ELECTRONIC DEVICES AND CIRCUITS

UNIT I Diode & Diode Applications

Diode: PN junction Diode – Characteristics, Current equation, Temperature dependence, Static and Dynamic resistances, Equivalent circuit, Diffusion and Transition Capacitances.

Diode Applications: Rectifier - Half Wave Rectifier, Full Wave Rectifier, Bridge Rectifier, Rectifiers with Capacitive Filter, Clippers, Clampers.

1.1 Basics

Atom:

- The smallest particle of an element that can exist either alone or in combination.
- Atoms consist of a heavy central nucleus surrounded by a cloud of negatively charged particles called electrons.
- The nucleus contains positive particles (protons) and electrically neutral particles (neutrons).

Electronics:

- The branch of science that deals with the study of flow and control of electrons and the study of their behavior and effects in vacuums, gases, and semiconductors.

Passive Components:

- Those devices or components which do not required external source to their operation.

  Examples: Resistor, capacitor and inductor.

Active Components:

- Those devices or components which required external source to their operation.

  Examples: Diode, Transistors, SCR, Integrated Circuits, TRIACs, SCRs, LEDs, etc.

DC (Direct Current):

- The electrons flow in one direction only. Current flow is from negative to positive.

AC (Alternating Current):

- The electrons flow in both directions in a cyclic manner.

Frequency:

- The rate of change of direction determines the frequency, measured in Hertz (cycles per second).

Valence Electrons:

- Valence electrons are the electrons present in the outermost orbit of an atom.

Free Electrons (or) Conduction Electrons:

- Free electrons are electrons that are not attached to an atom.

Energy band:

- The range of energies possessed by an electron in an atom.

Conduction band:

- The range of energies possessed by conduction electrons in an atom.

Valence Band:

- The range of energies possessed by valence electrons in an atom.

Energy band diagram:

- It is a diagram between interatomic spacing and energy

Forbidden Energy Gap:

- The separation between conduction band and valance band o the energy band diagram

1.1.1 Classification of Solid state materials

Insulators:

- Insulators are the materials which are not allowing flow of electric current through them.

  Examples – Glass, Wood, Rubber, Plastic and air.

Conductors:

- Conductors are the materials which are easily allowing flow of electric current through them.

  Examples – Copper, Aluminum, Iron and silver

Semiconductors:

- Semiconductors are the materials whose electrical conductivity lies in between insulators and conductors.

  Examples – silicon, Germanium and Gallium

1.2 Qualitative Theory of P-N Junction

1.2.1 Types of Semiconductor

- Semiconductors can be classified into two types:
  - Intrinsic Semiconductors or Pure of Semiconductors
  - Extrinsic Semiconductors or Impure of Semiconductors

1.2.1.1 Intrinsic semiconductors:

- The normal (pure) silicon and Germanium are intrinsic semiconductors.
- The number of electrons present in the outermost orbit of intrinsic semiconductor is four
- So, intrinsic semiconductors are tetra valent in nature.

1.2.1.2 Doping:

- The process of adding impurities to an intrinsic semiconductor is known as doping.

1.2.1.3 Extrinsic Semiconductors:

- With respect to the type of impurity added, extrinsic semiconductors are classified into two types.
    - N- type semiconductors
    - P- type semiconductors

1.2.1.3.1 N- type semiconductors

- When a small amount of penta valent impurity (e.g. Antimony, Arsenic) is added to a pure semiconductor, we will get N - type semiconductor.
- The addition of penta valent gives a large number of free electrons in the semiconductors crystal.

Tetra valent	+	Penta valent	= N- type Semiconductor
(4 electrons)	+	(5 electrons)	= 9 electrons
			= 9 Negative charges
			= Excess of an electron

- The Majority Carriers in N - type are electrons (Negative charges) and Minority carriers are holes (positive charges).
- N – type semiconductors are known as Donor impurities because they donate free electrons to the semiconductor crystal.

1.2.1.3.2 P - type semiconductors

- When a small amount of trivalent material (e.g. Indium, Gallium) is added to a pure semiconductor, we will get P - type semiconductor.
- The addition of trivalent impurity gives a large number of holes in the semiconductor.
- The hole shows absence of an electron.

Tetra valent	+	Tri valent	= P – type Semiconductor
(4 electrons)	+	(3 electrons)	= 7 electrons
			= Shortage of an electron
			= One positive charge
			= Hole

- In a P - type semiconductor, Majority carriers are holes and Minority carriers are electrons.
- P - type semiconductors are called Acceptor Impurities because the holes created can accept the electrons.

1.3 P-N Junction as a Diode

- A junction is formed by joining P - type semiconductor with N – type semiconductor, the structure is called PN Junction or PN Diode.
- The structure of PN junction diode is shown in figure 1.1.

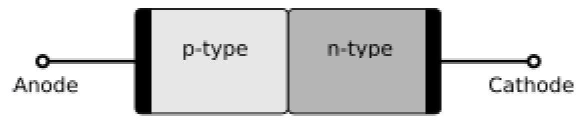


Fig.1.1 PN Junction diode

- Symbol of diode is given in figure 1.2.

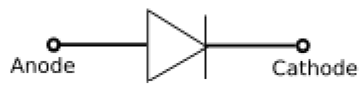


Fig. 1.2 Symbol of PN Junction diode

1.3.1 Parameters used in PN Junction diode

- Figure 1.3 shows the open circuited PN Junction.

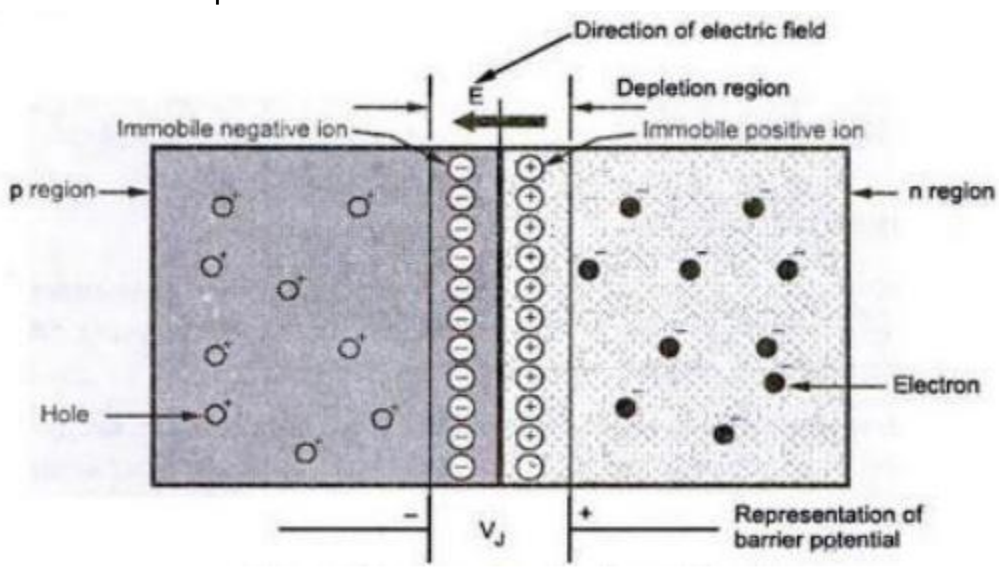


Fig. 1.3 Open circuited (No Biasing) PN Junction

- The free electrons from the n-region start diffusing into the p-region.
- The holes from p-side diffuse across the junction into the n-region.
- As more and more electrons recombine in p-region and holes in n-region, more charges get formed near the junction.
- Hence in equilibrium condition there exists a layer of negative charges in p-region and positive charges in n-region, near the junction.

1.3.1.1 Diffusion:

- Diffusion is the process by which electrons move from high concentration area towards low concentration area.

1.3.1.2 Depletion region:

- A region is formed with empty free charge carriers at both the sides of junctions are called as depletion region (or) depletion layer (or) space charge region.

1.3.1.3 Potential barrier:

- The barrier which does not allow charge flow across the junction is called as potential barrier.

Semiconductor material	Symbol	Barrier potential
Silicon	Si	0.6 V
Germanium	Ge	0.2 V

- The barrier potential depends on,
  - Type of semiconductor
  - The acceptor impurity added
  - The donor impurity added
  - The temperature
  - Intrinsic concentration

1.3.1.4 Biasing:

- Applying external D.C. voltage to any electronic device is called biasing.

1.4 Operation of PN Junction Diode

- Operation of a PN junction diode can be explained in two ways.
  - Forward Biasing
  - Reverse Biasing

1.4.1 Forward Biasing:

- If an external d.c voltage is connected in such a way that the p-region terminal is connected to the positive terminal of the d.c. voltage and the n-region is connected to the negative terminal of the d.c, voltage.

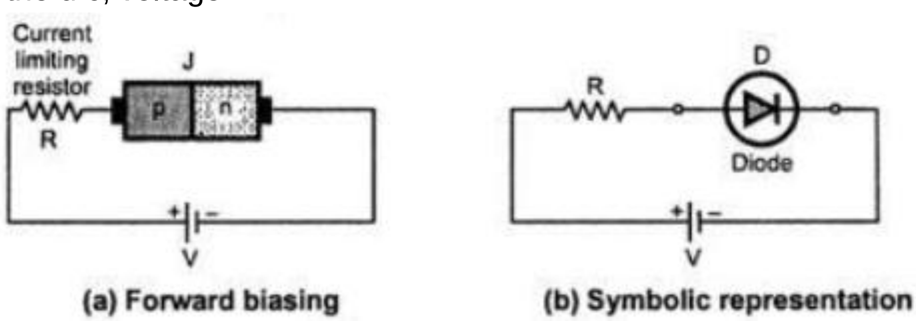


Fig. 1.4 Forward biasing of PN Junction Diode

1.4.1.1 Construction

- The Fig. 1.4 (a) shows the connection of forward biasing of a p-n junction.
- To limit the current, practically a current limiting resistor is connected in series with the p-n junction diode.
- The Fig. 1.4 (b) shows the symbolic representation of a forward biased diode.

1.4.1.2 Operation:

- As long as the applied voltage is less than the barrier potential, there cannot be any conduction.
- When the applied voltage becomes more than the barrier potential, the negative terminal of battery pushes the free electrons against barrier potential from n to p-region, and positive terminal pushes the holes from p to n-region.
- Thus holes get repelled by positive terminal & electrons get repelled by negative terminal and cross the junction against barrier potential.
- Thus the applied voltage overcomes the barrier potential, which reduces the width of depletion region.
- As forward voltage is increased, at a particular value the depletion region becomes very much narrow such that large number of majority charge carriers can cross the junction.
- Hence the overall forward current is due to the majority charge carriers.

1.4.1.3 Forward V-I Characteristics of PN Junction Diode

- The Fig. 1.5 shows the forward biased diode.

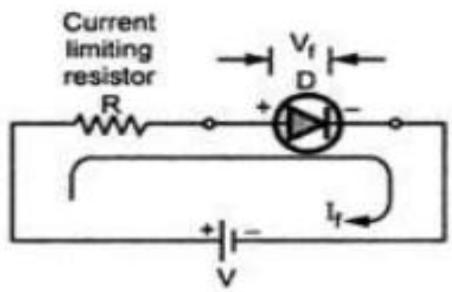


Fig. 1.5 Forward biased diode

- The applied voltage is V while the voltage across the diode is V_f and the current flowing in the circuit is the forward current I_f.
- The graph of forward current I_f against the forward voltage V_f across the diode is called forward characteristics of a diode and is shown in fig. 1.6.

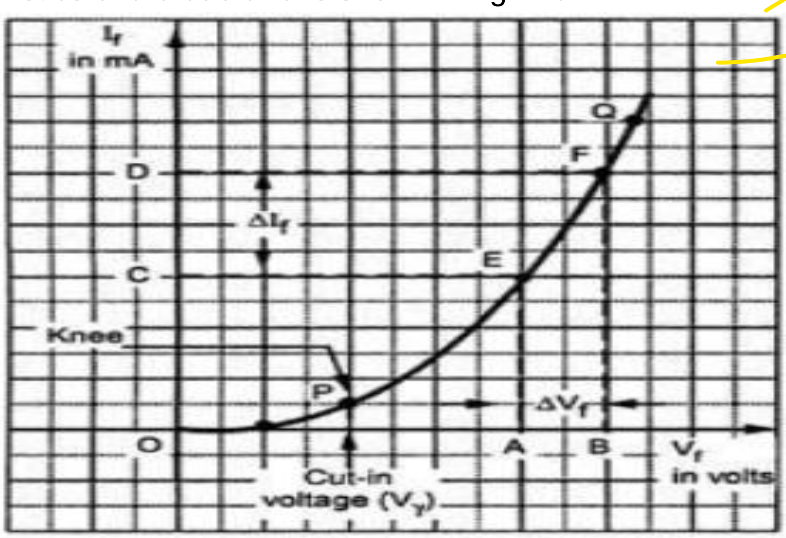


Fig. 1.6 Forward characteristics of a diode

Cut-in voltage:

- Minimum forward voltage required to conduct the diode.

Knee:

- The point P, after which the forward current starts increasing exponentially is called knee of the curve

1.4.1.4 Operation of forward characteristics

- **Region O to P (From Fig. 1.6):**
  - As long as V_f is less than cut in voltage (V_γ), the current flowing is very small.

- **Region P to Q and onwards (From Fig. 1.6):**
  - As V_f increases towards V_γ the width of depletion region goes on reducing.
  - When V_f exceeds V_γ i.e. cut-in voltage, the depletion region becomes very thin and current I_f Increases suddenly.
  - This increase in the current is exponential as shown in the Fig. 1.6 by the region P to Q.
  - The forward current is treated as positive and the forward voltage V_f is also treated positive.
  - Hence the forward characteristic is plotted in the first quadrant.

1.4.1.5 Forward Resistance of Diode

- The resistance offered by the p-n junction diode in forward biased condition is called forward resistance. The forward resistance is defined in two ways.

1.4.1.5.1 Static forward resistance:

- The resistance offered by the p-n junction under d.c, conditions is called static resistance and it is denoted as R_f
- It is calculated at any particular point on the forward characteristics.
- The static resistance R_f is defined as the ratio of the d.c, voltage applied across the p-n junction to the d.c. current flowing through the p-n junction.

$$R_f = \frac{\text{Forward d.c. voltage}}{\text{Forward d.c. current}} = \frac{OA}{OC} \text{ at point E}$$

1.4.1.5.2 Dynamic forward resistance:

- The resistance offered by the p-n junction under a.c, conditions is called as dynamic resistance and it is denoted as r_f.
- Consider the change in applied voltage from point A to B shown In the Fig. 1.6 and denoted as ΔV_f.
- The corresponding change in the forward current is from point C to D and denoted as ΔI_f.

$$r_f = \frac{\Delta V_f}{\Delta I_f} = \frac{1}{(\Delta I_f / \Delta V_f)} = \frac{1}{\text{Slope of forward characteristics}}$$

1.4.2 Reverse Biasing of P-N Junction Diode

- If an external d.c voltage is connected in such a way that the p-region terminal of a p-n junction is connected to the negative terminal of the battery and the n-region terminal of a p-n junction is connected to the positive terminal of the battery.

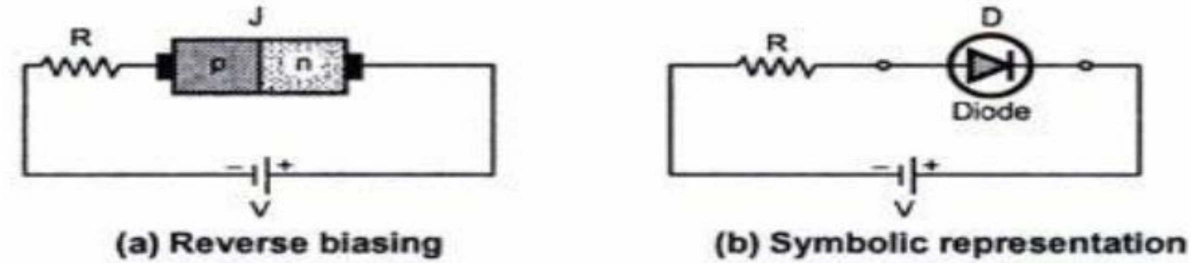


Fig. 1.7 Reverse biasing of PN Junction Diode

1.4.2.1 Construction

- The Fig. 1.7 (a) & 1.7 (b) shows the connection of a reverse biasing and symbolic representation of a p-n junction.

1.4.2.2 Operation:

- When the p-n junction is reverse biased, the negative terminal of battery attracts the holes in the p-region and it is away from the junction.
- The positive terminal of battery attracts the free electrons in the n-region and it is away from the junction.
- No charge carrier is able to cross the junction.
- As electrons and holes both move away from the junction, the depletion region widens.
- As depletion region widens, barrier potential across the junction also increases.
- The electrons on p side and holes on n side are minority charge carriers, which constitute the current in reverse biased condition.
- The current flow due to minority charge carriers alone is called as reverse saturation current (I_O) which are small in number.
- The generation of minority charge carriers depends on the temperature and not on the applied reverse bias voltage.

1.4.2.3 Reverse V-I Characteristics of PN Junction Diode

- The Fig. 1.8 shows the reverse biased diode.
- The reverse voltage across the diode is V_R while the current flowing is reverse current I_R due to minority charge carriers.
- The reverse voltage is taken as negative and reverse saturation current is also taken as negative.

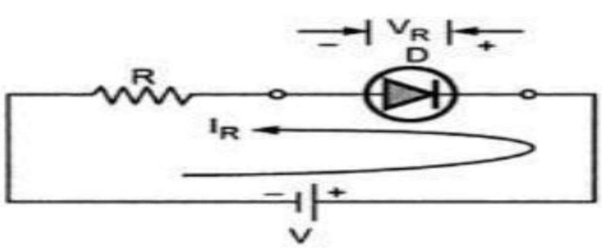


Fig. 1.8 Reverse biased diode

- The graph of I_R against V_R is called reverse characteristics of a diode and is shown in figure 1.9.

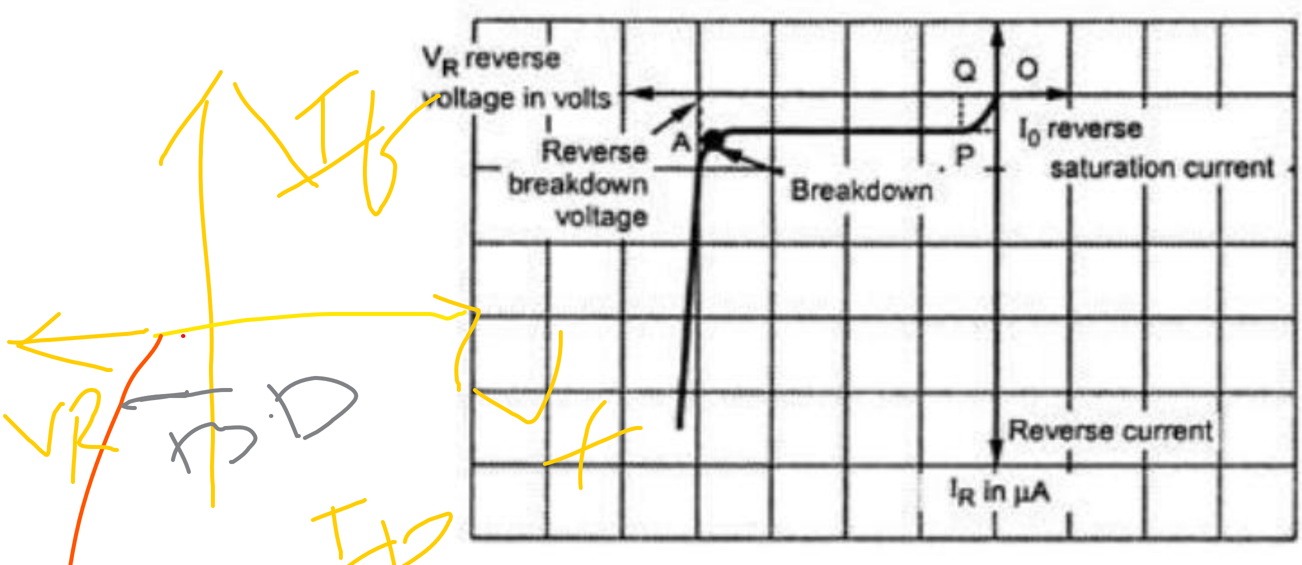


Fig. 1.9 Reverse characteristics of a diode

- As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current I_O, though reverse voltage is increased.
- The point A where breakdown occurs and reverse current Increases rapidly is called knee of the reverse characteristics.

Reverse Breakdown Voltage

- The maximum voltage at which breakdown occurs is called as reverse breakdown voltage.

1.4.2.4 Reverse Resistance of Diode

- The p-n junction offers large resistance in the reverse biased condition and is as called reverse resistance.
- This is also defined in two ways.

1.4.2.4.1 Reverse static resistance:

- This is reverse resistance under d.c conditions and it is denoted as R_r.
- It is the ratio of applied reverse voltage to the reverse saturation current I_O.

