fluctuating components, the conversion from ac to dc by a rectifier is not perfect. The ripple factor gives a measure of this imperfection or the fluctuating components. The ripple factor, r, is defined by:

$$r = \frac{\text{rms value of the alternating components of the load current}}{\text{average value of the load current}}$$

The ripple factor r is given by:

$$r = \sqrt{\left(\frac{I_{\mathrm{rms}}}{I_{\mathrm{dc}}}\right)^2 - 1} \tag{3-34}$$

From the expressions of dc and rms current, we can derive the ripple factor. Thus, we obtain:

$$r = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1}$$

which, after calculation stands at 1.21.
Therefore, ripple factor = 1.21 or 121%.

Efficiency. The effectiveness of a rectifier in delivering the dc output power is generally measured by the rectification efficiency:

$$\eta_R = \frac{P_{o(\mathrm{dc})}}{P_{o(\mathrm{ac})}} = \frac{(V_m/\pi)^2/R}{(V_m/2)^2/R} = \frac{4}{\pi^2} = 40.5\% \qquad (3\text{-}35)$$

Efficiency can also be defined as:

$$\left(\frac{I_{\mathrm{rms}}}{I_{\mathrm{dc}}}\right) = \frac{I_m/2}{I_m/\pi} = \frac{\pi}{2} = 1.571\,\% \qquad (3.36)$$

From the above, we see that $(I_{\mathrm{dc}}/I_{\mathrm{rms}}) = 2/\pi$ and putting the value in Eq. (3-35), we get

$$\eta_R = \frac{40.6}{1 + R_f/R_L}\,\text{percent} \qquad (3\text{-}37)$$

Full-wave rectifier

Peak inverse voltage. This is the peak voltage that the diode must be able to withstand without any breakdown. In other words, it is the largest reverse voltage that is expected to appear across the diodes.

In this case:

$$\mathrm{PIV} = -2\ \mathrm{V}$$

where, V is the voltage peak of the input waveform.

DC voltage. The average output voltage:

$$V_{o(\mathrm{dc})} = 0.636\ V_m \qquad (3\text{-}38)$$

The rms voltage:

$$V_{\mathrm{rms}} = 0.483 V_{o(\mathrm{dc})} \qquad (3\text{-}39)$$

Average load current. From the definition of the load current, we obtain:

$$I_{\mathrm{dc}} = \frac{2}{2\pi}\int_0^{\pi} I_m \sin\omega t\, d(\omega t) = \frac{2I_m}{\pi} \qquad (3\text{-}40)$$

And the rms value of the current is given by:

$$I_{\text{rms}} = \left[\frac{2}{2\pi}\int_0^{\pi} I_m{}^2 \sin^2 \omega t d(\omega t)\right]^{1/2} = \frac{I_m}{\sqrt{2}} \qquad (3\text{-}41)$$

Thus, we obtain:

$$\left(\frac{I_{\text{rms}}}{I_{\text{dc}}}\right) = \frac{I_m/\sqrt{2}}{2I_m/\pi} = \frac{\pi}{2\sqrt{2}} = 1.11 \qquad (3\text{-}42)$$

Current ripple factor. Periodically, the fluctuating component—ripples—are superimposed on I_{dc} to give the actual load current. Due to these fluctuating components, the conversion of ac to dc by a rectifier is not perfect. The ripple factor gives a measure of this imperfection or the fluctuating components. The ripple factor is defined by:

$$r = \frac{\text{rms value of the alternating components of the load current}}{\text{average value of the load current}}$$

The ripple factor r is given by:

$$r = \sqrt{\left(\frac{I_{\text{rms}}}{I_{\text{dc}}}\right)^2 - 1} \qquad (3\text{-}43)$$

From Eqs. (3-40) and (3-41) we get:

$$I_{\text{rms}} = I_m/\sqrt{2}$$

$$r = \sqrt{\frac{\left(\frac{I_m}{2}\right)^2}{\left(\frac{2I_m}{\pi}\right)} - 1} \qquad (3\text{-}44)$$

$$r = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1}$$
$$= 0.482$$

Efficiency. The rectification efficiency is given by:

$$\eta = \frac{P_{\text{dc}}}{P_{\text{ac}}} \times 100\% \qquad (3\text{-}45)$$

For a full-wave rectifier circuit:

$$P_{dc} = (I_{dc})^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 \frac{1}{(R_f + R_L)^2} = \frac{4V_m^{\,2} R_L}{\pi^2 (R_f + R_L)^2} \tag{3-46}$$

$$P_{ac} = (I_{rms})^2 (R_f + R_L) = \frac{V_m^{\,2}}{2(R_f + R_L)} \tag{3-47}$$

$$\eta = \frac{P_{dc}}{P_{ac}} \times 100\% = \frac{0.812}{\left(1 + \frac{R_f}{R_L}\right)} \times 100\% \tag{3-48}$$

Solved Examples

Example 3-5 Show that the maximum dc output power $P_{dc} = V_{dc} I_{dc}$ in a half-wave single-phase circuit occurs when the load resistance equals the diode resistance R_f.

Solution:
We have:

$$P_{dc} = I_{dc}^2 R_L = \frac{V_m^2 R_L}{\pi^2 (R_f + R_L)^2}$$

For max,

$$P_{dc} \text{ set } \frac{dP_{dc}}{dR_L} = 0$$

or,

$$\frac{V_m^2}{\pi}\left[\frac{(R_f + R_L)^2 - 2\,(R_f + R_L)\,R_L}{(R_f + R_L)^4}\right] = 0$$

Then, $R_f + R_L = 2R_L$

$$\therefore R_L = R_f$$

Example 3-6 The efficiency of the rectification η_r is defined as the ratio of the dc output power $P_{dc} = V_{dc} I_{dc}$ to the input power $P_i = (1/2\pi) \int_0^{2\pi} v_i i d\alpha$.

a. Show that, for the half-wave rectifier circuit:

$$\eta_r = \frac{40.6}{1 + R_f/R_L}\%$$

b. Show that, for the full-wave rectifier, η_r has twice the value of the value given in part (a).

Solution:

a.

$$\eta_r = \frac{P_{dc}}{P_i} \times 100\% = \frac{I_{dc}^2 R_L \times 100\%}{I_{rms}^2 (R_f + R_L)} = \left(\frac{I_{dc}}{I_{rms}}\right)^2 \frac{100\%}{1 + \frac{R_f}{R_L}}$$

$$= \left(\frac{I_m}{\pi/I_m/2}\right)^2 \frac{100\%}{1 + \frac{R_f}{R_L}} = \frac{40.6}{1 + \frac{R_f}{R_L}}\%$$

b.

$$\eta_r = \left(\frac{I_{dc}}{I_{rms}}\right)^2 \frac{100\%}{1 + \frac{R_f}{R_L}} = \left(\frac{2I_m/\pi}{I_m/2}\right)^2 \frac{100\%}{1 + \frac{R_f}{R_L}} = \frac{81.2}{1 + \frac{R_f}{R_L}}\%$$

Example 3-7 Prove that the regulation of both the half-wave and the full-wave rectifier is given by: Percentage regulation = $R_f/R_L \times 100\%$.

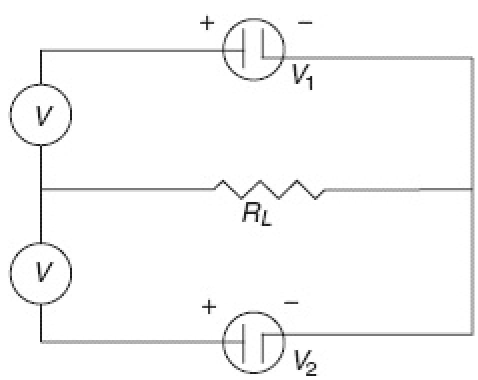
Solution:

Consider a half-wave rectifier: $V_{NL} = \frac{V_m}{\pi}$ and $V_{FL} = \frac{V_m}{\pi} \frac{R_L}{R_L + R_f}$

$$\therefore \text{Percentage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{\frac{V_m}{\pi}\left(1 - \frac{R_L}{R_L + R_f}\right)}{\frac{V_m}{\pi} \frac{R_L}{R_L + R_f}} = \frac{R_f}{R_L} \times 100\%$$

For a full-wave rectifier, V_{NL} and V_{FL} are doubled, and hence, the regulation remains the same as above.

Example 3-8 A full-wave single phase rectifier consists of a double diode, the internal resistance of each element of which may be considered to be constant and equal to 500 Ω. These feed into a pure resistance load of 2,000 Ω. The secondary transformer voltage to centre tap is 280 V. Calculate (a) the dc load current, (b) the direct current in each tube, (c) the ac voltage across each diode, (d) the dc output power, and (e) the percentage regulation.



Solution:

a.

$$I_{dc} = \frac{2I_m}{\pi} = \frac{2V_m}{\pi\,(R_L + R_f)} = \frac{2 \times 280}{R2/\pi\,(2500)} = 101 \text{ mA.}$$

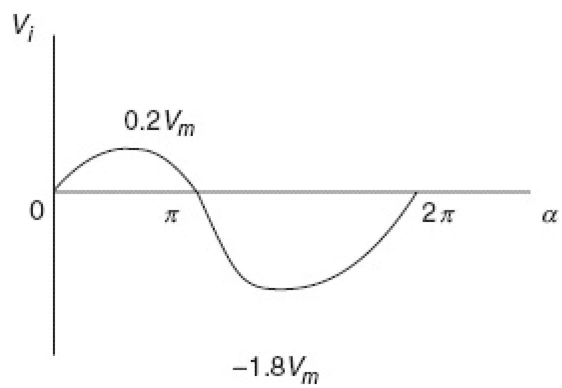
b.

$$(I_{dc})_{tube} = \frac{1}{2} I_{dc} = 50.5 \text{ mA.}$$

c. The voltage to centre tap is impressed across R_f in series with the R_L.
Hence, the voltage across the conducting is sinusoidal with a peak value:

$$V_m \frac{500}{2500} = 0.2\, V_m$$

During non-conduction of V_1, we see by transversing the outside path of the circuit sketched that $v_1 = -2v - v_2$.
Since, V_2 is now conducting, its peak value is 0.2 V_m and that of v_1 is $-2V_m + 0.2V_m = -1.8\, V_m$.



Thus, the voltage v_1 across V_1 is as shown, and its ac value is:

$$V_{rms}^2 = \frac{1}{2\pi} = \int_0^{\pi} (0.2V_m)^2 \sin^2\alpha\, d\alpha + \frac{1}{2\pi} \int_{\pi}^{2\pi} (-1.8V_m)^2 \sin^2\alpha\, d\alpha = \frac{V_m^2}{4}\left[(0.2)^2 + (1.8)^2\right]$$

Hence, $V_{rms} = 0.905\, V_m = 0.905 \times 280\sqrt{2} = 358$ V.

d.

$$P_{dc} = I_{dc}^2 R_L = (0.101)^2\,(2000) = 20.4 \text{ W}$$

e.

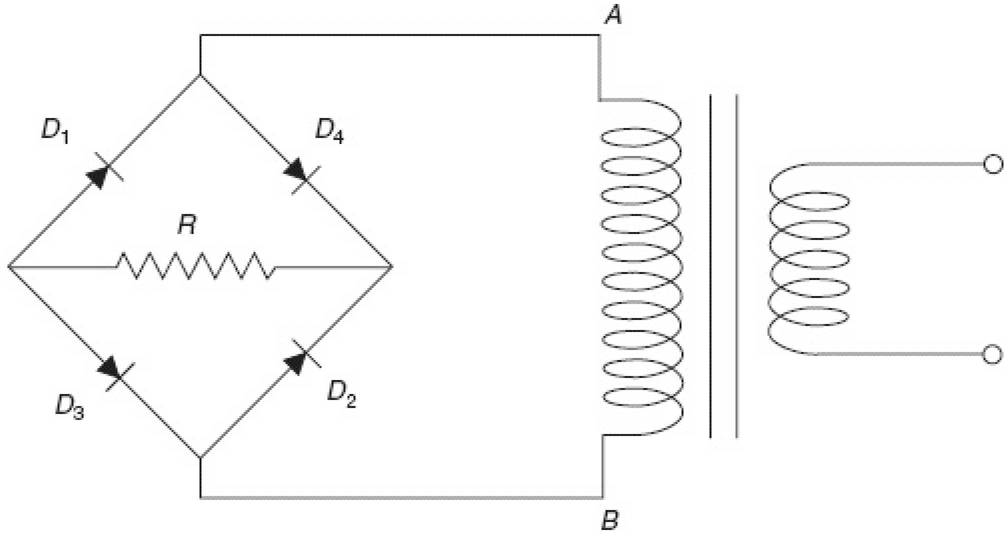
$$\text{Percentage regulation} = \frac{R_f}{R_L} \times 100\% = \frac{500}{2000} \times 100\% = 25\%$$

Example 3-9 In the full-wave single phase bridge, can the transformer and the load be interchanged?

Explain carefully.

Solution:

The load and the transformer cannot be interchanged. If they were, the circuit shown would be the result. Note that if *A* is positive with respect to *B*, all diodes will be reverse-biased. If *B* is positive with respect to *A*, then all four diodes conduct, thus, short circuiting the transformer.



Example 3-10 A 1 mA dc metre whose resistance is 20 Ω is calibrated to read rms volts when used in a bridge circuit with semiconductor diodes. The effective resistance of each element may be considered to be zero in the forward direction and infinite in the reverse direction. The sinusoidal input voltage is applied in series with a 5 K resistance. What is the full-scale reading of this metre?

Solution:

$$I_{dc} = \frac{2I_m}{\pi} = \frac{2V_m}{\pi R_L} = \frac{2R2V_{rms}}{\pi\ (5020)} = 1 \times 10^{-3}$$

Hence,

$$v_{0(max)} = 14\text{ V}$$

Example 3-11 An ac supply of 220 V is applied to a half-wave rectifier circuit through transformer with a turns ratio 10:1. Find (a) dc output voltage and (b) PIV. Assume the diode to be an ideal one.

Solution:

Given $V_i = 220$ V, $N_2/N_1 = 10$.

a. The secondary voltage:

$$V_2 = V_1 \times \frac{N_2}{N_1} = 220 \times \frac{1}{10} = 22 \text{ V}$$

$$V_m = \sqrt{2} V_2 = \sqrt{2} \times 22 = 31.11 \text{ V}$$

$$V_{dc} = 0.318 \, V_m = 0.318 \times 31.11 = 9.89 \text{ V}$$

b. PIV of a diode is given by PIV = V_m = 31.11 V

Example 3-12 In a half-wave rectifier circuit the input voltage is 230 V and transformer ratio is 3:1. Determine the maximum and the average values of power delivered to the load. Take R_L equal to 200 Ω.

Solution:

Given, $V_1 = 230$ V, $\frac{N_2}{N_1} = \frac{1}{3}$, $R_L = 200\Omega$.

The rms value of secondary voltage is given by:

$$V_2 = V_1 \times \frac{N_2}{N_1} = 230 \times \frac{1}{3} = 76.67 \text{ V}$$

Maximum value of the secondary voltage is:

$$V_m = \sqrt{2} V_2 = 1.414 \times 76.67 = 108.41 \text{ V}$$

Maximum value of the load current is then given by:

$$I_m = \frac{V_m}{R_L} = \frac{108.41}{200} = 0.542 \text{ A}$$

Maximum load power:

$$\begin{aligned} P_{max} &= I_m^2 \times R_L \\ &= (0.542)^2 \times 200 = 58.75 \text{ W} \end{aligned}$$

Average value of output voltage, $V_{dc} = 0.318 V_m = 0.318 \times 108.41 = 34.47$ V

Average value of load current:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{34.47}{200} = 0.172 \text{ A}$$

Average value of load power, $P_{dc} = I_{dc}^2 \times R_L = (0.172)^2 \times 200 = 5.92$ W

Example 3-13 A half-wave rectifier is used to supply 30 V dc to a resistive load of 500 ohms. The diode has a forward resistance of 25 Ω. Find the maximum value of the ac voltage required at the input.

