Semiconductor Diode and Its Applications

Objectives

After studying this unit you should be able to:

- Explain how barrier potential is set up in a *p-n* junction diode.
- Explain the meaning of Zener breakdown, avalanche breakdown, static resistance and dynamic resistance.
- Explain the conduction property of forward-biased and reverse-biased diodes.
- Explain the difference between germanium diode and silicon diode.
- Calculate the static and dynamic resistance of a diode from its VI characteristics.
- Explain the need of rectifier, clipper and clamper in electronics.
- Explain the working of half-wave rectifier.
- Explain the working of full-wave rectifier.
- Explain the working of Zener diode with its applications.

2.1 *P-N* JUNCTION

A ***p-n* junction** is formed by joining *p*-type and *n*-type semiconductors together in very close contact. The term *junction* refers to the boundary interface where the two regions of the semiconductor meet. If they were constructed of two separate pieces this would introduce a grain boundary, so *p-n* junctions are created in a single crystal of semiconductor by doping, for example, by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant).

p-n junctions are elementary "building blocks" of almost all semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place. For example, a common charge. The regions nearby the *p-n* interfaces lose their neutrality and become charged, forming the space charge region or depletion layer.

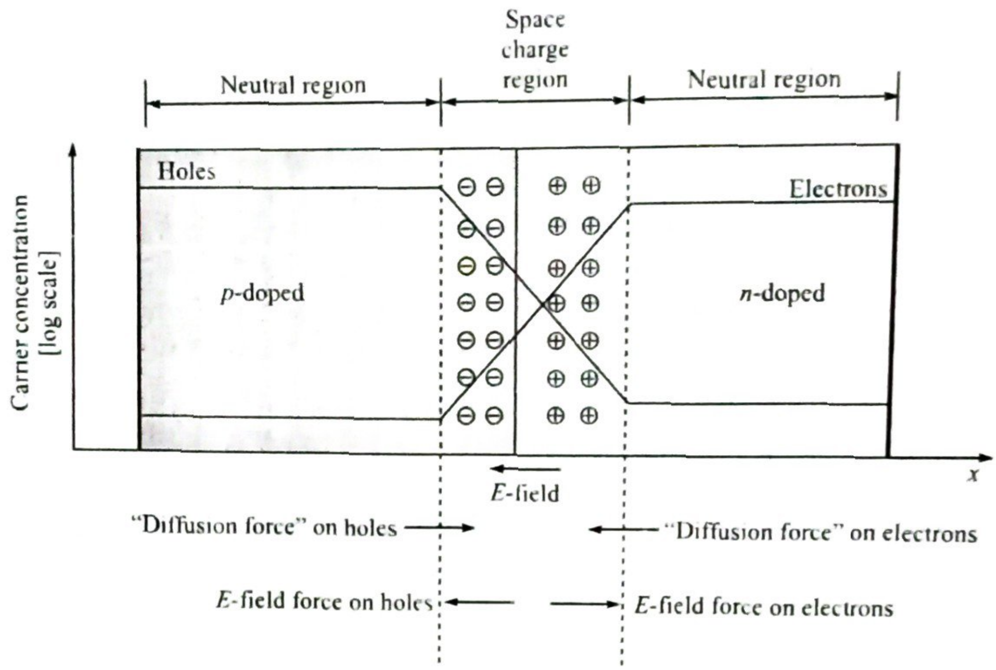


Figure 2.1 A *p-n* junction in thermal equilibrium with zero bias voltage applied

The electric field created by the space charge region opposes the diffusion process for both electrons and holes. There are two concurrent phenomena: the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion. The carrier concentration profile at equilibrium is shown in Fig. 2.1.

The space charge region is a zone with a net charge provided by the fixed ions (donors or acceptors) that have been left *uncovered* by majority carrier diffusion. When equilibrium is reached, the charge density is approximated by the displayed step function. In fact, the region is completely depleted of majority carriers (leaving a charge density equal to the net doping level), and the edge between the space charge region and the neutral region is quite sharp. The space charge region has the same charge on both sides of the *p-n* interfaces, thus it extends farther on the less doped side.

2.3 FORWARD BIASING AND REVERSE BIASING

Forward Biasing

When external voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow is called forward biasing. To apply forward bias, connect +ve terminal of the battery to *p*-type and –ve terminal to *n*-type as shown in Fig. 2.2. The applied forward potential establishes the electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction as shown in Fig. 2.2. Since the potential barrier voltage is very small, a small forward voltage is sufficient to completely eliminate the barrier. Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called *forward current*.

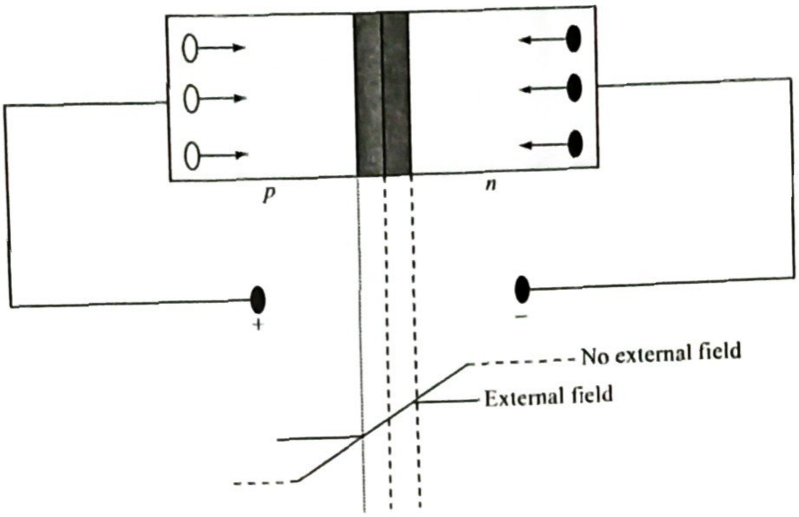


Figure 2.2 Forward biasing of *p-n* junction

Reverse Biasing

When the external voltage applied to the junction is in such a direction the potential barrier is increased it is called reverse biasing. To apply reverse bias, connect –ve terminal of the battery to *p*-type and +ve terminal to *n*-type as shown in Fig. 2.3.

The applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant field at the junction is strengthened and the barrier height is increased as shown in Fig. 2.3. The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a high resistance path is established for the entire circuit and hence current does not flow.

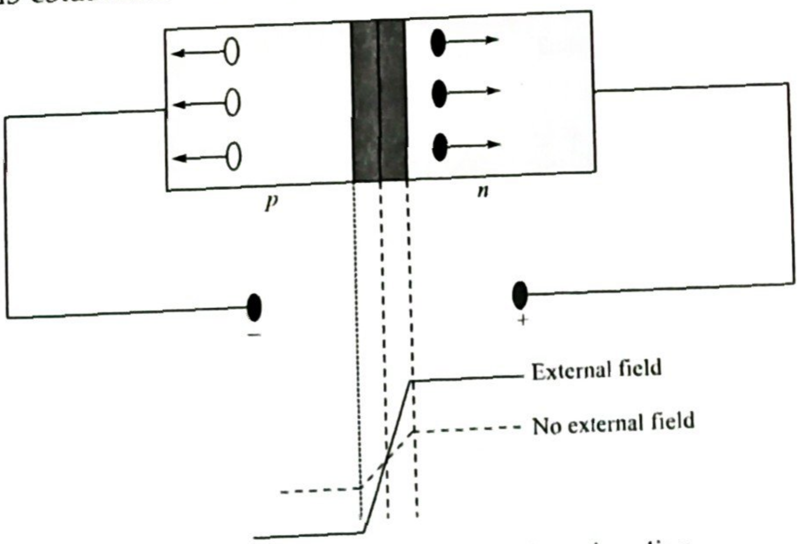


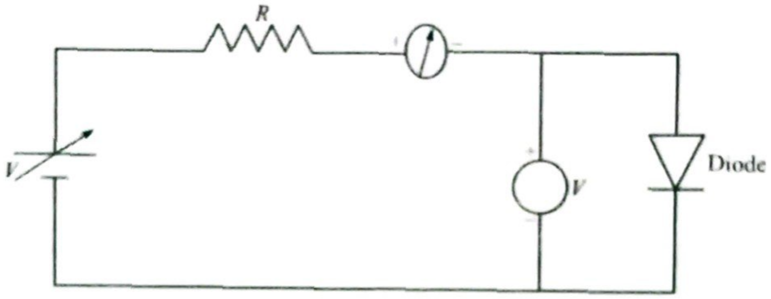
Figure 2.3 Reverse biasing of *p-n* junction

2.4 VOLT-AMPERE (*V-I*) CHARACTERISTICS OF *P-N* JUNCTION DIODE

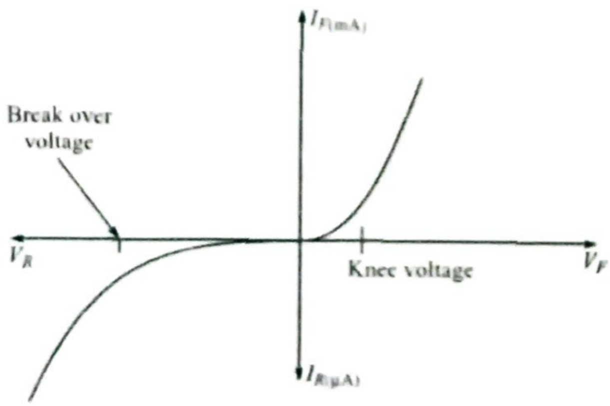
The *V-I* characteristics of a semiconductor diode can be obtained with the help of the circuit shown in Fig. 2.4 (i). The supply voltage *V* is a regulated power supply, the diode is forward biased in the circuit shown. The resistor *R* is a current limiting resistor. The voltage across the diode is measured with the help of voltmeter and the current is recorded using an ammeter.

By varying the supply voltage different sets of voltage and currents are obtained. By plotting these values on a graph, the forward characteristics can be obtained. It can be noted from the graph the current remains zero till the diode voltage attains the barrier potential.

For silicon diode, the barrier potential is 0.7 V and for germanium diode, it is 0.3 V. The barrier potential is also called *knee voltage* or *cut-in voltage*. The reverse characteristics can be obtained by reverse biasing the diode. It can be noted that at a particular reverse voltage, the reverse current increases rapidly. This voltage is called *breakdown voltage*.



(i)



(ii)

Figure 2.4 *V-I* characteristics of *p-n* junction diode.
(i) Circuit diagram
(ii) Characteristics

2.5 DIODE CURRENT EQUATION

The current in a diode is given by the diode current equation

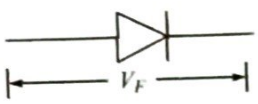
$$I = I_o(e^{V/\eta V_T} - 1) \tag{2.1}$$

where, I = Diode current
I_o = Reverse saturation current
V = Diode voltage
η = Semiconductor constant
= 1 for Ge
= 2 for Si.
V_T = Voltage equivalent of temperature = $T/11,600$ (temperature T is in kelvin)

Note: If the temperature is given in °C then it can be converted to kelvin with the help of the following relation, °C + 273 = K

2.6 DIODE EQUIVALENT CIRCUIT

It is generally profitable to replace a device or system by its equivalent circuit. Once the device is replaced by its equivalent circuit, the resulting network can be solved by traditional circuit analysis technique.