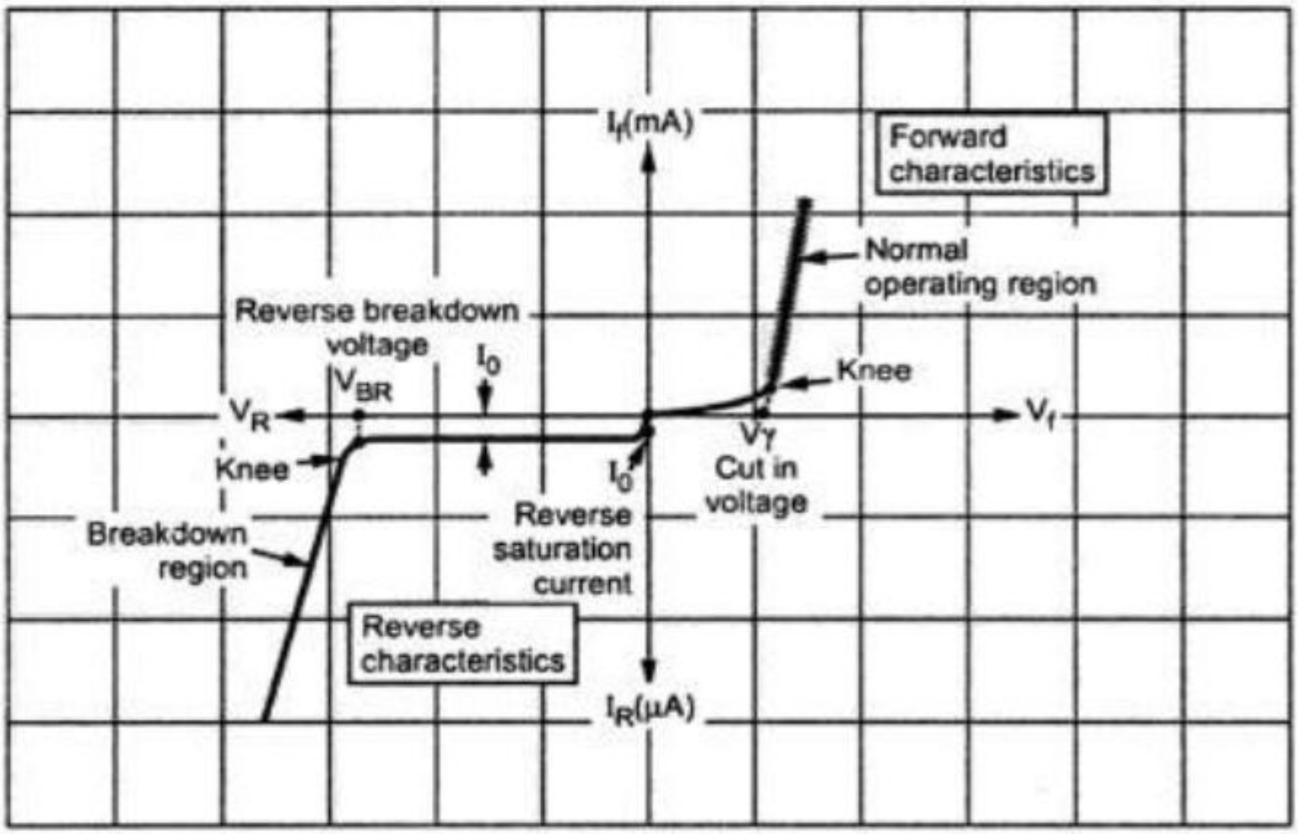
$$R_r = \frac{OQ}{I_0} = \frac{\text{Applied reverse voltage}}{\text{Reverse saturation current}}$$

1.4.2.4.2 Reverse dynamic resistance:

- This is the reverse resistance under the a.c. conditions and it is denoted as r_r.
- It is the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

$$r_r = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{Change in reverse voltage}}{\text{Change in reverse current}}$$

1.5 Complete V-I Characteristics of a Diode



1.10 Complete V-I Characteristics of a Diode

1.6 Diode Equation

- Let us study the derivation of the mathematical expression for the current through a diode, which gives its V-I characteristics.
- Let

  p_p = Hole concentration in p type at the edge of depletion region
  n_n = Electron concentration in n type at the edge of depletion region
  p_n = Hole concentration in n type at the edge of depletion region
  n_p = Electron concentration in p type at the edge of depletion region
- Under unbiased condition, when holes move from p side to n side due to diffusion, their concentration behaves exponentially.
- This is mathematically expressed as,

$$p_p = p_n e^{V_J / V_T} \quad \text{------- (1)}$$

Where V_J = Barrier potential or junction potential

- Now consider forward biased diode as shown in the Fig. 1.11.

- The junction is at x = 0.

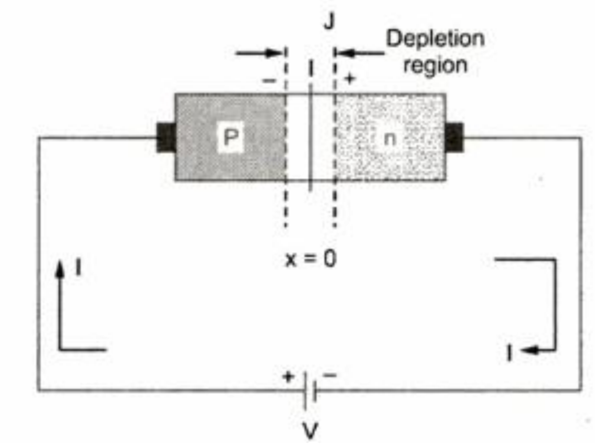


Fig. 1.11 p-n Junction Diode

- Though the proportion of holes and electrons in constituting a current through the p-region is changing the hole concentration throughout the entire p-region is constant and denoted as,

  P_{p0} = Hole concentration in p-region

- As holes cross the junction, this concentration becomes $p_n(0)$ which is concentration of holes on n-side just near the junction.
- This further behaves exponential as given in the equation (1).
- From equation (1) we can write,

$$p_{p0} = p_n(0)\,e^{(V_J - V)/V_T} \quad \text{----- (2)}$$

- The equation (2) can be written for open circuited unbiased p-n junction diode by putting V = 0 as,

$$p_{p0} = p_{n0}\,e^{V_J/V_T} \quad \text{... (3)}$$

- Where p_{n0} is the concentration of holes on n-side just near the junction when diode is open circuited i.e. at thermal equilibrium and hence different than $p_n(0)$.
- As the concentration of holes in entire p-region is constant equating (2) and (3) we get,

$$p_n(0)\,e^{(V_J - V)/V_T} = p_{n0}\,e^{V_J/V_T}$$

$$p_n(0) = p_{n0}\,e^{V/V_T} \quad \text{------ (4)}$$

- This equation represents boundary condition and called law of junction.
- This indicates that the hole concentration $P_n(0)$ at the junction under forward biased condition is greater than its thermal equilibrium value P_{n0}.
- For large forward biasing $P_n(0)$ becomes much larger compared to P_{n0}.
- This discussion is equally applicable for the electron Concentration on the p-side.
- Thus, $$n_p(0) = n_{p0}\, e^{V/V_T} \quad \text{----- (5)}$$
- Now the difference between two concentrations at the junction under unbiased condition is called injected or excess concentration denoted as $P_n(0)$.

$$P_n(0) = p_n(0) - p_{n0} \quad \text{---- (6)}$$

- Using (4) in (6),

$$P_n(0) = p_{n0}\, e^{V/V_T} - p_{n0}$$

$$P_n(0) = p_{n0}(e^{V/V_T} - 1) \quad \text{------ (7)}$$

- Similarly, $$N_p(0) = n_{p0}(e^{V/V_T} - 1) \quad \text{----- (8)}$$
- The hole current crossing the junction from p-side to n-side is given by,

$$I_{pn}(0) = \frac{AqD_p P_n(0)}{L_p} \quad \text{----- (9)}$$

- While an electron current crossing the junction from n-side to p-side is given by,

$$I_{np}(0) = \frac{AqD_n N_p(0)}{L_n} \quad \text{----- (10)}$$

Where

A = Area of cross-section of junction
D_p = Diffusion constant for holes
D_n = Diffusion constant for electrons
L_p = Diffusion length for holes
L_n = Diffusion length for electrons

- Using (7), (8) in (9), (10), the total current I at the junction is given by,

$$I = I_{pn}(0) + I_{np}(0)$$

$$= \frac{AqD_p P_n(0)}{L_p} + \frac{AqD_n N_p(0)}{L_n}$$

$$= \left[\frac{AqD_p P_{n0}}{L_p} + \frac{AqD_n N_{p0}}{L_n}\right](e^{V/V_T} - 1)$$

$$I = I_0(e^{V/V_T} - 1) \quad \text{---- (11)}$$

Where I_0 = Reverse Saturation Current

$$I_0 = \frac{AqD_p P_{n0}}{L_p} + \frac{AqD_n N_{p0}}{L_n}$$

- The equation (11) is the required expression for diode current.
- To consider the generation and recombination effect in the depletion region, which is dominant in Si diodes, the factor η is introduced in the equation and is given by

$$\boxed{I = I_0(e^{V/\eta V_T} - 1)}$$

- The mathematical representation of V-I characteristics of diode is called V-I characteristics equation or diode current equation.
- It gives the mathematical relationship between applied voltage V and the diode current I and is given by,

$$\boxed{I = I_0\left[e^{V/\eta V_T} - 1\right] \ A} \quad \dots (1)$$

where

I_0 = Reverse saturation current in amperes

V = Applied voltage

η = 1 for germanium diode

= 2 for silicon diode

V_T = Voltage equivalent of temperature in volts.

- The factor η is called an emission coefficient or Ideality factor.
- This factor takes into account the effect of recombination taking place in the depletion region.

- The voltage equivalent of temperature indicates dependence of diode current on temperature.
- The voltage equivalent of temperature V_T for a given diode at temperature T is calculated as,

$$V_T = kT \text{ volts} \qquad \ldots (2)$$

where k = Boltzmann's constant = 8.62×10^{-5} eV/°K

T = temperature in °K.

At room temperature of 27 °C i.e. T = 27 + 273 = 300 °K and the value of V_T is 26 mV,

- The value of V_T also can be expressed as,

$$V_T = \frac{T}{\left(\frac{1}{k}\right)} = \frac{T}{\left(\frac{1}{8.62 \times 10^{-5}}\right)} = \frac{T}{11600} \qquad \ldots (3)$$

- The diode current equation is applicable for all the conditions of diode i.e, unbiased, forward biased and reverse biased.
- When unbiased V=0 tends to I=0
- For forward bias V=Positive value tends to I=Positive value
- For Reverse bias V=Negative value tends to I=Negative value

Example : *The voltage across a silicon diode at room temperature of 300°K is 0.71 V when 2.5 mA current flows through it. If the voltage increases to 0.8 V, calculate the new diode current.*

Solution : The current equation of a diode is

$$I = I_0 \left(e^{V/\eta V_T} - 1\right)$$

At 300 °K, $V_T = 26 \text{ mV} = 26 \times 10^{-3}$ V

$V = 0.71$ V for I = 2.5 mA

and $\eta = 2$ for silicon

$$\therefore \quad 2.5 \times 10^{-3} = I_0 \left[e^{(0.71/2 \times 26 \times 10^{-3})} - 1 \right]$$

$$\therefore \quad I_0 = \mathbf{2.93 \times 10^{-9} \ V}$$

Now V = 0.8 V, I_0 remains same.

$$\therefore \quad I = 2.93 \times 10^{-9} \left[e^{(0.8/2 \times 26 \times 10^{-3})} - 1 \right] = 0.0141 \text{ A} = \mathbf{14.11 \ mA}$$

Example : *A germanium diode has a reverse saturation current of 3 μA. Calculate the voltage at which 1 % of the rated current will flow through the diode, at room temperature if diode is rated for 1 A.*

Solution :

$\eta = 1$ for germanium, $\quad I_0 = 3\ \mu A = 3 \times 10^{-6}$ A

Rated current is 1 A, and $\quad I = 1$ % of rated current $= 0.01$ A.

$V_T = 26$ mV at room temperature.

Using current equation of a diode,

$$I = I_0 \left[e^{V/\eta V_T} - 1\right]$$

$$\therefore \quad 0.01 = 3 \times 10^{-6} \left[e^{V/1 \times 26 \times 10^{-3}} - 1\right]$$

$$\therefore \quad 3333.33 = e^{V/1 \times 26 \times 10^{-3}} - 1$$

$$\therefore \quad e^{V/1 \times 26 \times 10^{-3}} = 3334.33$$

$$\therefore \quad \frac{V}{26 \times 10^{-3}} = 8.112$$

$$\therefore \quad V = \mathbf{0.2109\ V}$$

1.7 Temperature dependence of V-I characteristic on PN Junction diode

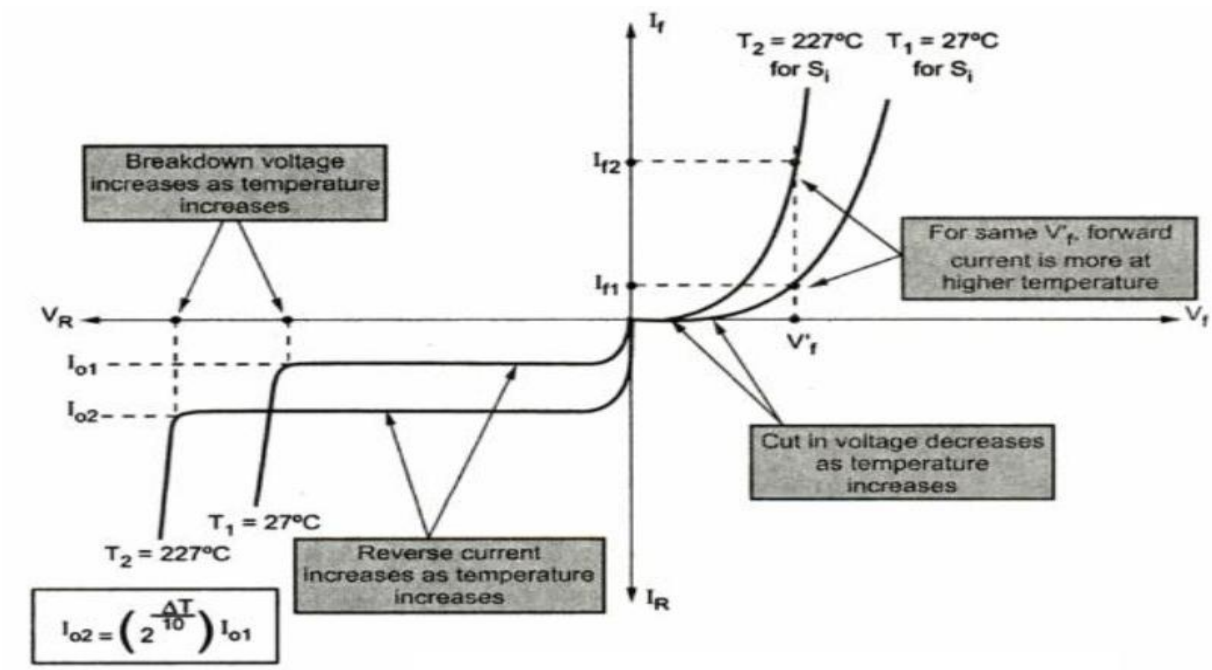


Fig. 1.12 Effect of temperature on PN Junction diode

- The temperature has following effects on the diode parameters and is shown in the fig. 1.12.
    - The cut-in voltage decreases as the temperature increases.
    - The forward current increases as the temperature increases.
    - The Break down voltage increases as the temperature increases.
    - The reverse saturation current increases as temperature increases.
- This increase in reverse current I_O is such that it doubles at every 10^0C rise in temperature. Mathematically,

$$\boxed{I_{o2} = 2^{(\Delta T/10)} I_{o1}}$$

where

$$I_{o2} = \text{Reverse current at } T_2 \,^\circ C$$
$$I_{o1} = \text{Reverse current at } T_1 \,^\circ C$$
$$\Delta T = (T_2 - T_1)$$

- The diode power dissipation is given by,

$$P_D = V_f I_f \quad \text{Watts}$$

- To avoid the overheating and damage of the device, the maximum safe value of power dissipation is mentioned in the datasheet of the diode. It is $(P_D)_{max}$.
- At higher temperature, as the device junction temperature is higher, it can dissipate less power.
- Thus maximum power dissipation of the device must be derated at high temperatures and is shown in Fig. 1.13.

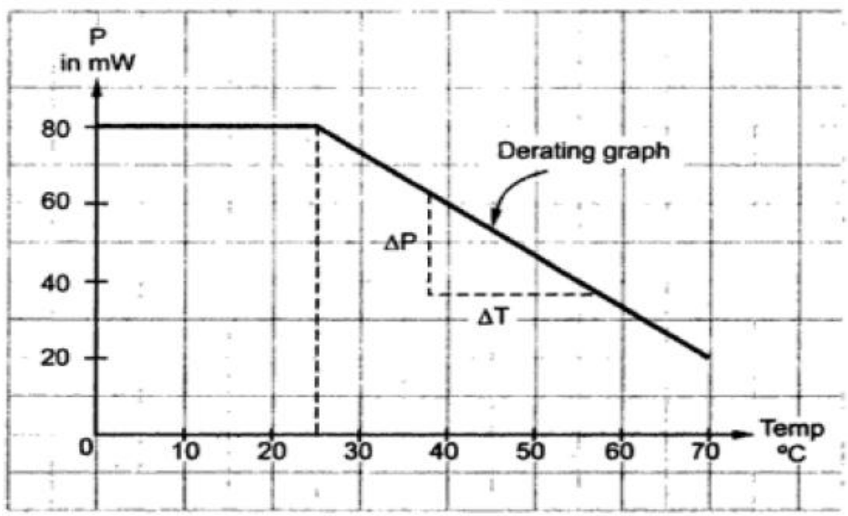


Fig. 1.13 Power derated at high temperatures

Example *A silicon diode has a saturation current of 7.5 µA at room temperature 300 K. Calculate the saturation current at 400 K.*

Solution Given $I_{o1} = 7.5 \times 10^{-6}$A at $T_1 = 300\text{K} = 27^\circ\text{C}$ and $T_2 = 400\text{K} = 127\,^\circ\text{C}$

Therefore, the saturation current at 400 K is

$$I_{o2} = I_{o1} \times 2^{(T_2 - T_1)/10}$$

$$= 7.5 \times 10^{-6} \times 2^{(127-27)/10}$$

$$= 7.68 \text{ mA}$$

Example : *A diode is rated for 500 mW at 27 °C. It has a derating factor of 4 mW/ °C. Find maximum forward current at i) 27 °C and ii) 77 °C, assuming silicon diode.*

Solution : $P_1 = 500$ mW, $T_1 = 27$ °C, Derating factor = 4 mW/ °C

i) At $T_1 = 27$ °C, $P_1 = V_f \, I_{f1}$

For silicon diode, assume $V_f = 0.7$ V constant.

$$\therefore \quad I_{f1} = \frac{P_1}{V_f} = \frac{500 \times 10^{-3}}{0.7} = \mathbf{0.7142\ A}$$

ii) At $T_2 = 77$ °C, $P_2 = (P_1 \text{ at } T_1) - [\Delta T \times \text{Derating factor}]$

$$\therefore \quad P_2 = [500 \times 10^{-3}] - \left[(77-27) \times 4 \times 10^{-3}\right] = 300 \text{ mW}$$

$$\therefore \quad I_{f2} = \frac{P_2}{V_f} = \frac{300 \times 10^{-3}}{0.7} = \mathbf{0.4285\ A}$$

1.8 Junction Capacitances

- Depending upon the biasing condition, two types of capacitive effects exist in the diodes. These are.
  - Transition capacitance (C_T) under reverse biased condition.
  - Diffusion capacitance (C_D) under forward biased condition.

1.8.1 Transition Capacitance (C_T or C_{pn})

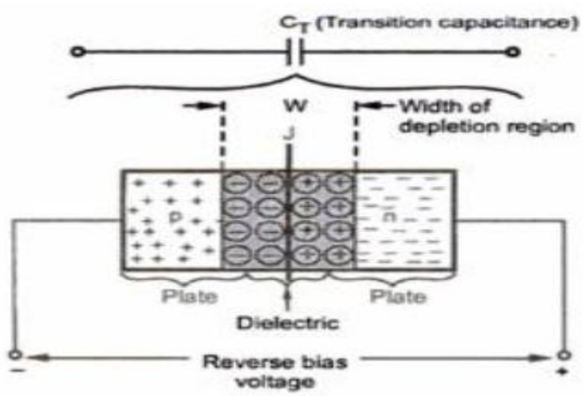


Fig. 1.14 Transition Capacitance

- When a diode is reverse biased, the width of the depletion region increases.
- So there are more positive and negative charges present in the depletion region.

- Due to this, the p-region and n-region act like the plates of capacitor while the depletion region acts like dielectric.
- Thus there exists a capacitance at the p-n junction called as transition capacitance.
- It is denoted as C_T and is shown in figure 1.14.
- Mathematically it is given by the expression,

$$\boxed{C_T = \frac{\varepsilon A}{W}}$$

where

$$\varepsilon = \text{permittivity of semiconductor} = \varepsilon_0 \varepsilon_r$$

$$\varepsilon_0 = \frac{1}{36\pi \times 10^9} = 8.849 \times 10^{-12} \text{ F/m}$$

$$\varepsilon_r = \text{relative permittivity of semiconductor} = 16 \text{ for Ge}, 12 \text{ for Si}$$

$$A = \text{area of cross section}$$

$$W = \text{width of depletion region}$$

- As the reverse bias applied to the diode increases, the width of the depletion region (W) increases. Thus the transition capacitance C_T decreases.
- In short, the capacitance can be controlled by the applied voltage. The variation of C_T with respect to the applied reverse bias voltage is shown in the Fig. 1.15.

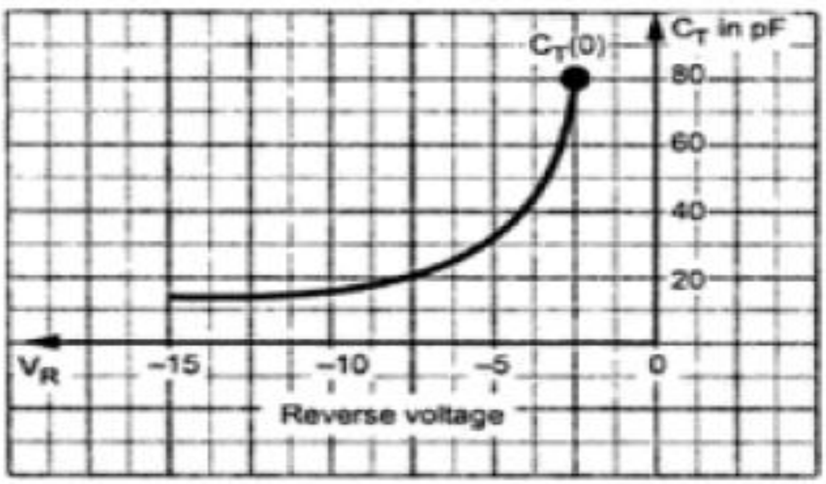


Fig. 1.15 Variation of C_T versus Reverse voltage

- As reverse voltage is negative, graph is shown in the second quadrant.
- The value of transition capacitance is of the order of pico farads.
- For a particular diode shown, C_T varies from 80 pF to less than 5 pF as V_R changes from 2 V to 15 V.

1.8.2 Diffusion Capacitance (C_D)

- During forward biased condition, another capacitance comes into existence called diffusion capacitance (or) storage capacitance and denoted as C_D.

- In forward biased condition, the width of the depletion region decreases and holes from p side get diffused in n side while electrons from n side move into the p-side.
- As the applied voltage increases, concentration of injected charged particles increases.
- This rate of change of the Injected charge with applied voltage is defined as a capacitance called diffusion capacitance.

$$\boxed{C_D = \frac{dQ}{dV}}$$

- The diffusion capacitance expression can also be given as

$$\boxed{C_D = \frac{\tau I}{\eta V_T}}$$

where

τ = mean life time for holes.