Solution:
Given, $V_{dc} = 30$ V, $r_f = 25\ \Omega$, $R_L = 500\ \Omega$.

Average value of the load current:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{30}{500} = 0.06\ \text{A}$$

Maximum value of the load current, $I_m = \pi \times I_{dc} = 3.142 \times 0.06 = 0.188$ A
Voltage required at the input is given by:

$$\begin{aligned} V_{i(\max)} &= I_m^2\,(r_f + R_L) \\ &= (0.188)^2\,(25 + 500) = 18.55\ \text{V} \end{aligned}$$

Example 3-14 A half-wave rectifier is used to supply 100 V_{dc} to a load of 500 Ω. The diode has a resistance of 20 Ω. Calculate (a) the ac voltage required and (b) the efficiency of rectification.

Solution:
Given, $V_{dc} = 100$V, $R_L = 500\ \Omega$, $r_f = 20\ \Omega$.

a. DC voltage:

$$V_{dc} = \frac{V_m}{\pi} = \frac{I_m\,(R_L + r_f)}{\pi}$$

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{100}{500} = 0.2\ \text{A}$$

$$I_m = I_{dc} \times \pi = 3.142 \times 0.2\ \text{A} = 0.6284\ \text{A}$$

$$V_m = I_m\,(R_L + r_f) = 0.6284\,(500 + 20) = 326.77\ \text{V}$$

b. Rectification efficiency is given by:

$$\eta = \frac{0.406}{1 + \frac{r_f}{R_L}} = \frac{0.406}{1 + 20/500} = 0.39 = 39\%$$

Example 3-15 A half-wave rectifier circuit has a load of 5000 Ω. Find the values of (a) current in the circuit, (b) dc output voltage across R_L, and (c) voltage across the load. Given $v = 50 \sin 100\pi t$, $r_f = 20\ \Omega$.

Solution:

Given, $v = 50 \sin 100\pi t$.

Comparing the given equation with the standard equation $v = V_m \sin 2\pi ft$, we have:

$$V_m = 50 \text{ V}, f = 50 \text{ Hz}$$

Since the diode conducts only during the positive half of the input voltage, we have:

$$I_m = \frac{V_m}{R_L + r_f} = \frac{50}{5000 + 20} \approx 10 \text{ mA}$$

a. Hence current $i = 10 \sin 100\pi t$ for $\pi < 100\,\pi t < 2\,\pi$
   $= 0$ for $0 < 100\,\pi t < \pi$
b. DC Output voltage, $V_{dc} = I_{dc} \times R_L$

$$= \frac{I_m}{\pi} \times R_L = \frac{10 \times 10^{-3}}{3.142} \times 5000 = 15.9 \text{ V}$$

   Output voltage, $V_o = 15.9 \sin 100\,\pi t$ for $\pi < 100\,\pi t < 2\pi = 0$
c. Assuming the diode is an ideal diode, the voltage across it is zero during the forward-biased. When the diode is reverse-biased, the voltage across diode is:

$$v = 15.9 \sin 100\,\pi t \text{ for } 0 < 100\,\pi t < \pi = 0 \text{ for } \pi < 100\,\pi t < 2\pi$$

Example 3-16 In a half-wave rectifier circuit fed from 230 V, 50 Hz mains, it is desired to have a ripple factor $\gamma << 0.004$. Estimate the value of the capacitance needed. Given, $I_L = 0.5$ A.

Solution:

Given $V_{rms} = 230$ V, $f = 50$ Hz, $\gamma \leq 0.005$, $I_L = 0.5$ A. Take $\gamma = 0.003$.

Load current is given by:

$$I_L = \frac{I_m}{\pi} = I_{dc}$$

$$V_m = \sqrt{2} \times V_{rms} = 1.4 \times 230 = 322 \text{ V}$$

$$V_{dc} = \frac{V_m}{\pi} \frac{322}{3.14} = 102.5 \text{ V}$$

Load resistance:

$$R_L = \frac{V_{dc}}{I_{dc}} = \frac{102.5}{0.5} = 205\ \Omega = 200\ \Omega$$

Ripple factor:

$$\gamma = \frac{1}{2\sqrt{3}\, fCR_L}$$

$$= \frac{1}{2\sqrt{3}\, f\gamma R_L} = \frac{1}{2\sqrt{3} \times 50 \times 200 \times 0.003} = 9.62 \text{ mF}$$

Example 3-17 The voltage across half the secondary winding in a centre-tapped transformer used in a full-wave rectifier is 230sin 314t. The forward-bias resistance of each diode is 20 Ω and the load resistance is 3.15 kΩ. Calculate the ripple factor.

Solution:

Given, R_L = 3.15 k Ω, r_f = 20 Ω.

Instantaneous voltage, $v = V_m \sin 2\pi ft$

$= 230 \sin 314t$

Comparing, we have, V_m = 230 V, f = 50 Hz

The rms value of current:

$$I_{\text{rms}} = 0.707\left(\frac{V_m}{R_L + r_f}\right) = 0.707\left(\frac{230}{3150 + 20}\right)$$

$$= 0.707 \times 0.0726 = 0.0513 \text{ A}$$

DC value of current, $I_{\text{dc}} = 0.637 I_m = 0.637 \times 0.0726 = 0.0331$ A

Therefore, ripple factor:

$$\gamma = \sqrt{\left(\frac{I_{\text{rms}}}{I_{\text{dc}}}\right)^2 - 1} = \sqrt{\left(\frac{0.0513}{0.0331}\right)^2 - 1} = 0.48$$

Example 3-18 Ideal diodes are used in a bridge rectifier with a source of 230 V, 50 Hz. If the load resistance is 150 Ω and turns ratio of transformer is 1:4, find the dc output voltage and pulse frequency of the output.

Solution:

Given, V_p = 230 V, f = 50 Hz, R_L = 200 Ω, $N_S : N_P = 1 : 4$.

We know that:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

The rms secondary voltage:

$$V_S = V_P \times \frac{N_S}{N_P} = 230 \times \frac{1}{4} = 57.5 \text{ V}$$

$$V_S = V_{\text{rms}} = 57.5 \text{ V}$$

Maximum voltage across secondary, $V_m = V_{\text{rms}} \times \sqrt{2} = 57.5 \times \sqrt{2} = 81.3$ V

Average current:

$$I_{\text{dc}} = \frac{2V_m}{\pi R_L} = \frac{2 \times 81.3}{3.14 \times 200} = 0.26\ \text{A}$$

DC output voltage, $V_{\text{dc}} = I_{\text{dc}} \times R_L = 0.26 \times 150 = 39$ V

As there are two output pulses for each complete cycle of the input ac voltage in full-wave rectification, the output frequency is twice that of the ac supply frequency.

∴

$$f_{\text{out}} = 2 f_{\text{in}} = 2 \times 50 = 100\ \text{Hz}$$

Example 3-19 Find the maximum dc voltage that can be obtained from the full-wave rectifier circuit.

Solution:
Given, $V_p = 220$ V, $f_i = 50$ Hz, $R_L, = 1.5$ kΩ, $N_p = 1000$, $N_s = 100$.
We know that:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

The rms secondry voltage:

$$V_S = V_P \times \frac{N_S}{N_P} = 220 \times \frac{100}{1000} = 22\ \text{V}$$

Maximum secondary voltage, $V_{\text{rms}} = 22 \times \sqrt{2} = 30.8$ V

Maximum voltage across half-secondary winding, $V_m = \frac{30.8}{2} = 15.4$ V

Average current:

$$I_{\text{dc}} = \frac{2V_m}{\pi R_L} = \frac{2 \times 15.4}{3.14 \times 1500} = 6.53 \times 10^{-3}\ \text{A}$$

Dc output voltage, $V_{\text{dc}} = I_{\text{dc}} \times R_L = 6.53 \times 10^{-3} \times 1500 = 9.79$ V

Example 3-20 A full-wave rectifier using a capacitor filter is to supply 30 V dc to a 1 kΩ load. Assuming the diode and transformer winding resistance to be negligible, calculate the input voltage required and the value of the filter capacitor for a ripple of 0.015.

Solution:

Given, $V_{dc} = 30$ V, $R_L = 1$ kΩ and γ = 0.015.

DC output current:

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{30\text{ V}}{1\text{ k}\Omega} = 30\text{ mA}$$

DC output voltage:

$$V_{dc} = V_m - \frac{5000\, I_{dc}}{C}$$

In order to determine V_m, we must calculate the value of C. We know that ripple factor:

$$\gamma = \frac{2900}{CR_L} = 0.01$$

Hence,

$$C = \frac{2900}{0.015 \times 1000}\ \mu\text{F} = 193\ \mu\text{F}$$

–

$$V_m = V_{dc} + \frac{5000\, I_{dc}}{C} = 30 + \frac{5000 \times 0.03}{193} = 30.78\text{ V}$$

Line-to-line secondary voltage:

$$\frac{2V_m}{\sqrt{2}} = \frac{2 \times 30.78}{\sqrt{2}} = 43.52\text{ V}$$

Example 3-21 The output of a full-wave rectifier is fed from a 40–0–40 V transformer. The load current is 0.1 A. The two 40 μF capacitors are available. The circuit resistance exclusive of the load is 40 Ω.

(a) Calculate the value of inductance for a two-stage L-section filter. The inductances are to be equal. The ripple factor is to be 0.0001. (b) Calculate the output voltage.

Solution:

a.

$$LC = 1.76\left(\frac{0.472}{r}\right)^{\frac{1}{n}}$$

$$L = \frac{1.76}{40\times10^{-6}}\left(\frac{0.472}{0.0001}\right)^{\frac{1}{2}}$$

$$= 3.02\text{ H}$$

b.

$$V_{dc} = \frac{2V_m}{\pi} - I_{dc}R$$

$$= \frac{(2\sqrt{2})\,40}{\pi} - 0.1 \times 40$$

$$= 36 - 4 = 32\text{ V}$$

Example 3-22 A full-wave single-phase rectifier employs a π-section filter consisting of two 4 μF capacitances and a 20 H choke. The load current is 50 μA. Calculate the dc output voltage and ripple voltage. The resistance of the choke is 200 Ω.

Solution:

$$V_{dc} = V_m - \frac{4170}{C} I_{dc} - I_{dc}R$$

$$= 300\sqrt{2} - \frac{4170}{C}(0.05)\,0 - (0.05) \times 200$$

$$= 362.13\text{ V}$$

$$r = \frac{3300}{CC_1LR_L}$$

$$= \frac{3300 \times 0.05}{4 \times 4 \times 20 \times 353}$$

$$= 1.46 \times 10^{-3}$$

$$V_{rms} = rV_{dc} = 0.015\text{ V}$$

3-6 CLIPPER AND CLAMPER CIRCUITS

3-6-1 Clipper

A clipper is a type of diode network that has the ability to “clip off” a portion of the input signal without distorting the remaining part of the alternating 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 input signal is “clipped” off.

There are two general categories of clippers: *series* and *parallel.* The series configuration is defined as one where the diode is in series with the load, while the parallel clipper has the diode in a branch parallel to the load.

Series clipper

A series clipper and its response for two types of alternating waveforms are provided in Figs. 3-17(a) and 3-17(b).

From the Fig. 3-17(b) of the half-wave rectifier, we see that there are no clear cut restrictions on the type of signals that can be applied at the input. The addition of a dc supply, as shown in Fig. 3-18, can have a pronounced effect on the output of a clipper.

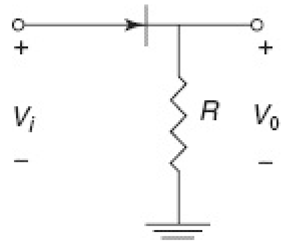


Figure 3-17(a) Series clipper circuit

Key points

i. The first step is to find out in which interval of the input signal the diode is in forward-bias.
ii. For Fig. 3-18, the direction of the diode suggests that the signal v_i must be positive to turn it on. The dc supply further requires the voltage v_i to be greater than v volts to turn the diode on. The negative region of the input signal turns the diode into the OFF state. Therefore, in the negative region the diode is an open circuit.
iii. Determine the applied voltage (transition voltage) that will cause a change in state for the diode. For the ideal diode the transition between states will occur at that point on the characteristics where $v_d = 0$ V and $i_d = 0$ A. Applying this condition to Fig. 3-18 will result in the configuration of Fig. 3-19 and it is recognized that the level of v_i that will cause a transition in state is:

$$v_i = \mathrm{V}$$

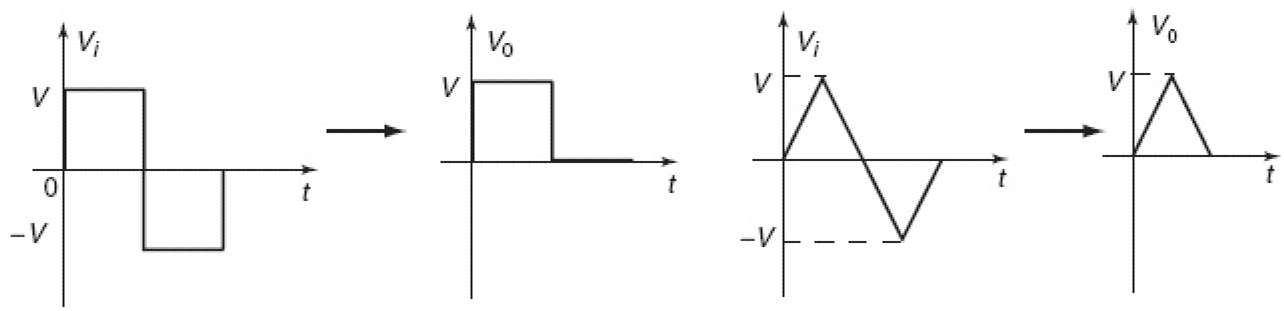


Figure 3-17(b) Response of clipper circuit

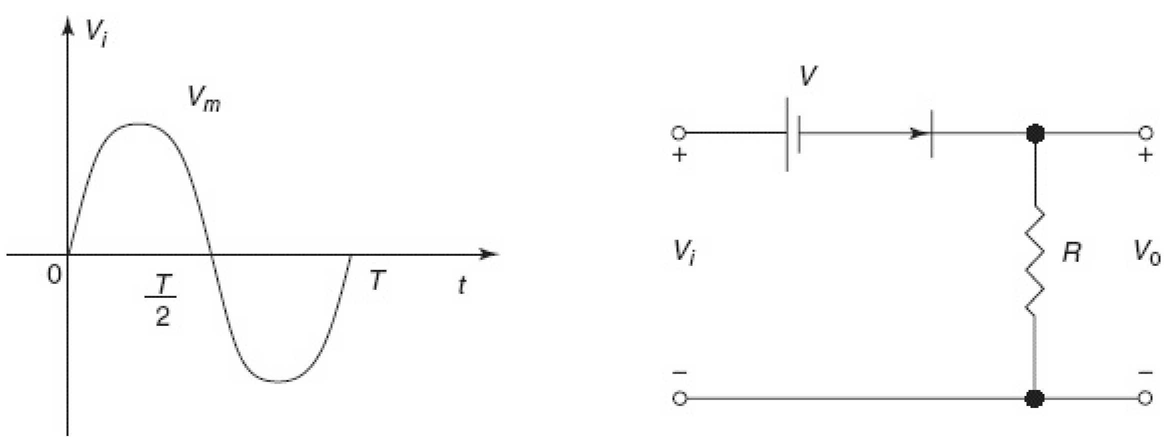


Figure 3-18 Series clipper with a dc supply

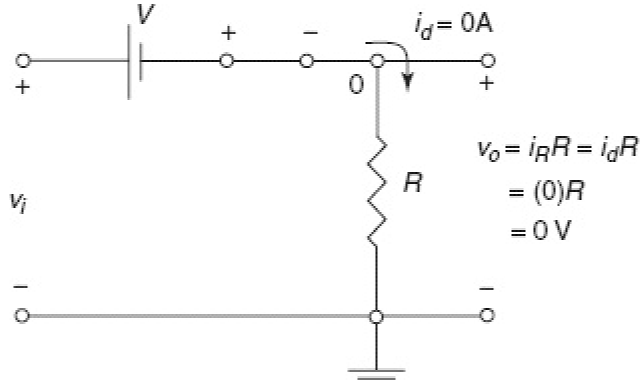


Figure 3-19 Determining the transition level of the input signal

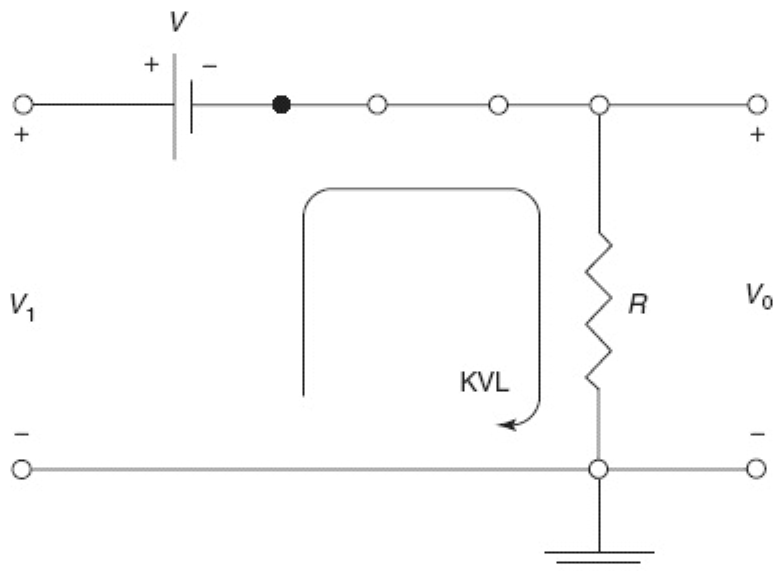


Figure 3-20 Determining v_o in the clipper circuit

For an input voltage greater than V volts, the diode is in the short-circuit state, while for input voltage less than V volts it is in the open-circuit or OFF state (as it is reverse-biased).

iv. Be continually aware of the defined terminals and polarity of v_o. When the diode is in the short-circuit state, as shown in Fig. 3-20, the output voltage v_o can be determined by applying KVL in the clock-wise direction:

$$v_i - V - v_o = 0$$

or,

$$v_0 = v_i - V$$

v. It can be helpful to sketch the input signal above the output and determine the output at instantaneous values of the input. It is then possible to sketch the output voltage from the resulting data points of v_o, as shown in Fig. 3-21.

At $v_i = V_m$, the network to be analysed is shown in Fig. 3-22.

For $V_m > V$, the diode is in the short-circuit state and $v_0 = V_m - V$. At $v_i = V$, the diode changes state and $v_i = -V_m$, $v_o = 0$ V. The complete curve for v_o can be sketched, as shown in Fig. 3-23.

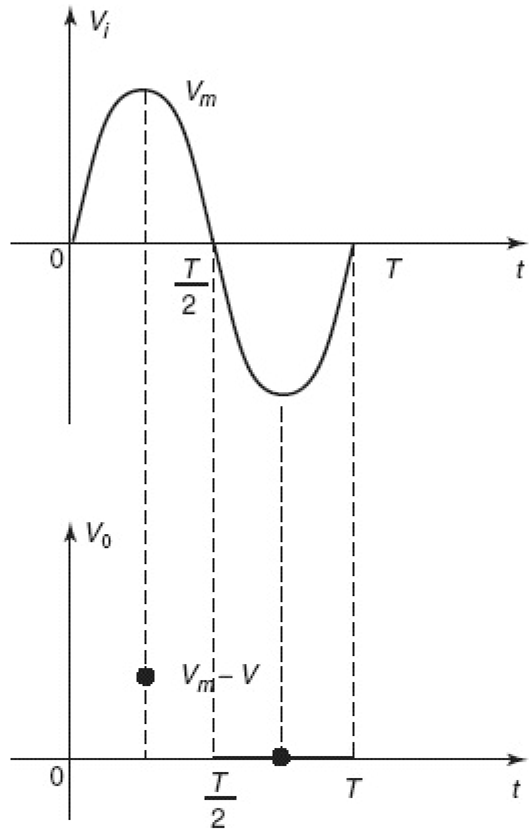


Figure 3-21 Determining levels of v_o

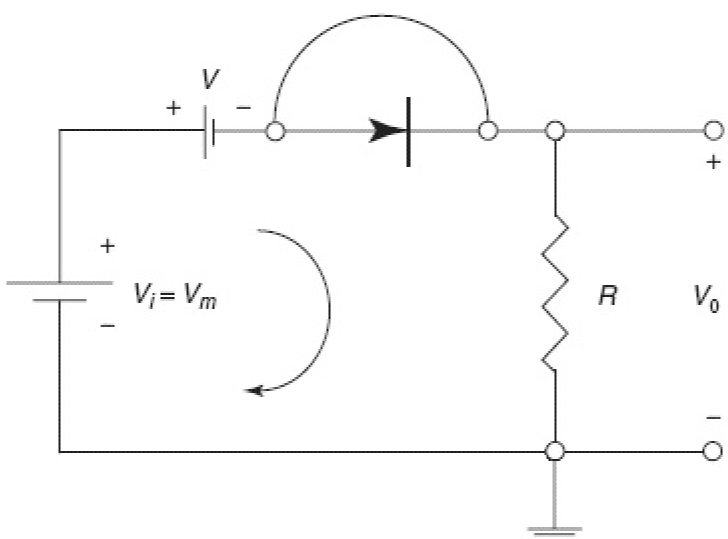


Figure 3-22 Determining v_o when $v_i = V_m$

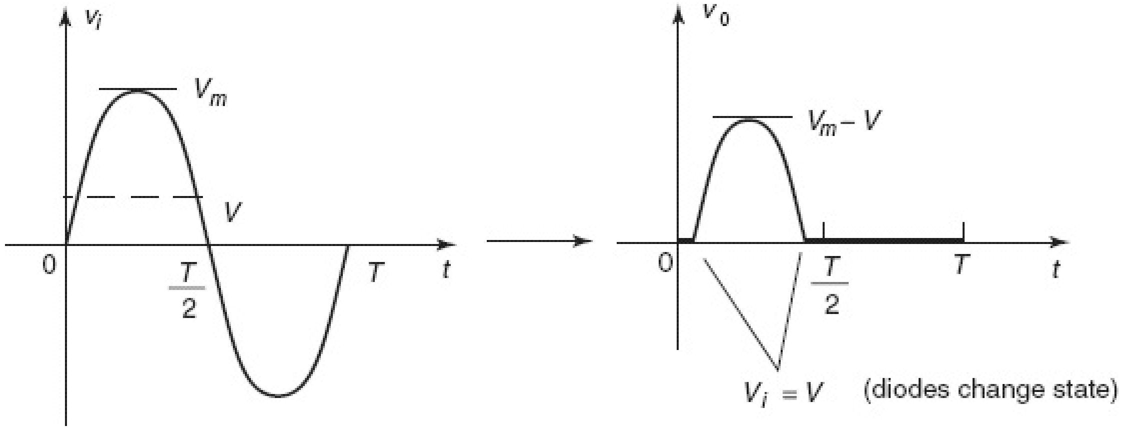


Figure 3-23 Sketch for v_o

Parallel clipper

A simple parallel clipper and its response are shown in Fig. 3-24 and Fig. 3-25 respectively. Input v_i is applied for the output v_o. The analysis of parallel configuration is very similar to the series configuration.

Break region

There is a discontinuity at the voltage V_γ. Actually the transition of a diode state is not exactly abrupt but gradual. Thus, a waveform, which is transmitted through the clipper circuit, will not show an abrupt clipping. Instead, it will show a gradual broken region, exhibiting the regions of un-attenuated and attenuated transmission. Now, we will estimate the range of this break region. The output current of a diode is given by:

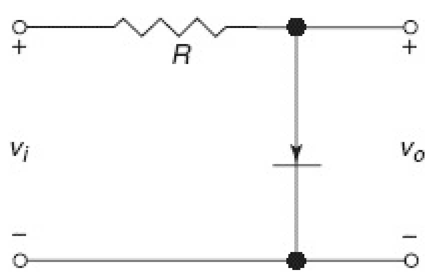


Figure 3-24 Parallel clipper

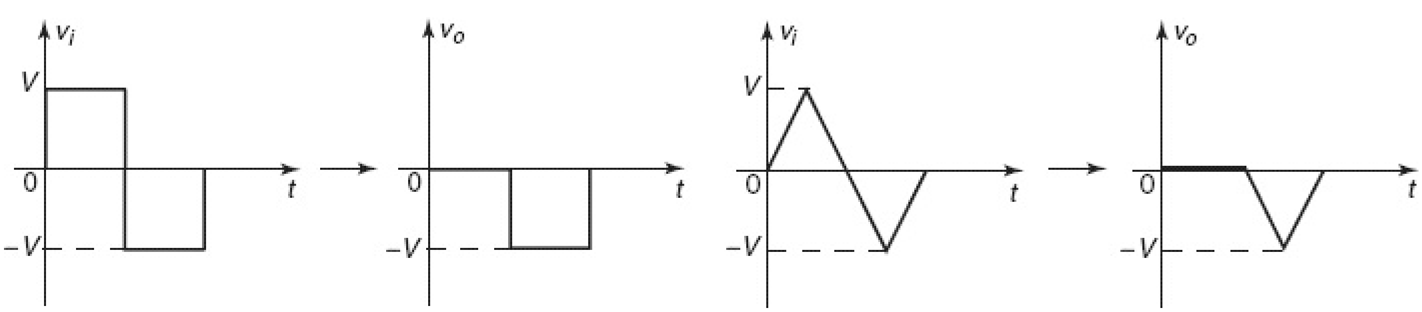


Figure 3-25 Response of parallel clipper

$$I = I_o (e^{V/\eta V_T} - 1) \quad (3\text{-}49)$$

Beyond the diode break point, the expression of the current that is large, compared to I_o, may be given by:

$$I = I_o e^{V/\eta V_T}$$

The incremental diode resistance $r = dv/dI$ and as obtained from the Eq. (3-49) is given by:

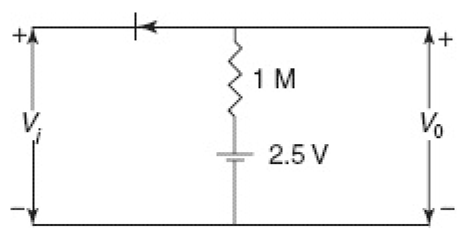
$$r = \frac{\eta V_T}{I_o} e^{-V/\eta V_T} = \frac{\eta V_T}{I} \quad (3\text{-}50)$$

From Eq. (3-50), we note that r varies inversely with the quiescent current, and directly with the absolute temperature. We also note that the break region is independent of the quiescent current.

Again for meaningful clipping to be done, the applied signal must vary from one side of the break point to a point well on the other side. If the signal is only of the order of magnitude of the extent of the break region, the output will not display sharp limiting.

Solved Examples

Example 3-23 A symmetrical 5 kHz square wave whose output varies between +10 V and −10 V is impressed upon the clipping circuit shown. Assume, $R_f = 0$, $R_r = 2$ M, and $V_\gamma = 0$. Sketch the steady-state output waveform, indicating numerical values of the maximum, minimum, and constant portions.

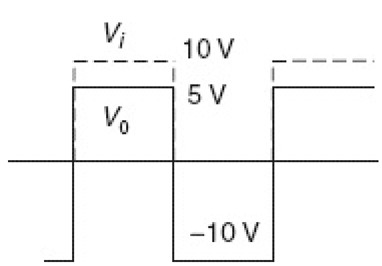


Solution:

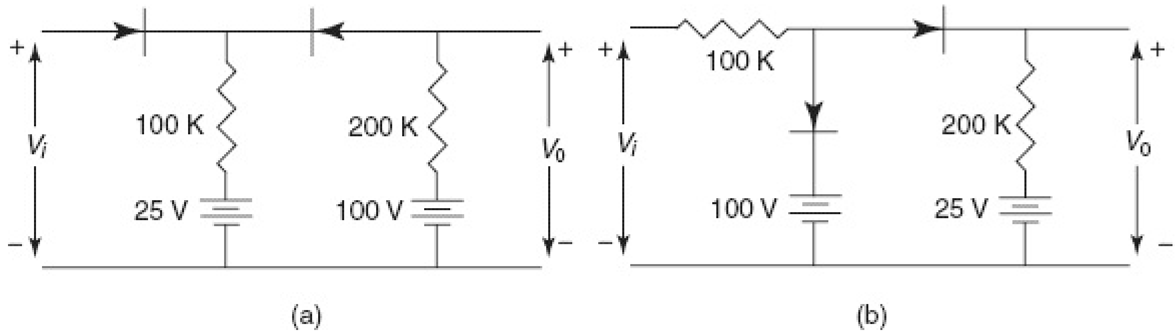
The diode conducts when, $v_i < 2.5$ V. The diode is open when:

$$v_i > 2.5 \text{ V and } v_o = 2.5 \text{ V} + \frac{v_i - 2.5 \text{ V}}{3}$$

When diode conducts, $v_i = v_o < 2.5$ V.



Example 3-24 (a) The input voltage v_i to the two level clippers shown in Fig. (a) of the figure varies linearly from 0 to 150 V. Sketch the output voltage v_o to the same time scale as the input voltage. Assume ideal diodes.



(b) Repeat part (a) for the circuit shown in Fig. (b).