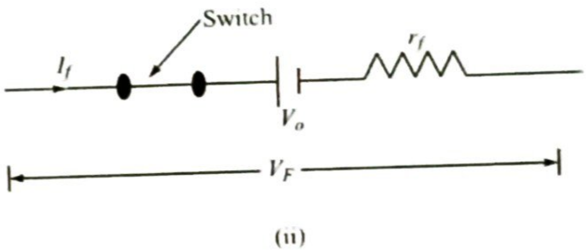


Figure 2.5 Diode equivalent circuit. (i) Symbol (ii) equivalent circuit

The forward current I_f flowing through the diode causes a voltage drop in its internal resistance, r_f. Therefore, the forward voltage V_F applied across the actual diode has to overcome

1. potential barrier V_o
2. internal drop $I_f r_f$

$$V_f = V_o + I_f r_f \tag{2.2}$$

For silicon diode V_o = 0.7 V whereas for germanium diode V_o = 0.3 V.
For ideal diode r_f = 0.

Basic Definitions

Knee Voltage or Cut-in Voltage

It is the forward voltage at which the diode starts conducting.

Breakdown Voltage

It is the reverse voltage at which the diode (*p-n* junction) breaks down with a sudden rise in reverse current.

Peak-inverse Voltage (PIV)

It is the maximum reverse voltage that can be applied to a *p-n* junction without causing damage to the junction. If the reverse voltage across the junction exceeds its peak-inverse voltage, then the junction exceeds its peak-inverse voltage, and the junction gets destroyed because of excessive heat. In rectification, care should be taken that reverse voltage across the diode during –ve half cycle of ac doesn't exceed the peak-inverse voltage of the diode.

Maximum Forward Current

It is the maximum instantaneous forward current that a *p-n* junction can conduct without damaging the junction. If the forward current is more than the specified rating then the junction gets destroyed due to overheating.

Maximum Power Rating

It is the maximum power that can be dissipated at the junction without damaging it. The power dissipated across the junction is equal to the product of junction current and the voltage across the junction.

2.7 VOLT-AMPERE (*V-I*) CHARACTERISTICS OF IDEAL DIODE

Diode permits only unidirectional conduction. It conducts well in forward direction and poorly in reverse direction. It would have been ideal if a diode acted as a perfect conductor (with zero voltage across it) when forward-biased, and as a perfect insulator (with no current through it) when reverse-biased. The *V-I* characteristics of such an ideal diode would be as shown in Fig. 2.6. An ideal diode acts like an automatic switch. When the current tries to flow in the forward direction, the switch is closed. On the other hand, when the current tries to flow in the reverse direction, the switch is open.

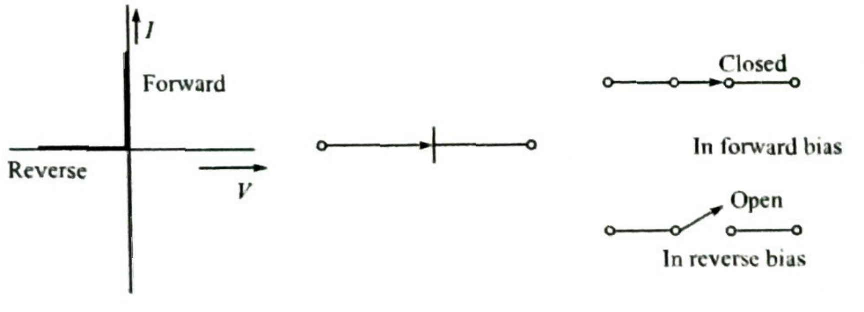


Figure 2.6 Ideal diode characteristics and switch analogy

2.8 STATIC AND DYNAMIC RESISTANCE OF A DIODE

DC or Static Resistance

When diode is forward biased, it offers a definite resistance in the circuit. This resistance is known as dc resistance or static resistance (R_F). It is simply the ratio of the dc voltage (V_D) across the diode to the dc current (I_D) flowing through it as shown in Fig. 2.7.

$$R_F = \frac{V_D}{I_D} \tag{2.3}$$

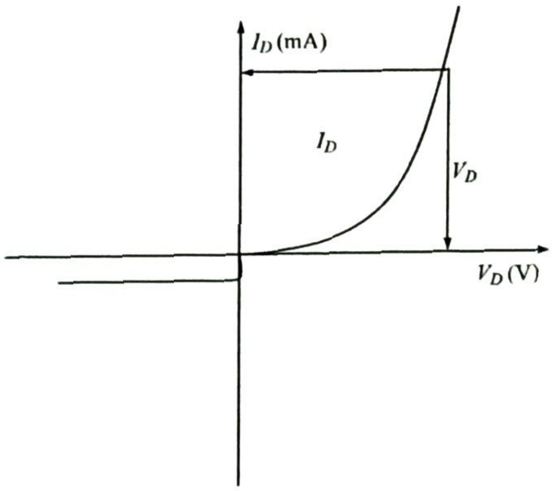


Figure 2.7 Determining the dc resistance of a diode at a particular operating point

PROBLEM 2.1: Determine the dc resistance level for the diode of Fig. 2.8 at

(a) $I_D = 2$ mA
(b) $I_D = 20$ mA

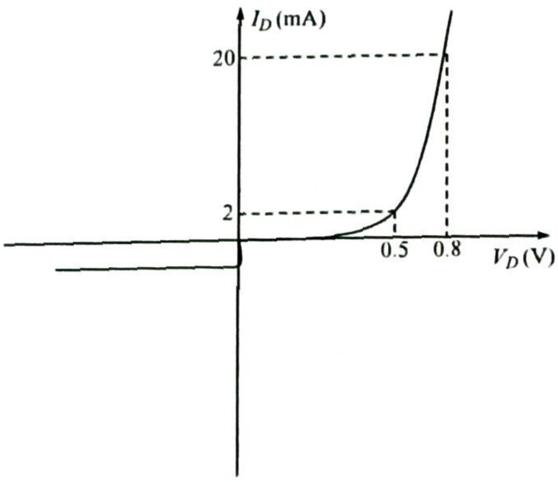


Figure 2.8 Problem 2.1

Solution:

(a) At $I_D = 2$ mA, $V_D = 0.5$ volt (from the curve)

$$R_F = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = 250\ \Omega$$

(b) At $I_D = 20$ mA, $V_D = 0.8$ volt (from the curve)

$$R_F = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = 40\ \Omega$$

AC or Dynamic Resistance

The ac or dynamic resistance of a diode, at a particular dc voltage, is equal to the reciprocal of the slope of the characteristics at that point, as shown in Fig. 2.9.

$$r_f = \frac{\Delta V_D}{\Delta I_D} \tag{2.4}$$

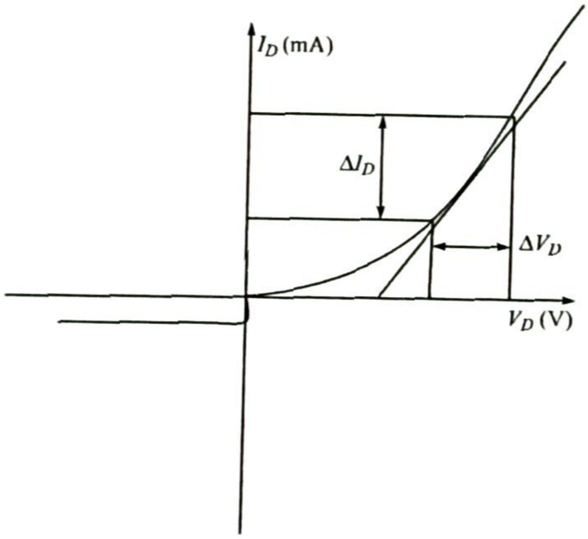
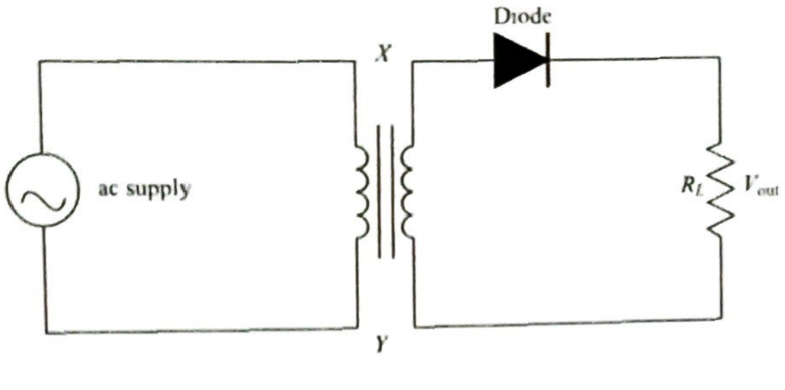


Figure 2.9 Determining the ac resistance of a diode at a particular operating point

2.9 HALF-WAVE RECTIFIER

The circuit diagram of a half-wave rectifier is shown in Fig. 2.10 along with the I/P and O/P waveforms.



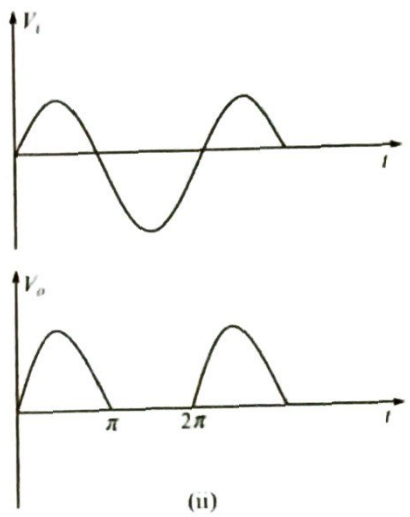


Figure 2.10 Half-wave rectifier (i) Circuit diagram (ii) I/P and O/P waveforms

The transformer is employed in order to step-down the supply voltage and also to prevent from shocks. The diode is used to rectify the ac signal while the pulsating dc is taken across the load resistor R_L. During the +ve half-cycle, the end X of the secondary is +ve and end Y is −ve. Thus, forward biasing the diode. As the diode is forward biased, the current flows through the load R_L and a voltage is developed across it.

During the −ve half-cycle the end Y is +ve and end X is −ve thus, reverse biasing the diode. As the diode is reverse biased there is no flow of current through R_L thereby the output voltage is zero.

Efficiency of a Rectifier

The ratio of dc power to the applied input ac power is known as rectifier efficiency.

$$\text{Rectifier efficiency } \eta = \frac{\text{dc power output}}{\text{input ac power}}$$

Let $V = V_m \sin\theta$ be the voltage across the secondary winding

$$r_f = \text{diode resistance}$$
$$R_L = \text{load resistance}$$

dc Power

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i \cdot d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin\theta}{r_L + R_L} d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}\int_0^{\pi} \sin\theta \, d\theta$$

$$= \frac{2V_m}{2\pi(r_f + R_L)} = \frac{I_m}{\pi}$$

dc power $$P_{dc} = I_{dc}^2 \times R_L$$

$$= \left(\frac{I_m}{\pi}\right)^2 \times R_L \tag{2.5}$$

ac Power Input

The ac power input is given by $P_{ac} = I_{rms}^2 (r_f + R_L)$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta}$$

Squaring both sides, we get

$$I_{rms}^2 = \frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta$$

But $i = I_m \sin\theta$

$I_{rms}^2 = \frac{1}{2\pi}\int_0^{\pi} (I_m \sin\theta)^2 d\theta$ (current flows through diode only for duration 0 to Π)

$$I_{rms}^2 = \frac{I_m^2}{4}$$

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

$$\therefore \quad P_{ac} = \left(\frac{I_m}{2}\right)^2 (r_f + R_L) \tag{2.6}$$

$$\therefore \quad \eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{I_m}{\pi}\right)^2}{\left(\frac{I_m}{2}\right)^2} \times \frac{R_L}{(r_f + R_L)}$$

$$\eta = \frac{0.406}{1 + \frac{r_f}{R_L}} \tag{2.7}$$

The efficiency is maximum if r_f is negligible as compared to R_L. Therefore, maximum rectifier efficiency = 40.6%

2.10 FULL-WAVE RECTIFIER

Full-wave rectifiers are of two types:

1. Centre tapped full-wave rectifier
2. Bridge rectifier

2.10.1 Centre Tapped Full-wave Rectifier

The circuit diagram of a centre tapped full-wave rectifier is shown in Fig. 2.11. It employs two diodes and a centre tap transformer. The ac signal to be rectified is applied to the primary of the transformer and the dc output is taken across the load, R_L.