- So diffusion capacitance is proportional to the current.
- For forward biased condition, the value of diffusion capacitance is of the order of nano farads to micro farads while transition capacitance is of the order of pico farads.
- So $C_D >> C_T$.
- The graph of C_D against the applied forward voltage is shown in the Fig. 1.16.
- As the applied forward voltage increases, current I increases hence diffusion capacitance C_D increases.

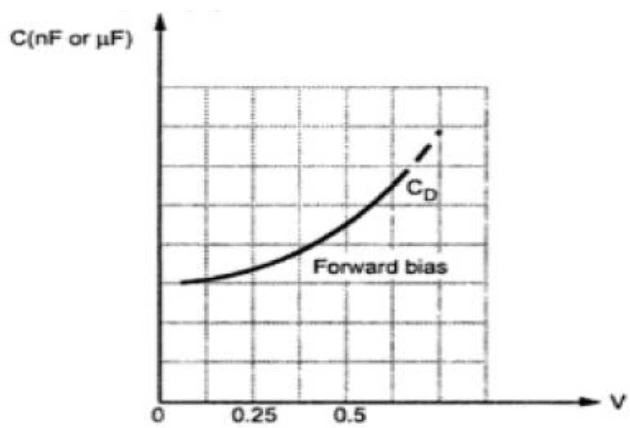


Fig. 1.16 Diffusion capacitance versus applied forward voltage

1.9 Diode Equivalent Circuits

- The diode is required to be replaced by the equivalent circuit in many practical electronic circuits, for the analysis purpose. Such an equivalent circuit of a diode is called circuit model of a diode.
- There are three methods of replacing diode by its circuit model, which are,
  - Practical diode model
  - Ideal diode model
  - Piecewise linear model

- When the diode is forward biased, the total voltage drop across the diode is V_f which is equal to sum of the drop due to barrier potential(cut-in voltage V_γ) and the drop across the internal forward dynamic resistance r_f of the diode.
- When the diode is reverse biased, reverse saturation current is very small and practically neglected. Hence reverse biased diode is practically assumed to be open circuit.

1.9.1 Practical Diode Model

- In forward bias, the practical diode model consists of a battery equal to cut-in voltage and the forward resistance in series with an ideal diode which is shown in fig.1.17 (a).
- In reverse bias, it is open circuited and is shown in fig. 1.17 (b).
- While the Fig. 1.17 (c) shows the corresponding V-I characteristics.

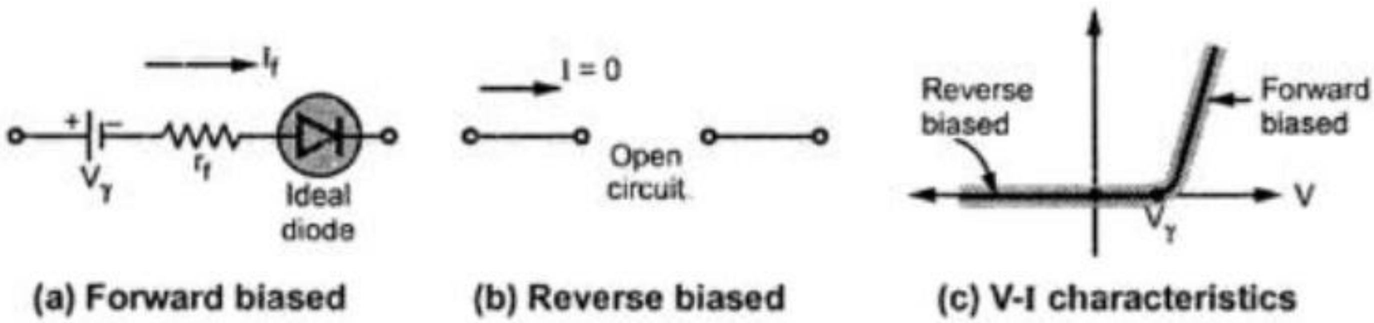


Fig. 1.17 Practical diode model

1.9.2 Ideal Diode Model

- In many cases, as the forward resistance of diode is small and cut-in voltage is also small, the diode is assumed to be an ideal diode.
- In case of ideal diode, it is assumed that it starts conducting instantaneously when applied voltage V_D is just greater than zero and the drop across the conducting diode is zero.
- So conducting diode can be ideally replaced by a short circuit, for the analysis of various diode circuits.
- The Fig. 1.18 shows the ideal diode characteristics.

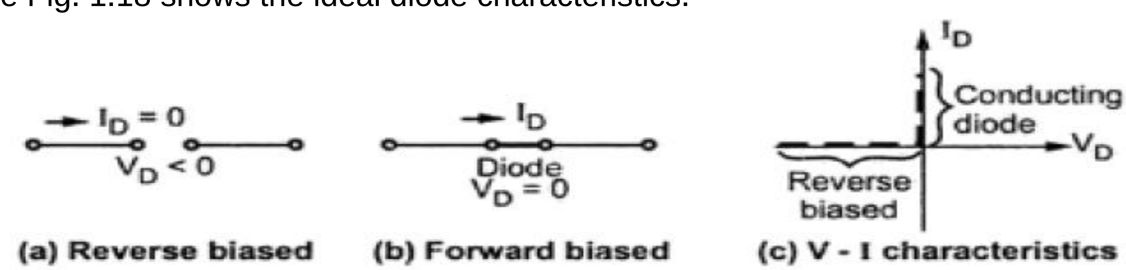


Fig. 1.18 Ideal diode model

1.9.3 Piecewise linear Model of Diode

- Another way to analyze the diode circuits is to approximate the V-I characteristics of a diode using only straight lines i.e. linear relationships.

- In such approximation, the diode forward resistance is neglected and the diode is assumed to conduct instantaneously when applied forward biased voltage V_D is equal to cut-in voltage V_Y and is shown in the fig. 1.19 (a).
- When the diode is in reverse biased condition i.e $V_D < 0$, the diode does not conduct at all and is shown in the Fig. 1.19 (b).
- As the diode conducts at $V_D=V_Y$, the V-I characteristics with straight lines is as shown in the Fig. 1.19 (c).

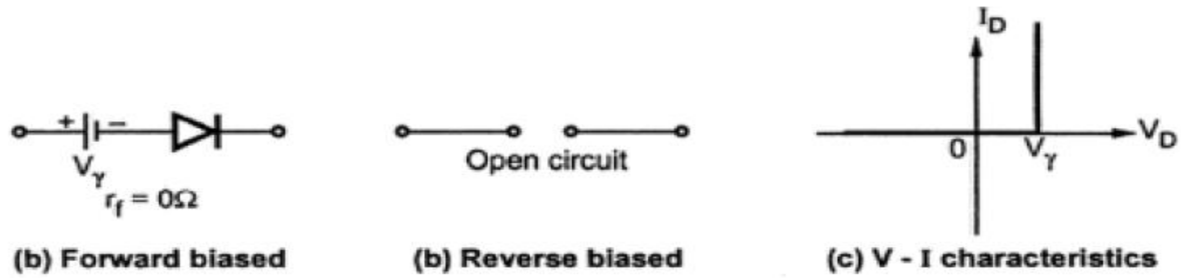


Fig. 1.19 Linear piecewise model of diode when $r_f = 0$

- If forward resistance is considered to be finite, then forward biased characteristic is a straight line with a slope equal to reciprocal of r_f and is shown in the fig. 1.20 (a).
- In reverse bias, the diode is still assumed to be open circuited and is shown in the fig. 1.20 (b).
- The linear piecewise model with finite forward resistance r_f is shown in the Fig. 1.20 (c).

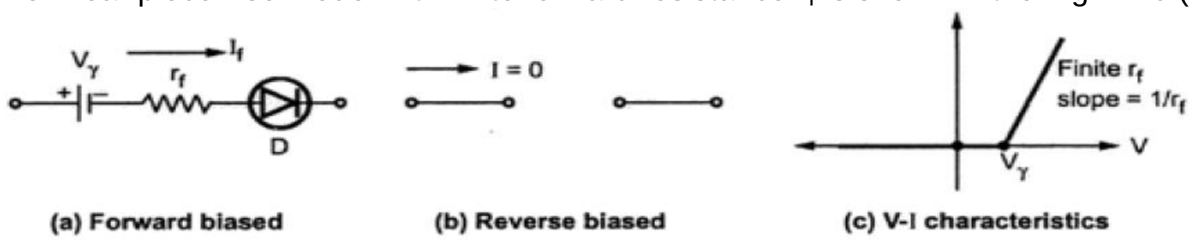


Fig. 1.20 Linear piecewise model of diode with finite r_f

1.10 Introduction to Rectifiers (Need of Rectifier)

- The p-n junction diode conducts only in one direction.
- It conducts when forward biased while practically it does not conduct when reverse biased.
- Thus if an alternating voltage is applied across a p-n junction diode, during positive half cycle the diode will be forward biased and will conduct successfully.
- While during the negative half cycle it will be reversed biased and will not conduct at all.

1.10.1 Rectifier

- A rectifier is a device which converts a.c. voltage to pulsating d.c. voltage, using one or more p-n junction diode.

1.10.2 The Important Characteristics of a Rectifier Circuit

- Waveform of the load current
- Regulation of the output voltage

- Rectifier efficiency
- Peak value of current
- Peak value of voltage across the rectifier element in the reverse direction (PIV)
- Ripple factor

1.10.3 Types of Rectifier Circuits

- Using one or more diodes, following rectifier circuits can be designed.
  - Half wave rectifier (HWR)
  - Full wave rectifier (FWR)
  - Bridge rectifier(BR)

1.11 Half Wave Rectifier

- In half wave rectifier, diode conducts only during positive half cycle of input a.c. supply.
- During negative half cycles of a.c, supply, there is no output at the load.

1.11.1 Construction

- This rectifier circuit consists of a.c. voltage source, rectifying element (p-n junction diode) and resistive load , all are connected in series.
- The circuit diagram is shown in the Fig. 1.21.

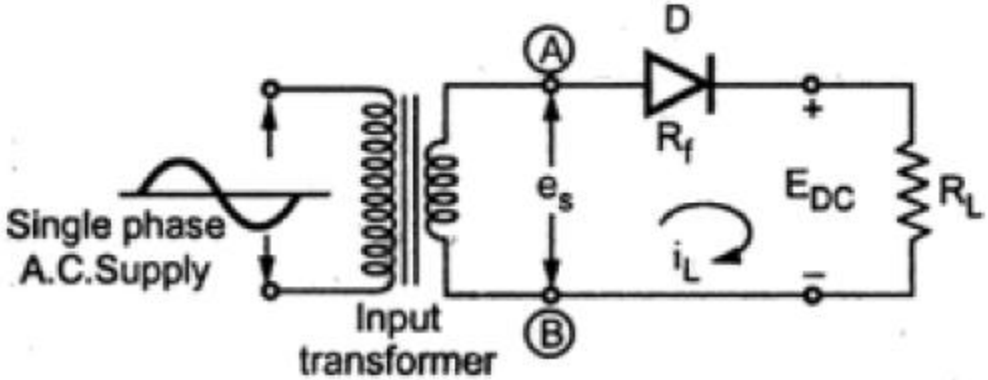


Fig. 1.21 Half wave rectifier

- To obtain the desired d.c voltage across the load, the a.c voltage is applied to rectifier circuit using suitable step-down transformer with necessary turns ratio.
- The input voltage to the half wave rectifier circuit is a sinusoidal a.c voltage, having a supply frequency of 50 Hz and is given by

$$e_s = E_{sm} \sin \omega t$$

Where

$$\omega = 2\pi f$$
$$f = \text{Supply frequency}$$

- The transformer decides the peak value of the secondary voltage.
- If N_1 are the primary number of turns and N_2 are the secondary number of turns and E_{pm} is the peak (or) maximum value of the primary voltage and E_{sm} is the peak (or) maximum value of the secondary voltage then,

$$\frac{N_2}{N_1} = \frac{E_{sm}}{E_{pm}}$$

- R_f represents the forward resistance of the diode.

1.11.2 Operation

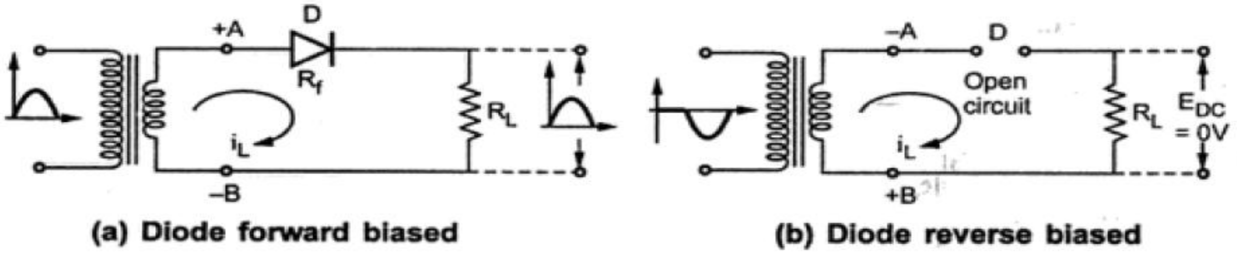


Fig. 1.22 Operation of Half wave Rectifier

- During the positive half cycle of secondary a.c voltage, terminal (A) becomes positive with respect to terminal (B).
- The diode is forward biased and the current flows in the circuit in the clockwise direction, as shown in the Fig. 1.22 (a).
- The current will flow for almost full positive half cycle. This current is also flowing through load resistance R_L hence denoted as load current i_L.
- During negative half cycle when terminal (A) is negative with respect to terminal (B), diode becomes reverse biased.
- Hence no current flows in the circuit as shown in the Fig. 1.22 (b).

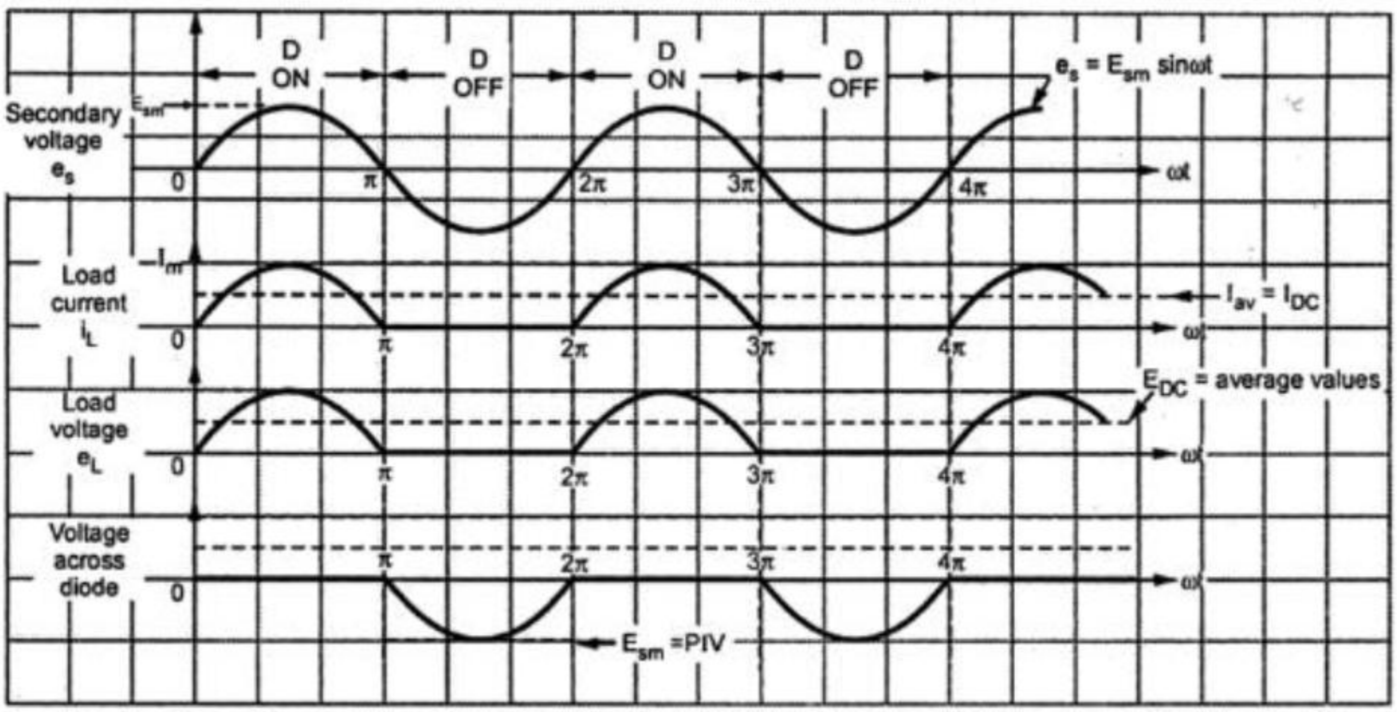


Fig. 1.23 Waveforms of Half wave Rectifier

- Thus the circuit current, which is also the load current, is in the form of half sinusoidal pulses.

- The load voltage, being the product of load current and load resistance, will also be in the form of half sinusoidal pulses.
- The different waveforms are illustrated in Fig. 1.23.

1.11.3 Parameters of Half Wave Rectifier

- Average D.C. Load Current (I_{DC})
- Average D.C. Load Voltage (E_{DC})
- R.M.S. Value of Load Current (I_{RMS})
- D.C. Power Output (P_{DC})
- A.C. Power Input (P_{AC})
- Rectifier Efficiency (η)
- Ripple Factor (ϒ)
- Peak Inverse Voltage (PIV)
- Transformer Utilization Factor (TUF)
- Voltage Regulation

1.11.3.1 Average D.C. Load Current (I_{DC})

- The average or d.c value of alternating current is obtained by integration.
- For finding out the average value of an alternating waveform, we have to determine the area under the curve over one complete cycle i.e. from 0 to 2π and then dividing it by the base 2π.
- Mathematically, current waveform can be described as,

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

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

where

$$I_m = \text{Peak value of load current}$$

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i_L \, d(\omega t) = \frac{1}{2\pi}\int_0^{2\pi} I_m \sin(\omega t)\, d(\omega t)$$

- As no current flows during negative half cycle of a.c, input voltage, i.e. between ωt = π to ωt =2π, we change the limits of integration.

$$I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\, d(\omega t) = \frac{I_m}{2\pi}\left[-\cos(\omega t)\right]_0^{\pi}$$

$$= -\frac{I_m}{2\pi}\left[\cos(\pi) - \cos(0)\right] = -\frac{I_m}{2\pi}[-1-1] = \frac{I_m}{\pi}$$

$$\boxed{I_{DC} = \frac{I_m}{\pi} = \text{Average value}}$$

- Applying Kirchhoff's voltage law we can write,

$$\boxed{I_m = \frac{E_{sm}}{R_f + R_L + R_s}}$$

Where R_S = Resistance of secondary winding of transformer.

1.11.3.2 Average D.C. Load Voltage (E_{DC})

- It is the product of average D.C. load current and the load resistance R_L.

$$E_{DC} = I_{DC} R_L$$

- Substituting value of I_{DC} in the above equation

$$E_{DC} = \frac{I_m}{\pi} R_L$$

$$= \frac{E_{sm}}{(R_f + R_L + R_s)\pi} R_L$$

$$\boxed{E_{DC} = \frac{E_{sm}}{\pi\left[\frac{R_f + R_s}{R_L} + 1\right]}}$$

- The winding resistance R_S and forward diode resistance R_f are practically very small compared to R_L.
- $(R_f + R_S)/R_L$ is negligibly small compared to 1. So we get,

$$\boxed{E_{DC} \approx \frac{E_{sm}}{\pi}}$$

1.11.3.3 R.M.S. Value of Load Current (I_{RMS})

- The R.M.S means squaring, finding mean and then finding square root. Hence R.M.S. value of load current can be obtained as,

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} (I_m \sin \omega t)^2 \, d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} \left(I_m{}^2 \sin^2 \omega t \, d(\omega t)\right)}$$

$$= I_m \sqrt{\frac{1}{2\pi}\int_0^{\pi} \frac{[1 - \cos(2\omega t)]\, d(\omega t)}{2}} = I_m \sqrt{\frac{1}{2\pi}\left\{\frac{\omega t}{2} - \frac{\sin(2\omega t)}{4}\right\}_0^{\pi}}$$

$$= I_m \sqrt{\frac{1}{2\pi}\left(\frac{\pi}{2}\right)} \qquad \text{as } \sin(2\pi) = \sin(0) = 0$$

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

$$\boxed{I_{RMS} = \frac{I_m}{2}}$$

1.11.3.4 D.C. Power Output (P_{DC})

- The d.c. power output can be obtained as,

$$\boxed{P_{DC} = E_{DC} I_{DC} = I_{DC}^2 R_L}$$

- For half wave rectifier, we have $I_{DC} = I_m / \pi$

$$P_{DC} = I_{DC}^2 R_L$$

$$= \left[\frac{I_m}{\pi}\right]^2 R_L$$

$$P_{DC} = \frac{{I_m}^2}{\pi^2} R_L$$

where

$$I_m = \frac{E_{sm}}{R_f + R_L + R_s}$$

$$\therefore \quad \boxed{P_{DC} = \frac{{E_{sm}}^2 R_L}{\pi^2 [R_f + R_L + R_s]^2}}$$

1.11.3.5 A.C. Power Input (P_{AC})

- The a.c. power is given by,

$$\boxed{P_{AC} = I_{RMS}^2 [R_L + R_f + R_s]}$$

- For half wave rectifier, we have $I_{RMS} = I_m / 2$

$$\boxed{P_{AC} = \frac{I_m^2}{4} [R_L + R_f + R_s]}$$

1.11.3.6 Rectifier Efficiency (η)

- The rectifier efficiency is defined as the ratio of D.C. output power to A.C. input power.

$$\eta = \frac{\text{D.C. output power}}{\text{A.C. input power}} = \frac{P_{DC}}{P_{AC}}$$

$$\eta = \frac{\frac{I_m^2}{\pi^2} R_L}{\frac{I_m^2}{4} [R_f + R_L + R_s]} = \frac{(4/\pi^2) R_L}{(R_f + R_L + R_s)}$$

$$\therefore \quad \boxed{\eta = \frac{0.406}{1 + \left(\frac{R_f + R_s}{R_L}\right)}}$$

- We know that, $(R_f + R_S) << R_L$. So we get the maximum theoretical efficiency of half wave rectifier as,

$$\boxed{\% \eta_{max} = 0.406 \times 100 = 40.6 \%}$$

- If the efficiency of rectifier Is 40 % then what happens to the remaining 60 % power.
- It is present in terms of ripples in the output which is fluctuating component present in the output.