Solution:

a. When $v_i < 50$ V, the first diode is open and second diode conducts, and:

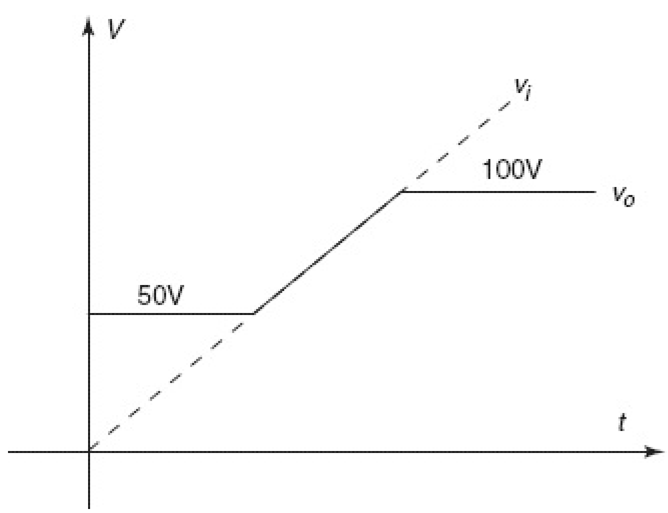
$$v_O = 100 - \frac{2}{3} \times 27 = 50 \text{ V}$$

When $50 < v_i < 100$, both diodes conduct, and $v_O = v_i$. When $v_i > 100$, the first diode is conducting but the second diode is open, so $v_O = 100$ V.

b. When $v_i < 25$ V neither diode conducts and $v_o = 25$ V. When $v_i > 25$ V, the upper diode conducts and:

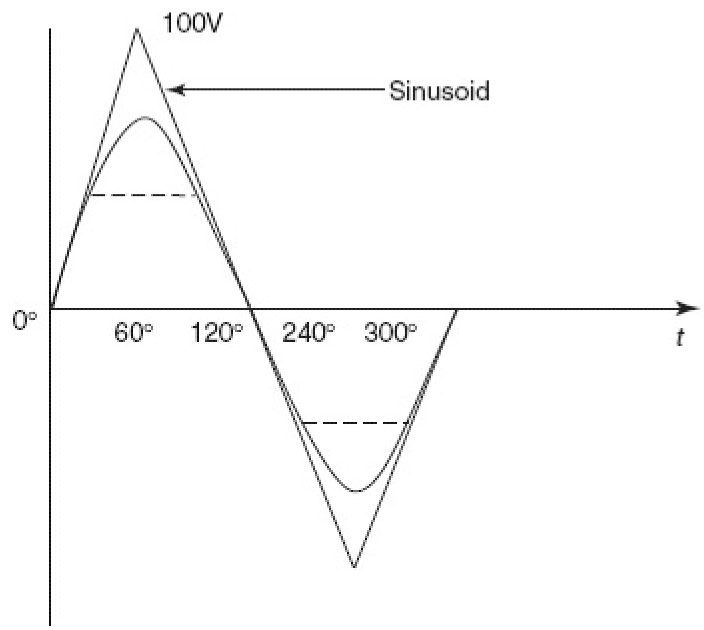
$$v_O = (v_i - 25)\,\frac{2}{3} + 25$$

When v_o reaches 100 V, v_i rises to 137.5 V For larger v_i, both diodes conduct and $v_O = 100$ V (if $v_i = 40 \sin \omega t$, then $v_0 = 20 \sin \omega t$).



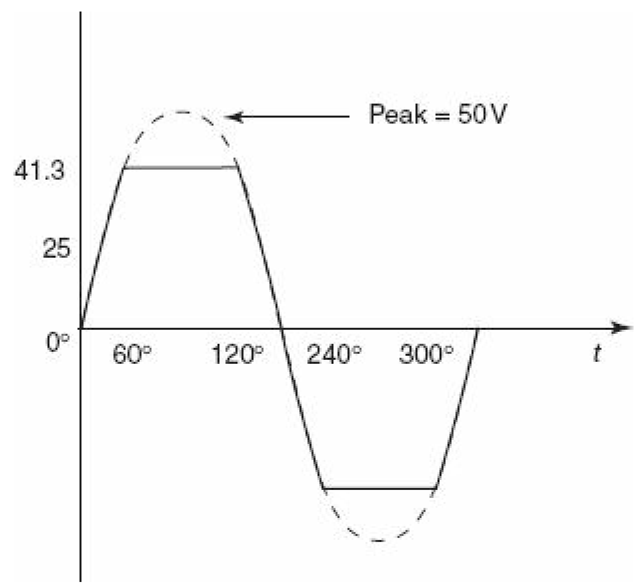
Example 3-25 The triangular waveform shown is to be converted into a sine wave by using clipping diodes. Consider the dashed waveform sketched as a first approximation to the sinusoid. The dashed

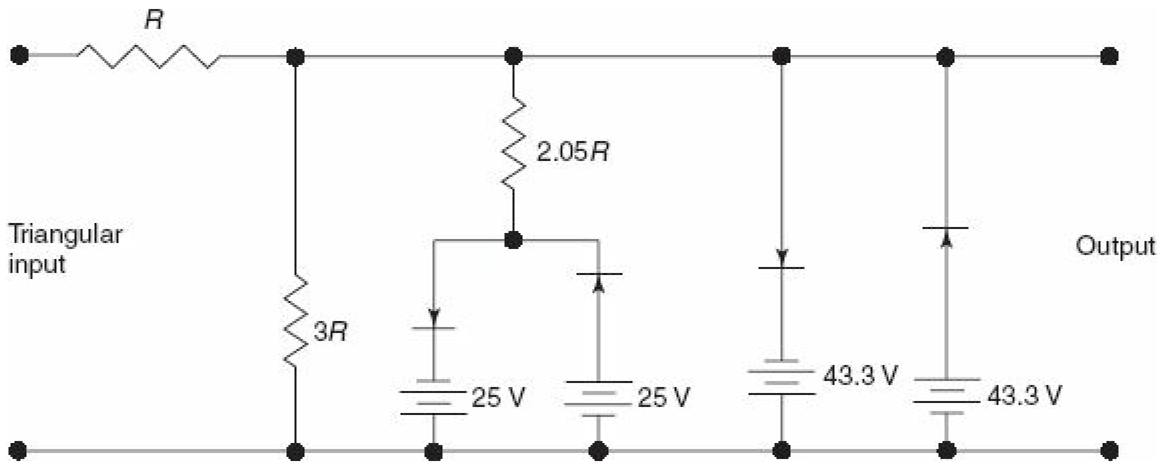
waveform is coincident with the sinusoid at 0°, 30°, 60°, etc. Devise a circuit whose output is this broken-line waveform when the input is the triangular waveform. Assume ideal diodes and calculate the values of all supply voltages and resistances used. The peak value of the sinusoid is 50 V.

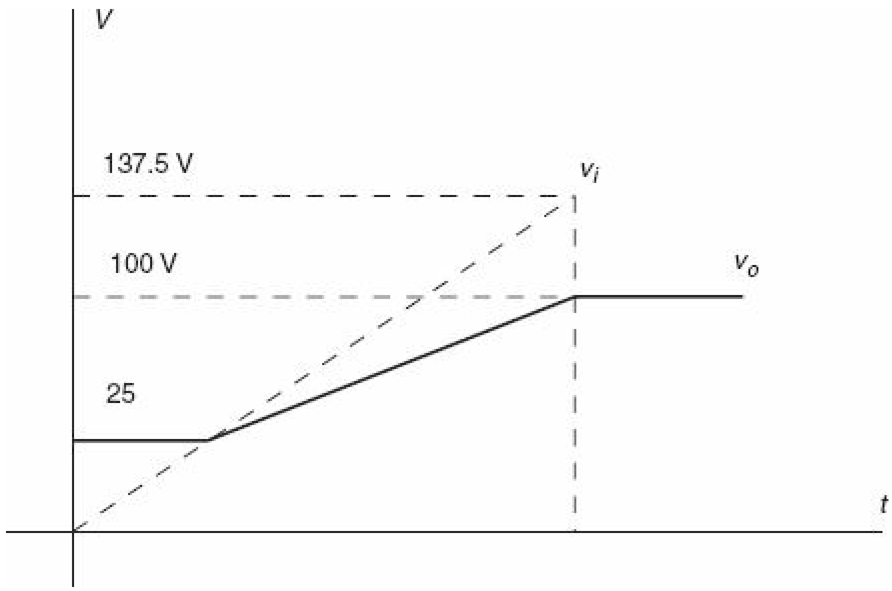


Solution:

Desired output:







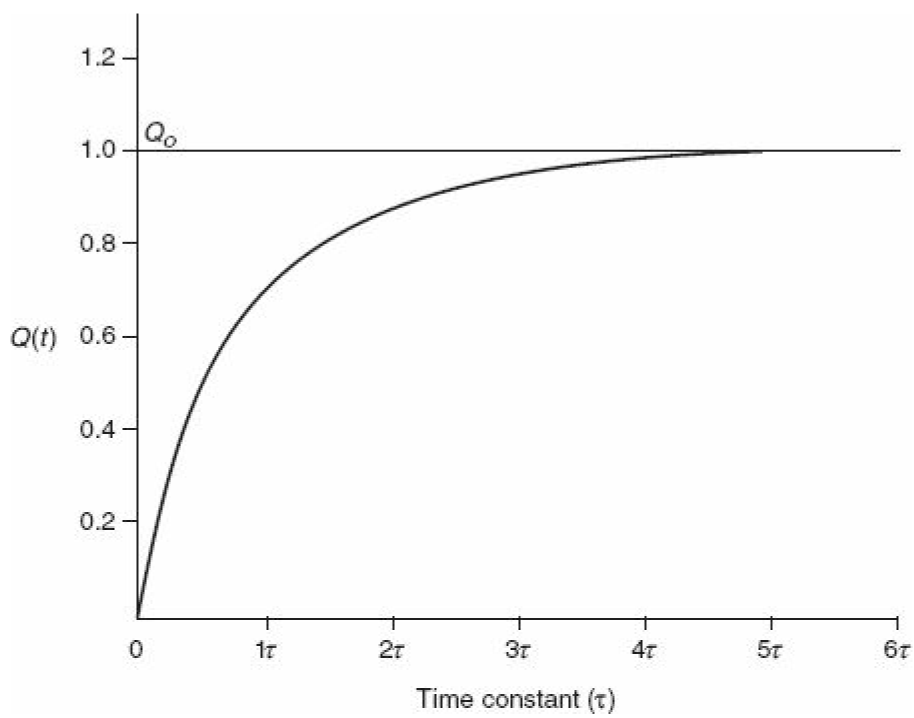


Figure 3-26 Charging of a *RC* circuit

3-6-2 Clamper

A clamping network is one that will "clamp" a signal to a different dc level. The network must have a capacitor, a diode, and a resistive element, but it can also employ an independent dc supply to introduce an additional shift. Before further probing into the clamper circuit one must have a basic understanding of a transient *RC* circuit.

From the basic understanding of a series *RC* transient circuit applied across a dc voltage E_o the instantaneous charge across the capacitor at any time is given by

$$Q(t) = Q_O(1 - e^{-t/RC})$$

$Q_o = E_oC$ where, C is the capacitance of the capacitor.

We know that the time constant of the *RC* circuit is given by $\tau = RC$. This was the case when the capacitor was being charged from zero voltage level. From Fig. 3-26 it is at once interpreted that the rise time becomes smaller if we decrease the time constant.

Hence, to reach the maximum charging level quickly, we need to reduce the time constant. In case of discharge through a *RC* circuit, it can again be shown that, $Q(t) = Q_oe^{-t/RC}$ where, Q_o is the initial charge on the capacitor.

Here also the time constant has the same value, and from Fig. 3-27 we can instantly say that the discharge will occur quickly if the time constant of the circuit is decreased. In other words, we can state, that to hold the charge in a capacitor for a sufficiently longer time, we need to increase the time constant of the circuit.

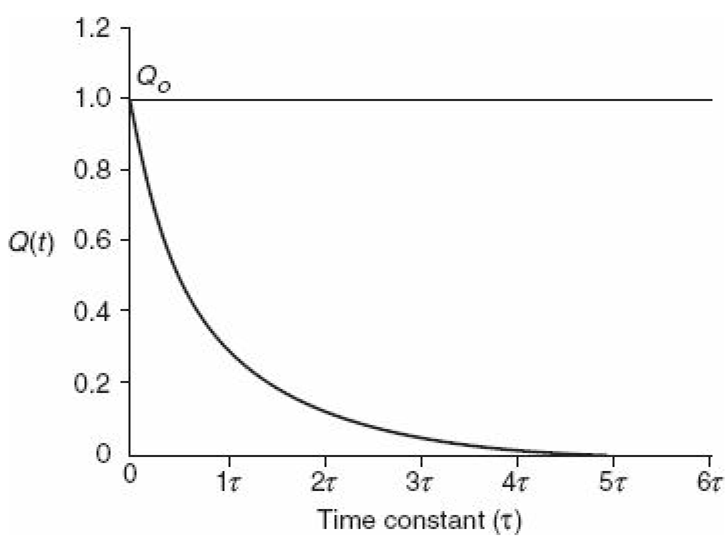
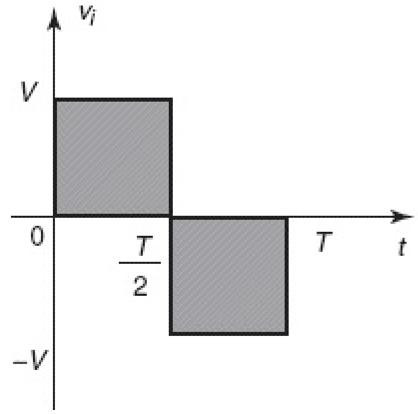


Figure 3-27 Discharging of an *RC* circuit



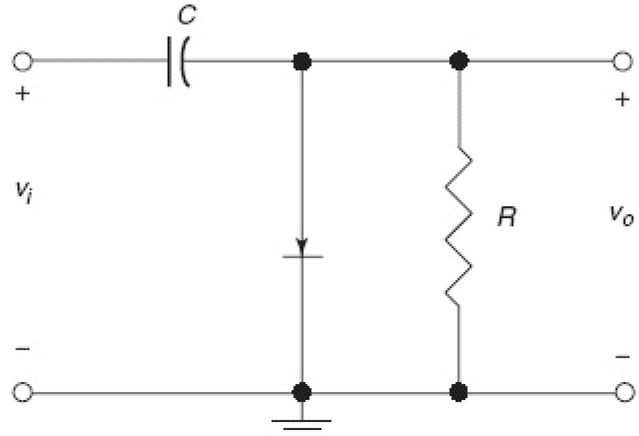


Figure 3-28 Simple clamper circuit

In electronic circuits, clamping usually refers to holding voltage at its maximum value for a desired period of time. In order to do that, the magnitude of *R* and *C* must be so chosen that the time constant, $\tau = RC$, is large enough to ensure that the voltage across the capacitor does not discharge significantly during the interval the diode is non-conducting. Figure 3-28 shows the clamping circuit that will clamp the input signal to the zero level.

During the interval 0–*T/2* the network will appear, as shown in Fig. 3-29, with the diode in the ON state effectively "shorting out" the effect of the resistor *R*.

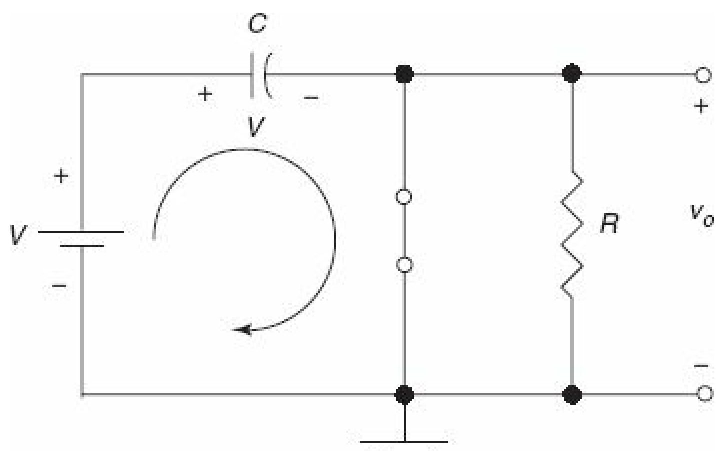


Figure 3-29 State of the circuit when v_i is more than v_{diode}

The resulting *RC* time constant is so small that the capacitor will charge to *V* volts very quickly. During this interval the output voltage is directly across the short circuit and $v_o = 0$ V.

When the input switches to −*V* state, the network will appear as shown in Fig. 3-30.