During the +ve half-cycle end X is +ve and end Y is –ve. This makes diode D_1 forward biased and thus a current i_1 flows through it and load resistor R_L. Diode D_2 is reverse biased and the current i_2 is zero. During the –ve half-cycle end Y is +ve and end X is –ve. Now diode D_2 is forward biased and thus a current i_2 flows through it and load resistor R_L. Diode D_1 is reversed and the current i_1 = 0.

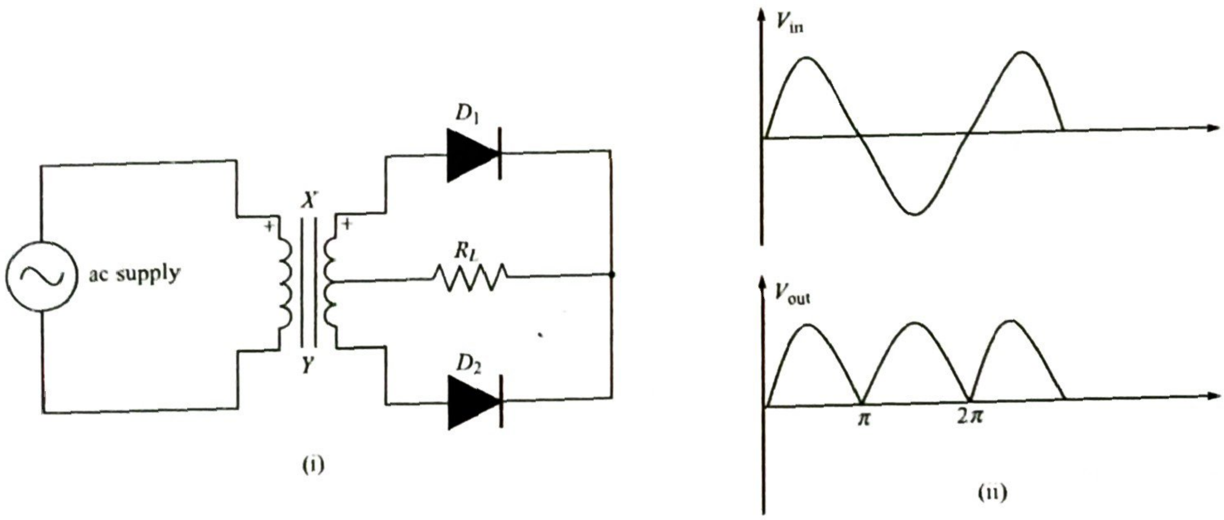


Figure 2.11 Centre tapped full-wave rectifier (i) Circuit diagram (ii) I/P and O/P waveforms

Disadvantages

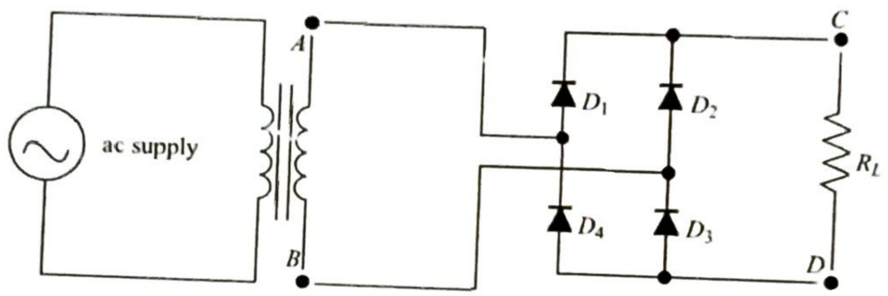
- Since each diode uses only one-half of the transformer secondary voltage the dc output is comparatively small.

- It is difficult to locate the centre-tap on secondary winding of the transformer.
- The diodes used must have high peak-inverse voltage.

2.10.2 Full-wave Bridge Rectifier

The circuit diagram of a bridge rectifier is shown in Fig. 2.12. It uses four diodes and one transformer. During the +ve half-cycle, end A is +ve and end B is –ve thus diodes D_1 and D_3 are forward bias while diodes D_2 and D_4 are reverse biased thus a current flows through diode D_1, load R_L (C to D) and diode D_3.

During the –ve half-cycle, end B is +ve and end A is –ve thus diodes D_2 and D_4 are forward biased while the diodes D_1 and D_3 are reverse biased. Now the flow of current is through diode D_4 load R_L (D to C) and diode D_2. Thus, the waveform is same as in the case of centre-tapped full-wave rectifier.



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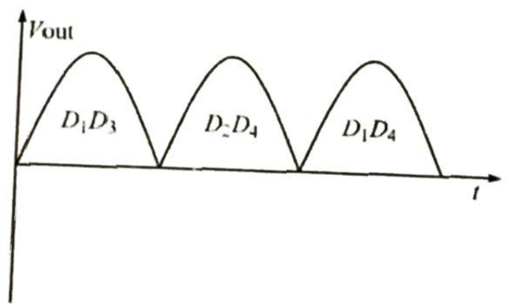


(ii)

Figure 2.12 Full-wave bridge wave rectifier (i) Circuit diagram (ii) Output waveforms

Advantages

- The need for centre-tapped transformer is eliminated.
- The output is twice when compared to centre-tapped full-wave rectifier. for the same secondary voltage.
- The peak inverse voltage is one-half (1/2) compared to centre-tapped full-wave rectifier.
- Can be used where large amount of power is required.

Disadvantages

- It requires four diodes.
- The use of two extra diodes causes an additional voltage drop thereby reducing the output voltage.

Efficiency of Full-wave Rectifier

Let $V = V_m \sin\theta$ be the voltage across the secondary winding
$I = I_m \sin\theta$ be the current flowing in secondary circuit
r_f = diode resistance
R_L = load resistance

dc power output

$$P_{dc} = I_{dc}^2 R_L \tag{2.8}$$

$$I_{dc} = I_{av} = 2\frac{1}{2\pi}\int_0^{\pi} i \cdot d\theta$$

$$I_{av} = 2\frac{1}{2\pi}\int_0^{\pi} I_m \sin\theta \cdot d\theta \tag{2.9}$$

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

$\therefore$

$$P_{dc} = \left(\frac{2I_m}{\pi}\right)^2 R_L \tag{2.10}$$

input ac power

$$P_{ac} = I_{rms}^2 (r_f + R_L) \tag{2.11}$$

$$I_{rms} = \sqrt{2\frac{1}{2\pi}\int_0^{\pi} i^2 d\theta}$$

Squaring both sides, we get

$$I_{rms}^2 = \frac{1}{\pi}\int_0^{\pi} i^2 d\theta$$

$$I_{rms}^2 = \frac{1}{\pi}\int_0^{\pi} (I_m \sin\theta)^2 d\theta$$

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

$$I_{rms} = \frac{I_m}{\sqrt{2}} \tag{2.12}$$

$$P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L) \tag{2.13}$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{2I_m}{\pi}\right)^2}{\left(\frac{I_m}{\sqrt{2}}\right)^2} \times \frac{R_L}{(r_f + R_L)}$$

$$\eta = \frac{0.812}{1 + \frac{r_f}{R_L}} \tag{2.14}$$

The efficiency will be maximum if r_f is negligible as compared to R_L.
Hence, maximum efficiency = 81.2%

This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

Ripple Factor

The pulsating output of a rectifier consists of dc component and ac component (also known as ripple). The ac component is undesirable and accounts for the pulsations in the rectifier output. The effectiveness of a rectifier depends on the magnitude of ac component in the output : the smaller this component, the more effective is the rectifier.

" The ratio of rms value of ac component to the dc component in the rectifier output is known as ripple factor".

$$r = \frac{I_{ac}}{I_{dc}} \tag{2.15}$$

Ripple Factor for Half-wave Rectification

By definition the effective (i.e., rms) value of total load current is given by

$$I_{rms} = \sqrt{I_{ac}^2 + I_{dc}^2}$$

or

$$I_{rms} = \sqrt{I_{ac}^2 + I_{dc}^2}$$

where I_{dc} = value of dc component

I_{ac} = rms value of ac component

Divide both RHS and LHS by I_{dc}, we get

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}} \sqrt{I_{rms}^2 - I_{dc}^2}$$

$$r = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} \tag{2.16}$$

For half-wave rectification, we have $I_{rms} = \dfrac{I_m}{2}$

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

Substituting values of I_{rms} and I_{dc} in Eq. 2.16, we get

ripple factor $r = 1.21$

It is clear that ac component exceeds dc component in the output of a half-wave rectifier.

Ripple Factor for Full-wave Rectification

For full-wave rectification, we have $I_{rms} = \dfrac{I_m}{\sqrt{2}}$

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

Substituting I_{rms}, I_{dc} values in Eq. 2.16, we get,

Ripple factor $r = 0.48$

This shows that in the output of full-wave rectifier, the dc component is more than the ac component.

2.11 COMPARISON OF RECTIFIERS

Particulars	Half-wave rectifier	Centre-tapped full-wave rectifier	Bridge rectifier
1. No. of diodes	1	2	4
2. I_{dc}	I_m/Π	$2I_m/\Pi$	$2I_m/\Pi$
3. V_{dc}	V_m/Π	$2V_m/\Pi$	$2V_m/\Pi$
4. I_{rms}	$I_m/2$	$I_m/\sqrt{2}$	$I_m/\sqrt{2}$
5. Efficiency	40.6%	81.2%	81.2%
6. PIV	V_m	$2V_m$	V_m
7. Ripple factor	1.21	0.48	0.48

Note

- The relation between turns ratio and voltages of primary and secondary of the transformer is given by

  $N_1/N_2 = V_p/V_s$

- RMS value of voltage and maximum value of voltage is related by the equation.

  $V_{rms} = V_m/\sqrt{2}$ (for full-cycle of ac)

- If the type of diode is not specified then assume the diode to be of silicon type.
- For an ideal diode, forward resistance $r_f = 0$ and cut-in voltage, $V_\gamma = 0$.

2.12 FILTERS

We know that the output of the rectifier is pulsating dc, i.e., the output obtained by the rectifier is not pure dc but it contains some ac components along with the dc *o/p*. These ac components are called ripples, which are undesirable or unwanted. To minimize the ripples in the rectifier output filter circuits are used. These circuits are normally connected between the rectifier and load as shown below.

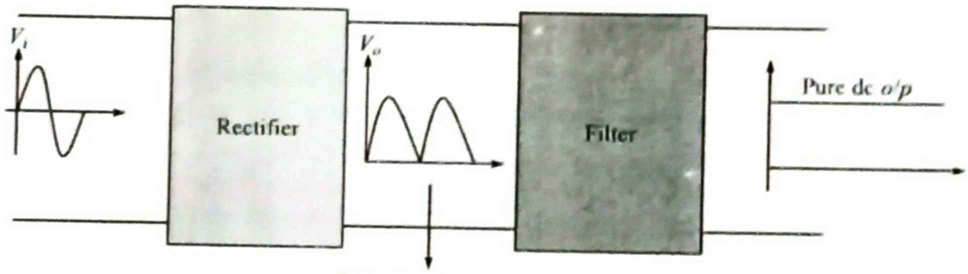


Figure 2.13 Filter

Filter is a circuit which converts pulsating dc output from a rectifier to a steady dc output. In other words, filters are used to reduce the amplitudes of the unwanted ac components in the rectifier.