1.11.3.7 Ripple Factor (ɤ)

- It is seen that the output of half wave rectifier is not pure d.c, but a pulsating d.c.
- The output contains pulsating components called ripples.
- The measure of ripples present in the output is with the help of a factor called ripple factor denoted by ɤ.
- Mathematically ripple factor is defined as the ratio of R.M.S. value of the a.c. component in the output to the average or d.c. component present in the output.

$$\boxed{\text{Ripple factor} \quad \gamma = \frac{\text{R.M.S. value of a.c. component of output}}{\text{Average or d.c. component of output}}}$$

- Now the output current is composed of a.c. component as well as d.c. component.

Let

I_{ac} = r.m.s. value of a. c. component present in output

I_{DC} = d.c. component present in output

I_{RMS} = R.M.S. value of total output current

$$I_{RMS} = \sqrt{I_{ac}^2 + I_{DC}^2}$$

$$I_{ac} = \sqrt{I_{RMS}^2 - I_{DC}^2}$$

- As per definition

$$\boxed{\text{Ripple factor} = \frac{I_{ac}}{I_{DC}}}$$

$$\gamma = \frac{\sqrt{I_{RMS}^2 - I_{DC}^2}}{I_{DC}}$$

$$\boxed{\gamma = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1}}$$

- This is the general expression for ripple factor and can be used for any rectifier circuit.

1.11.3.7.1 Ripple Factor (ɤ) for half wave rectifier

- Now for a half wave circuit, we have

$$I_{RMS} = \frac{I_m}{2} \quad \text{while} \quad I_{DC} = \frac{I_m}{\pi}$$

$$\gamma = \sqrt{\left[\frac{\left(\frac{I_m}{2}\right)}{\left(\frac{I_m}{\pi}\right)}\right]^2 - 1} = \sqrt{\frac{\pi^2}{4} - 1} = \sqrt{1.4674}$$

$$\boxed{\gamma = 1.211} \qquad \text{.. Halfwave}$$

- This indicates that the ripple contents in the output are 1.211 times the d.c. component

1.11.3.8 Peak Inverse Voltage (PIV)

- The Peak Inverse Voltage is the peak voltage across the diode in the reverse direction i.e., when the diode is reverse biased.
- In half wave rectifier, the load current is ideally zero when the diode is reverse biased and hence the maximum value of the voltage that can exist across the diode is nothing but E_{sm}.

$$\therefore \quad \boxed{\text{PIV of diode} = E_{sm} = \text{Maximum value of secondary voltage} = \pi \, E_{DC}\big|_{I_{DC}=0}}$$

1.11.3.9 Transformer Utilization Factor (TUF)

- The factor which indicates how much is the utilization of the transformer in the circuit is called Transformer Utilization Factor (TUF)

$$\text{T.U.F.} = \frac{\text{D.C. power delivered to the load}}{\text{A.C. power rating of the transformer}}$$

- A.C. power rating of transformer = $E_{RMS}\, I_{RMS}$

$$= \frac{E_{sm}}{\sqrt{2}} \cdot \frac{I_m}{2}$$

$$= \frac{E_{sm}\, I_m}{2\sqrt{2}}$$

- D.C. power delivered to the load = $I_{DC}^2\, R_L$

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

$$\text{T.U.F.} = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{E_{sm} I_m}{2\sqrt{2}}\right)}$$

- Neglecting the drop across R_f and R_S we can write,

$$E_{sm} = I_m R_L$$

$$T.U.F = \frac{I_m^2}{\pi^2} \cdot \frac{R_L \cdot 2\sqrt{2}}{I_m^2 R_L}$$

$$= \frac{2\sqrt{2}}{\pi^2}$$

$$\boxed{T.U.F = 0.287}$$

- The value of T.U.F. is low which shows that in half wave rectifier circuit, the transformer is not fully utilized.

1.11.3.10 Voltage Regulation

- The voltage regulation is defined as the change in the d.c output voltage as load changes from no load to full load condition.

If $(V_{dc})_{NL}$ = D.C. voltage on no load

$(V_{dc})_{FL}$ = D.C. voltage on full load.

- Then voltage regulation is defined as,

$$\boxed{\text{Voltage regulation} = \frac{(V_{dc})_{NL} - (V_{dc})_{FL}}{(V_{dc})_{FL}}}$$

Where

$$(V_{dc})_{NL} = \frac{E_{sm}}{\pi}$$

$$(V_{dc})_{FL} = I_{DC} R_L = \frac{I_m}{\pi} R_L = \frac{E_{sm}}{\pi[R_f + R_s + R_L]} \times R_L$$

1.11.4 Advantages of Half Wave Rectifier

- Only one diode is required
- Circuit is easy to design
- No centre transformer is necessary

1.11.5 Disadvantages of Half Wave Rectifier

- The ripple factor of half wave rectifier circuit is 1.21, which is quite high
- The maximum theoretical rectification efficiency is found to be 40% which is very low.
- TUF is very low showing that the transformer is not fully utilized.
- To minimize the saturation, transformer size have to be increased which increases the cost

Example : *A half wave rectifier circuit connected to a 230 V, 50 Hz source, through a transformer of turn ratio of 10 : 1. The rectifier circuit is to supply power to a 500 Ω, 1 watt resistor and diode forward resistance is 100 Ω .*

Calculate :

1) Maximum, average and r.m.s. value of current and voltage.

2) Efficiency of rectification.

3) Percentage regulation.

Solution : $E_p(\text{r.m.s.}) = 230$ V, $N_1/N_2 = 10{:}1$, $R_L = 500\ \Omega$, $R_f = 100\ \Omega$

$$\frac{N_2}{N_1} = \frac{1}{10} = \frac{E_{s\,(\text{r.m.s.})}}{E_{p\,(\text{r.m.s.})}}$$

$$\therefore \quad E_{s\,(\text{r.m.s.})} = \frac{1}{10} \times 230 = 23 \text{ V}$$

$$\therefore \quad E_{sm} = \sqrt{2} \times E_{s(\text{r.m.s.})} = \sqrt{2} \times 23 = 32.5269 \text{ V.}$$

1) $\therefore \quad I_m = \dfrac{E_{sm}}{R_f + R_L} = \dfrac{32.5269}{100+500} = \mathbf{54.2115\ mA}$ ...Maximum current

$\therefore \quad I_{av} = I_{DC} = \dfrac{I_m}{\pi} = \mathbf{17.2561\ mA}$ ...Average current

$\therefore \quad I_{R.M.S.} = \dfrac{I_m}{2}$ for half wave $= \mathbf{27.1058\ mA}$

$\therefore \quad E_{DC} = I_{DC} R_L = \mathbf{8.628\ V}$

2) $\therefore \quad P_{DC} = I_{DC}^2 R_L = 0.14888$ W

$P_{AC} = I_{RMS}^2 (R_L + R_f) = 0.44083$ W

$\therefore \quad \%\,\eta = \dfrac{P_{DC}}{P_{AC}} \times 100 = \dfrac{0.14888}{0.44083} \times 100 = \mathbf{33.7723\ \%}$

3) $(V_{d.c.})_{NL} = \dfrac{E_{sm}}{\pi} = \dfrac{32.5269}{\pi} = 10.3536$ V

$(V_{d.c.})_L = E_{DC} = 8.628$ V

$\therefore \quad \%\,R = \dfrac{(V_{dc})_{NL} - (V_{dc})_L}{(V_{dc})_L} \times 100 = \mathbf{20\ \%}$

Example *A voltage of 200 cos wt is applied to HWR with the load resistance of 5 kΩ. Find the maximum d.c. current component, r.m.s current, ripple factor, TUF and the rectifier efficiency.*

Solution : Comparing input voltage to E_{sm} sin $(\omega t+\phi)$, $\phi = 90°$

$$\therefore \quad E_{sm} = 200 \text{ V}, \quad R_L = 5 \text{ k}\Omega$$

$$\therefore \quad I_m = \frac{E_{sm}}{R_L + R_f + R_s} = \frac{200}{5\times 10^3} = \mathbf{40 \ mA} \qquad \ldots R_f = R_s = 0$$

$$\therefore \quad I_{RMS} = \frac{I_m}{2} = \frac{40}{2} = \mathbf{20 \ mA} \qquad \ldots \text{Half wave}$$

$$\gamma = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1} \quad \text{where} \quad I_{DC} = \frac{I_m}{\pi} = 12.7324 \text{ mA}$$

$$= \sqrt{\left(\frac{20}{12.7324}\right)^2 - 1} = \mathbf{1.21}$$

$$\text{TUF} = \frac{\text{D.C. power output}}{\text{A.C. power rating of transformer}} = \frac{I_{DC}^2 R_L}{\left(\frac{E_{sm}}{\sqrt{2}} \frac{I_{sm}}{2}\right)}$$

$$= \frac{(12.7324\times 10^{-3})^2 \times 5\times 10^3}{\left(\frac{200}{\sqrt{2}}\right)\left(\frac{40\times 10^{-3}}{2}\right)} = \mathbf{0.2865}$$

Note that for half wave rectifier $I_{RMS} = \frac{I_m}{2}$

$$P_{AC} = I_{RMS}^2 R_L = (20\times 10^{-3})^2 \times 5\times 10^3 = 2 \text{ W}$$

$$P_{DC} = I_{DC}^2 R_L = (12.7324\times 10^{-3})^2 \times 5\times 10^3 = 0.8105 \text{ W}$$

$$\therefore \quad \% \ \eta = \frac{P_{DC}}{P_{AC}} \times 100 = \frac{0.8105}{2} \times 100 = \mathbf{40.528 \ \%}$$

1.12 Full Wave Rectifier

- The full wave rectifier conducts during both positive and negative half cycles of input a.c supply.
- In order to rectify both the half cycles of a.c. input, two diodes are used in this circuit.
- The diodes feed a common load R_L with the help of a centre tap transformer.
- The a.c voltage is applied through a suitable power transformer with proper turns ratio.
- The full wave rectifier circuit is shown in the Fig. 1.24.

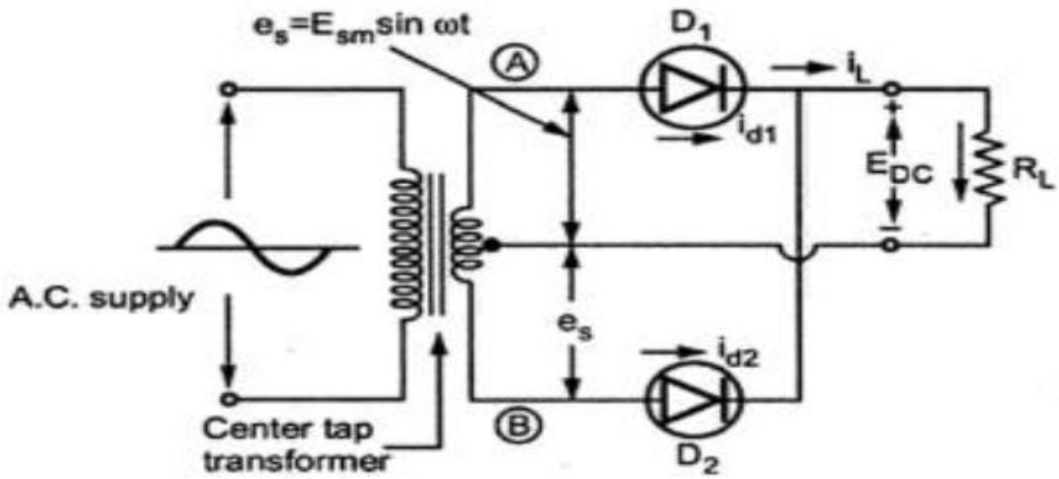


Fig. 1.24 Full wave Rectifier

1.12.1 Operation

- Consider the positive half cycle of a.c input voltage in which terminal (A) is positive and terminal (B) negative.
- The diode D_1 will be forward biased and hence will conduct.
- While diode D_2 will be reverse biased and will act as an open circuit and will not conduct.
- The diode D_1 supplies the load current, i.e. $i_L = i_{d1}$. This current is flowing through upper half of secondary winding.
- This is illustrated in the Fig. 1.25.

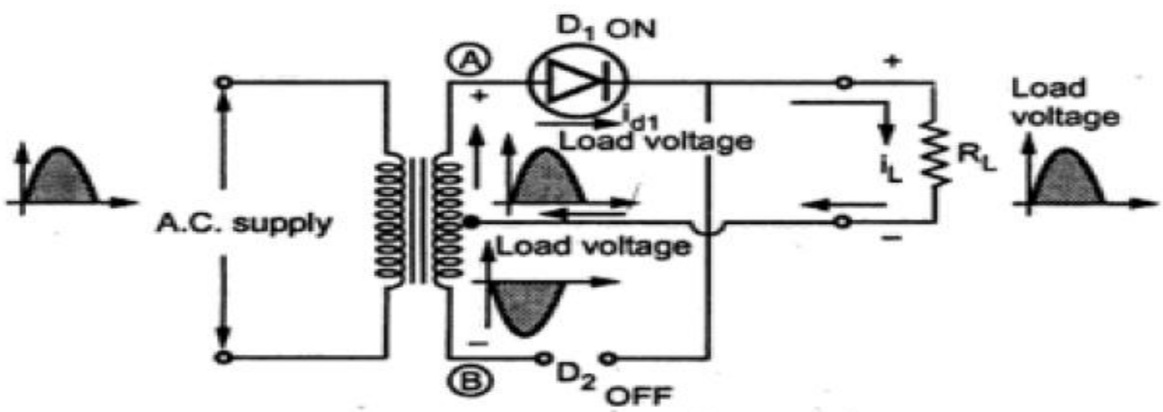


Fig. 1.25 current flow during positive half cycle

- During negative half cycle of a.c voltage, polarity reverses and terminal (A) becomes negative and (B) is positive.
- The diode D_2 conducts, being forward biased, while D_1 does not, being reverse biased.
- The diode D_2 supplies the load current, i.e. $i_L = i_{d2}$. Now the lower half of the secondary winding carries the current.
- This is shown in the Fig. 1.26.
- It is noted that the load current flows in both the half cycles of a.c voltage and in the same direction through the load resistance.
- Hence we get rectified output across the load.
- The load current is sum of individual diode currents flowing in corresponding half cycles.

- It is also noted that the two diodes do not conduct simultaneously but in alternate half cycles.

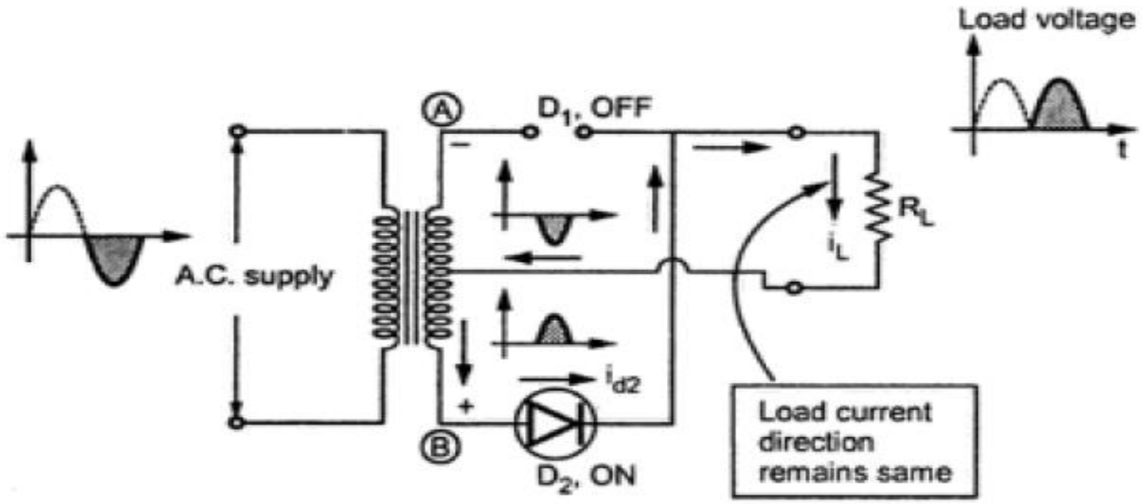


Fig. 1.26 current flow during negative half cycle

- The individual diode currents and the load current are shown in the Fig. 1.27.
- The output load current is still pulsating d.c and not pure d.c.

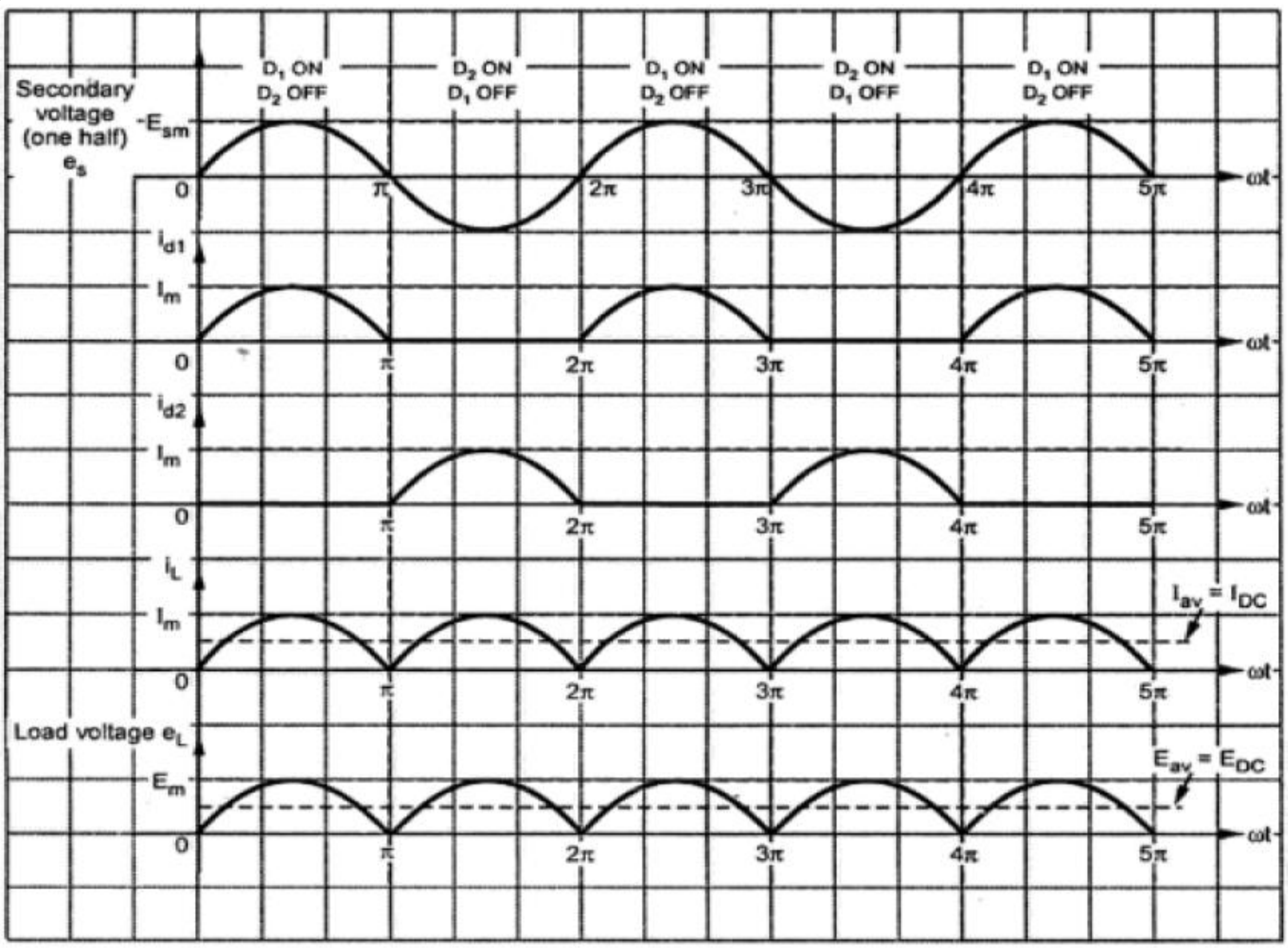


Fig. 1.27 Waveforms for Full wave rectifier

1.12.2 Parameters of FWR

- Average D.C. Load Current (I_{DC})
- Average D.C. Load Voltage (E_{DC})
- R.M.S. Value of Load Current (I_{RMS})
- D.C. Power Output (P_{DC})
- A.C. Power Input (P_{AC})
- Rectifier Efficiency (η)
- Ripple Factor (ϒ)
- Peak Inverse Voltage (PIV)
- Transformer Utilization Factor (TUF)
- Voltage Regulation

1.12.2.1 Average D.C. Load Current (I_{DC})

- Consider one cycle of the load current i_L from 0 to π to obtain the average' value which is d.c. value of load current.

$$i_L = I_m \sin \omega t \qquad 0 \le \omega t \le \pi$$

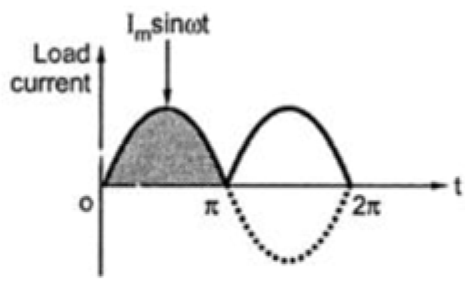


Fig. 1.28 Load Current waveform

$$I_{av} = I_{DC} = \frac{1}{\pi}\int_0^{\pi} i_L \, d(\omega t)$$

$$= \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t \, d\omega t$$

$$= \frac{I_m}{\pi}\left[(-\cos \omega t)_0^{\pi}\right]$$

$$= \frac{I_m}{\pi}[-\cos \pi - (-\cos 0)]$$

$$= \frac{I_m}{\pi}(+1 - (-1)] \qquad \text{... } \cos \pi = -1$$

$$\therefore \quad \boxed{I_{DC} = \frac{2I_m}{\pi}} \quad \text{for full wave rectifier}$$

1.12.2.2 Average D.C. Load Voltage (E_{DC})

- The d,c. load voltage is,

$$E_{DC} = I_{DC}R_L = \frac{2I_m R_L}{\pi}$$

- Substituting value of I_m in the above equation

$$E_{DC} = \frac{2\, E_{sm}\, R_L}{\pi\, [R_f + R_s + R_L]}$$

$$= \frac{2\, E_{sm}}{\pi \left[1 + \frac{R_f + R_s}{R_L}\right]}$$

- But as R_f & R_S << R_L hence (R_f & R_S)/ R_L << 1

$$\boxed{E_{DC} = \frac{2E_{sm}}{\pi}}$$

1.12.2.3 R.M.S. Value of Load Current (I_{RMS})

- The R.M.S value of current can be obtained as follows.