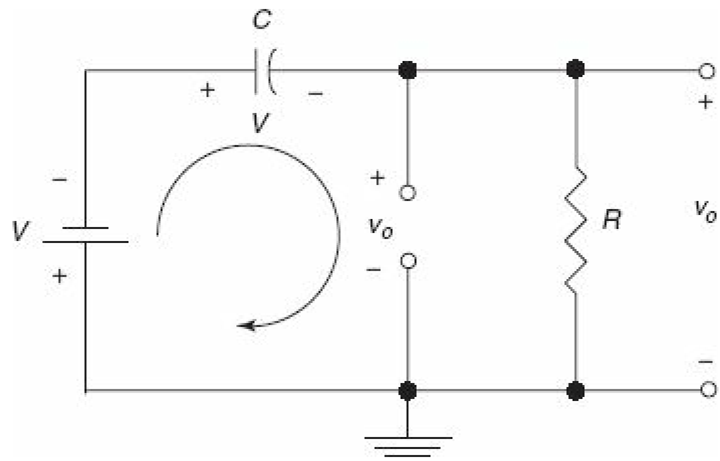


Figure 3.30 State of the circuit in the negative half-cycle

The diode will now be in the open-state condition. Applying KVL around the input loop of Fig. 3-30 will result in:

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

or,

$$v_o = -2\text{ V}$$

The negative sign results from the fact that the polarity of 2 V is opposite to the polarity defined for v_o. The resulting output waveform appears with the input signal. The output signal is clamped to 0 V for the interval 0–*T/2* but maintains the same total swing (2 V) as the input. For a clamping network the total swing of the output is equal to the total swing of the input.

Analysis of clamping networks

In general, the following steps must be kept in mind when analysing the clamping networks.

i. The first step is to calculate the interval of the input signal in which the diode is in forward bias.
ii. The second step is to determine the voltage across the capacitor. This is assumed to rise instantaneously.
iii. Due to the longer time constant of the circuit, the capacitor will hold on to its established voltage level.
iv. During the whole process, the analysis maintains a continual awareness of the location and reference polarity for v_o to ensure that the proper levels for v_o are obtained.
v. The general rule that the total swing of the output must match the swing of the input signal, should be kept in mind.

3-7 COMPARATORS

The diode circuit which has been used in the design of the clipping circuit can also be used for the purpose of comparison, hence the name comparator. The basic principle on which the comparator works is the switching of the diodes. This action corresponds to the phase when the diode conducts; and when it does, the comparator circuit is used to compare the input arbitrary voltage with the reference voltage. This reference voltage is predefined, and the output attains a sharp slope when the input waveform crosses the predefined level. The basic and foremost difference between a clipper and a comparator is that, in case of a comparator, we are not interested in reproducing the input waveform or any of its parts. In general the comparator output consists of a sharp departure from its quiescent point as the input signal attains the reference level, but otherwise the circuit remains unaffected by the input signal. The basic operation is given in Fig. 3-31. It also gives a comparative study of the input and the output, as can be understood from Fig. 3-32.

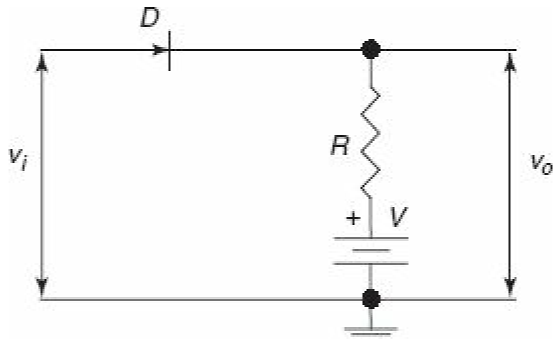


Figure 3-31 A diode comparator

Figure 3-31 shows that as long as the input signal is below the total threshold voltage, i.e., *cutin voltage* of the diode and that of the voltage source, the output is not affected at all. The output is just the reference voltage of the voltage source. But, as soon as the input voltage exceeds the predefined threshold voltage, the output gives a sharp response and executes the ultimate purpose of the comparator. Thus, the output of the circuit in Fig. 3-33 shows that the output is very different when the input is below the threshold level than when it is above the threshold value. Consequently, we obtain a device that can make a sharp demarcation in the cases as described earlier.

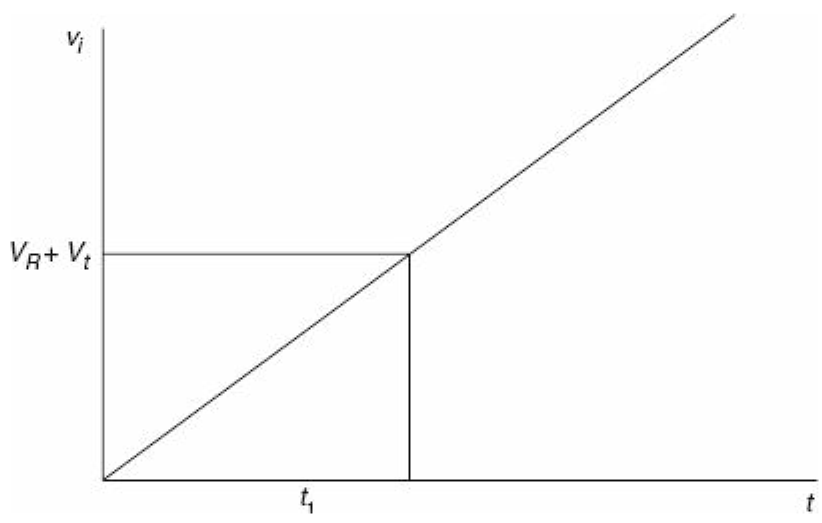


Figure 3-32 Input signal with the threshold voltage

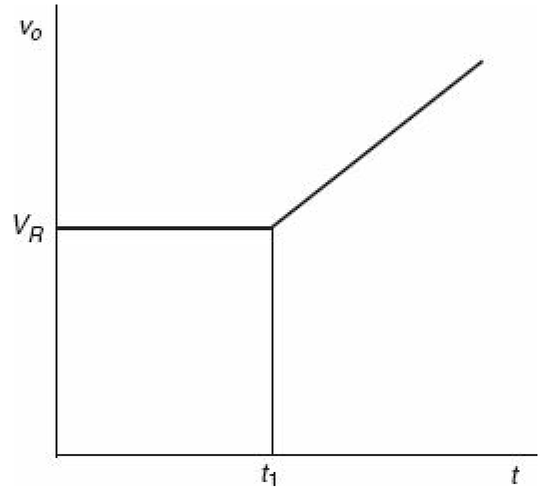


Figure 3-33 Corresponding output waveform

3-8 ADDITIONAL DIODE CIRCUITS

3-8-1 Voltage Multiplier

The voltage multiplier is a passive circuit, similar to the rectifier circuit and gives an output which is approximately equal to a certain multiple of the peak value of the peak input voltage. Here it is possible to obtain a dc voltage equal to the peak value of the applied ac voltage.

The circuit of a half-wave doubler is as shown in Fig. 3-34. With terminal *A* of the ac source assumed positive, diode D_2 is forward-biased and diode D_1 is reverse-biased, i.e., open. The diode D_2 charges the capacitor to the peak supply voltage. In the next half-cycle, the same case is repeated with the second diode, i.e., D_1, and consequently, as seen from the circuit, the diode D_2 is reverse-biased. Again, in this case, the capacitor C_1 charges to its fullest.

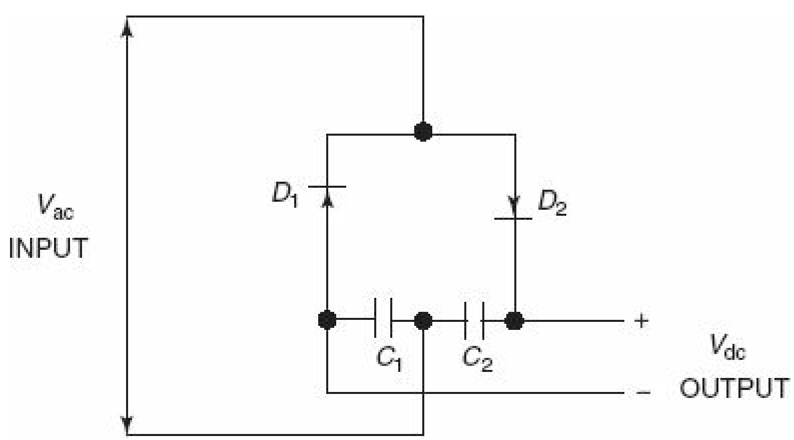


Figure 3-34 Voltage doublers

Now, the capacitors C_1 and C_2 are in series for the dc output circuit; and at no load, the dc voltage is equal to the sum of the positive and negative peaks of the applied voltage. In other words, the output voltage is equal to twice the peaks of the applied voltage. It should be noted, that for the proper operation of the circuit, the input has to be symmetrical.

Another important requirement is that the values of the capacitors C_1 and C_2 have to be sufficiently large so that they maintain the voltage level over the intervals in which each diode is conducting.

Similarly, with such designs, various types of multipliers—triplers and quadruplers—can be designed with a proper choice of such components and by suitably connecting them.

3-8-2 Peak Detector

The half-wave rectifier circuit can be suitably manipulated to obtain the peak detector circuit. The working principle depends on the charging and discharging of the capacitor, and also on the conducting and non-conducting regions of the diode. Its simple circuit consists of a diode kept in series with a resistor and a load at the end. The circuit of a peak detector is as shown in Fig. 3-35.

When the input signal forward-biases the diode, the diode conducts and the voltage is obtained at the load. In this process, the output voltage is available across the capacitor, which in this process charges itself to the full.

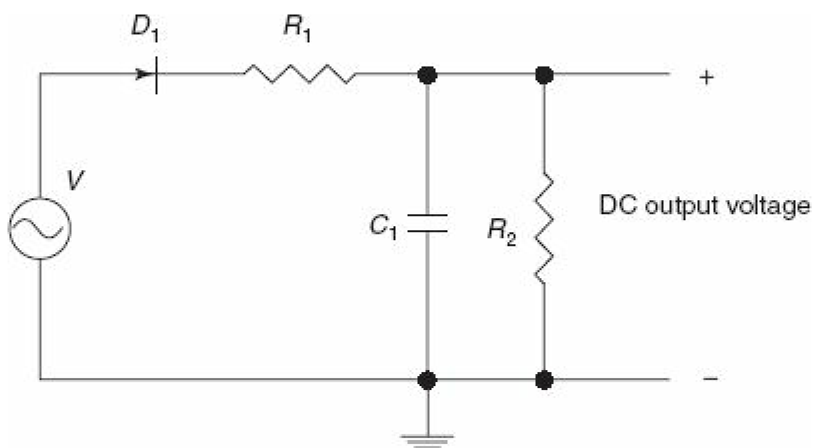


Figure 3-35 Peak detector

Again, when the diode is reverse-biased, the diode does not conduct, and the input voltage is not obtainable at the output. During this time, because the capacitor is charged to the maximum, it begins to discharge and an almost steady voltage is obtained at the output. This process continues till the input voltage again forward-biases the diode.

In this sequence of steps, the output becomes the envelope of the input voltage. But proper care has to be taken regarding the value of the capacitor. Its time constant has to be properly set so that proper replication of the envelope is obtained. These circuits are used extensively for communication purposes in various detection devices.

3-8-3 Digital Circuits

In various kinds of analog to digital converters, and in many digital circuits, diodes are extensively brought to use. Their primary domain of operation is switching, i.e., to keep a portion of a large circuit in the ON state, selectively for a given interval of time. They, in coherent action with resistors, form many important logic families, which are used in digital electronic circuits.

3-8-4 Switching Regulators

Power supplies with switching regulators offer great versatility, as the design of power supplies employing this type of regulator can be lighter and more compact. Another advantage of these power supplies is that the circuit can be designed to give an output voltage that is higher than the unregulated voltage or, has a different polarity.

But there is also a disadvantage. The circuit becomes more complex because of the control circuitry, which is the filtering required to remove the switching noise from the output and the electromagnetic interference that can degrade the performance of the device.

Specifically, a switching regulator has two parts: a converter circuit to perform the switching action and a feedback system to control the switching rate. The structure of the converter can be of three types: *buck, boost* and *buck-boost.* Let us first study the buck-type converter.

Buck converter

The basic circuit of the buck converter is as shown in Fig. 3-36.

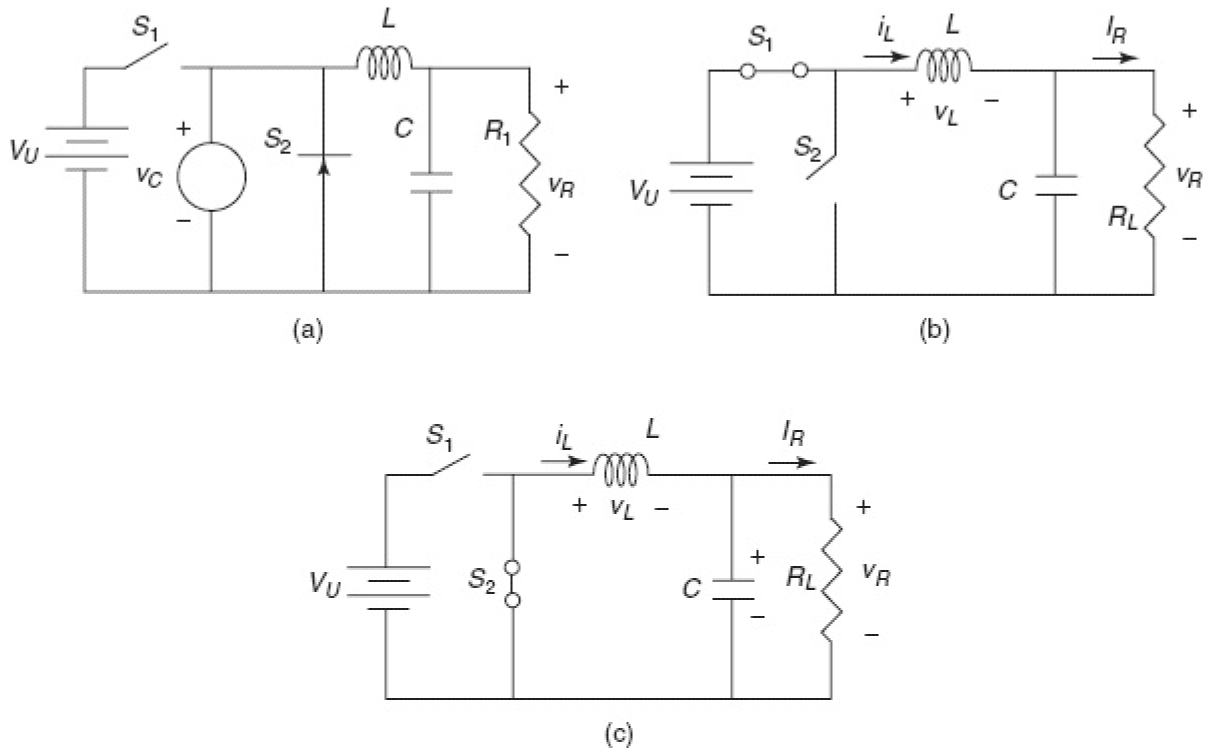


Figure 3-36 Various stages in the operation of a buck-type switching converter

The total output voltage of the supply is $v_R = V_R + v_r$ where, V_R is the regulated dc output voltage and v_r is a small ac ripple. From Fig. 3-36, we find that we have the switches with two voltage controlled devices that can be switched ON and OFF by critically controlling the control voltage V_C. In Fig. 3-36(b), it is seen that the voltage across L is:

$$v_L \approx V_U - V_R \tag{3-51}$$

While forming Eq. (3-51), it is assumed that the capacitor is previously charged to V_R, the regulated voltage. At this stage we consider δ to be the duty cycle of the control voltage. This duty cycle has to be chosen very accurately as it figures out the operational performance of the device. Here, in the period 0-$\delta\ T_S$, the switch S_1 is closed and the switch S_2 is open. After δT_S, both S_1 and S_2 are open. Consequently, from Lenz's law—as the inductor must resist the cause of such a change—v_L becomes negative, and the inductor tries to maintain the constant current. At this stage, the voltage v_L is given by:

$$v_L \approx -V_R \qquad (3\text{-}52)$$

As the cycle expires, the previous state is restored, resulting in the closing of both S_1 and S_2. Figure 3-37 gives the inductor voltage waveform.