Types of Filters

1. Capacitor filter (C-filter)
2. Inductor filter
3. Choke input filter (LC-filter)
4. Capacitor input filter (Π-filter)

2.13 CAPACITOR FILTER(C-FILTER)

When the input signal rises from *o* to *a* the diode is forward biased therefore it starts conducting since the capacitor acts as a short circuit for ac signal. It gets charged up to the peak of the input signal and the dc component flows through the load, R_L. When the input signal falls from a to b the diode gets reverse biased. This is mainly because of the voltage across the capacitor obtained during the period o to a is more when compared to V_i. Therefore, there is no conduction of current through the diode.

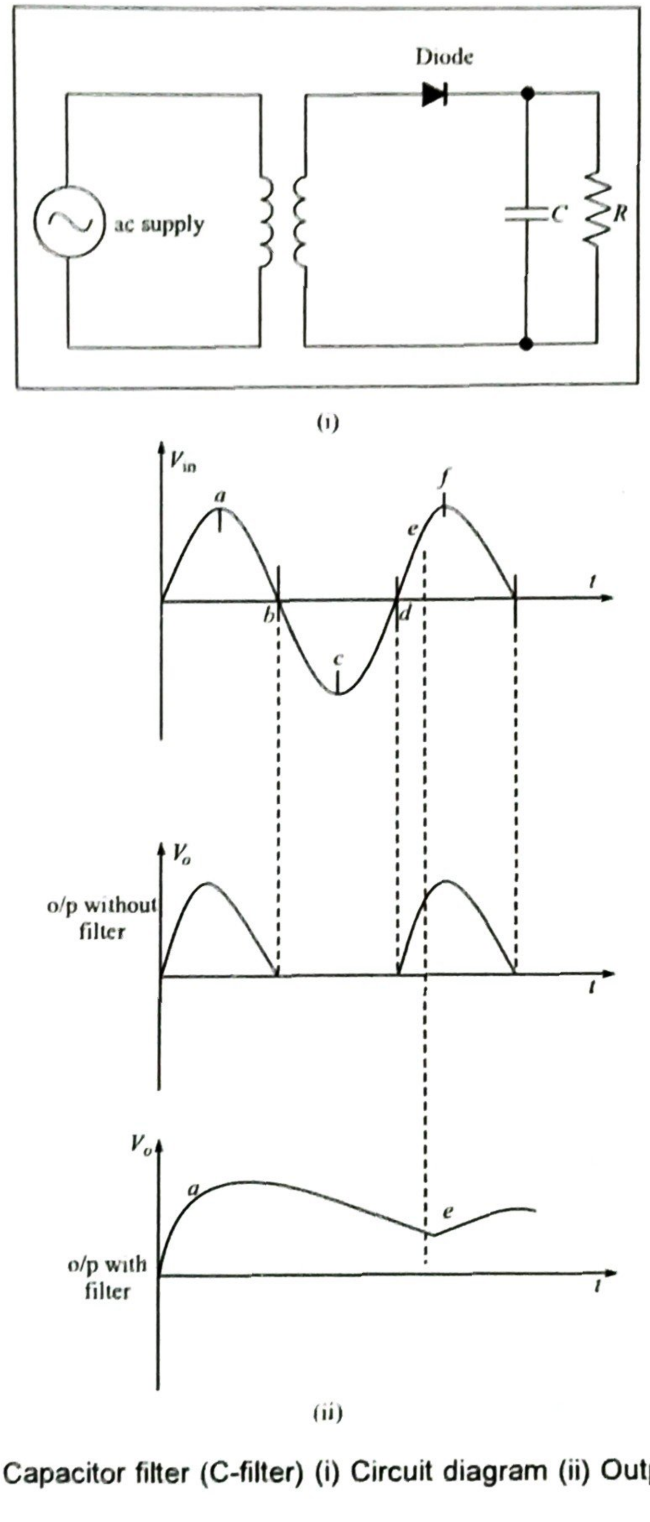


Figure 2.14 Capacitor filter (C-filter) (i) Circuit diagram (ii) Output waveforms

Now the charged capacitor acts as a battery and it starts discharging through the load, R_L. Meanwhile the input signal passes through *b, c, d* sections. When the signal reaches the point *d* the diode is still reverse biased since the capacitor voltage is more than the input voltage. When the signal reaches point *e*, the input voltage can be expected to be more than the capacitor voltage. When the input signal moves from *e* to *f* the capacitor gets charged to its peak value again. The diode gets reverse biased and the capacitor starts discharging. The final output across R_L is shown in Fig. 2.14.

The ripple factor for a half-wave rectifier with C-filter is given by

$$r = 1/2\sqrt{3}\, f_C R_L \tag{2.17}$$

f = the line frequency (Hz)
C = capacitance (F)
R_L = load resistance (Ω)

Ripple factor for full-wave rectifier with C-filter is given by $r = 1/4\sqrt{3}\, f_C R_L$

Advantages of C-Filter

- Low cost, small size and good characteristics.
- It is preferred for small load currents (up to 50 mA)
- It is commonly used in transistor radio, batteries eliminator, etc.

PROBLEM 2.2: The applied input ac power to a half-wave rectifier is 100 watts. The dc output power obtained is 40 watts.

(i) What is the rectification efficiency?
(ii) What happens to remaining 60 watts?

Solution

(i) Rectifier efficiency = dc output power/ac input power

$$= 40/100 = 0.4 = 40\%$$

(ii) 40% efficiency of rectification does not mean that 60% of power is lost in the rectifier circuit. In fact, a crystal diode consumes little power due to its small internal resistance. The 100 W ac power contained as 50 watts in positive half-cycle and 50 watts in negative half cycles. The 50 watts in negative half-cycle are not supplied at all. Only 50 watts in the positive half cycles are converted into 40 watts.

PROBLEM 2.3: An ac supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10:1. Find

(i) the output dc voltage
(ii) the peak inverse voltage. Assume the diode to be ideal.

Solution

$$\text{RMS primary voltage} = 230 \text{ volt}$$

$$\text{Secondary rms voltage, } V_{S(\text{rms})} = (N_2/N_1) \times \text{rms primary voltage}$$

$$= 1/10 \times 230 = 23 \text{ volt}$$

$$\text{Maximum voltage of secondary winding } V_{S(\max)} = \sqrt{2} \times 23 = 32.53$$

(i) Output dc voltage

$$V_{dc} = \frac{V_{S(\max)}}{\pi} = \frac{32.53}{\pi} = 10.36 \text{ V}$$

(ii) During the negative half cycle of ac supply, the diode is reverse biased and hence conducts no current . Therefore, the maximum voltage appearing across the diode is equal to the peak inverse voltage, i.e., 32.53 volt.

PROBLEM 2.4: A crystal diode having internal resistance 20 Ω is used for half-wave rectification. If the applied voltage $V = 50 \sin \omega t$ and load resistance is 800 Ω. Find

(i) I_{max}, I_{dc}, I_{rms}
(ii) ac power input and dc power input
(iii) dc output voltage
(iv) efficiency of rectification

Solution: Given $V = 50 \sin \omega t$, $V_{max} = 50$ V, $R_F = 20\ \Omega$, $R_L = 800\ \Omega$

(i)
$$I_{max} = \frac{V_{max}}{R_F + R_L} = \frac{50}{20 + 800} = 61 \text{ mA}$$

$$I_{dc} = \frac{I_m}{\pi} = \frac{61}{\pi} = 19.4 \text{ mA}$$

$$I_{rms} = \frac{I_{max}}{2} = \frac{61}{2} = 30.5 \text{ mA}$$

(ii) ac input power = $(I_{rms})^2 \times (R_F + R_L) = (30.5 \times 10^{-3})^2 \times (20 + 800) = 0.763$ W
dc output power = $(I_{dc})^2 \times R_L = (19.4 \times 10^{-3})^2 \times (800) = 0.301$ W
(iii) dc output voltage = $I_{dc} \times R_L = 19.4 \text{ mA} \times 800\ \Omega = 15.52$ volts
(iv) efficiency of rectification = $(0.301/0.763) \times 100 = 39.5\%$

PROBLEM 2.5: For a full-wave rectifier, it is given that load resistance $R = 1$ k ohm, forward dynamic resistance $R_F = 500$ ohm and input voltage applied is $V_i = 220 \sin 314\, t$. Find

(i) Peak value of current
(ii) Average value of current
(iii) RMS value of current
(iv) Efficiency
(v) Ripple factor

From Fig. 2.15 (a) it is seen that while the input is positive, diode D is reverse biased and so the output remains at zero, that is, positive half cycle is clipped off. During the negative half cycle of the input, the diode is forward biased and so the negative half cycle appears across the output.

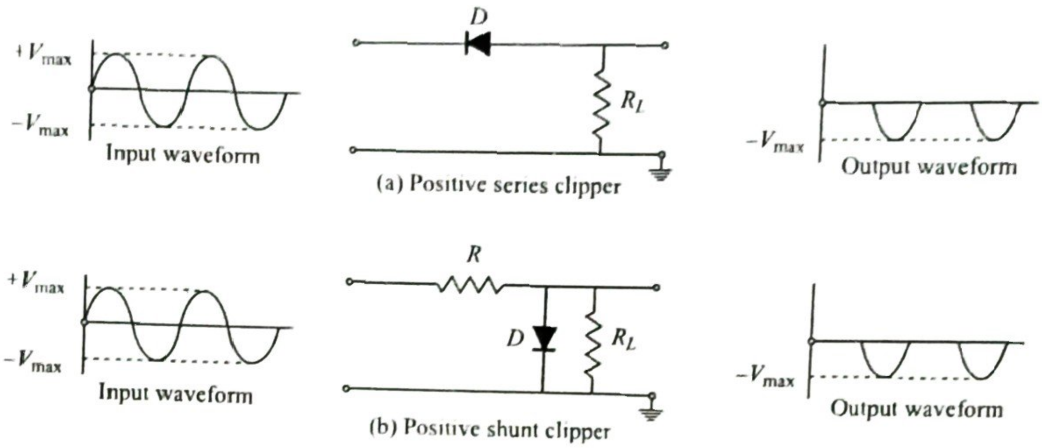


Figure 2.15 Positive series and shunt clipper

Figure 2.15 (b) illustrates the positive shunt clipper circuit (that is, diode in parallel with the load). From Fig. 2.15 (b) it is seen that while the input side is positive, diode D is forward biased and conducts heavily (that is, diode acts as a closed switch). So the voltage drop across the diode or across the load resistance R_L is zero.

Thus, output voltage during the positive half cycles is zero, as shown in the output waveform. During the negative half cycles of the input signal voltage, the diode D is reverse biased and behaves as an open switch. Consequently, the entire input voltage appears across the diode or across the load resistance R_L if R is much smaller than R_L.

Actually, the circuit behaves as a voltage divider with an output voltage of $[R_L/R + R_L]$

$$V_{max} = -V_{max} \quad \text{when} \quad R_L >> R \tag{2.18}$$

Note: If the diode in Fig. 2.15 (a) and (b) is reconnected with reversed polarity, the circuits will become for a negative series clipper and negative shunt clipper respectively.