$$I_{R.M.S.} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2\, d(\omega t)}$$

- Since two half wave rectifier are similar in operation we can write

$$I_{R.M.S.} = \sqrt{2\, \frac{1}{2\pi}\int_0^{\pi} [I_m \sin \omega t]^2 d(\omega t)}$$

$$= I_m \sqrt{\frac{1}{\pi}\int_0^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right] d(\omega t)} \qquad \text{as } \sin^2 \omega t = \frac{1-\cos 2\omega t}{2}$$

$$\therefore \qquad I_{R.M.S.} = I_m \sqrt{\frac{1}{2\pi}\left[[\omega t]_0^{\pi} - \left(\frac{\sin 2\omega t}{2}\right)_0^{\pi}\right]} = I_m \sqrt{\frac{1}{2\pi}[\pi - 0]}$$

$$= I_m \sqrt{\frac{1}{2\pi}(\pi)} \qquad \text{as } \sin (2\pi) = \sin (0) = 0$$

$$\therefore \qquad \boxed{I_{R.M.S.} = \frac{I_m}{\sqrt{2}}}$$

1.12.2.4 D.C. Power Output (P_{DC})

- D.C. power output $P_{DC} = E_{DC}\, I_{DC} = I_{DC}^2\, R_L$
- For full wave rectifier, we have $I_{DC} = 2I_m / \pi$

$$P_{DC} = I_{DC}^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 R_L$$

$$P_{DC} = \frac{4}{\pi^2} I_m^2 R_L$$

- Substituting value of I_m we get,

$$\boxed{P_{DC} = \frac{4}{\pi^2} \frac{E_{sm}^2}{(R_s + R_f + R_L)^2} \times R_L}$$

1.12.2.5 A.C. Power Input (P_{AC})

- The a.c. power input is given by,

$$\boxed{P_{AC} = I_{RMS}^2 (R_f + R_s + R_L) = \left(\frac{I_m}{\sqrt{2}}\right)^2 (R_f + R_s + R_L)}$$

$$P_{AC} = \frac{I_m^2 (R_f + R_s + R_L)}{2}$$

- Substituting value of I_m we get,

$$P_{AC} = \frac{E_{sm}^2}{(R_f + R_s + R_L)^2} \times \frac{1}{2} \times (R_f + R_s + R_L)$$

$$\boxed{P_{AC} = \frac{E_{sm}^2}{2(R_f + R_s + R_L)}}$$

1.12.2.6 Rectifier Efficiency (η)

- The Rectifier Efficiency is given by

$$\boxed{\eta = \frac{P_{DC} \text{ output}}{P_{AC} \text{ input}}}$$

$$\eta = \frac{\frac{4}{\pi^2} I_m^2 R_L}{\frac{I_m^2 (R_f + R_s + R_L)}{2}}$$

$$\eta = \frac{8 R_L}{\pi^2 (R_f + R_s + R_L)}$$

- But $(R_f + R_S) << R_L$,

$$\eta = \frac{8 R_L}{\pi^2 (R_L)} = \frac{8}{\pi^2}$$

$$\% \eta_{max} = \frac{8}{\pi^2} \times 100$$

$$\boxed{\% \eta_{max} = 81.2 \%}$$

1.12.2.7 Ripple Factor (ɤ)

- As derived earlier, a general expression the ripple factor is given by

$$\text{Ripple factor} = \sqrt{\left[\frac{I_{RMS}}{I_{DC}}\right]^2 - 1}$$

- For full wave rectifier $I_{RMS} = I_m/\sqrt{2}$ and $I_{DC} = 2I_m/\pi$
- Substitute the above values in ripple factor equation

$$\text{Ripple factor} = \sqrt{\left[\frac{I_m/\sqrt{2}}{2I_m/\pi}\right]^2 - 1} = \sqrt{\frac{\pi^2}{8} - 1}$$

$$\boxed{\text{Ripple factor} = \gamma = 0.48}$$

1.12.2.8 Peak Inverse Voltage (PIV)

- Figure 1.29 shows the circuit diagram of full wave rectifier.

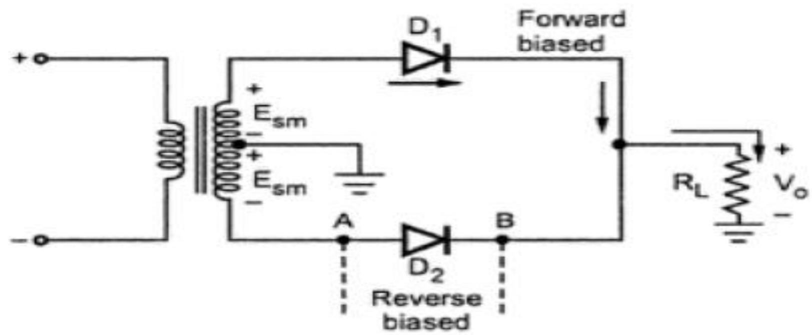


Fig. 1.29 PIV of Full wave rectifier

- It can be seen that when D_2 is reverse biased, point A is at - E_{sm} with respect to ground while point B is at + E_{sm} with respect to ground.
- Thus total peak voltage across D_2, is $2E_{sm}$.

$$\boxed{\text{PIV of diode} = 2\,E_{sm} = \pi E_{DC}\big|_{I_{DC}=0}}$$

1.12.2.9 Transformer Utilization Factor (TUF)

- In full wave rectifier, the secondary current flows through each half separately in every half cycle while the primary of transformer carries current continuously.
- Hence TUF is calculated for primary and secondary windings separately and then the average TUF is determined.

$$\text{Secondary T.U.F.} = \frac{\text{D.C. power to the load}}{\text{A.C. power rating of secondary}}$$

$$= \frac{I_{DC}^2\,R_L}{E_{RMS}\,I_{rms}} = \frac{\left(\frac{2}{\pi}I_m\right)^2 R_L}{\frac{E_{sm}}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}}$$

- Neglecting forward resistance R_f of diode, $E_{sm} = I_m R_L$

$$\text{Secondary T.U.F.} = \frac{\frac{4}{\pi^2} \times I_m^2 R_L}{\frac{I_m^2 R_L}{2}} = \frac{8}{\pi^2} = 0.812$$

- The primary of the transformer is feeding two half-wave rectifiers separately.

$$\text{T.U.F. for primary winding} = 2 \times \text{T.U.F. of half wave circuit}$$
$$= 2 \times 0.287 = 0.574.$$

- The average T.U.F for full wave rectifier circuit will be

$$\text{Average T.U.F. for full wave rectifier circuit} = \frac{\text{T.U.F. of primary} + \text{T.U.F. of secondary}}{2}$$
$$= \frac{0.574 + 0.812}{2} = \mathbf{0.693}$$

$$\boxed{\text{Average T.U.F. for full-wave rectifier} = 0.693}$$

1.12.2.10 Voltage Regulation

- For a full wave circuit,

$$(V_{dc})_{NL} = \frac{2 E_{sm}}{\pi}$$
$$(V_{dc})_{FL} = I_{DC} R_L$$

- The regulation can be expressed as,

$$\% R = \frac{(V_{dc})_{NL} - (V_{dc})_{FL}}{(V_{dc})_{FL}} \times 100$$

1.12.3 Advantages of Full Wave Rectifier

- The d.c load voltage and current are more than half wave.
- No d.c current through transformer windings hence no possibility of saturation.
- T.U.F. is better as transformer losses are less.
- The efficiency is higher.
- The large d.c power output.
- The ripple factor is less.

1.12.4 Disadvantages of Full Wave Rectifier

- The PIV rating of diode is higher.
- Higher PIV diodes are larger in size and costlier.
- The cost of centre tap transformer is higher.

Example : *A full-wave rectifier circuit is fed from a transformer having a centre-tapped secondary winding. The rms voltage from either end of secondary to center tap is 30 V. If the diode forward resistance is 2 Ω and that of the half secondary is 8 Ω, for a load of 1 kΩ, calculate,*

a) Power delivered to load, b) % Regulation at full load,
c) Efficiency of rectification, d) T.U.F. of secondary.

Solution : Given : $E_s = 30\,V,\ R_f = 2\Omega,\ R_s = 8\Omega,\ R_L = 1k\Omega$

$$E_s = E_{RMS} = 30\ V$$

$$E_{sm} = E_s\sqrt{2} = 30\sqrt{2}\ \text{volt} = 42.426\ V$$

$$I_m = \frac{E_{sm}}{R_f + R_L + R_s} = \frac{30\sqrt{2}}{2+1000+8}\ A$$

$$= 42\ mA$$

$$I_{DC} = \frac{2}{\pi}\ I_m = 26.74\ mA$$

a) Power delivered to the load $= I_{DC}^2\ R_L = (26.74 \times 10^{-3})^2\ (1k\Omega)$

$$= 0.715\ W$$

b) V_{DC}, no load $= \frac{2}{\pi}\ E_{sm} = \frac{2}{\pi} \times 30\sqrt{2} = 27\ V$

V_{DC}, full load $= I_{DC}\ R_L = (26.74\ mA)\ (1\ k\Omega)$

$$= 26.74\ V$$

$$\%\ \text{Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 = \frac{27 - 26.74}{26.74} \times 100$$

$$= 0.97\ \%$$

c) Efficiency of rectification $= \frac{D.C.\ output}{A.C.\ input}$

$$= \frac{8}{\pi^2} \times \frac{1}{1 + \frac{R_f + R_s}{R_L}} = \frac{8}{\pi^2} \times \frac{1}{1 + \frac{(2+8)}{1000}}$$

$$= 0.802\quad \text{i.e.}\ 80.2\ \%$$

d) Transformer secondary rating $= E_{RMS}\ I_{RMS} = [30\ V]\left[\frac{42\ mA}{\sqrt{2}}\right]$

$$= 0.89\ W$$

$\therefore$ $$T.U.F. = \frac{D.C.\ power\ output}{A.C.\ rating}$$

$$= \frac{0.715}{0.89} = 0.802$$

1.13 Bridge Rectifier

- The bridge rectifier circuit is essentially a full wave rectifier circuit, using four diodes, forming the four arms of an electrical bridge and is shown in figure 1.30.

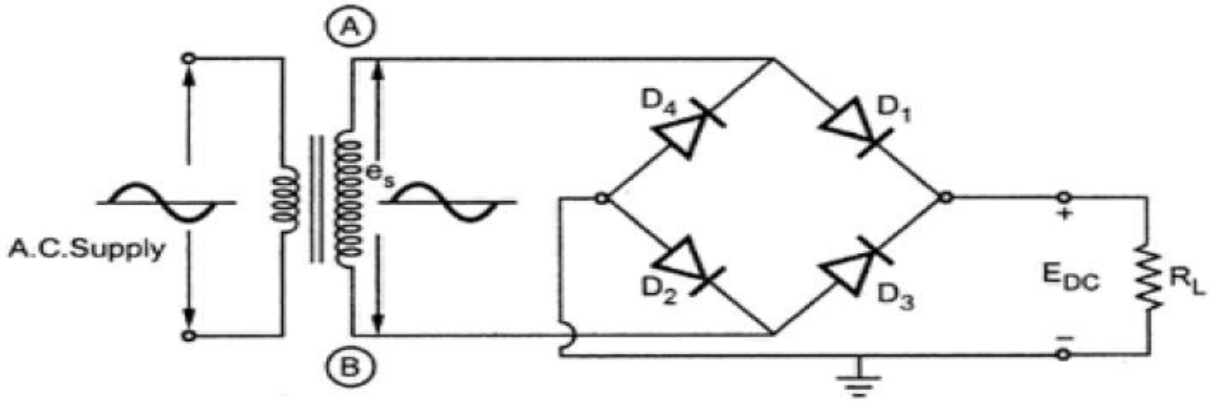


Fig. 1.30 Bridge Rectifier

- To one diagonal of the bridge, the a.c voltage is applied through a transformer and the rectified d.c voltage is taken from the other diagonal of the bridge.

1.13.1. Operation

- Consider the positive half of ac input voltage.
- The point A of secondary becomes positive. The diodes D_1 and D_2 will be forward biased, while D_3 and D_4 reverse biased.
- The two diodes D_1 and D_2 conduct in series with the load and the current flows as shown in Fig. 1.31.

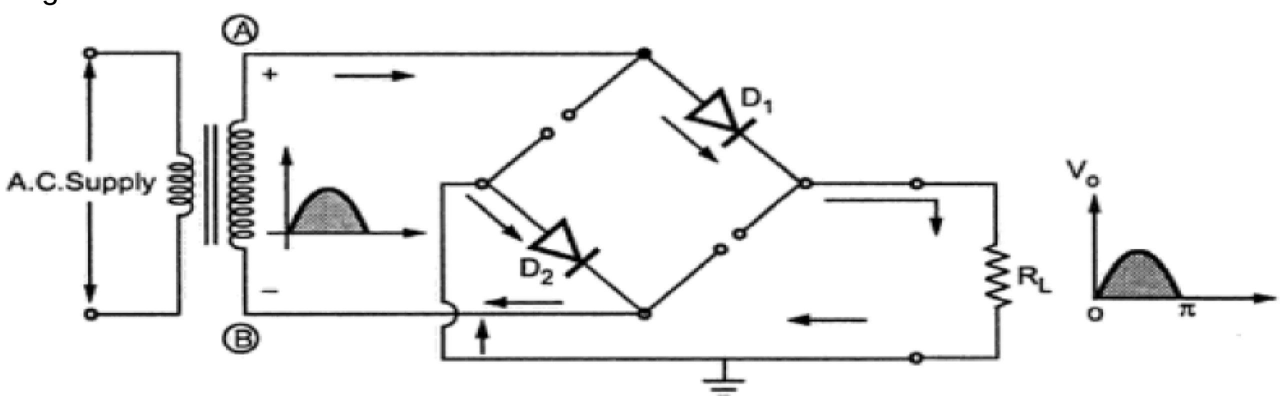


Fig. 1.31 Current flow during positive half cycle

- During negative hall cycle, the polarity of a.c voltage reverses hence point B becomes positive diodes D_3 and D_4 are forward biased, while D_1 and D_2 reverse biased.
- Now the diodes D_3 and D_4 conduct is series with the load and the current flows as shown in Fig. 1.32
- It is seen that in both cycles of a.c input, the load current is flowing in the same direction.

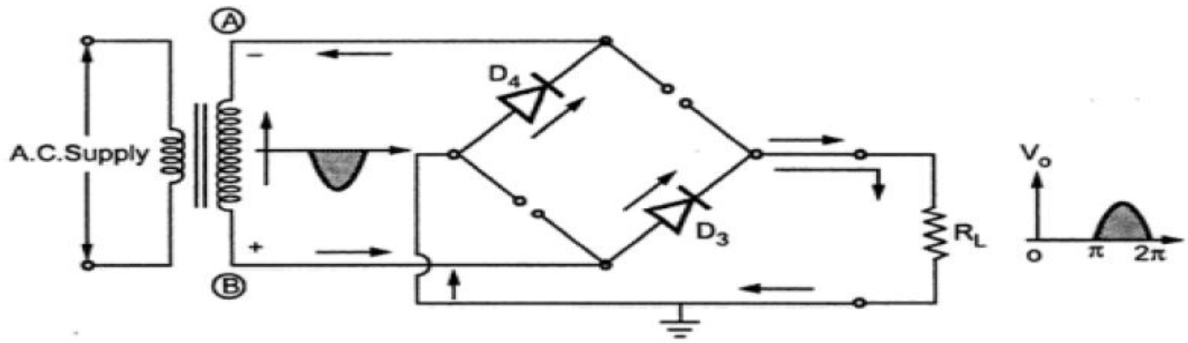


Fig. 1.32 Current flow during negative half cycle

- The waveforms of load current and voltage remain are shown in figure 1.33.

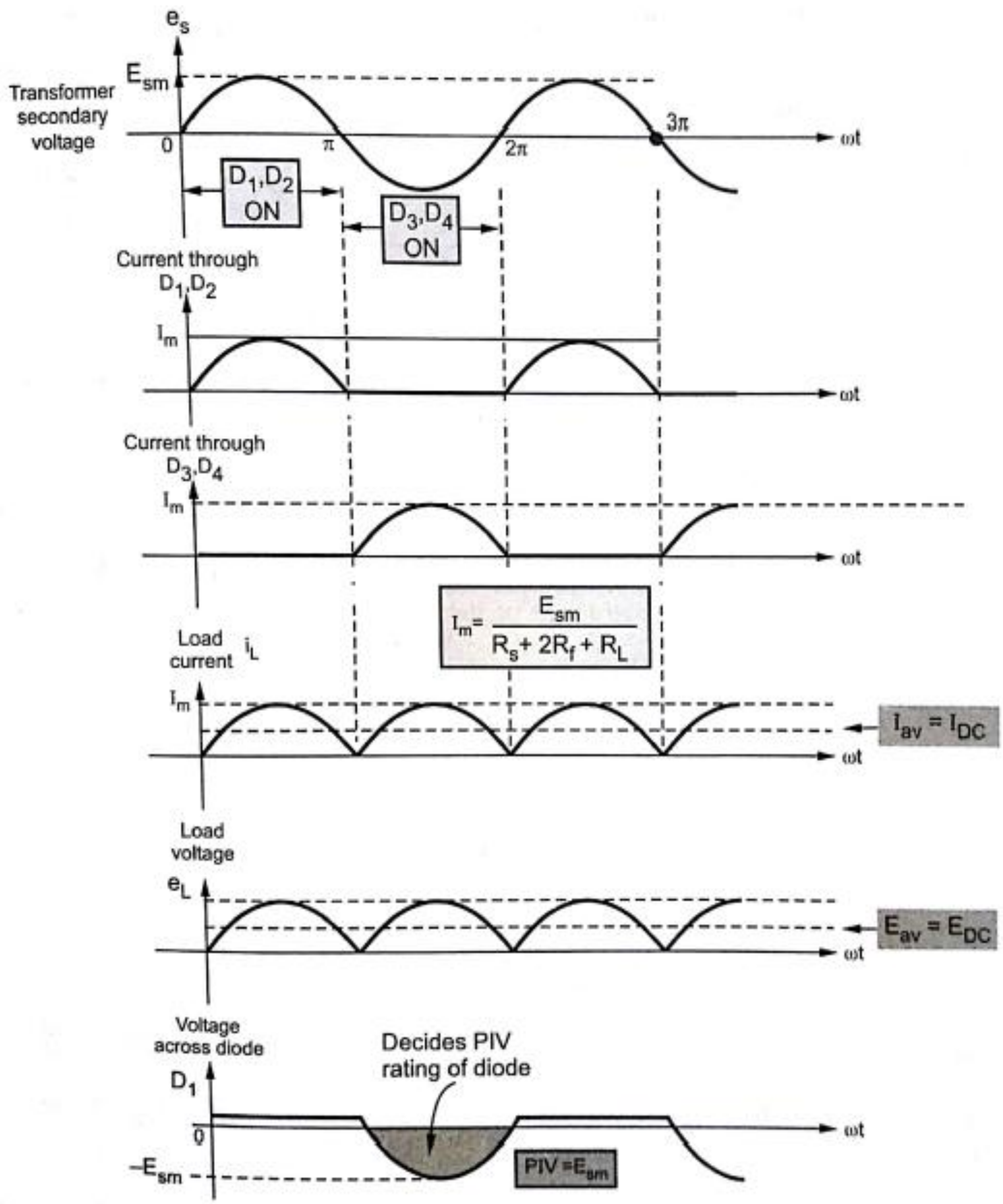


Fig. 1.33 waveforms of bridge Rectifier

1.13.2 Expressions for various parameters of Bridge Rectifier

- The bridge rectifier circuit, being basically a full wave rectifier circuit.
- All the derivations discussed previously for a full wave rectifier circuit using two diodes are applicable for a bridge rectifier circuit.
- The relation between I_m the maximum value of load current and I_{DC}, I_{RMS} remains same as derived earlier for the full wave rectifier circuit.

$$\boxed{I_{DC} = \frac{2I_m}{\pi} \quad \text{and} \quad I_{RMS} = \frac{I_m}{\sqrt{2}}}$$

- In each half cycle two diodes conduct simultaneously. Hence maximum value of Load current is,

$$\boxed{I_m = \frac{E_{sm}}{R_s + 2R_f + R_L}}$$

- The remaining expressions are identical to those derived for two diode full wave rectifier and reproduced for the convenience of the reader.

$$\begin{aligned}
E_{DC} &= I_{DC} R_L = \frac{2E_{sm}}{\pi} \\
P_{DC} &= I_{DC}^2 R_L = \frac{4}{\pi^2} I_m^2 R_L \\
P_{AC} &= I_{RMS}^2 (R_s + 2R_f + R_L) \\
&= \frac{I_m^2 (2R_f + R_s + R_L)}{2} \\
\eta &= \frac{8R_L}{\pi^2 (R_s + 2R_f + R_L)} \\
\% \eta_{max} &= 81.2 \% \\
\gamma &= 0.48
\end{aligned}$$

- The transformer utilization factor is 0.812.
- PIV rating of the diode is E_{sm}

1.13.3 Advantages of Bridge Rectifier

- Power transformer of a small size and less cost may be used.
- No centre tap is required in the transformer secondary.
- The transformer gets utilized effectively
- It is suitable for applications where large powers are required.
- It can be used for high voltage applications.