Just as the current through the capacitor is zero, so also must be the average voltage across the inductor. Consequently, it can be written as:

$$\frac{(V_U - V_R)\,\delta T_S + (-V_R)(1-\delta)\,T_S}{T_S} = 0$$

This gives us:

$$V_R = \delta V_U \qquad (3\text{-}53)$$

To obtain a regulated voltage V_R from an unregulated voltage V_U, v_C must provide the required duty cycle. In order to make V_R impervious to the changes in V_U, we need a feedback circuit to keep track of the output continuously and adjust the duty cycle as and when required.

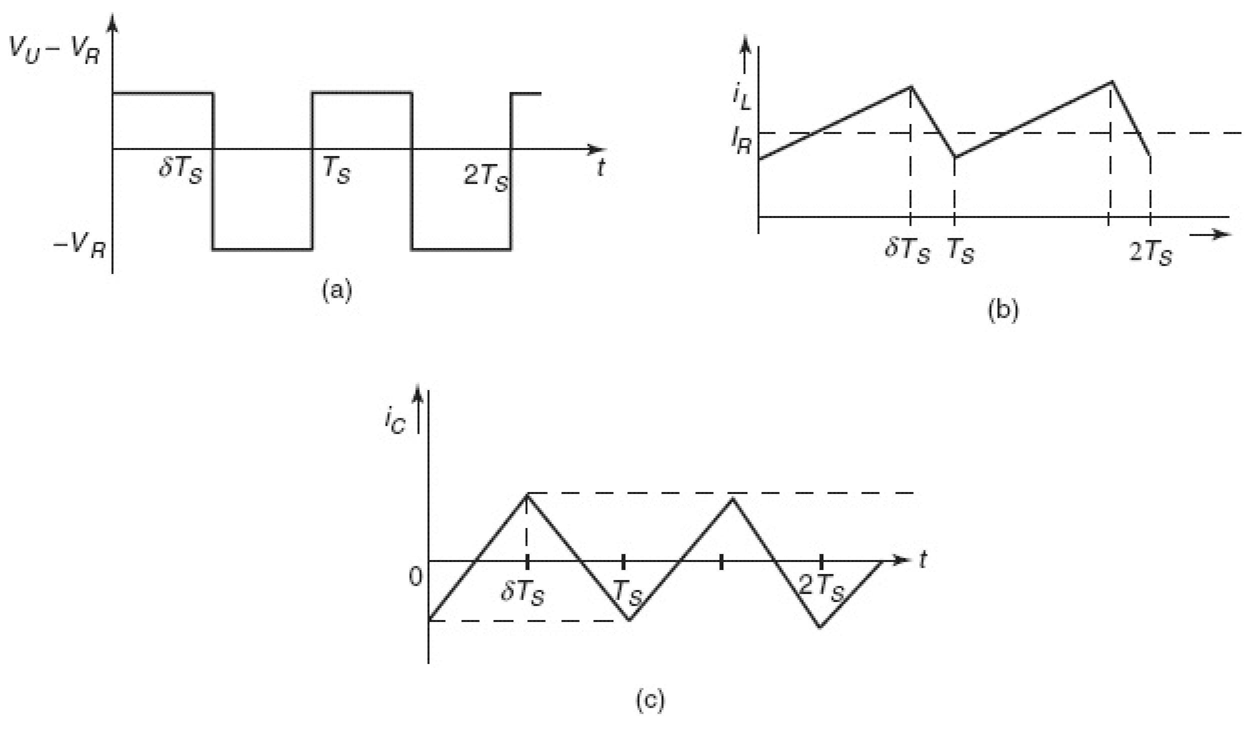


Figure 3-37 Key waveforms for buck-type converters

Let us now turn to the ripple, V_r. The inductor current is given by $i_L = 1/\mathrm{L} \int v_L(t)\, dt$, which is represented in Fig. 3-37(b). Also, we note that as the capacitor cannot carry the dc current and consequently the time varying part of i_1 must flow through the capacitor, therefore:

$$v_{L,avg} = \frac{V_U(\delta T_S) + V_R(1-\delta)T_S}{T_S} = 0$$

Subsequently, on solving this:

$$V_R = \frac{-\delta}{1-\delta} V_U \qquad (3\text{-}54)$$

Boost converter

The following circuits will also have the previously defined assumptions. The output ripple components can be ignored initially.

S_1 closes in the δT_s and is open for the subsequent part of the cycle.

S_2 closes as soon as S_1 opens.

The circuit for the basic boost converter is shown in Fig. 3-38.

Moving ahead, the average voltage across the inductor leads to:

$$v_{L_{avg}} = \frac{V_U(\delta T_S) + (V_U - V_R)(1-\delta)T_S}{T_S} = 0 \qquad (3\text{-}55)$$

And upon solving Eq. (3-55), we obtain the constraint $V_R = (1/1-\delta)V_U$. We also find that as δ is less than 1; and we obtain a boosted output, a higher value at the regulated output.

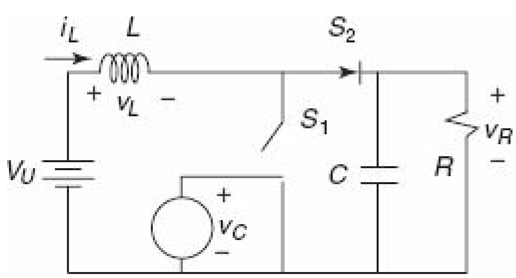


Figure 3-38 Boost converter

Buck-boost converter

The circuit of the buck-boost converter is shown in Fig. 3-39.

Applying the principles discussed earlier, we note that in this circuit also the average voltage across the inductor is zero. Therefore:

$$v_{L,avg} = \frac{V_U(\delta T_S) + V_R(1-\delta)T_S}{T_S} = 0$$

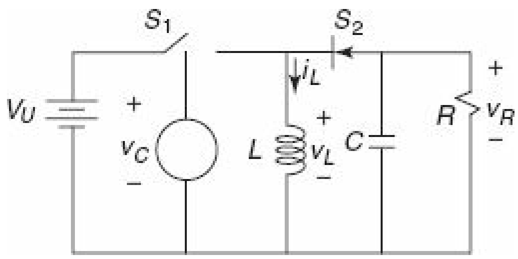


Figure 3-39 Buck-boost converter

Subsequently, on solving this:

$$V_R = \frac{-\delta}{1-\delta} V_U \tag{3-56}$$

As we concentrate, we find that in Eq. (3-56), the polarities of V_R and V_U are always opposite.

Solved Examples

Example 3-26 By direct integration find the average value of the diode voltage and the load voltage for a diode whose specifications are as given: $V_m = 2.4$ V, $V_\gamma = 0.6$ V, $R_f = 10\ \Omega$ and $R_L = 100\ \Omega$. Note that these two answers are numerically equal and explain why?

Solution:

$$\varphi = \arcsin \frac{V_\gamma}{V_m} = \arcsin \frac{1}{4} = 14.5°$$

For $a = \frac{\pi}{2}$

$$I_{\max} = \frac{1.8}{110} = 16.35 \text{ mA}$$

Hence, $v_{D\max} = 0.6 + 16.35 \times 10^{-3} \times 10 = 0.763$ V

$$\overline{v_L} = \frac{1}{T}\int_0^T iR_L d\alpha = \frac{1}{2\pi}\int_0^{2\pi} iR_L d\alpha = \frac{1}{2\pi}\left(\int_0^{\phi} iR_L d\alpha + \int_{\phi}^{\pi-\phi} iR_L d\alpha + \int_{\pi-\phi}^{2\pi} iR_L d\alpha\right)$$

$$= \frac{1}{2\pi}\left[0 + \int_{\phi}^{\pi-\phi} \frac{R_L}{R_L + R_f}(V_m \sin\alpha - V_\gamma)d\alpha + 0\right]$$

$$= \frac{1}{2\pi} \times \frac{R_L}{(R_L + R_f)}\left[V_m \cos\phi - V_m \cos(\pi - \phi)\right] - \frac{1}{2\pi}\frac{R_L}{R_L + R_f}V_\gamma(\pi - \phi - \phi)$$

$$= \frac{1}{2\pi} \times \frac{R_L}{R_L + R_f}\left[2V_m \cos\phi - V_\gamma(\pi - 2\phi)\right]$$

When the diode is ON:

$$v_D = V_\gamma + iR_f = \frac{R_L}{R_L + R_f}(V_m \sin\alpha + V_\gamma)$$

When the diode OFF:

$$v_D = V_m \sin\alpha - V_\gamma$$

Hence,

$$\overline{v}_D = \frac{1}{2\pi}\left[\int_0^{\phi}(V_m \sin\alpha - V_\gamma)\, d\alpha + \int_{\phi}^{\pi-\phi}\frac{R_L}{R_L + R_f}(V_m \sin\alpha - V_\gamma)\, d\alpha + \int_{\pi-\phi}^{2\pi}(V_m \sin\alpha - V_\gamma)d\alpha\right]$$

$$= -\frac{1}{2\pi} \times \frac{R_L}{R_L + R_f}\left[2V_m \cos\phi - V_\gamma(\pi - 2\phi)\right]$$

Since, $v_i = v_D + v_L$ when the diode is ON and $v_i = v_D + v_L = 0$ when the diode is OFF:

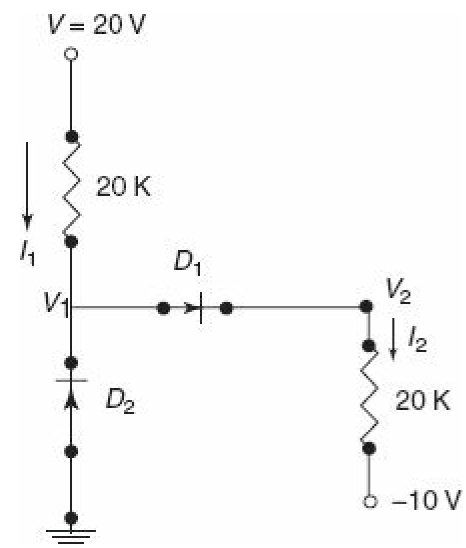
$$0 = \frac{1}{T}\int_0^T v_i dt = \frac{1}{T}\int_0^T v_D dt + \frac{1}{T}\int_0^T v_L dt$$

or,

$$\frac{1}{T}\int_0^T v_D dt = \overline{v_D} = -\frac{1}{T}\int_0^T v_L dt = -\overline{v_L}$$

Example 3-27 For the circuit shown find I_1, V_1, I_2, and V_2. Assume ideal diode.

Solution:
For ideal diode, $R_f = 0$.



The diode acts as short-circuited. Both the diodes are forward-biased.

$$V_1 = 0 \text{ V}$$

As D_2 is short-circuited, therefore:

$$I_1 = \frac{20 - V_i}{20 \text{ K}} = \frac{20}{20} \times 10^3$$

$$I_1 = 1 \text{ mA}$$

As D_1 is also short-circuited, therefore:

$$V_2 = 0$$

$$I_2 = \frac{V_2 - (-10)}{20 \text{ K}} = \frac{10}{20} - 10^3$$

$$I_2 = 0.5 \text{ mA}$$

Therefore,

$$V_1 = 0 \text{ V}$$

$$V_2 = 0 \text{ V}$$

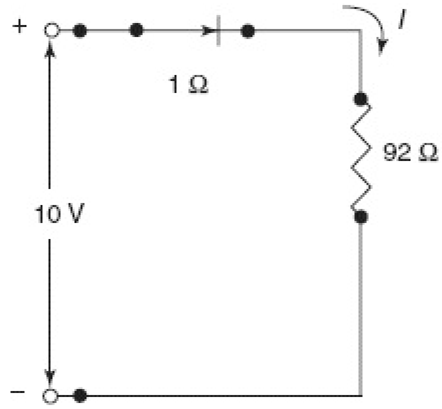
$$I_1 = 1 \text{ mA}$$

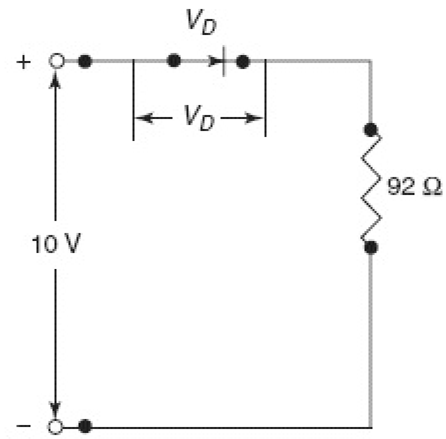
$$I_2 = 0.5 \text{ mA}$$

Example 3-28 Consider the circuit and its V-1 characteristics, find voltage across diode V_D.

Solution:

From the given figure:





Voltage across diode V_D

$$V_D = IR_D$$

$$= 0.1075 \times 1$$

Therefore,

$$V_D = 0.1075 \text{ V}$$

Example 3-29 A silicon diode is in forward-biased state with constant voltage V. Prove that the temperature coefficient of the forward current is given by:

$$\frac{(V_{Go} - V)}{\eta_T V_T}$$

Solution:

Forward voltage is given by:

$$Vf = IRf$$

Forward resistance:

$$Rf = \frac{\eta V_T}{I}$$

The voltage temperature coefficient is given by:

$$\frac{dV}{dT} = \frac{V - (V_{Go} - \eta V_T)}{T}$$

$$Rf\tfrac{dI}{dT} = \frac{V - (V_{Go} + \eta V_T)}{T} + Rf$$

Therefore,

$$\frac{dI}{dT} = \frac{V - (V_{Go} + \eta V_T)}{T.Rf}$$

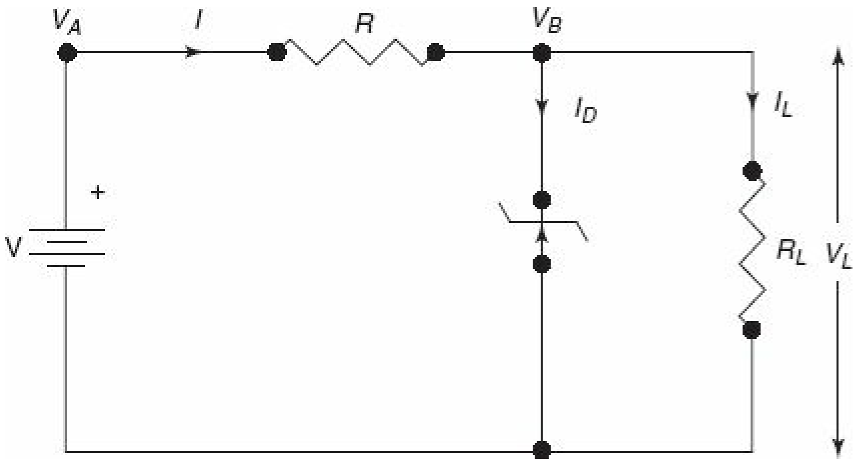
Putting up the value of Rf:

$$\frac{dI}{dT} = \frac{V - V_{Go} + \eta V_T}{T} \times \frac{I}{\eta V_T}$$

Therefore,

$$\frac{dI}{dT} = \frac{V_{Go} - V}{\eta V_T T}$$

Example 3-30 The avalanche diode regulates at 50 V The range of diode current from 5-40 mA. The supply voltage $V_i = 200$ V. Calculate R to allow voltage regulation from a load current of $I_L = 0$ up to I_{Lmax}. Hence find I_{Lmax}



Solution:

Given data:

$$V_0 = V_L = 50 \text{ V (Zener Voltage)}$$

$$I_L = 0$$

Diode current ranges from 10 to 40 mA.