2.14.2 Negative Clipper

The negative series and negative shunt clippers are shown in Fig. 2.16 (a) and (b) as given below.

In the above discussion, the diode is considered to be ideal one. If the second approximation for diode is considered the barrier potential (0.7 V for silicon and 0.3 V for germanium) of diode, will be taken into account. Then the output waveforms for positive and negative clippers will be of the shape as shown in the Fig. 2.17.

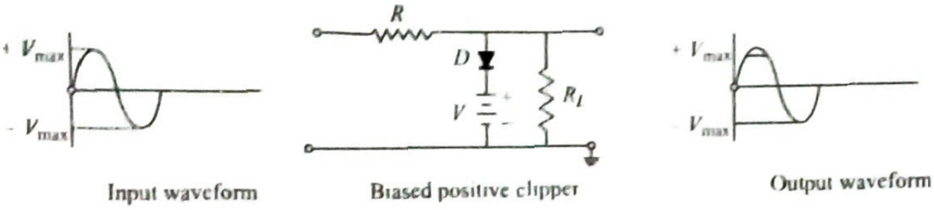


Figure 2.18 Biased positive clipper

2.14.4 Combination Clipper

When a portion of both positive and negative of each half-cycle of the input voltage is to be clipped (or removed), combination clipper is employed. The circuit for such a clipper is given in the Fig. 2.19.

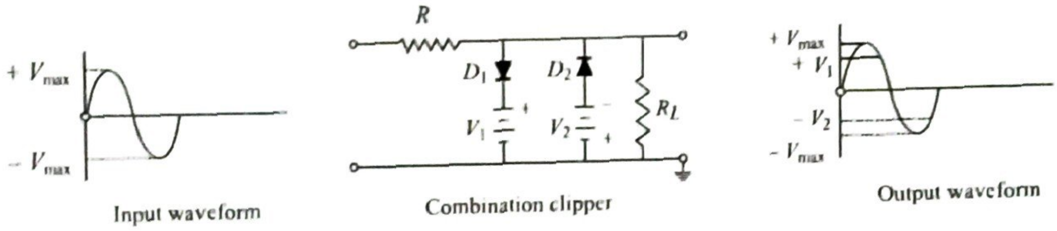


Figure 2.19 Combination clipper

The action of the circuit is summarized below. For positive input voltage signal when input voltage exceeds battery voltage $+V_1$ diode D_1 conducts heavily while diode D_2 is reversed biased and so voltage $+V_1$ appears across the output. This output voltage $+V_1$ stays as long as the input signal voltage exceeds $+V_1$. On the other hand, for the negative input voltage signal, diode D_1 remains reverse biased and diode D_2 conducts heavily only when input voltage exceeds battery voltage V_2 in magnitude.

Thus, during the negative half-cycle the output stays at $-V_2$ so long as the input signal voltage is greater than $-V_2$.

2.14.5 Drawbacks of Series and Shunt Diode Clippers

In series clippers, when the diode is in 'off' position, there should be no transmission of input signal to output. But in case of high frequency signals transmission occurs through diode capacitance which is undesirable. This is the drawback of using diode as a series element in such clippers.

In shunt clippers, when the diode is in the 'off condition, transmission of input signal should take place to output. But in case of high frequency input signals, diode capacitance affects the circuit operation adversely and the signal gets attenuated (that is, it passes through diode capacitance to ground).

signal; it offsets the input signal so that all of the waveform is greater than 0 V. A negative clamp is the opposite of this — this clamp outputs a purely negative waveform from an input signal. A bias voltage between the diode and ground offsets the output voltage by that amount.

For example, an input signal of peak value 5 V (V_{in} = 5 V) is applied to a positive clamp with a bias of 3 V (V_{bias} = 3 V), the peak output voltage will be

$$V_{out} = 2\,V_{in} + V_{bias}$$
$$V_{out} = 2 \times 5\text{ V} + 3\text{ V} = 13\text{ V}$$

2.15.2 Positive Unbiased Clamper

In the negative cycle of the input ac signal, the diode is forward biased and conducts, charging the capacitor to the peak positive value of V_{in}. During the positive cycle, the diode is reverse biased and thus does not conduct. The output voltage is therefore equal to the voltage stored in the capacitor plus the input voltage again, so $V_{out} = 2\,V_{in}$.

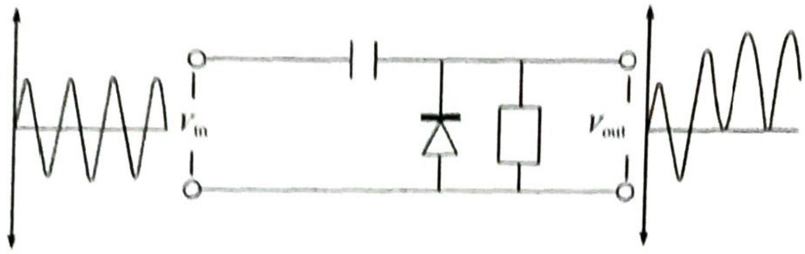


Figure 2.21 Positive unbiased clamper

2.15.3 Negative Unbiased Clamper

A negative unbiased clamp is the opposite of the equivalent positive clamp. In the positive cycle of the input ac signal, the diode is forward biased and conducts, charging the capacitor to the peak value of V_{in}. During the negative cycle, the diode is reverse biased and thus does not conduct. The output voltage is therefore equal to the voltage stored in the capacitor plus the input voltage again, so $V_{out} = -2\,V_{in}$.

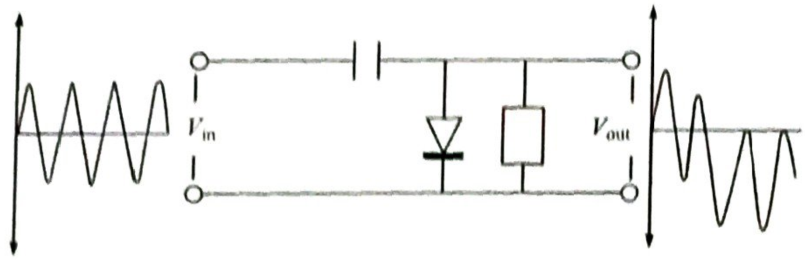


Figure 2.22 Negative unbiased clamper

2.15.4 Positive Biased Clamper

A positive biased voltage clamp is identical to an equivalent unbiased clamp but with the output voltage offset by the bias amount V_{bias}. Thus, $V_{out} = 2V_{in} + V_{bias}$.

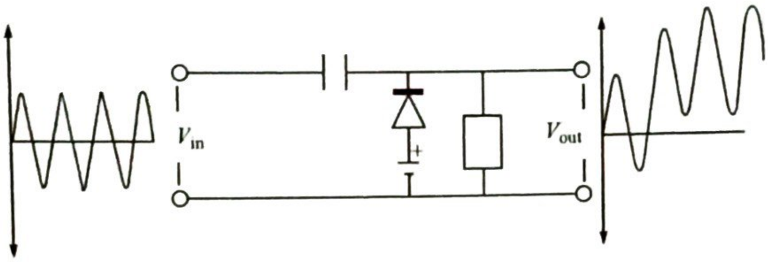


Figure 2.23 Positive biased clamper

2.15.5 Negative Biased Clamper

A negative biased voltage clamp is likewise identical to an equivalent unbiased clamp but with the output voltage offset in the negative direction by the bias amount V_{bias}.

Thus,
$$V_{out} = -2V_{in} - V_{bias}$$

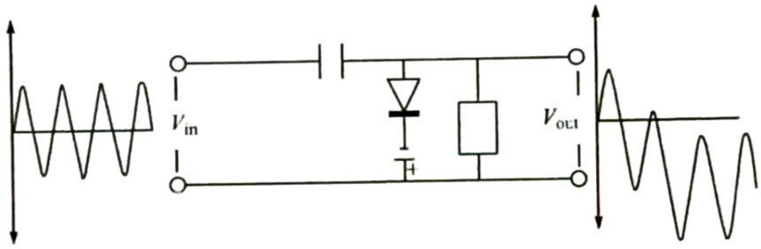


Figure 2.24 Negative biased clamper

2.15.6 Positive Clamping and Negative Clamping Circuit

The necessity to establish the extremity of the positive or negative signal excursion at some reference level (that is, to introduce a dc component to the input signal) arises in connection with a signal that has passed through a capacitive coupling network and lost its dc component, as in the case of television receivers. However, normally the dc component introduced is not identical with the dc component lost in transmission.

In fact, a clamp circuit adds a dc component (positive or negative) to the input signal so as to push it either on the positive side, as illustrated in Fig. 2.25 (a) or on the negative side, as illustrated in Fig. 2.25 (b). When the circuit pushes the signal on the positive side or upward, the negative peak of the signal coincides with the zero level and the circuit is called the *positive clamper*. On the other hand, when the signal is pushed on the negative side or downward, as illustrated in Fig. 2.25 (a), the positive peak of the input signal coincides with the zero level and the circuit is called the *negative clamper*.

forward biased and capacitor C is charged with the polarity shown. During the positive half-cycle of input, the output voltage is equal to the barrier potential of the diode, V_o and the capacitor is charged to $(V - V_Q)$. When the input goes negative, the diode is reverse-biased and acts as an open circuit and thus has no effect on the capacitor voltage. R being of very high value, cannot discharge C by very much during the negative portion of the input waveform. Thus, during negative input, the output voltage being the sum of the input voltage and the capacitor voltage is equal to $- V - (V - V_o)$ or $-(2V - V_o)$. Thus, peak-to-peak output being the difference of the negative and positive peak voltage levels is equal to $V_o - [-(2V - V_o)]$ or $2V$.

If the diode in Fig. 2.26 shown below is reconnected with reversed polarity, the circuit becomes a positive clamping circuit. The positive clamping circuit shifts the original signal in a vertical upward direction. A positive clamping circuit is shown in Fig 2.27. It contains diode D and capacitor C in a negative clamper. The only difference in the circuit is that the polarity of the diode is reversed. Because of this reason the circuit acts as a positive clamper. The remaining explanation regarding the working of the circuit is same as it is explained for the negative clamper.

To remember which way the dc level of a signal moves, see Figure 2.26. Notice that the diode arrows point downward, the same direction as the dc shift.

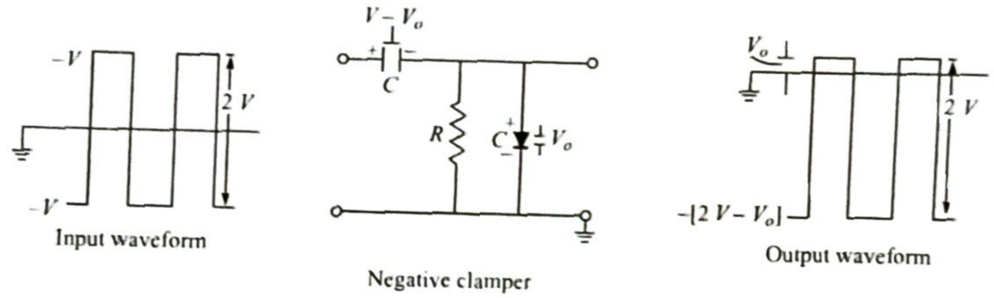


Figure 2.26 Negative clamper

Similarly, in Fig. 2.27 shown below, the diode arrow points upward, again the same direction as the dc shifts. It means that when the diode points upward, we have a positive dc clamper and when the diode points downward, the circuit is a negative dc clamper.