1.13.3 Disadvantages of Bridge Rectifier

- Use of four diodes
- Due to $2R_f$, this reduces the output voltage

Example : *A full-wave bridge rectifier is supplied from 230 V, 50 Hz and uses a transformer of turns ratio of 15 : 1. It uses load resistance of 50 Ω. Calculate load voltage and ripple voltage. Assume ideal diode and transformer. Assume standard value of ripple factor for full wave rectifier.*

Solution :

$$E_P \text{ (r.m.s.)} = 230 \text{ V}, \frac{N_2}{N_1} = \frac{1}{15}, R_L = 50 \ \Omega$$

$$R_f = R_s = 0 \ \Omega \quad \text{as ideal}$$

Now $$\frac{E_P \text{ (r.m.s.)}}{E_s \text{ (r.m.s.)}} = \frac{N_1}{N_2}$$

$$\therefore \quad E_s \text{ (r.m.s.)} = \frac{N_2}{N_1} \times E_P \text{ (r.m.s.)}$$

$$= \frac{1}{15} \times 230 = 15.333 \text{ V}$$

$$\therefore \quad E_{sm} = \sqrt{2} \ E_s \text{ (r.m.s.)} = 21.684 \text{ V}$$

$$\therefore \quad I_m = \frac{E_{sm}}{R_s + 2 \ R_f + R_L}$$

$$= \frac{21.684}{50} = 0.4336 \text{ A}$$

$$\therefore \quad I_{DC} = \frac{2 \ I_m}{\pi} = \frac{2 \times 0.4336}{\pi} = 0.276 \text{ A}$$

$$\therefore \quad E_{DC} = \text{Load voltage} = I_{DC} \ R_L = 0.276 \times 50 = \mathbf{13.8 \ V}$$

$$\text{Ripple factor} = 0.482 \qquad \text{... For full wave rectifier}$$

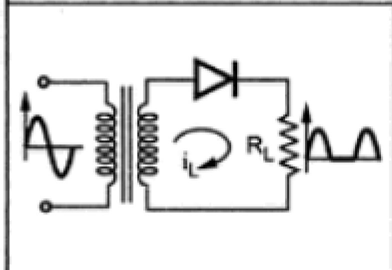
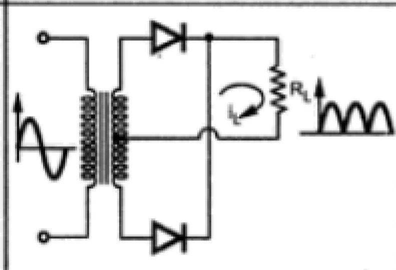
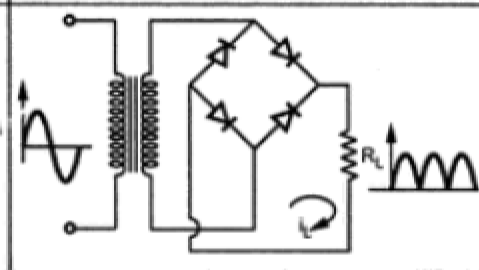
$$\text{Ripple factor} = \frac{\text{A.C. r.m.s. output}}{\text{D.C. output}}$$

$$= \frac{\text{Ripple voltage}}{E_{DC}}$$

$$\therefore \quad 0.482 = \frac{\text{Ripple voltage}}{13.8}$$

$$\therefore \quad \text{Ripple voltage} = 13.8 \times 0.482 = \mathbf{6.6516 \ V}$$

1.14 Comparison of Rectifier Circuits

Circuit diagrams		
Half wave	**Full wave**	**Bridge**
		

Sr. No.	Parameter	Half wave	Full wave	Bridge
1.	Number of diodes	1	2	4
2.	Average D.C. current (I_{DC})	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
3.	Average D.C. voltage (E_{DC})	$\frac{E_{sm}}{\pi}$	$\frac{2E_{sm}}{\pi}$	$\frac{2E_{sm}}{\pi}$
4.	R.M.S. current (I_{RMS})	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
5.	D.C. power output (P_{DC})	$\frac{I_m^2 R_L}{\pi^2}$	$\frac{4}{\pi^2} I_m^2 R_L$	$\frac{4}{\pi^2} I_m^2 R_L$
6.	A.C. power input (P_{AC})	$\frac{I_m^2(R_L + R_f + R_s)}{4}$	$\frac{I_m^2(R_f + R_s + R_L)}{2}$	$\frac{I_m^2(2R_f + R_s + R_L)}{2}$
7.	Maximum rectifier efficiency (η)	40.6 %	81.2 %	81.2 %
8.	Ripple factor (γ)	1.21	0.482	0.482
9.	Maximum load current (I_m)	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + 2R_f + R_L}$
10.	PIV rating of diode	E_{sm}	$2\ E_{sm}$	E_{sm}
11.	Ripple frequency	50 Hz	100 Hz	100 Hz
12.	T.U.F.	0.287	0.693	0.812

1.15 Filter Circuits

- It is seen that the output a half wave or full wave rectifier circuit is not pure d.c.
- But it contains fluctuations or ripple, which are undesired.
- To minimize the ripple content in the output, filter circuits are used.
- These circuits are connected between the rectifier and load as shown in the Fig. 1.34.
- An a.c input is applied to the rectifier.
- At the output of the rectifier, there will be d.c and ripple voltage present, which is the input to the filter.
- Ideally the output of the filter should be pure d.c.
- Practically, the filter circuit will try to minimize the ripple at the output, as far as possible.

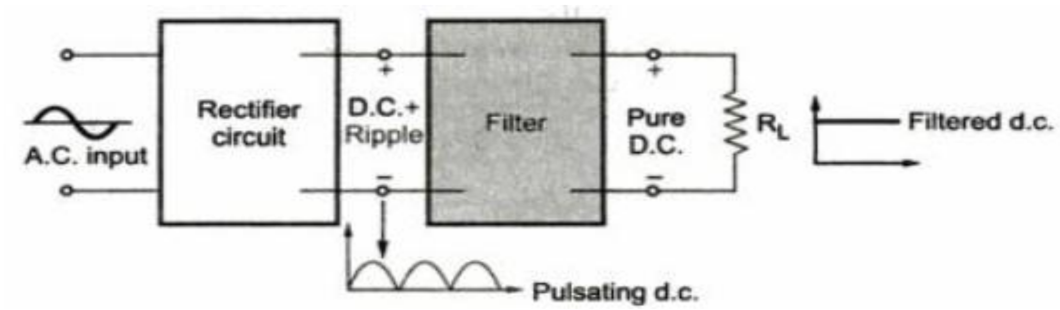


Fig. 1.34 Rectifier and filter

- Two components which are used in filter circuits are inductance and capacitance.
- Ideally, the inductance acts as a short circuit for d.c.
- Similarly, the capacitor acts as open for d.c.
- In a filter circuit, the inductance is always connected in series with the load.
- In a filter circuit, the capacitance is always connected in parallel with the load.

Definition of filter:

- A filter is an electronic circuit composed of capacitor, inductor or combination of both and connected between the rectifier and the load so as to convert pulsating d.c to pure d.c.

1.15.1 Types of filter circuits

- Capacitor input filter (C Filter)
- Inductor input filter (or) Choke filter (L Filter)
- L Section filter (or) LC Filter (or) Choke input filter
- π- Section Filter (CLC Filter)

1.15.2 Capacitor input filter (C Filter)

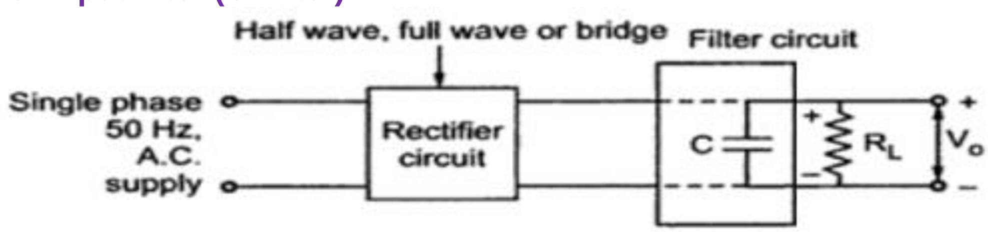


Fig. 1.35 Block Schematic of capacitor input filter

- The block schematic of capacitor input filler is shown in the Fig. 1.35.
- Looking from the rectifier side the first element in filter is a capacitor.

1.16 Half Wave Rectifier with Capacitive Filter

- The Fig. 1.36 shows a half wave rectifier with a capacitor input filter.
- The filter uses a single capacitor connected in parallel with the load, represented by the resistance R_L.
- In order to minimize the ripple in the output, the capacitor C used in the filter circuit is quite large, if the order of tens of microfarads.

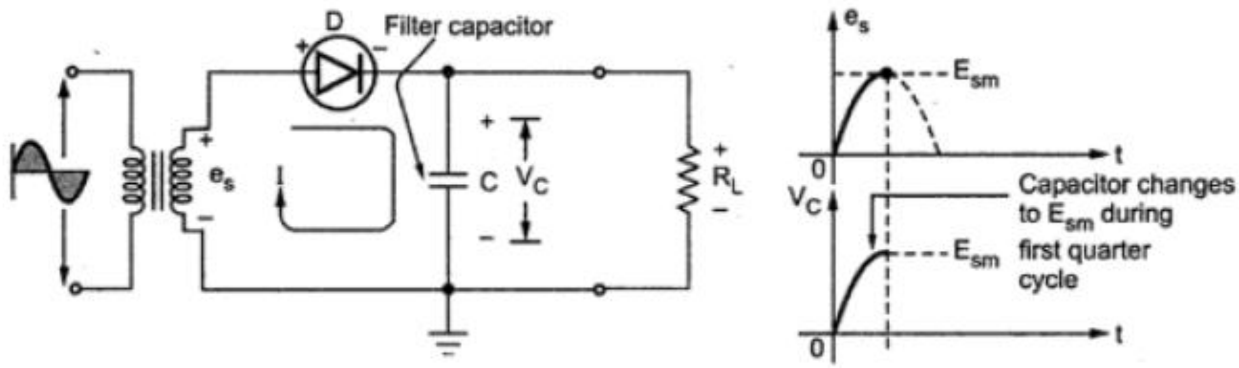


Fig. 1.36 Operation of capacitor Input filter

- During the positive quarter cycle of the input signal e_s, the diode is forward biased.
- This charges the capacitor C to peak value of input E_{sm}.
- Practically the capacitor C charges to (E_{sm} - 0.7) V, due to diode forward voltage drop.
- When the input starts decreasing below its peak value, the capacitor remains charged at E_{sm} and the ideal diode gets reverse biased.
- So during the entire negative half cycle and some part of the next positive half cycle, capacitor discharges through R_L as shown in the Fig. 1.37.

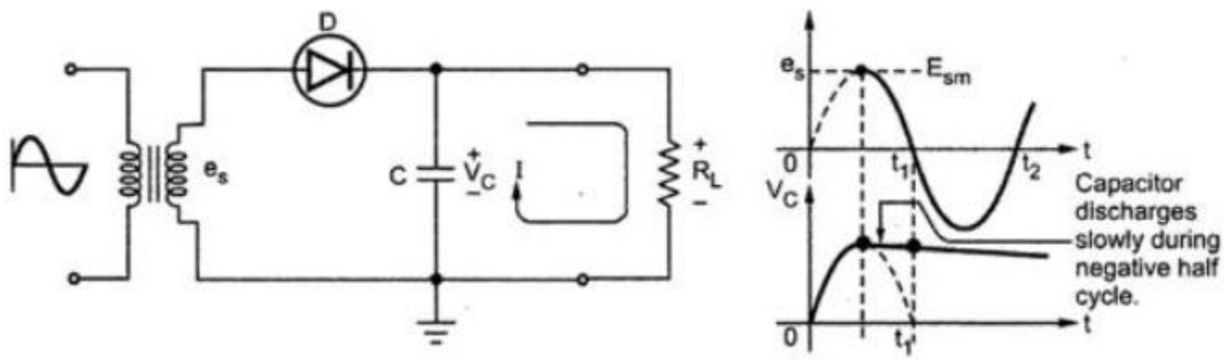


Fig. 1.37 Capacitor discharges through load resistance

- The discharging of capacitor is decided by R_LC time constant which is very large and hence capacitor discharges very little from E_{sm}.
- In the next positive half cycle, when e_s becomes more than capacitor Voltage, the diode becomes forward biased and charges the capacitor C back to E_{sm}.
- This is shown in the fig. 1.38.

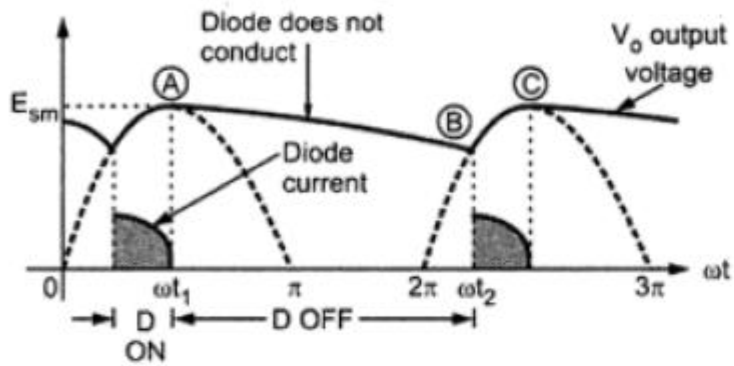


Fig. 1.38 Diode conducts only for part of positive cycle

- Thus diode conducts only for part of the positive half cycle for the period from B to C.

- The discharging of the capacitor is from A to B.
- The capacitor voltage is same as the output voltage as it is in parallel with R_L.

1.17 Operation of Capacitor input filter with Full Wave Rectifier

- The capacitor filter used in full wave rectifier circuit as shown in the Fig. 1.39.

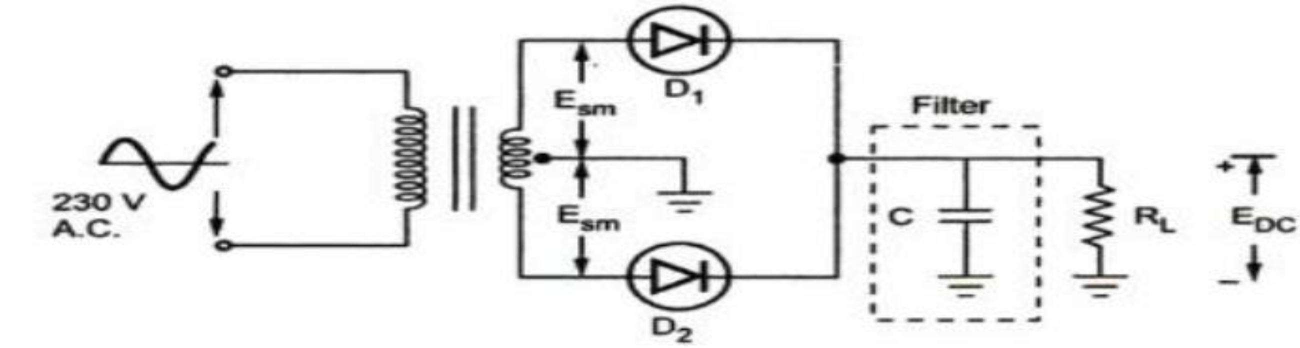


Fig. 1.39 Capacitor input filter with Full wave rectifier

- When power is turned on, the capacitor C gets charged through forward biased diode D_1 to E_{sm}, during first quarter cycle of the rectified output voltage.
- In the next quarter cycle from π/2 to π the capacitor starts discharging through R_L.
- Once capacitor gets charged to E_{sm}, the diode D_1 becomes reverse biased and stops conducting. So during the period from π/2 to π the capacitor C supplies the load current.
- It discharges to point B shown in the Fig. 1.40.

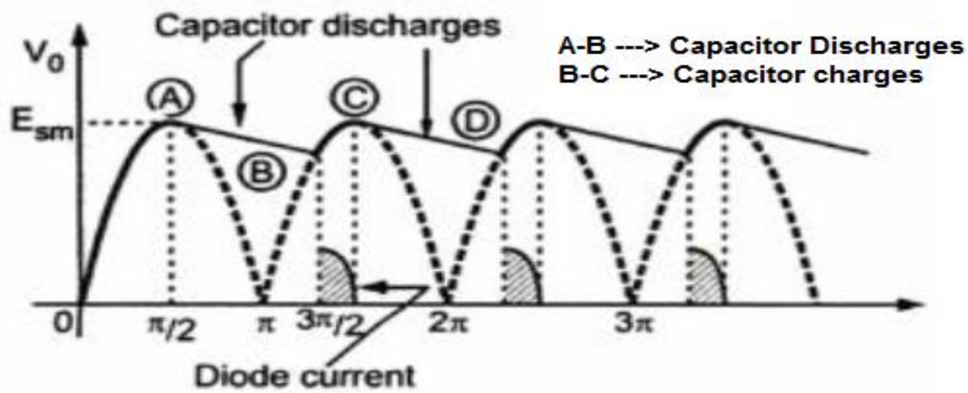


Fig. 1.40 Waveforms of Capacitor input filter with Full wave rectifier

- At point B, lying in the quarter π to 3π/2 of the rectified output voltage, the input voltage exceeds capacitor voltage, making D_2 forward biased. This charges capacitor back to E_{sm} at point C.
- The time required by capacitor C to charge to E_{sm} is quite small and only for this period, diode D_2 is conducting.
- Again at point C, diode D_2 stops conducting and capacitor supplies load and starts discharging upto point D in the next quarter cycle of the rectified output voltage as shown in the Fig. 1.40.
- At this point, the diode D_1 conducts to charge capacitor back to E_{sm}.
- The diode currents are shown shaded in the Fig. 1.41.

- When the capacitor is discharging through the load resistance R_L both the diodes are non-conducting. The capacitor supplies the load current.

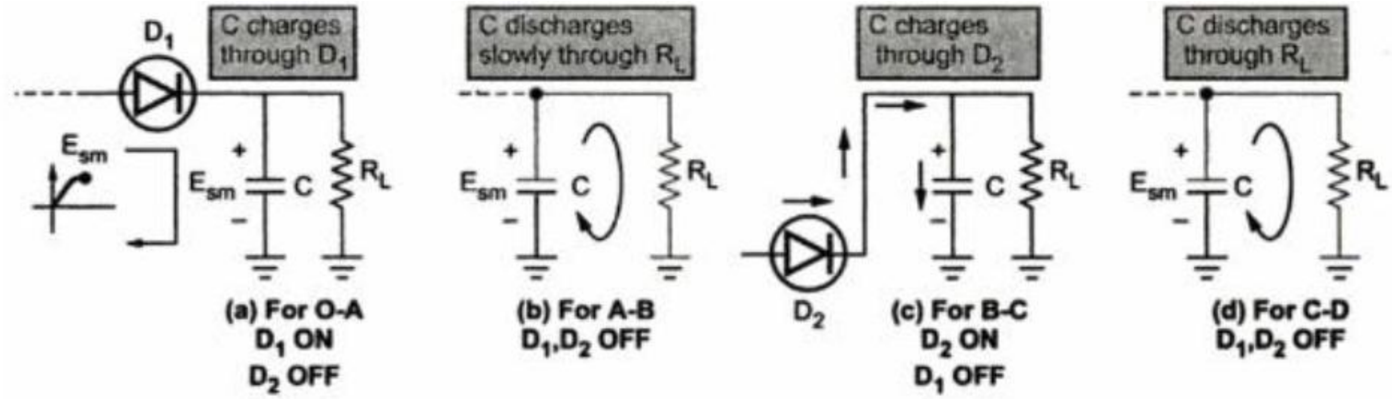


Fig. 1.41 Operation of Capacitor input filter with Full wave rectifier

1.17.1 Expression for ripple factor

- Consider an output waveform for a full wave rectifier circuit using a capacitor input filter, as shown in the Fig. 1.42.

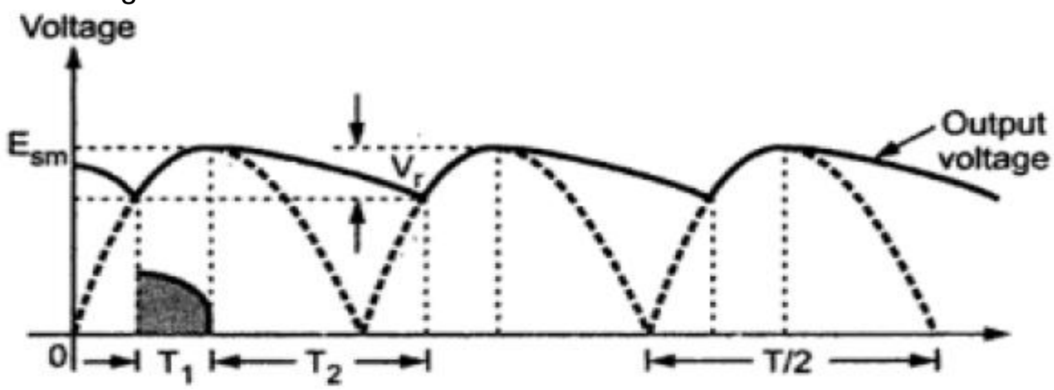


Fig. 1.42 Derivation of ripple factor

Let

T = Time period of the a.c. input voltage

$\frac{T}{2}$ = Half of the time period

T_1 = Time for which diode is conducting

T_2 = Time for which aiode is non-conducting

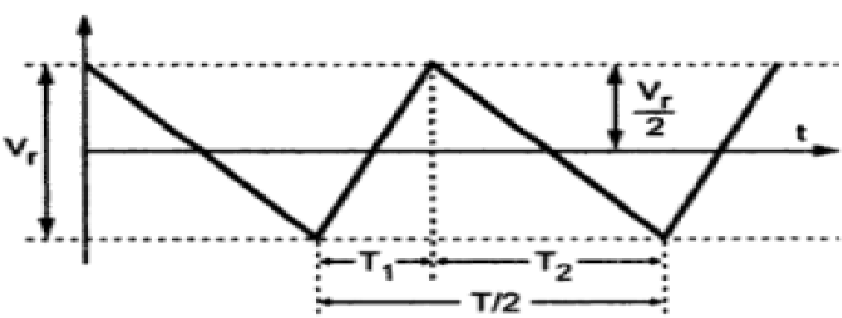


Fig. 1.43 Triangular approximation of ripple voltage

- During time T_1, capacitor gets charged and this process is quick.
- During time T_2, capacitor gets discharged through R_L.
- As time constant R_LC is very large, discharging process is very slow and hence $T_2 >> T_1$.
- Let V_r be the peak to peak value of ripple voltage, which is assumed to be triangular as shown in the Fig. 1.43.
- It is known mathematically that the r.m.s. value of such a triangular waveform is,

$$\boxed{V_{rms} = \frac{V_r}{2\sqrt{3}}} \qquad \text{... (1)}$$

- During the time interval T_2, the capacitor C is discharging through the load resistance R_L.
- The charge lost is,

$$Q = CV_r \qquad \text{... (2)}$$

$$\text{But} \qquad i = \frac{dQ}{dt}$$

$$Q = \int_0^{T_2} i\,dt = I_{DC}\,T_2 \qquad \text{... (3)}$$

- Equate equation number (2) & (3)

$$I_{DC}\,T_2 = CV_r$$

$$V_r = \frac{I_{DC}\,T_2}{C} \qquad \text{... (4)}$$

- From figure 1.43, we can write

$$T_1 + T_2 = \frac{T}{2} \qquad \text{Normally, } T_2 >> T_1$$

$$T_1 + T_2 \approx T_2 = \frac{T}{2} \qquad \text{where } T = \frac{1}{f}$$

- Apply the value of T_2 in equation number (4)

$$V_r = \frac{I_{DC}}{C}\left[\frac{T}{2}\right] = \frac{I_{DC} \times T}{2C} = \frac{I_{DC}}{2\,fC}$$

- We have $I_{DC} = E_{DC} / R_L$ and apply I_{DC} value in the above equation

$$V_r = \frac{E_{DC}}{2\,f\,C\,R_L} \qquad \text{... (5)}$$

- Apply V_r value in equation number (5) into equation number (1)

$$V_{rms} = \frac{\frac{E_{DC}}{2\,f\,C\,R_L}}{2\sqrt{3}}$$

- We know that Ripple factor = V_{rms} / E_{DC}

$$\boxed{\text{Ripple factor} = \frac{1}{4\sqrt{3}\,f\,C\,R_L} \quad \text{for full wave}} \qquad \text{... (6)}$$

$$\boxed{\text{Ripple factor} = \frac{1}{2\sqrt{3}\,f\,C\,R_L} \quad \text{for half wave}} \qquad \text{...(7)}$$

- The product CR_L is the time constant of the filter circuit.
- From the expression of the ripple factor, it is dear that increasing the value of capacitor C, the ripple factor gets decreased.
- Thus the output can be made smoother, reducing the ripple content by selecting large value of capacitor.