Therefore,

$$I_D < 40 \text{ mA} = I$$

Therefore,

$$R = \frac{V_A - V_B}{I_D} = \frac{200 - 50}{40 \times 10^{-3}}$$

∴

$$I_L = I_{\max} \text{ when, } I_D = I_{D\,\min} = 10 \text{ mA}$$

∴

$$\text{Maximum load current is, } I_{L\,\max} = 40 - 10$$

= 30 mA

POINTS TO REMEMBER

1. A basic diode circuit consists of a diode in series with a voltage source. It mainly corresponds to the inclusion of a diode in the concerned circuit or a diode as a circuit element.
2. The circuit analysis of a diode in a circuit is made simpler by analysing it using the concept of load line.
3. A load line corresponds to the basic equation of the circuit concerned. It mainly deals with the relation of the voltage across the diode and the current flowing through it.
4. A load line actually has an impact on the region of operation of the device. It is an analysis performed in a graphical manner—a line drawn on the characteristics of the device that represents the applied load.
5. The intersection of the load line with the characteristic curve of the device determines the point of operation.
6. Dynamic load line can be obtained from different load resistances. This dynamic load line is important because with the help of this, we can directly obtain the diode current for any given input voltage, as the corresponding current can be obtained from the graph.
7. The principle behind the use of the Zener diode as a voltage regulator is the fact that it maintains a constant output voltage even though the current through it changes. For proper operation, the voltage of an unregulated power supply must be greater than the Zener voltage of the diode selected. If the input voltage is less, the diode does not conduct.
8. A rectifier mainly works on the principle of conduction through the diode, i.e., it conducts when forward-biased, and not when reverse-biased. Depending on the design of the circuit, two types of rectifiers result—half-wave rectifiers and full-wave rectifiers.
9. In case of half-wave rectifiers, diode conducts for only one half-cycle of the input signal till the diode is forward-biased. Also, the rectified voltage appearing at the load is 0.7 V less than the input signal, the loss owing to the cut in the voltage of the diode concerned.
10. Depending upon the design implemented, two different types of rectifiers result:
    a. Centre-tapped transformer rectifiers that use a bulky centre tapped transformer with three terminals and two diodes.
    b. Bridge-rectifiers use a lightweight, simple transformer with four diodes in the circuit.
11. Advantages of a bridge rectifier:
    a. A transformer without a centre tap can be used in a bridge circuit.
    b. Since both the primary and the secondary currents in the transformer are sinusoidal, the bridge circuit requires a smaller transformer than that needed by a full-wave rectifier giving the same dc output voltage.
    c. The peak inverse voltage rating of a diode in a bridge rectifier is half of that of a full-wave circuit yielding the same dc output voltage. The bridge circuit is therefore suitable for high voltage applications.
    d. Crystal diodes are usually used to construct the bridge rectifier and the assembly of four such diodes is available in the market in a block form. The bridge circuit is therefore more compact and cheaper.
12. Disadvantages of the bridge rectifier:
    a. A full-wave rectifier uses two diodes whereas a bridge rectifier uses four diodes.
    b. Since the current flows through two diodes in a series in a bridge circuit, a large power is dissipated in the diodes. Hence, the bridge is not efficient for the low voltages.
    c. Vacuum diodes with directly heated cathodes are not convenient for a bridge circuits because the cathodes for the diodes do not have the same potential.

    Hence, they cannot be connected in parallel across a transformer secondary meant for a filament supply. Bridge circuits generally employ Se and copper oxide rectifiers.
13. Comparison between half- and full-wave rectifiers:
    a. In a half-wave rectifier, a single diode exists and the load current flows through it for only the positive half-cycle. On the other hand, in a full-wave rectifier, the current flows throughout the cycles of the input signals.
    b. In a full-wave rectifier, we usually require a centre-tapped transformer. For a half-wave rectifier, only a simple transformer is required.
    c. The peak inverse voltage in a half-wave rectifier is the maximum voltage across the transformer secondary. Whereas in the case of full-wave rectifier, the PIV for each diode is two times the maximum voltage between the centre tap and at the either end of the transformer secondary.
    d. In the case of a half-wave rectifier, the frequency of the load current is the same as that of the input signal and it is twice the frequency of the input supply for a full-wave rectifier.

e. The dc load current and conversion efficiency for a full-wave rectifier is twice that of a half-wave rectifier. Also, we see the ripple factor of the full-wave rectifier is less than that of the half-wave circuit. This indicates that the performance of the full-wave rectifier is better than the half-wave rectifier.
f. In a full-wave rectifier two diode currents flow through the two halves of the centre-tapped transformer secondary in opposite directions, so that there is no direct current magnetization of the core. The transformer losses being smaller, a smaller transformer can be used for a full-wave rectifier. This is an important advantage of the half-wave rectifier over a full-wave rectifier.

14. Filters form an integral part of a rectifier for obtaining a regulated, steady dc output at the end of a rectifier.
15. Clipper is a type of diode circuit where the diode network is able to clip off a portion of the input signal without disturbing the remaining portion of the input signal.
16. A clamper circuit clamps a signal to a different dc level. The network must have a capacitor, a diode, a resistive network and should also employ an independent voltage source which introduces an additional voltage shift.
17. Comparators are circuits that employ diode for comparisons between two different input voltages. The basic principle on which the comparator works is the switching of the diodes i.e., the action corresponding to the portion when the diode conducts and when it does not.

IMPORTANT FORMULAE

1. For a simple diode circuit with a diode connected in series with a resistor and a voltage source, the equation governing the behaviour of the circuit is given by:

$$V_\alpha = V - iR_L$$

2. Average value of load current is given by:

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_L d(\omega t)$$

3. Ripple factor is given by:

$$\gamma = \frac{(I_{rms}^2 - I_{dc}^2)^{1/2}}{I} = \frac{(V_{rms}^2 - V_{dc}^2)^{1/2}}{V_{dc}}$$

4. Rectification efficiency is given by:

$$\eta = \frac{P_{dc}}{P_i} \times 100\% = \left(\frac{I_{dc}^2}{I_{rms}^2}\right)\frac{1}{1+\frac{R_f}{R_L}} \times 100\%$$

5. For a half-wave rectifier:

$$I_{dc} = \frac{I_m}{\pi}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$\gamma = \left[\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1\right]^{1/2} = 1.21$$

$$\eta = \frac{40.6}{1 + R_f/R_L}\%$$

6. For a full-wave rectifier:

$$I_{dc} = \frac{2I_m}{\pi}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$\gamma = 0.482$$

$$\eta = \frac{81.2}{1 + R_f/R_L}\%$$

7. Percentage voltage regulation:

$$\frac{V_{NL} - V_{RL}}{V_{RL}} \times 100\%$$

OBJECTIVE QUESTIONS

1. A More Zener diode is based on the principle of:
    a. Thermionic emission
    b. Tunneling of charge carriers across the junction
    c. Diffusion of charge carriers across the junction
    d. None of the above
2. Silicon diode is less suited for low voltage rectifier operation because:
    a. Its breakdown voltage is high
    b. Its reverse saturation current is low
    c. Its cut-in voltage is high
    d. None of the above
3. Silicon is not suitable for fabrication of light-emitting diodes because it is:
    a. An indirect band gap semiconductor
    b. A direct band gap semiconductor
    c. A wide band gap semiconductor
    d. None of the above
4. For an abrupt junction Varactor diode, the dependence of the device capacitance (*C*), an applied reverse-bias (*V*) is given by:
    a. *C* ∝ *Vl*/3
    b. *C* ∝ *VI*/2
    c. *C* ∝ *V-I*/3
    d. None of the above
5. A Zener diode:
    a. Has a high forward voltage rating
    b. Has a sharp breakdown at low reverse voltage
    c. Is useful as an amplifier
    d. None of the above
6. Which of these is a best description of a Zener diode?
    a. It operates in the reverse region
    b. It is a constant voltage device

    c. It is a constant current device
    d. None of the above
7. When two Zener diodes each of 10 V and 15 V are connected in series, then the overall voltage between them when they are in conduction is
    a. 10 V
    b. 25 V
    c. 15 V
    d. Zero
8. In a standard regulator circuit that uses Zener diode 10 V, the input voltage varies from 25 to 40 V, load current varies from 10 to 20 mA, and the minimum Zener current is 5 mA, the value of the series resistance in ohms will be:
    a. 1500
    b. 1200
    c. 600
    d. None of the above
9. The LED is usually made of materials like:
    a. GaAs
    b. C and Si
    c. GeAs
    d. None of the above
10. Varactor diodes are used in FM receivers to obtain:
    a. Automatic frequency control
    b. Automatic gain control
    c. Automatic volume control
    d. None of the above
11. No-load voltage of power supply is 100 V and full-load voltage is 80 V, the percentage of regulation is:
    a. 0
    b. 25
    c. 15.75
    d. None of the above
12. Zener diodes are used as:
    a. Reference voltage elements
    b. Reference current elements
    c. Reference resistance
13. Zener diodes are:
    a. Specially doped *p—n* junction
    b. Normally doped *p—n* junction
    c. Lightly doped *p—n* junction
    d. None of the above
14. Silicon diode is less suited for low voltage rectifier operation because:
    a. It can withstand high temperatures
    b. Its reverse saturation current is low
    c. Its breakdown voltage is high
    d. None of the above
15. Silicon is not suitable for fabrication of light emitting diodes because it is:
    a. An indirect band gap semiconductor
    b. A direct band gap semiconductor
    c. A wide band gap semiconductor
    d. None of the above
16. In an abrupt junction Varactor diode, the dependence of the device capacitance (C) and applied reverse-bias (V) is given by:
    a. $C \propto VI/3$
    b. $C \propto VI/2$
    c. $C \propto V\text{-}I/3$
    d. None of the above
17. A general propose diode is more likely to suffer an avalanche breakdown rather than a Zener breakdown because:
    a. It is lightly doped

b. It is heavily doped
c. It has weak covalent bonds
d. None of the above

18. A Zener diode:
    a. Has a high forward voltage rating
    b. Is useful as an amplifier
    c. Has a sharp breakdown at low reverse voltage
    d. None of the above.
19. If the junction temperature of LED is increased the radiant output power:
    a. Decreases
    b. Increases
    c. Remains the same
    d. None of the above
20. The Zener effect is valid approximately:
    a. Below 5 V
    b. Above 5 V
    c. Equal to 5 V
    d. None of these
21. Each diode of full-wave centre-tapped rectifier conducts for:
    a. 360°
    b. 270°
    c. 90°
    d. 180°
22. When a capacitor filter is used, the PIV for a half-wave rectifier:
    a. Increases
    b. Decreases
    c. Remains unaltered
    d. None of the above
23. The transfer characteristics of a diode relates to:
    a. The diode current and the input voltage
    b. The diode current and the output voltage
    c. The output voltage and the input voltage
    d. None of the above
24. The clipping action of a diode requires that its forward resistance:
    a. Be zero
    b. Have a finite value
    c. Be infinite
    d. None of the above
25. For a low voltage rectification:
    a. Two diode full-wave rectifier is suitable
    b. Both bridge and full-wave rectifier are suitable
    c. Bridge rectifier is suitable
    d. None of the above
26. If V_m is the peak value of an applied voltage in a half-wave rectifier with a large capacitor across the load, then PIV is:
    a. V_m
    b. $V_m/2$
    c. $2V_m$
    d. None of the above
27. The induction filter is mostly used for rectifiers with:
    a. Half-wave rectifiers
    b. Light loads
    c. High loads
    d. None of the above
28. The most significant component of ripple voltage in a half-wave rectifier is contained in:

a. Fundamental frequency
b. Second harmonic
c. DC component
d. None of the above

29. The disadvantages of capacitor input *LC* filter are:
    a. High cost, more weight and external field produced by a series inductor
    b. High cost, less weight
    c. Low cost, more weight
    d. None of the above
30. Larger the value of the capacitor filter:
    a. Smaller the dc voltage across the load
    b. Longer the time that current pulse flows through the diode
    c. Larger the peak current in the rectifying diode
    d. None of the above
31. Which rectifier requires four diodes?
    a. Half-wave voltage doublers
    b. Full-wave voltage doublers
    c. Full-wave bridge circuit
    d. None of the above

REVIEW QUESTIONS

1. What is the dynamic characteristic of a diode? How can you obtain it from the dynamic characteristics?
2. What is a load line in connection with a diode connected to a supply voltage through a series load resistance? How does the load line change with the change of the supply voltage, the load resistance, and the type of diode?
3. What do you mean by rectification? How can you study the performance of the diode rectifier with the help of its dynamic characteristic?
4. Draw the circuit diagram of a half-wave rectifier and explain the operation of the circuit.
5. Draw the circuit of a full-wave rectifier and explain the operation of the circuit.
6. Distinguish between the following:
    a. Full-wave rectifier and half-wave rectifier
    b. Full-wave rectifier and bridge rectifier.
7. Draw the waveforms of the diode current and the load voltage for a sinusoidal input voltage applied to
    a. Half-wave rectifier
    b. Full-wave rectifier

    Is it necessary for the two diodes of the rectifier to be identical?
8. Draw the circuit diagram of a full-wave rectifier using junction diodes and explain clearly its action.
9. Discuss how a semiconductor diode can be used as a rectifier. Do you prefer a valve diode or a junction diode for rectification?
10. Explain the phenomena of a bridge rectifier with the help of a circuit diagram. Mention its advantages and disadvantages when compared with a full-wave rectifier with a centre-tapped transformer.
11. Explain the term peak inverse voltage in connection with a diode rectifier. Is it different for half and full-wave rectifiers with a centre tap? Does it change if we use a capacitor filter?
12. Define the following terms:
    a. dc load current
    b. Ripple factor
    c. Conversion efficiency
13. For a half-wave rectifier, calculate
    a. The dc load current
    b. The peak load current
    c. The rms load current
    d. The rms value of ripple current
    e. The ripple factor
    f. The dc power output

g. The efficiency of the rectifier

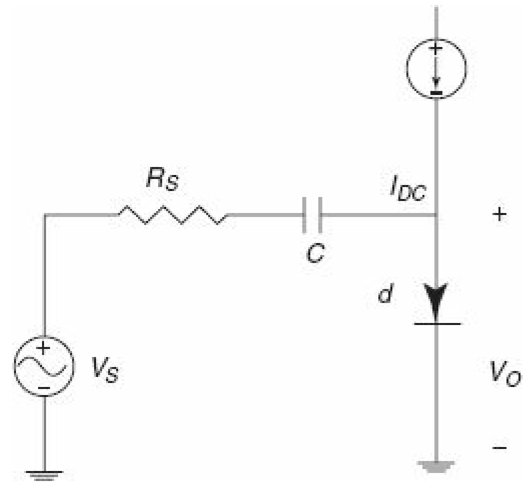
14. What do you mean by the regulation characteristics of a rectifier? Figure out the main quantity determining the regulation characteristics. Define percentage voltage regulation.
15. Explain the significance of percentage voltage regulation. Find the percentage voltage regulation for both the half and full-wave rectifiers.
16. Why is a filter used in a rectifier? Enumerate the different types of filters used at the output of the rectifiers.
17. Explain how the dc voltage of a full-wave rectifier is improved when a capacitor filter is used. Draw waveforms of the load voltage and the diode current.
18. Derive expressions of the percentage regulation for a half-wave, full-wave and a bridge rectifier circuit each employing the same capacitor and the same load resistance.
19. What is a voltage multiplier? Draw the circuit diagram of a half-wave voltage doubler and explain its operation. What is the advantage of the circuit?
20. What is the function of the clipping circuit? Draw the circuit diagram of a diode clipper that limits the positive peak of the input voltage. Explain how the circuit works.
21. Draw the neat diagram of a full-wave voltage doubler and explain its operation. How can you construct a voltage tripler?
22. What is the transfer characteristic of a diode? What is the utility of this characteristic?
23. Explain the working of a diode clipper that limits the lower portion of the input voltage.
24. What is a double diode clipper? Draw the circuit diagram of a double diode clipper and explain.
25. What do you understand by a clamping circuit? Draw the circuit diagram of a dc restorer. How does the circuit function?