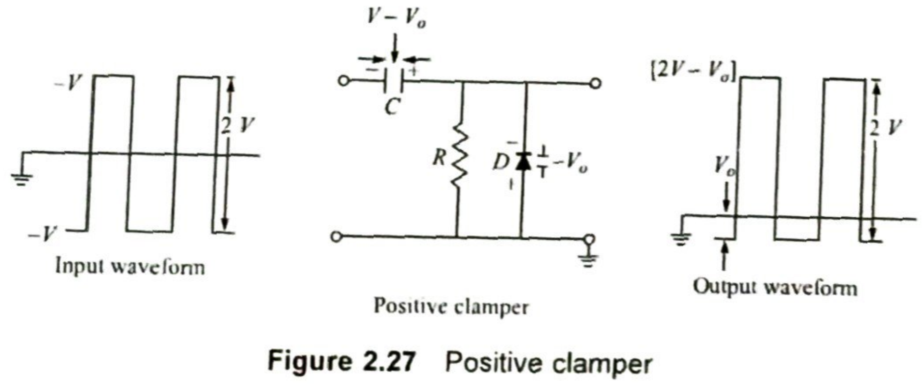


Figure 2.27 Positive clamper

2.15.7 Application of Clamper Circuit

Clamping circuits are often employed in television receivers as dc restorers. The incoming composite video signal normally processes through coactively coupled amplifiers which eliminate the dc component thereby losing the black and white reference levels and the blanking level. These reference levels have to be restored before applying the video signal to the picture tube. This is accomplished by employing clamping circuits. Clamping circuits are also used in storage counter, analog frequency meter, capacitance meter, divider and staircase waveform generator.

2.16 BREAKDOWN PHENOMENON

The breakdown in the Zener diode at voltage V_z may be due to any of the following mechanisms.

2.16.1 Avalanche Breakdown

We know that when a diode is reverse biased a small reverse saturation current I_0 flows across the junction because of the minority carriers in the depletion region. The velocity of the minority charge carriers is directly proportional to the applied voltage. Hence, when the reverse bias voltage is increased, the velocity of minority charge carriers will also increase and consequently their energy content will also increase.

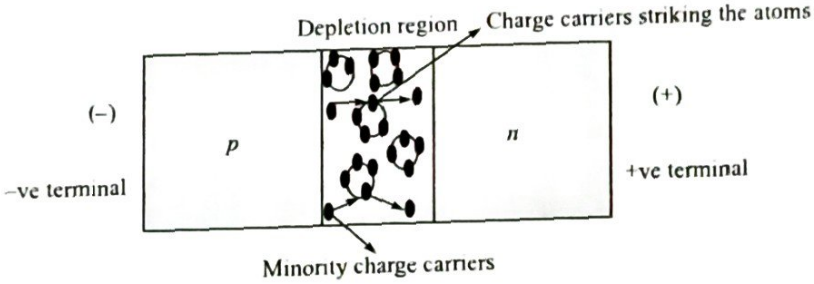


Figure 2.28 Avalanche breakdown in Zener diode

When these high energy charge carriers strike the atom within the depletion region they cause other charge carriers to break away from their atoms and join the flow of the current across the junction as shown above. The additional charge carriers generated in this way strike other atoms and generate new carriers by making them to break away from their atoms. This cumulative process is referred to as *avalanche multiplication* which results in the flow of large reverse current and this breakdown of the diode is called avalanche breakdown.

2.16.2 Zener Breakdown

We have electric field strength = Reverse voltage/Depletion region

2.17.1 Zener Voltage Regulator

The circuit diagram of a Zener voltage regulator is shown in Fig. 2.32.

A Zener diode of breakdown voltage V_Z is connected in reverse biased condition across the load R_L such that it operates in breakdown region. Any fluctuations in the current are absorbed by the series resistance R_s. The Zener will maintain a constant voltage V_Z (equal to V_o) across the load unless the input voltage does not fall below the Zener breakdown voltage V_Z.

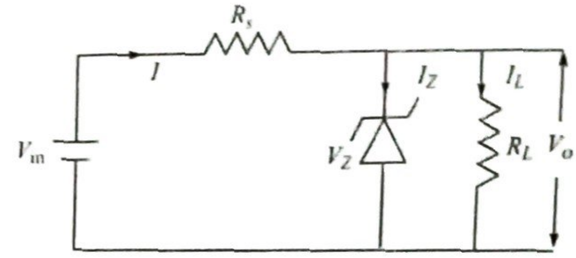
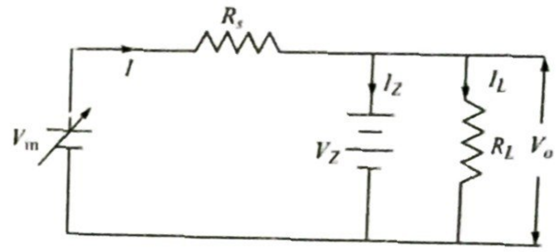


Figure 2.32 Zener voltage regulator

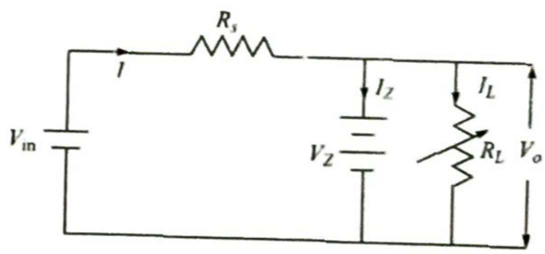
Case (i) when input voltage V_{in} varies and R_L is constant

If the input voltage increases, the Zener diode which is in the breakdown region is equivalent to a battery V_Z as shown in the figure. The output voltage remains constant at V_Z (equal to V_o) and the excess voltage is dropped across the series resistance, R_S. We know that for a Zener diode under breakdown region large change in current produces very small change in voltage, thereby the output voltage remains constant.



Case (ii) When V_{in} is constant and R_L varies

If there is a decrease in the load resistance R_L and the input voltage remains constant then there is a increase in the load current. Since V_{in} is constant the current cannot come from the source. This addition load current is driven from the battery V_Z and we know that even for a large decrease in current the Zener output voltage V_Z remains same. Hence, the output voltage across the load is also constant.



PROBLEM 2.6: A Zener diode is specified as having a breakdown voltage of 9.1 V, with a maximum power dissipation of 364 mW. What is the maximum current the diode can handle?

Solution: The maximum possible current is

$$I_{Z\max} = \frac{p}{V_z} = \frac{364 \times 10^{-3}}{9.1} = 40 \text{ mA}$$

PROBLEM 2.10: A silicon diode has reverse saturation current of 3 μA at 300°K. Find forward voltage for forward current of 15 mA.

Solution: As we know $I = I_o(e^{V/\eta V_T} - 1)$

Substituting forward current I = 15 mA, reverse saturation current $I_o = 3 \times 10^{-6}$ A in the above equation, we have

$$0.015 \text{ A} = 3 \times 10^{-6} \, (e^{V/\eta V_T} - 1)$$

or
$$e^{V/\eta V_T} = \frac{0.015}{3 \times 10^{-6}} + 1 = 5 \times 10^3 + 1 = 5001$$

or
$$\frac{V}{\eta V_T} = \ln 5001$$

$$V = \eta V_T \ln 5001$$

$$V = 2 \times 0.026 \times \ln 5001 = 0.44 \text{ V}$$

As η = 2 for Si and V_T = 26 mV at 300 K.

PROBLEM 2.11: At what voltage the reverse current flowing through a germanium diode will reach 60% of its saturation value at room temperature?

Solution: As we know $I = I_o(e^{V/\eta V_T} - 1)$

Hence,
$$-0.6 \, I_o = I_o(e^{V/\eta V_T} - 1)$$

or
$$e^{V/\eta V_T} = -0.6 + 1 = 0.4$$

Substituting η = 1 and V_T = 0.026 V in the above equation, we get

$$e^{V/0.026} = 0.4$$

or
$$V = 0.026 \ln 0.4 = -0.0238 \text{ V}$$

PROBLEM 2.12: Find the dynamic resistance of a *p-n* junction diode at a forward current of 3 mA. Assume $\frac{kT}{q}$ = 26 mV at room temperature.

Solution: Forward current, I = 3 mA or 0.003 A

Volt equivalent of temperature $V_T = \frac{kT}{q}$ = 26 mV or 0.026 V

Dynamic resistance is given approximately by $r = \frac{\eta V_T}{I}$

Substituting η = 1, V_T = 0.026 V and I = 0.003 A in the above equation, we have

Dynamic resistance r = 0.026/0.003 = 8.66 ohms.

Dividing Eq. (a) by (b)

$$\frac{20 \times 10^{-3}}{0.6 \times 10^{-3}} = \frac{I_o(e^{\frac{20}{\eta}})}{I_o(e^{\frac{16}{\eta}})}$$

or
$$\frac{100}{3} = e^{\frac{4}{\eta}}$$

or
$$\eta = 1.14$$

PROBLEM 2.18: Determine the dc resistance level for the diode shown in Fig. 2.33 at (i) $I_D = 2$ mA, (ii) $I_D = 20$ mA (iii) $V_D = -10$ V.

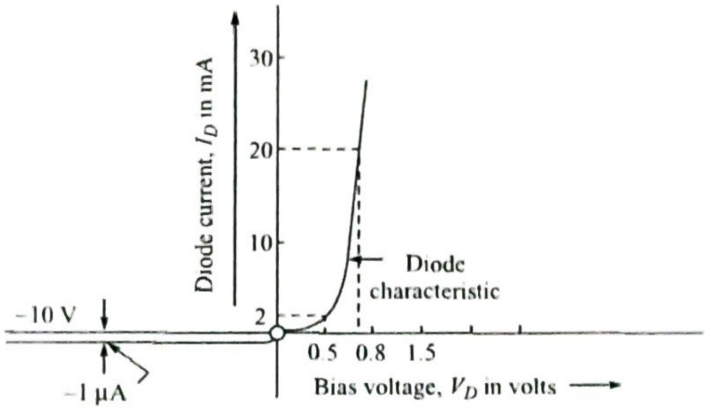


Figure 2.33

Solution

(i) When $I_D = 2$ mA, $V_D = 0.5$ V from graph.
So resistance $R = V_D/I_D = 0.5\text{ V}/(2 \times 10^{-3}\text{ A}) = 250\ \Omega$

(ii) When $I_D = 20$ mA, $V_D = 0.8$ V from graph.
So resistance $R = V_D/I_D = 0.8\text{ V}/(20 \times 10^{-3}\text{ A}) = 40\ \Omega$

(ii) When $V_D = -10$ V, $I_D = -1\ \mu$A from graph.
So resistance $R = V_D/I_D = -10\text{ V}/(-1 \times 10^{-6}\text{ A}) = 10\text{ M}\Omega$

PROBLEM 2.19: A diode is connected in series with a load resistance of 160 Ω across a DC supply voltage of 10 V.

Draw a DC load line and determine the voltage drop across the diode and diode current. Diode characteristics are given in Fig. 2.35.

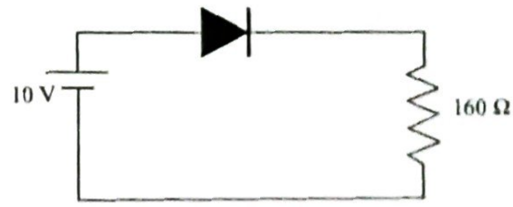


Figure 2.34

PROBLEM 2.20: A 5 V Zener is rated at 2 watt. What is the maximum safe current of the Zener?

Solution:

$$\text{Maximum safe current of Zener} = \frac{\text{Wattage rating}}{\text{Voltage rating}} = 2 \text{ watt}/5 \text{ V} = 0.4 \text{ A}$$

PROBLEM 2.21: Determine the temperature coefficient of a 10 volt Zener diode at 25°C if the nominal voltage drops to 9.8 volt at a temperature of 100°C.