1.17.2 Why Capacitor Filter Is not Suitable for Variable Loads?

- The another factor controlling the ripple factor is load resistance R_L.
- As the load current drawn increases, for the same d.c. output voltage, the load resistance decreases. This increases the ripple contents in the output.
- Hence the filter is not suitable for the variable loads.

1.17.3 How to Decrease Ripple Factor?

- Increase the value of filter capacitor.
- Increase the value of load resistance.

1.17.4 Advantages of C filter

- Less number of components.
- Low ripple factor hence low ripple voltage.
- Suitable for high voltage at small load currents.

1.17.5 Disadvantages of C filter

- Ripple factor depends on load resistance.
- Not suitable for variable loads as ripple content increases as R_L decreases.
- Regulation is poor.
- Diodes are subjected to high surge currents hence must be selected accordingly.

Example : *Determine the peak to peak ripple voltage and the ripple factor for a bridge rectifier using capacitor input filter. The load resistance is 2 kΩ while the d.c. voltage across the load is 12 V. Assume supply frequency to be 50 Hz and ideal diodes. The capacitor of 100 μF is used in the filter circuit.*

Solution : $R_L = 2\ k\Omega$, $E_{DC} = 12\ V$, $f = 50\ Hz$, $C = 100\ \mu F$

$$V_r = \frac{E_{DC}}{2\,f\,C\,R_L} = \text{Peak to peak ripple voltage}$$

$$= \frac{12}{2\times 50\times 100\times 10^{-6}\times 2\times 10^{3}} = \mathbf{0.6\ V}$$

The ripple factor is ,

$$\gamma = \frac{1}{4\sqrt{3}\,f\,C\,R_L} = \frac{1}{4\sqrt{3}\times 50\times 100\times 10^{-6}\times 2\times 10^{3}}$$

$$= \mathbf{0.0144\ i.e.\ 1.44\ \%}$$

Example : *A full wave rectifier is operated from 50 Hz supply with 120 V (rms). It is connected to a load drawing 50 mA and using 100 μF filter capacitor. Calculate the d.c. output voltage and the r.m.s. value of ripple voltage. Also calculate the ripple factor.*

Solution : $E_{s(rms)} = 120$ V, f = 50 Hz, $I_{DC} = 50$ mA, C = 100 μF

$$E_{sm} = \sqrt{2}\, E_{s(rms)} = \sqrt{2}\times 120 = 169.7056 \text{ V}$$

For F.W.,
$$E_{DC} = E_{sm} - I_{DC}\left[\frac{1}{4\,fC}\right]$$

$$= 169.7056 - \frac{50\times 10^{-3}}{4\times 50\times 100\times 10^{-6}} = \mathbf{167.2056\ V}$$

$$V_{r(rms)} = \frac{I_{DC}}{4\sqrt{3}\,fC} = \frac{50\times 10^{-3}}{4\times\sqrt{3}\times 50\times 100\times 10^{-6}} = \mathbf{1.4433\ V}$$

The ripple factor is given by,

$$\gamma = \frac{V_{r(rms)}}{E_{DC}} = \frac{1.4433}{167.2056} = 8.63\times 10^{-3}$$

Example : *Calculate the value of 'C ' that has to be used for the capacitor filter of a full wave rectifier to get a ripple factor of 0.01 %. The rectifier supplies a load of 2 kΩ while the supply frequency is 50 Hz.*

Solution : The given values are,

$$\gamma = 0.01\ \%,\ R_L = 2\ k\Omega \text{ and } f = 50 \text{ Hz}$$

For a capacitor filter with full wave rectifier,

$$\%\,\gamma = \frac{1}{4\sqrt{3}\,f\,CR_L}\times 100$$

$$\therefore \quad 0.01 = \frac{1}{4\sqrt{3}\times 50\times C\times 2000}\times 100$$

$$\therefore \quad C = \mathbf{14.433\ mF}$$

1.18 Clipper Circuits or Limiters or Slicers

- The circuits which are used to clip off unwanted portion of the waveform, without distorting the remaining part of the waveform are called clipper circuits or clippers.
- The half wave rectifier is the best and simplest type of clipper circuit which clips off the negative portion of the input Signal.
- A diode is most important element of any clipper circuit.
- It acts as a switch.
- It makes the circuit open, when reverse biased while it makes the circuit closed when forward biased.

1.18.1 Classification of Clippers

- Series clipper
- Parallel Clipper

1.18.1.1 Series clipper

- When the diode is connected in series with the load, it is called Series clipper.
- A series clipper can be used to clip off the entire positive or negative half cycles of input waveforms.
- It also can be used to clip off the portion above the certain reference voltage or below the certain reference voltage.

1.18.1.2 Parallel Clipper

- When the diode is connected in parallel to the load, it is called Parallel Clipper.

1.18.2 Types of Series clipper

- Series Negative Clipper
- Series Positive Clipper
- Clipping Above Reference Voltage V_R
- Clipping Below Reference Voltage V_R

1.19 Series Negative Clipper Circuit

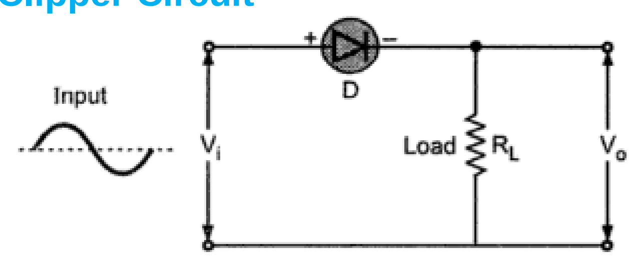


Fig. 1.44 Negative series clipper

1.19.1 Operation:

- Consider a circuit shown in the Fig. 1.44 where diode is connected in series with the load.
- For a positive half cycle, the diode D is forward biased and hence the voltage waveform across R_L looks like a positive half cycle of the input voltage.
- While for a negative half cycle, diode D is reverse biased and hence will not conduct at all. Hence there will not be any voltage available across resistance RL.
- Hence the negative half cycle of input voltage gets clipped off.
- The input waveform and the corresponding output voltage waveform is shown in the Fig. 1.45.

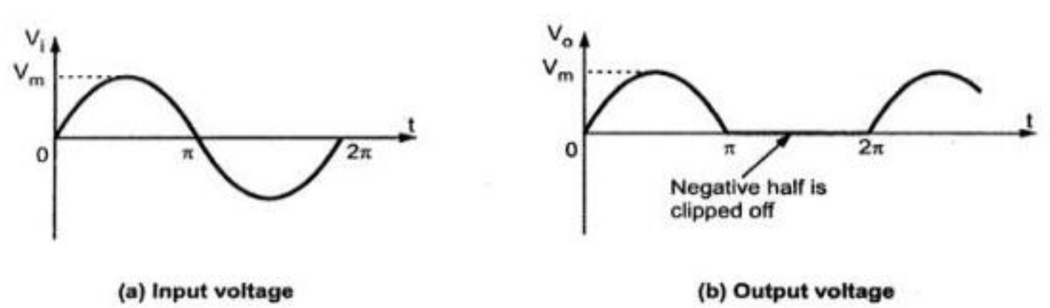


Fig.1.45 Input and Output waveforms

1.19.2 Transfer characteristics:

- The graph of output variable against input variable of the circuit is called transfer characteristics of the circuit.
- Thus for the negative series clipper, the graph of V_o against V_i is its transfer characteristics.
- The mathematical equation for such a graph, assuming ideal diode is given by,

$$V_o = V_i \qquad \text{... for } V_i \geq 0$$
$$V_o = 0, \qquad \text{... for } V_i < 0$$

- The graph showing above mathematical relationship is shown in the Fig. 1.46

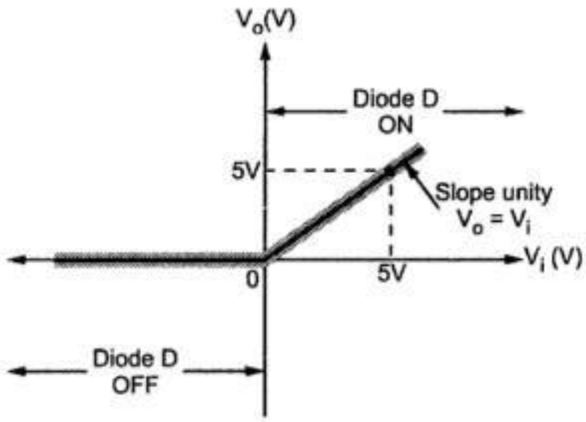


Fig. 1.46 Transfer characteristics with Ideal diode

1.20 Series Positive Clipper Circuit

- It is similar to series negative clipper, a circuit which clipps off positive part of the input can be obtained.
- The positive series clipper can be obtained by changing the direction of diode in negative clipper circuit.

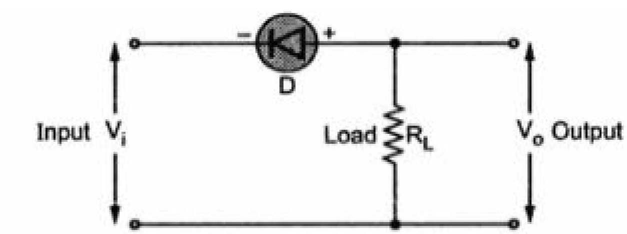


Fig. 1.47 Positive series clipper

- The Fig. 1.47 shows positive series clipper circuit in which diode direction is opposite to that in negative series clipper circuit.

1.20.1 Operation:

- For positive half cycle of input, V_i > 0V and diode is reverse biased. Hence it acts as open circuit and V_o=0V.
- For negative half cycle, when V_i <0, the diode conducts.
- The output voltage V_o available is same as input voltage.
- Thus entire negative half cycle of input is available at the output.
- The output waveforms for sinusoidal and triangular input waveforms are shown in the Fig. 1.48

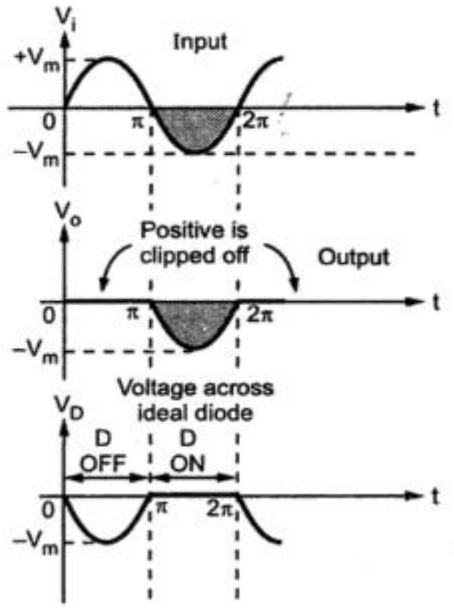


Fig. 1.48 Waveforms of series positive clipper

1.20.2 Transfer characteristics:

- With ideal diode, the equation for transfer characteristics is,

$$V_o = 0 \qquad \text{... for } V_i > 0 \text{ V}$$

$$V_o = V_i, \qquad \text{... for } V_i \leq 0 \text{ V}$$

- The transfer characteristics are shown in the Fig. 1.49.

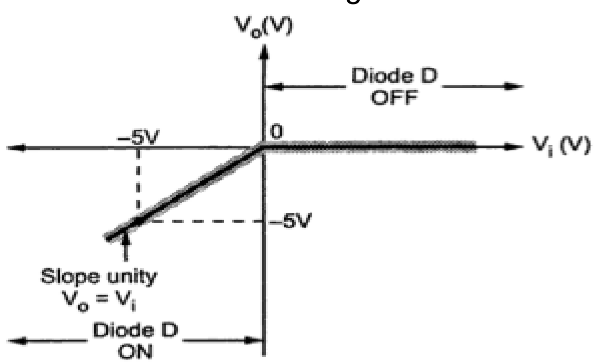


Fig. 1.49 Transfer characteristics with Ideal diode

1.21 Clipping above Reference Voltage V_R

- The output of the dipper can be adjusted as per the requirement by adding an additional voltage source in series with the load- resistance as shown in the Fig.1.50.

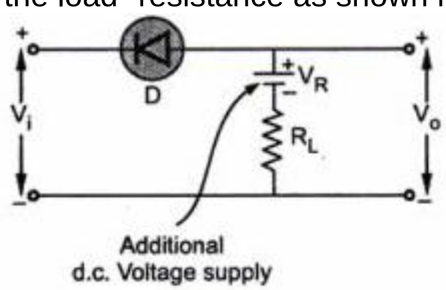


Fig. 1.50 Clipping above V_R

- The diode D is an ideal diode and hence there is no drop across it when it is forward biased.
- Thus when forward biased, it acts as a short circuit while when reverse biased it acts as open circuit.

1.21.1 Operation:

- When V_i is less than V_R, the diode becomes forward biased and the circuit can be reduced to as shown in the Fig. 1.51 (a).
- In this case the output voltage V_o is equal to input voltage V_i.
- When V_i is greater than V_R, the diode is reverse biased and circuit gets reduced to, as shown in the Fig. 1.51 (b).
- No current can flow in the circuit as circuit is open and hence output voltage V_o is equal to V_R.

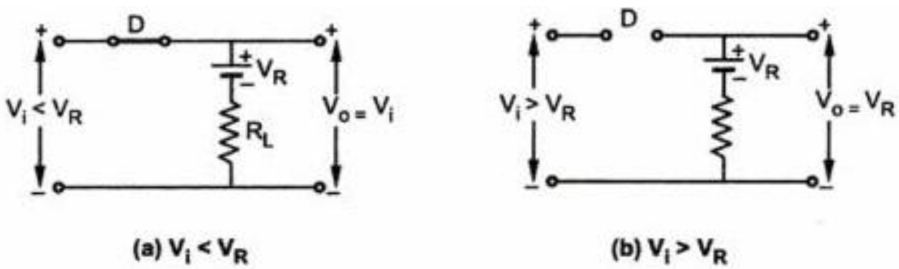


Fig. 1.51 Operation of Clipping above V_R

- The input and output waveforms for such a clipper are shown in the Fig. 1.52.

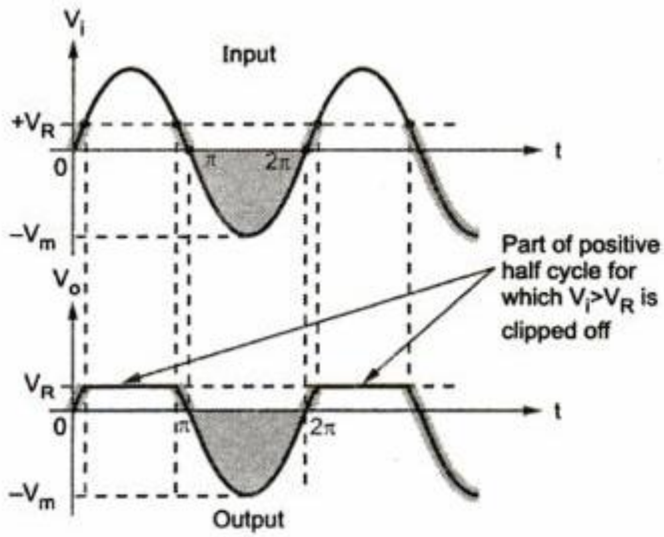


Fig. 1.52 Waveforms for clipping above V_R

1.21.2 Transfer characteristics:

- With ideal diode, the equation for transfer characteristics is,

$$V_o = V_i, \quad \text{... for } V_i < V_R$$

$$V_o = V_R, \quad \text{... for } V_i > V_R$$

- This mathematical representation helps us to sketch the transfer characteristics of the clipper circuit.
- The transfer characteristic is the graph of output voltage V_o against input voltage V_i.
- The transfer characteristic is shown in the Fig. 1.53.

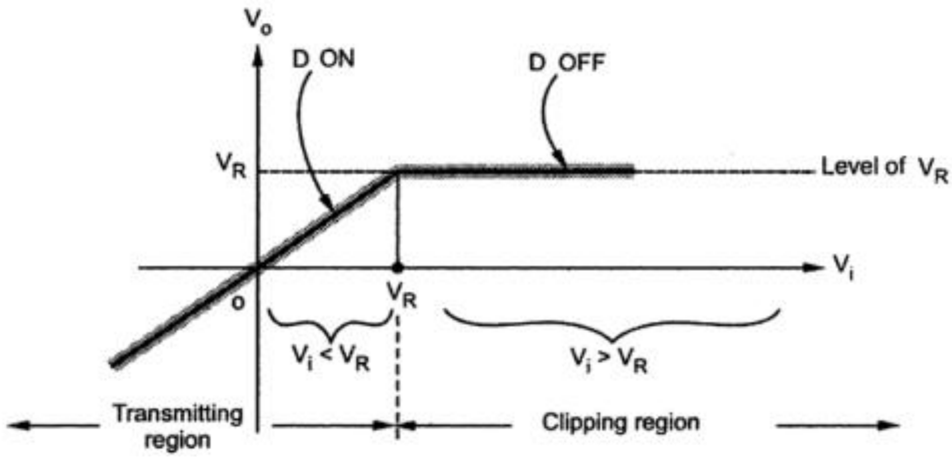


Fig. 1.53 Transfer characteristics

- For the portion till $V_i < V_R$, the graph is straight line. This region is called the transmission region as it transmits V_i at the output as it is.
- While the portion for $V_i > V_R$, the output is constant. This region is called clipping region.

1.22 Clipping below Reference Voltage V_R

- By changing the orientation of the diode in the circuit discussed above, we get the clipping circuit which clips the portion of waveform, below the reference voltage V_R.
- The circuit is shown in the Fig.1.54.

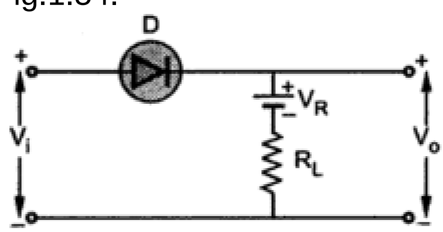


Fig. 1.54 Clipping below V_R

1.22.1 Operation

- When V_i is less than V_R, the diode is reversed biased and circuit becomes open. The output voltage is equal to V_R as no current flows in the circuit and is shown in the Fig. 1.55 (a).
- When V_i is greater than V_R, the diode D becomes forward biased and circuit becomes as shown in the Fig. 1.55 (b).
- The output voltage V_o is equal to the input voltage V_i.

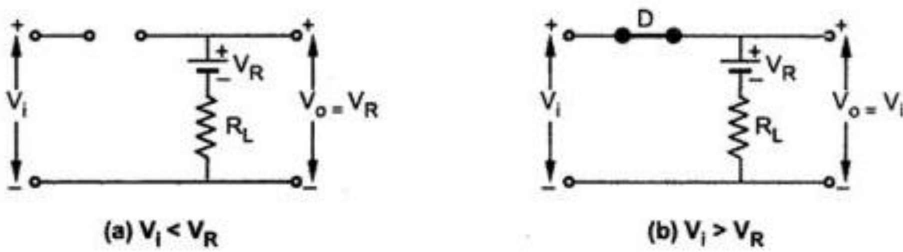


Fig. 1.55 Operation of Clipping below V_R

- The Fig. 1.56 (a) shows the sinusoidal input voltage V_i and the Fig. 1.56 (b) shows the corresponding output waveform.

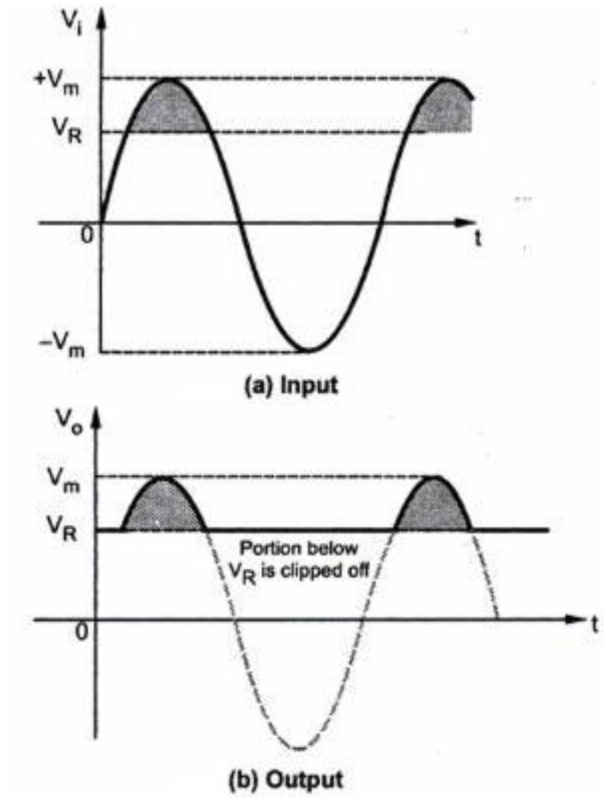


Fig. 1.56 Clipping below V_R

1.22.2 Transfer characteristics:

- With ideal diode, the equation for transfer characteristics is,

$$V_o = V_R, \quad \text{... for } V_i < V_R$$

$$V_o = V_i, \quad \text{... for } V_i > V_R$$

- The transfer characteristic is shown in the Fig. 1.57.