PRACTICE PROBLEMS

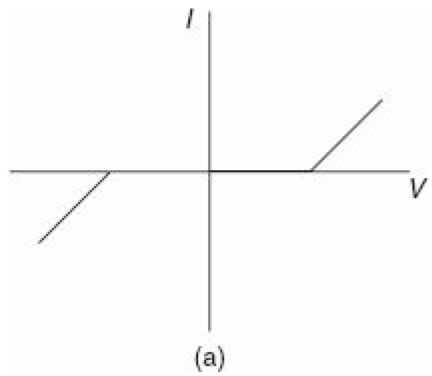
1. A 1 mA diode (i.e., one that has $v_D = 0.7$ V at $I_D = 1$ mA) is connected in series with a 200 Ω resistor to a 1 V supply. Provide a rough estimate of the diode current.
   If the diode is characterized by $n = 2$, estimate the diode current closely using iterative analysis.
2. Assuming the availability of the diodes for which $v_D = 0.7$ V and $I_D = 1$-mA and $n = 1$, design a circuit that utilizes four diodes in series with a resistor R connected to ac 15 V power supply. The voltage across the string of diodes is to be 3.0 V.
3. Find the parameters of a piecewise-linear model of a diode, for which $v_D = 0.7$ V at $I_D = 1$-mA and $n = 2$. The model is to fit exactly at 1-mA and 10 mA. Calculate the error—in millivolts—in predicting v_D, using the linear piecewise-linear model at I_D at 0.5, 5 and 14 mA.
4. A junction diode is operated in a circuit in which it is supplied with a constant current I. What is the effect on the forward voltage of the diode if an identical diode is connected in parallel? Assume $n = 1$.
5. A diode measured at two operating currents, 0.2 mA and 10 mA, is found to have corresponding voltages 0.650 and 0.750. Find the values of n and I_S.
6. A diode for which the forward voltage drop is 0.7 V at 1.0 mA, and for which $n = 1$, is operated at 0.5 V. What is the value of the current?
7. When a 10-A current is applied to a particular diode it is found that the junction voltage immediately becomes 700 mV. However, as the power being dissipated in the diode raises its temperature, it is found that the voltage decreases and eventually reaches 600 mV. What is the apparent rise in junction temperature? What is the power dissipated in the diode in its final state? What is the temperature rise per watt of power dissipation?
8. The small-signal model is said to be valid for voltage variations of about 10 mV. To what percent current change does this correspond for:
   i. $n = 1$
   ii. $n = 2$
9. What is the incremental resistance of ten 1 mA diodes connected in parallel and fed with a dc current 10 mA. Let $n = 2$.
10. In the circuit given, I is the dc current and v_S is the sinusoidal signal. Capacitor C is very large; its function is to couple the signal to the diode but block the dc current from the source. Use the diode small signal model to show that the signal component of the output voltage is:

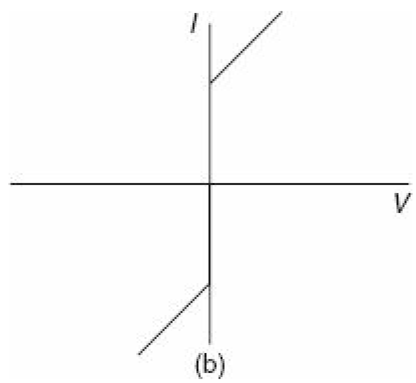
$$v_o = v_S \frac{nV_T}{nV_T + IR_S}$$

If $v_S = 10$ mV, find v_o for $I = 1$ mA, 0.1 mA and 1 μA. Let $R_S = 1$ kΩ and $n = 2$. At what value of I does v_o become one half of v_S?

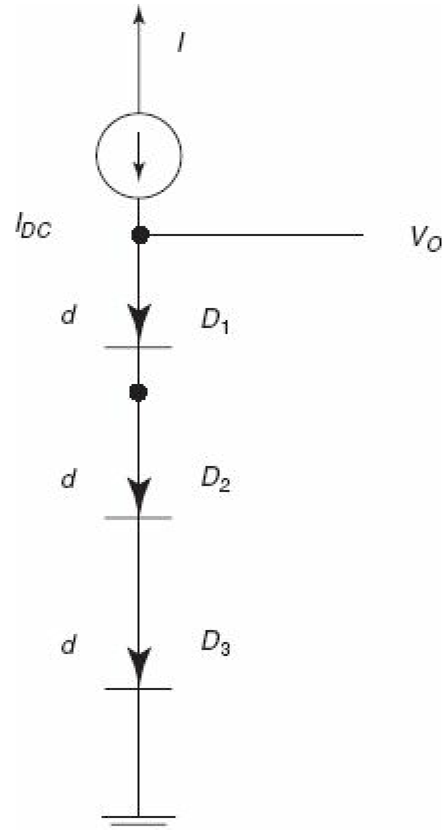


11. Construct circuits which exhibit terminal characteristics as shown in parts (a) and (b) of the given figure.

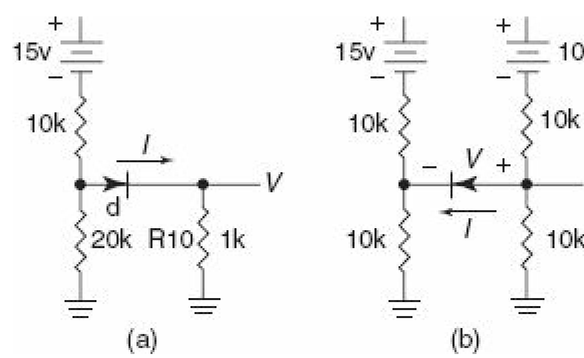




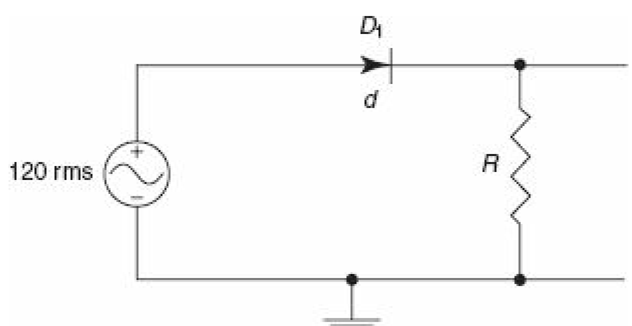
12. At what forward voltage does a diode for which $n = 2$ conduct a current equal to $1000I_S$? In terms of I_S, what current flows in the same diode when its forward voltage is 0.7 V?
13. A diode modeled by the 0.1 V/decade approximately operates in a series circuit with R and V. A designer, considering using a constant voltage model, is uncertain whether to use 0.7 V or 0.5 V for V_D. For what value of V is the difference only 1%? For $V = 2$ V and $R = 1$ K, what two currents would result from the use of the two values of V_D?
14. The circuit in the given figure utilizes three identical diodes having $n = 1$ and $I_S = 10^{-14}$ A. Find the value of the current I required to obtain an output voltage $V_O = 2$ V. If a current of 1 mA is drawn away from the output terminal by a load, what is the change in output voltage?



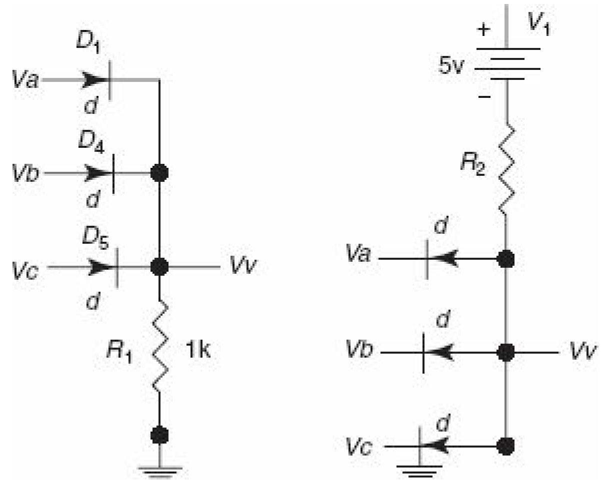
15. Assuming that the diodes in the circuits of the given figure are ideal, utilize Thevenin's theorem to simplify the circuits, and thus, find the values of the labeled currents and voltages.



16. For the rectifier circuit as given, let the input sine wave have 120 V rms value, and assume the diode to be ideal. Select a suitable value for R so that the peak diode current does not exceed 0.1 A. What is the greatest reverse voltage that will appear across the diode?



17. For the logic gate as shown in the following figure, assume ideal diodes and input voltage levels of 0 and + 5 V. Find a suitable value for R so that the current required from each of the input signal sources does not exceed 0.2 mA.



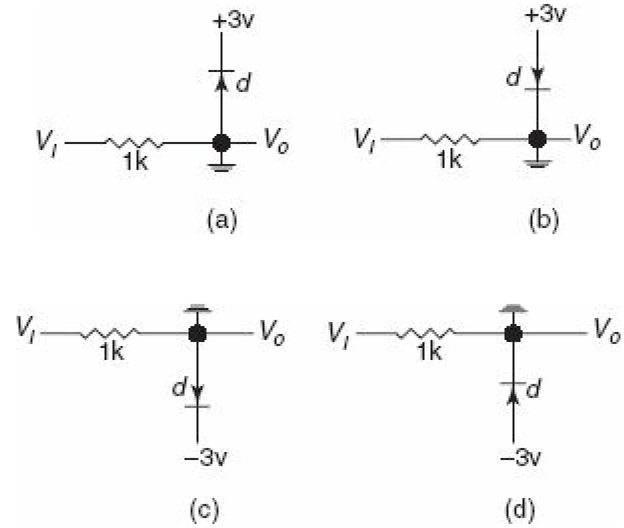
18. Consider the voltage regulator circuit as shown in the following figure, under the condition that a load current I_L is drawn from the output terminal. Denote the output voltage across the diode by V_o. If the value of I_L is sufficiency small so that the corresponding change in the regulator output voltage ΔV_o is small enough to justify using the diode small signal model, show that:

$$\pm\frac{\Delta V_0}{I_L} = -(r_d \,//\, R)$$

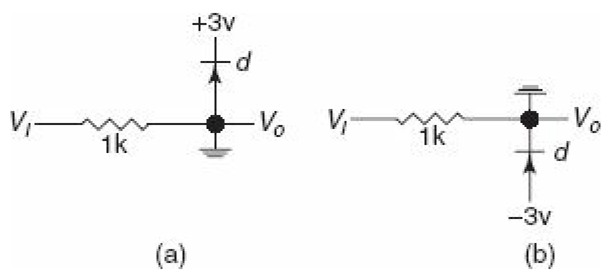
(Note: This quantity is known as the load regulation and is usually expressed in mV/mA.)
19. In the above problem, if the value of R is selected such that at no load the voltage across the diode is 0.7 V and the diode current is I_D, show that the expression derived becomes:

$$\frac{\Delta V_0}{I_L} = \frac{nV_T}{I_D}\frac{V^{+} - 0.7}{V^{+} - 0.7 + nV_T}$$

Select the lowest possible value for I_D that results in a load regulation <= 5 mV/mA. Assume n = 2. If V^+ is nominally 10 V, what value of R is required?
20. With reference to the Problem 18 and 19, generalize the expression derived in Problem 19 for the case of M diodes connected in series and R adjusted to obtain V_d = 0.7 mV, at no load.
21. A voltage regulator consisting of a 6.8 V Zener diode, a 100 ohm resistor, and intended for operation with a 9 V supply is accidentally connected to 15 V supply instead. Assuming the r_Z is very small; calculate the expected values of Zener current and the power dissipated in both the Zener diode and the resistor, for both the normal as well as aberrant situations. Also compare the ratios.
22. A shunt regulator utilizing a Zener with an incremental resistance of 6 ohms is fed through an 82 ohms resistor. If the raw supply changes by 1.4 V, what is the corresponding change in the regulated output voltage?
23. A 9.1 V Zener diode exhibits its nominal voltage at a current of 28 mA. At this current the incremental resistance is specified as 5 ohms. Find V_{ZO} of the Zener model. Find the Zener voltage at a current of 10 mA and at 100 mA.
24. Consider a half-wave peak rectifier fed with a voltage v_S having a triangular waveform with 20 V peak to peak amplitude, zero average and 1 Khz frequency. Assume that the diode has a 0.7 V drop when conducting. Let the load resistance R = 100 Ω and the filter capacitor C = 100 μF Find the average dc output voltage, the time interval during which the diode conducts—the average diode current during conduction, and the maximum diode current.
25. Sketch the transfer characteristics V_O, V_S, V_I for the limiter circuits as shown in the following figures. All diodes start conducting at a forward voltage drop of 0.5 V and display voltage drops of 0.7 V when fully conducting.



26. In the figure provided, (a) and (b) are connected as follows: The two input terminals are tied together, and the output terminals are tied together. Sketch the transfer characteristic of the resulting circuit, assuming that the cut in voltage of the diodes is 0.5 V and their voltage drop when fully conducting is 0.7 V.



27. Plot the transfer characteristics of the circuit as shown in the following figure by evaluating V_I corresponding to V_O = 0.5 V, 0.6 V, 0.7 V, 0.8 V, 0 V, −0.5 V, −0.6 V, −0.8 V Assume that the diodes are 1 mA units having a 0.1 V/decade logarithmic characteristi(c) Characterize the circuit as a hard or a soft limiter. What is the vale of *K?* Estimate L_+ and L.
28. A clamped capacitor using an ideal diode is supplied with a sine wave of 10 − V rms. What is the average dc value of the resulting output?
29. Design limiter circuits using only diodes and 10 k Ω resistors to provide an output signal limited to the range:
    a. −0.7 V and above
    b. −2.1 V and above
    c. ± 4.1 V

    Assume that each diode has a 0.7 V drop when conducting.

SUGGESTED READINGS

1. Millman, J. and H. Tau(b) 1965. *Pulse, Digital, and Switching Waveforms*. New York: McGraw-Hill Book Company.
2. Boylsted, R. and L. Nashelsky. 2007. *Electronic Devices and Circuit Theory.* New Delhi: Pearson Education.