Solution:

Change in voltage $\Delta V_Z = 9.8 - 10 = -0.2$ V

Change in temperature $(t - t_o) = 100 - 25 = 75°$C

$$\text{Temperature coefficient of Zener diode} = \frac{\Delta V_Z}{V_Z(t - t_o)} \times 100 = -0.0266\%$$

PROBLEM 2.22: A Zener diode has an impedance of 80 Ω in the range for I_Z = 1 mA to 10 mA. The voltage corresponding to I_Z of 1 mA is 10 V. For constant impedance over the given range, what minimum and maximum Zener voltage can be expected if the diode is used in an application where Zener current varies from 2 mA to 8 mA?

Solution: Voltage change between I_Z = 1 mA and 2 mA,

$$\Delta V_Z = \Delta I_Z r_Z = (2 \text{ mA} - 1 \text{ mA}) \times 80\ \Omega = 0.08 \text{ V}$$

So minimum Zener voltage $V_{Z\min} = V + \Delta V_Z = 10 + 0.08 = 10.08$ V

Voltage change between I_Z = 2 mA and 8 mA,

$$\Delta V_Z = \Delta I_Z r_Z = (8 \text{ mA} - 2 \text{ mA}) \times 80\ \Omega = 0.48 \text{ V}$$

So minimum Zener voltage $V_{Z\max} = V_{Z\min} + \Delta V_Z = 10.08 + 0.48 = 10.56$ V

PROBLEM 2.23: Draw the output waveform for the circuit shown in Fig. 2.37.

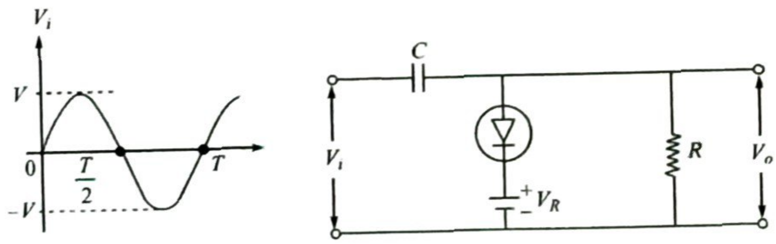


Figure 2.37

Solution: Assume that the diode is ideal. During the first quarter of the input cycle, when $V_i > V_R$, the diode is forward biased and C gets charged to $(V - V_R)$ volts as shown in Fig. 2.38.

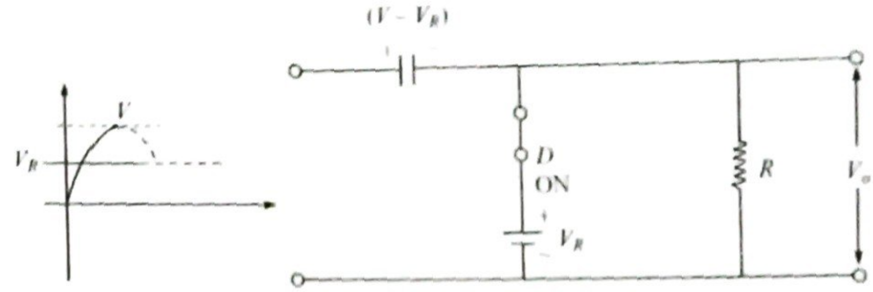


Figure 2.38

When V_{in} drops below V, the capacitor remains charged to $(V - V_R)$ with same polarities and the diode becomes reverse biased.

When $\qquad V_i = V,\ V_o = V_i - V_C = V_R$

When $\qquad V_i = 0,\ V_o = -V_C = -(V - V_R)$

In the negative half-cycle, the capacitor discharges through R as $RC >> 10\,T$. Thus, it remains charged at $(V - V_R)$ with same polarities as shown in Fig. 2.39, for entire negative half-cycle.

Therefore, $\qquad V_o = -V_i - (V - V_R)$

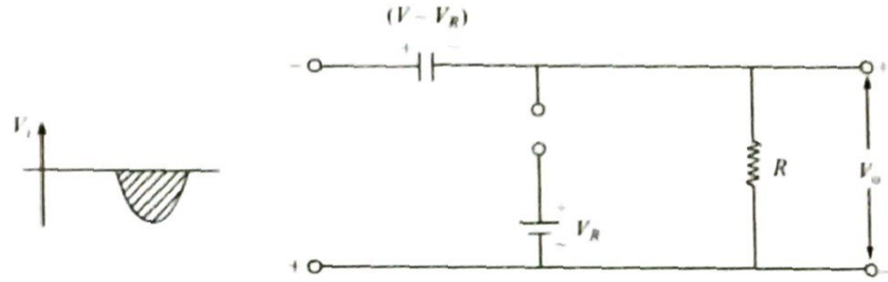


Figure 2.39

Hence, when $\qquad V_i = V,\ V_o = -V - V + V_R = -2V + V_R$

When $\qquad V_i = 0,\ V_o = -(V - V_R)$

Thus, the output voltage waveform will be as shown in Fig. 2.40:

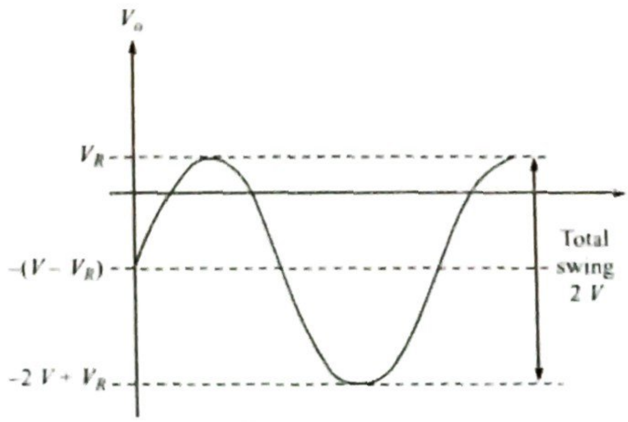


Figure 2.40

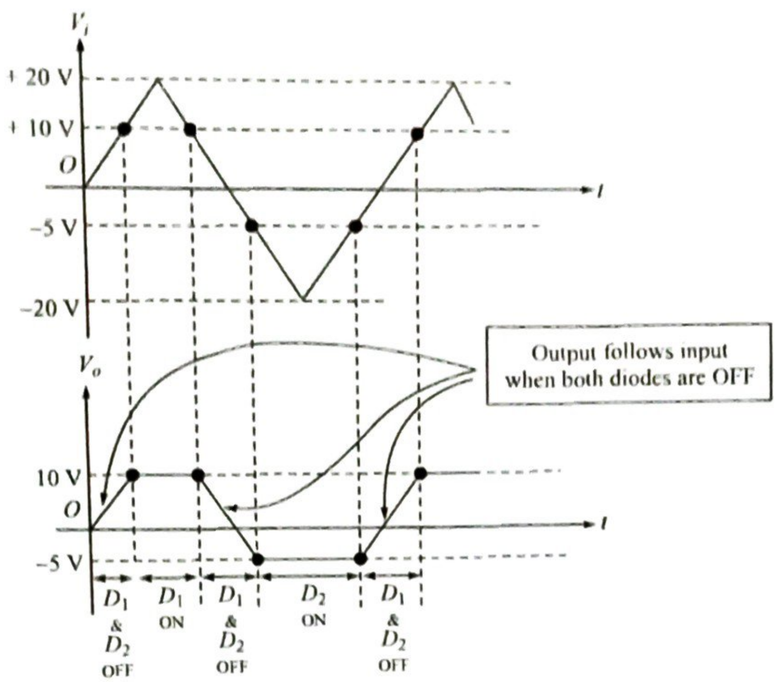


Figure 2.44

PROBLEM 2.25: Sketch i_R and V_o for the circuit shown in Fig. 2.45.

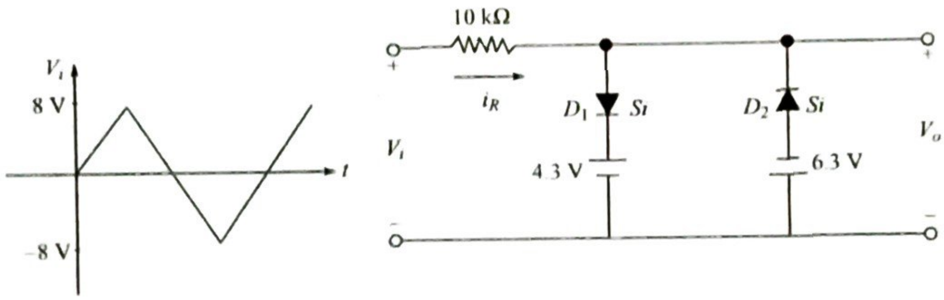


Figure 2.45

Solution: When V_i is greater than V_A, diode D_1 conducts and D_2 remains OFF and the circuit will be as shown in Fig. 2.46.

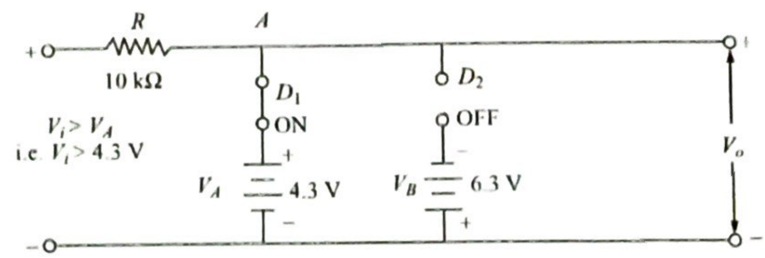


Figure 2.46

Thus, $$V_o = V_A = 4.3 \text{ V}$$

Current through R: $i_R = (V_i - V_A)/R = (8 - 4.3)/(10 \times 10^3) = 0.378$ mA

When V_i is less than V_B, diode D_2 conducts and D_1 remains OFF and the circuit will be as shown in Fig. 2.47.

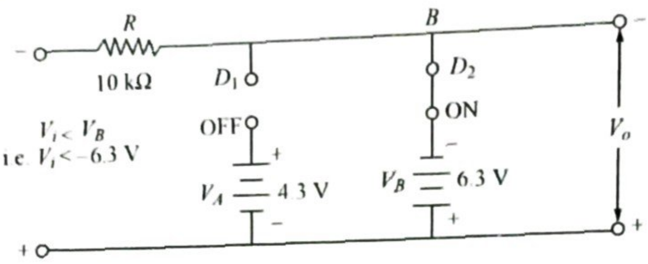


Figure 2.47

Thus, $$V_o = V_B = -6.3 \text{ V}$$

Current through R: $i_R = (V_i - V_B)/R = \{-8 - (-6.3\}/(10 \times 10^3) = -0.17$ mA

When $V_i < 4.3$ V and $V_i > -6.3$ V, the output voltage and current follow the input as both the diodes reverse biased. The input and output waveforms are shown in Fig. 2.48.