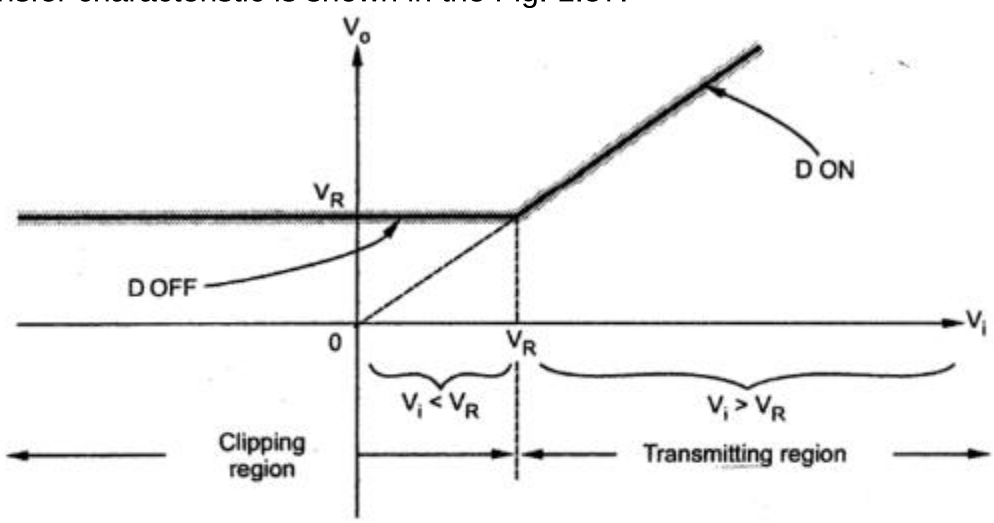


Fig. 1.57 Transfer characteristics

- The region for $V_i < V_R$ is the clipping region while the region for $V_i > V_R$ is the transmitting region.

1.23 Parallel Clippers

- In a parallel clipper circuit, the diode is connected across the load terminals.
- It can be used to clip or limit the positive or negative part of the input signal, as per the requirement.

1.23.1 Parallel Clipper with Positive Clipping

- The Fig. 1.58 shows the basic parallel clipper circuit in which diode D is connected across the load resistance R_L.
- The resistance R1 is current controlling resistance.

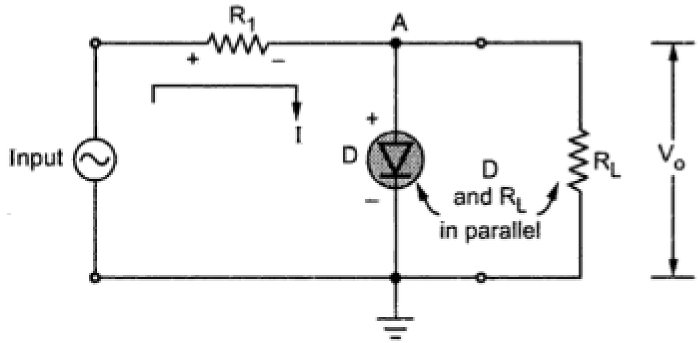


Fig. 1.58 Basic parallel clipper

1.23.1.1 Operation:

- During positive half cycle of the input V_i, the diode D becomes forward biased and remains forward biased for the entire half cycle of the input.
- As R_L is in parallel with diode no current flows through it and output voltage V_o = 0V as shown in the Fig. 1.59

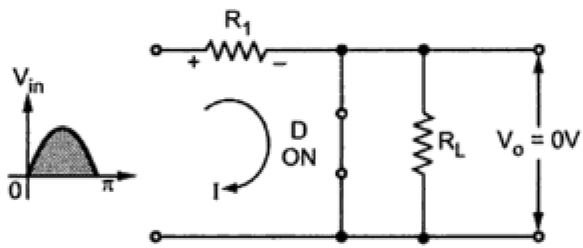


Fig. 1.59 Operation during positive half cycle

- During negative half cycle of input, the diode is reverse biased and acts as open circuit.
- The entire current flows through R_L as shown in the Fig. 1.60.

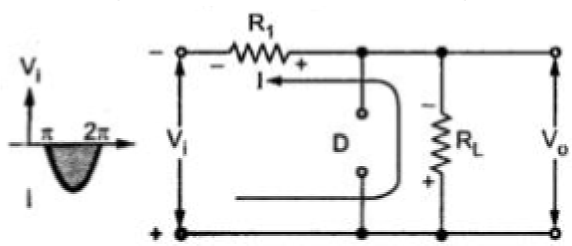


Fig. 1.60 Operation during negative half cycle

- Hence using potential divider rule $V_o = \frac{V_i R_L}{R_L + R_1}$.
- Thus V_o α V_i and there exists straight line relationship between the input and output voltage.
- The waveforms are shown in the Fig. 1.61.

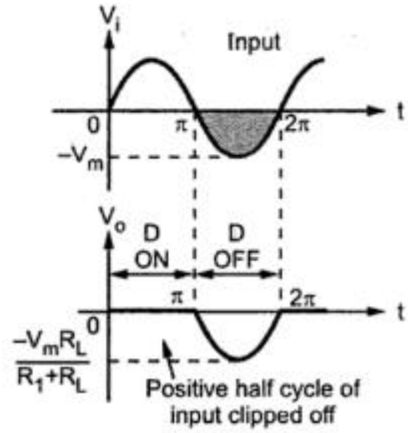


Fig. 1.61 Waveforms for parallel clipper

1.23.1.2 Transfer characteristics:

- The mathematical equations for the transfer characteristics are,

$$V_o = 0 \qquad \text{... for } V_i \geq 0$$

$$V_o = \frac{V_i R_L}{R_1 + R_L}, \qquad \text{... for } V_i < 0$$

- The transfer characteristics are shown in the Fig. 1.62.

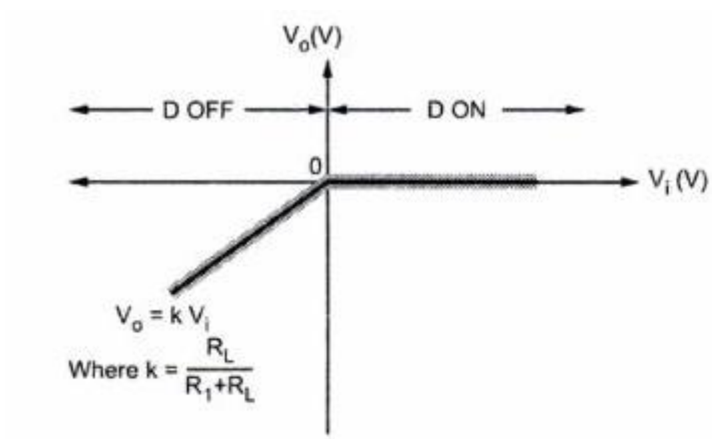


Fig. 1.62 Transfer characteristics of positive parallel clipper

1.24 Clamper Circuits

- The circuits which are used to add a d.c. level to the a.c. output signal are called damper circuits.
- The capacitor, diode and resistance are the three basic elements of a damper circuit. The damper circuits are also called d.c. restorer or d.c. inserter circuits.

- Depending upon whether the positive d.c. or negative d.c. shift is introduced in the output waveform, the dampers are classified as,
  - a) Negative dampers
  - b) Positive dampers

1.24.1 Negative Clamper

- A simple negative clamper which adds a negative level to the a.c. output is shown in the Fig. 1.63.
- It consists of a capacitor C, the ideal diode D and the load resistance R_L.

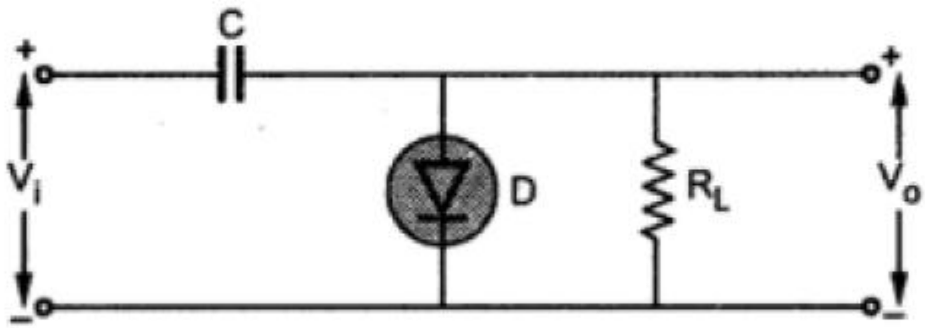


Fig. 1.63 Negative clamper

- The following assumptions are mode while analyzing the damper circuit;
  - The diode is ideal in behaviour.
  - The time constant Ʈ = RC is designed to be very large by selecting large values of Rand C.

1.24.1.1 Operation:

- During the first quarter of positive cycle of the input voltage V_i, the capacitor gets charged through forward biased diode D upto the maximum value V_m of the input signal V_i.
- The capacitor charging is almost instantaneous, which is possible by selecting proper values of C and R_L in the circuit.
- The capacitor once charged to V_m, acts as a battery of voltage V_m, as shown in the Fig. 1.64.

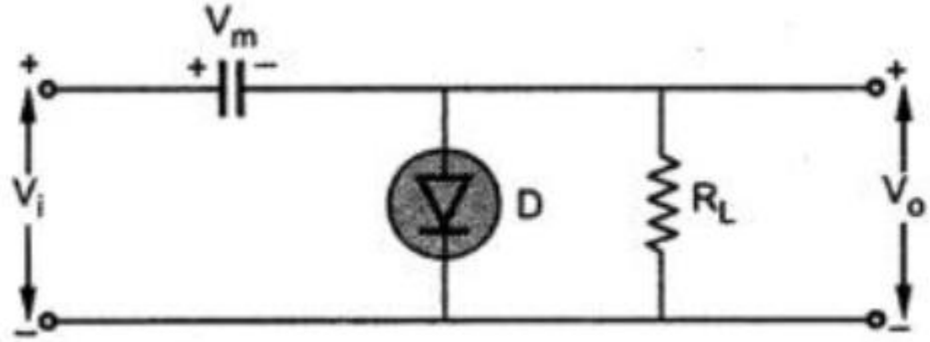


Fig.1.64 Operation of Negative clamper during first quarter of positive cycle

- Thus when D is ON, the output voltage V_o is zero.
- As input voltage decreases after attaining its maximum value V_m, the capacitor remains charged to V_m and the diode D becomes reverse biased.
- Due to large RC time constant the capacitor holds its entire charge and capacitor voltage remains as $V_c = V_m$ as shown in the Fig. 1.65.

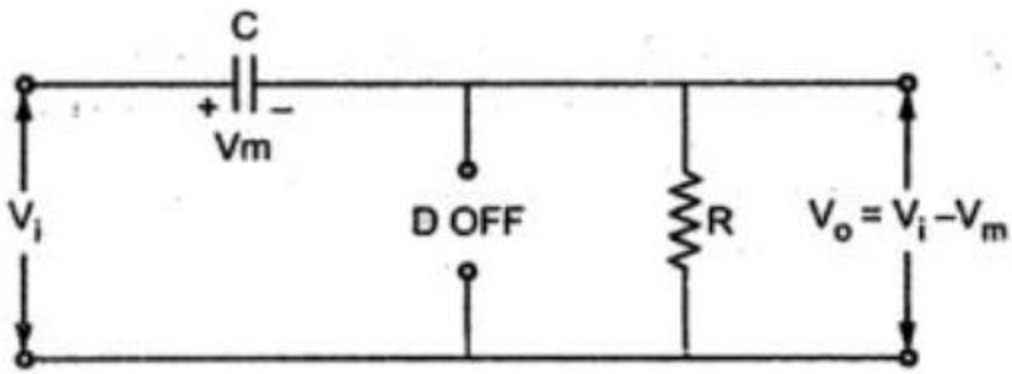


Fig.1.65 Operation of Negative clamper during positive half cycle

- The output voltage V_o is now given by,

$$V_o = V_i - V_c = V_i - V_m$$

- In the negative half cycle of V_i, the diode will remains reverse biased.
- The capacitor starts discharging through the resistance R_L.
- As the time constant R_LC is very large, it can be approximated that the capacitor holds all its charge and remains charged to V_m, during this period also.
- Hence we can write again that,

$$V_o = V_i - V_c = V_i - V_m \quad \text{for negative half cycle}$$

$$V_o = -V_m, \quad \text{for } V_i = 0$$

$$V_o = 0, \quad \text{for } V_i = V_m$$

$$V_o = -2V_m, \quad \text{for } V_i = -V_m$$

1.24.1.2 Waveforms:

- Assuming ideal diode, the input and output waveforms are shown in the Fig. 1.66.
- The peak to peak amplitude of the input is $2\,V_m$.
- Similarly the peak to peak amplitude of the output is also $2\,V_m$.
- Thus the total swing of the output is always same as the total swing of the input, for a clamper circuit.

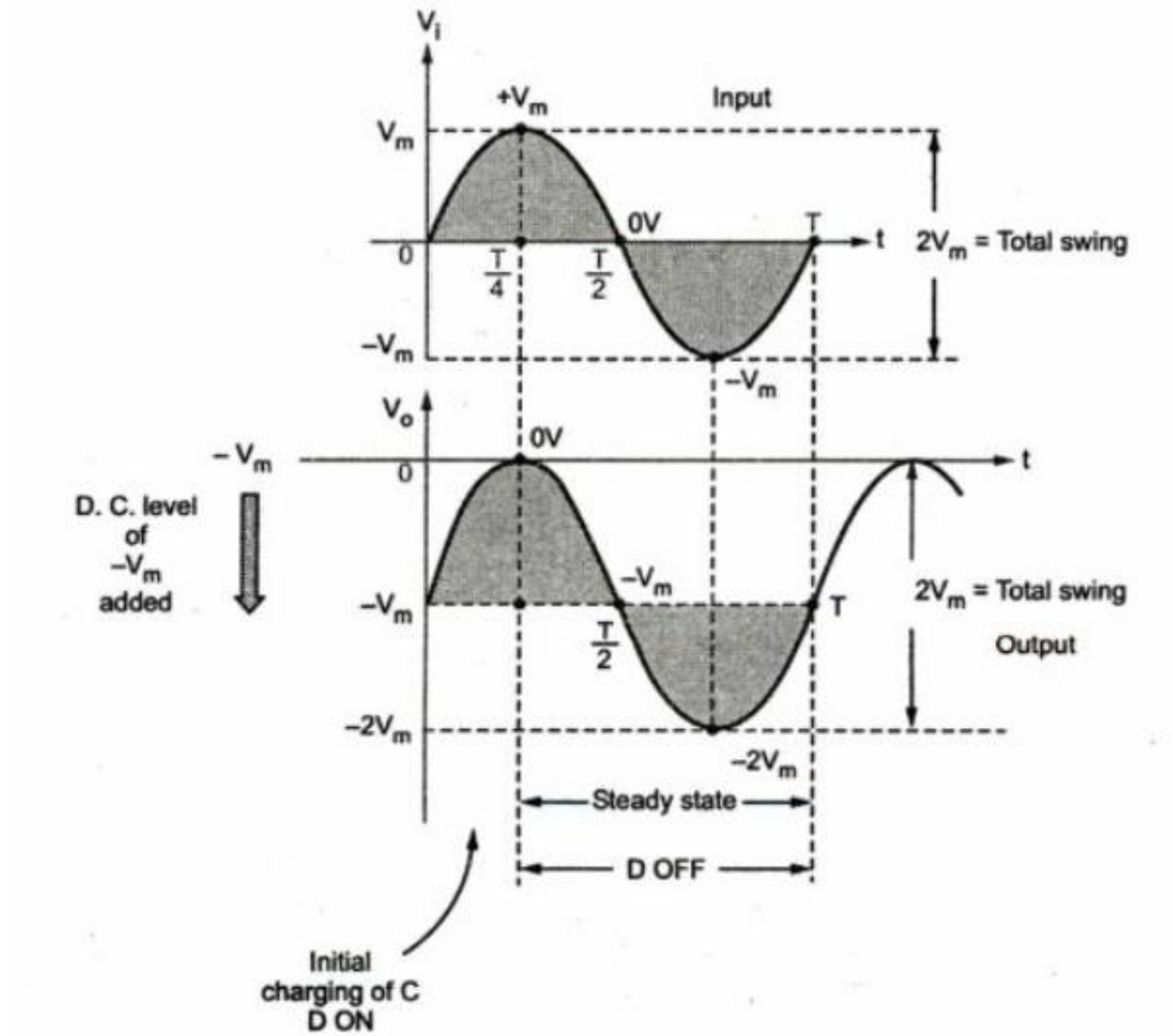


Fig. 1.66 Negative clamper waveforms

1.24.2 Positive Clamper

- By changing the orientation of the diode in the negative clamper, the positive clamper circuit can be achieved.
- The circuit is shown in the Fig. 1.67.

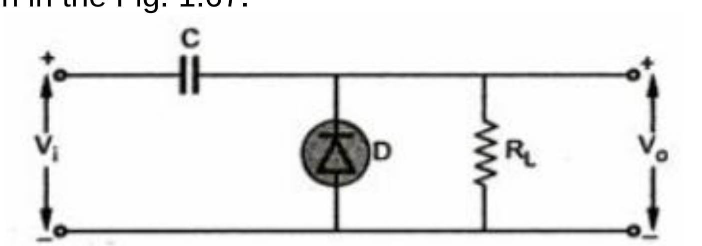


Fig. 1.67 Positive clamper

1.24.2.1 Operation:

- During the first quarter of negative half cycle of the input voltage V_i, diode D gets forward biased and almost instantaneously capacitor gets charged equal to the maximum value V_m of the input signal V_i with the polarities as shown in the Fig. 1.68.

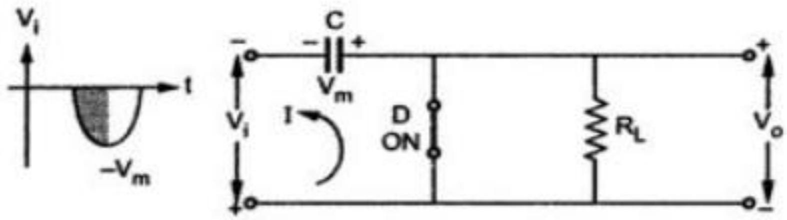


Fig.1.68 Operation of Positive clamper during first quarter of negative half cycle

- The capacitor once charged to V_m, acts as a battery of voltage V_m with the polarities as shown in the Fig. 1.68.
- This is because RC time constant is very large hence capacitor holds its entire charge all the time.
- Thus when $V_i = V_m$, the output voltage V_o is 2 V_m.
- Under steady state conditions we can write,

$$V_o = V_i + V_m$$

- In the positive half cycle, the diode D is reverse biased.
- The capacitor starts discharging through R_L.
- But due to large time constant, it hardly gets discharged during positive half cycle of V_i. This is shown in the Fig. 1.69

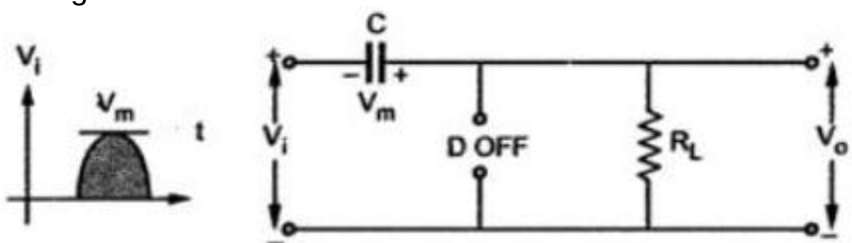


Fig. 1.69 Operation of Positive clamper during Positive half cycle

- Hence, $V_o = V_i + V_m$

$$V_o = V_m, \quad \text{for } V_i = 0$$

$$V_o = 2\,V_m, \quad \text{for } V_i = V_m$$

$$V_o = 0, \quad \text{for } V_i = -V_m$$

1.24.2.2 Waveforms:

- Assuming ideal diode, the input and output waveforms are shown in the fig. 1.70.

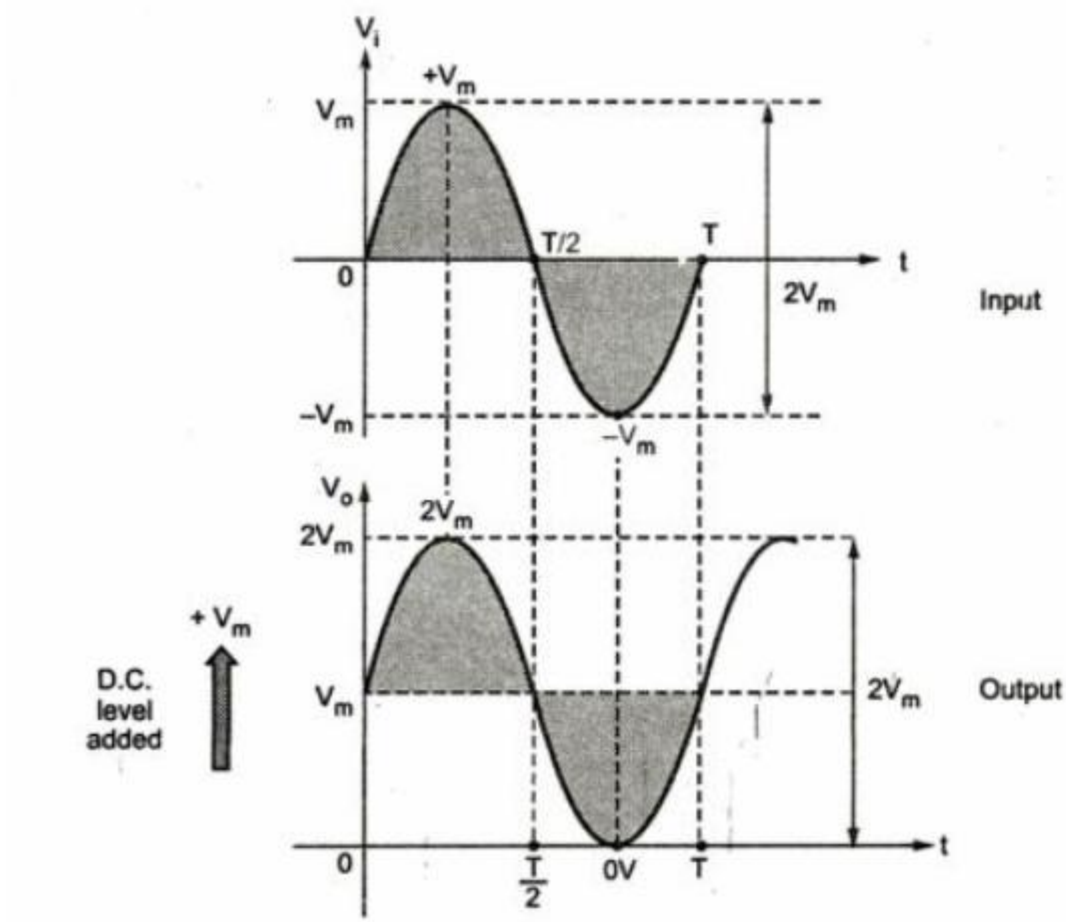


Fig. 1.70 Positive clamper waveforms