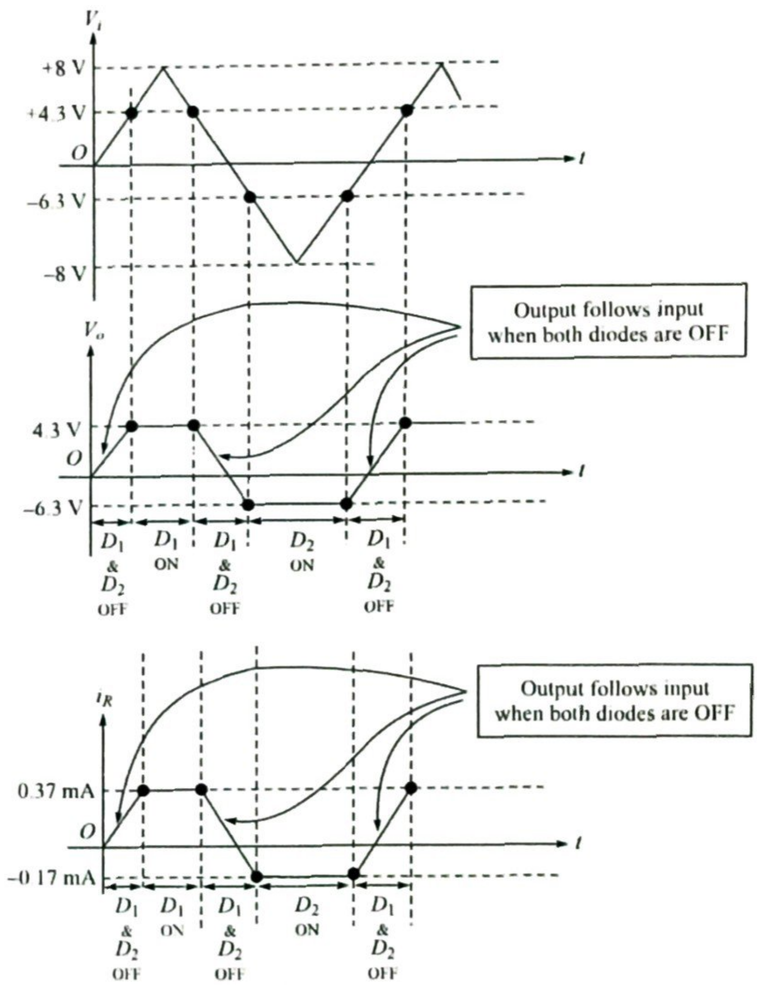


Figure 2.48

During Positive Half-Cycle of Input

Diode D_2 is forward biased for the entire positive half-cycle and diode D_1 is reverse biased. The circuit will be as shown in the Fig. 2.54.

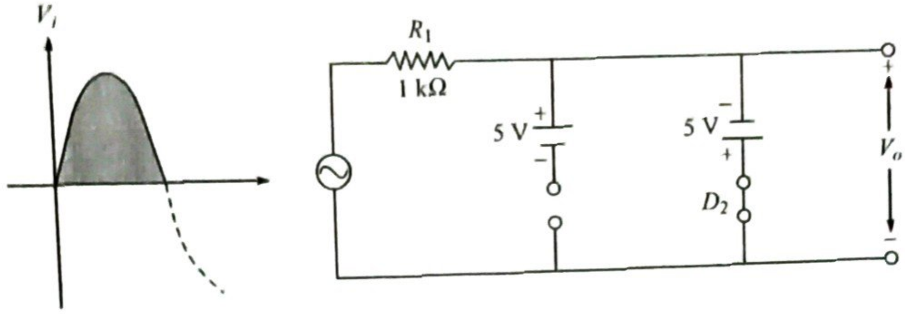


Figure 2.54

Thus $V_o = -5$ V for the entire positive half-cycle of the input.

During Negative Half-Cycle of Input

As long as the magnitude of V_i is less than 5 V, diode D_1 is reverse biased and diode D_2 is forward biased. Thus $V_o = 5$ V.

When V_i is less than -5 V, then diode D_1 is forward biased and diode D_2 is reverse biased. Thus, the circuit will be as shown in Fig. 2.55.

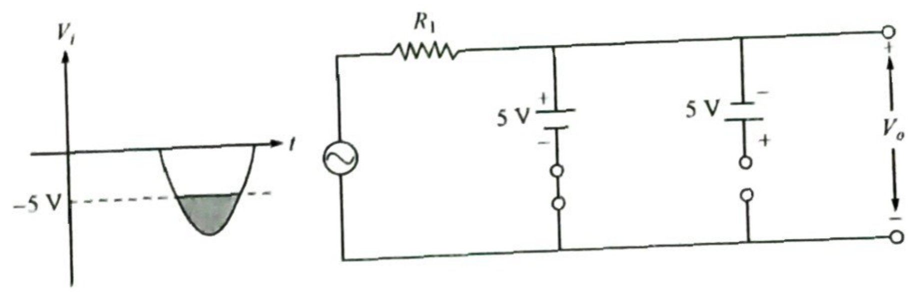


Figure 2.55

Thus, the output voltage $V_o = +5$ V

The input and output waveforms are shown in Fig. 2.56.

Applying Kirchhoff's voltage law to the loop, we get

$$-I \times (200 \times 10^3) - 100 + 25 - I \times 100 \times 10^3 = 0$$

Therefore,

$$I = -0.25 \text{ mA}$$

Hence, I is in upward direction.

Therefore, $V_o = 100 - IR_2 = 100 - 0.25 \times 10^{-3} \times 200 \times 10^3 = 50$ V

Case (ii) For 25 < V < 100 V

Let input voltage be $V_i = 50$ V.

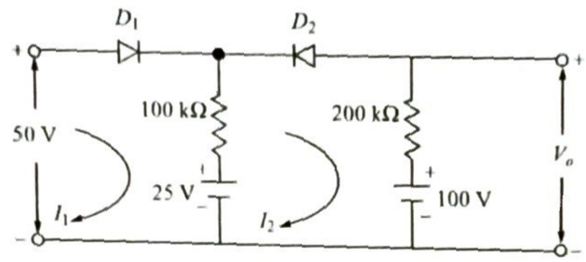


Figure 2.59

Applying Kirchhoff's voltage law, we get

$$-100(I_2 - I_1) - 25 + 50 = 0$$

or

$$4I_1 - 4I_2 = 1$$

and

$$-200I_2 - 100 + 25 - 100I(I_2 - I_1) = 0$$

or

$$4I_1 - 12I_2 = 3$$

Therefore,

$$I_1 = 0 \text{ A and } I_2 = 0.25 \text{ mA}$$

Thus,

$$V_o = 100 - 0.25 \times 200 = 50 \text{ V}.$$

Thus, the output follows the input.

If the input voltage $V_i = 75$ V, then the first equation gets modified as

$$2I_1 - 2I_2 = 1$$

and the other equation remains same as

$$4I_1 - 12I_2 = 3$$

Solving, we get

$$I_1 = 3/8 \text{ mA}$$
$$I_2 = -1/8 \text{ mA}$$

Thus,

$$V_o = 100 - (1/8) \times 200 = 75 \text{ V}$$

Again the output follows the input.

Thus, for the entire range of V_i is from 25 V to 100 V, the output follows the input.

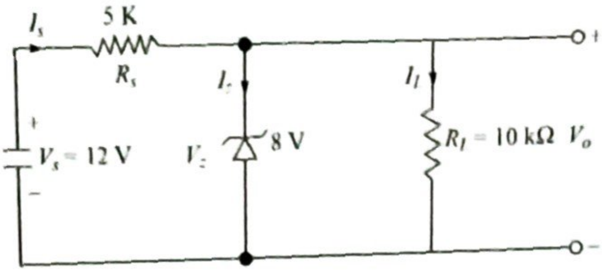


Figure 2.63

Given that

$$V_s = 12 \text{ V}, V_z = 8 \text{ V}, R_s = 5 \text{ k}\Omega \text{ and } R_L = 10 \text{ k}\Omega$$

(a) The output voltage or load voltage

$$V_o = V_z = 8 \text{ V}$$

(b) $$V_s = I_s R_s + V_z$$

Here, $$I_s = \frac{V_s - V_z}{R_s} = \frac{12-8}{5} \times 10^{-3} = \frac{4}{5} \times 10^{-3} = 0.8 \text{ mA}$$

Hence, the voltage drop across series resistance R_s is $= I_s R_s = 8 \times 10^{-3} \times 5 \times 10^3 = 4$ V

(c) We know that $V_o = I_l \cdot R_L$

Therefore, load current, $I_L = \dfrac{V_o}{R_L} = \dfrac{8}{10 \times 10^3} = 0.8$ mA

Current through the Zener diode is

$$I_s = I_z + I_L$$

Therefore, $$I_z = I_s - I_L = 0.8 \text{ mA} - 0.8 \text{ mA} = 0 \text{ A}$$

Since, $I_z = 0$, for the given value of load resistance, the Zener diode will come out of the breakdown region. Hence, the Zener diode will no longer work as a voltage regulator.

PROBLEM 2.30: Find the voltage drop across 5 kΩ resistance shown in Fig. 2.64.

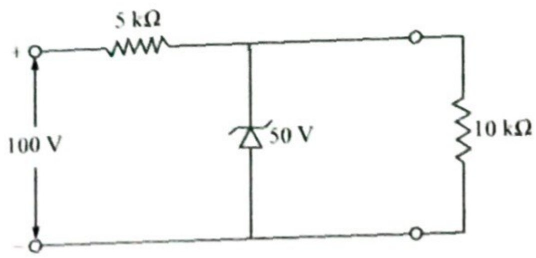


Figure 2.64

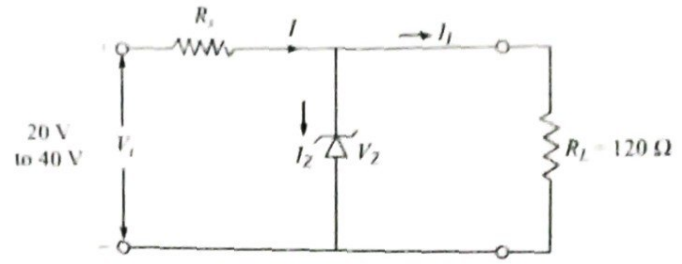


Figure 2.66

Solution: $I_{Z\max} = 200$ mA, $I_{Z\min} = 20$ mA, $V_L = 12$ V, $R_L = 120\ \Omega$

$$I_L = \frac{V_L}{R_L} = \frac{12}{120} = 0.1\text{ A} = 100\text{ mA}$$

$$I = I_Z + I_L$$

Here, I_L is constant. When $I = I_{\max}$, $I = I_{Z\max}$ and when $I = I_{\min}$, $I_Z = I_{Z\min}$
Therefore,

$$I_{\max} = I_L + I_{Z\max} = 100\text{ mA} + 200\text{ mA} = 300\text{ mA}$$
$$I_{\min} = I_L + I_{Z\min} = 100\text{ mA} + 20\text{ mA} = 120\text{ mA}$$

Now for minimum V_{dc}, the circuit should provide $I_{Z\min}$, i.e., $I_{\min}$.

$$I_{\min} = \frac{V_{dc\,(\min)} - V_L}{R_{in}}$$

Therefore, $$R_{in} = \frac{V_{dc(\max)} - V_L}{I_{\min}} = \frac{19.5 - 12}{300 \times 10^{-3}} = 25\ \Omega$$

Thus, for $V_{dc\,(\max)}$,

$$R_{in} = \frac{V_{dc\,(\max)} - V_L}{I_{\min}} = \frac{19.5 - 12}{300 \times 10^{-3}} = 25\ \Omega$$

Thus, $R_{in} = 25\ \Omega$

2.18 TERMINAL EXERCISES

2.18.1 Objective Type Questions

1. The dynamic resistance of a semiconductor diode is
   (1) Its resistance when it is forward biased
   (2) Its resistance when it is reverse biased
   (3) The ac opposition to the current flow
   (4) None of these
2. The dynamic impedance of a Zener diode
   (1) Is independent of current passing through it
   (2) Increases with increase in current passing through it