BMS College of Engineering, Bangalore

ELEMENTS OF ELECTRONIC ENGG

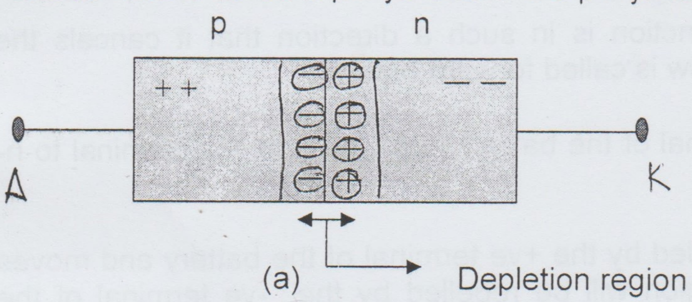
Semiconductor Diode & Applications

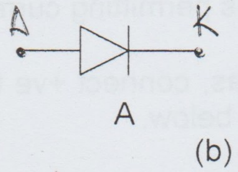
Semiconductor Diode & Applications: Diode: Working principle Characteristics, Parameters and Specifications, Shockley's Equation.
Application: Half-Wave and Bridge Rectifier: Working principle and parameters Ripple Factor and Efficiency Derivations, Peak Inverse Voltage, Shunt Capacitor Filter,
Zener Diode, Zener Diode as a Voltage Regulator, Regulated Power Supply.

09 hrs.

SEMICONDUCTOR DIODE

Construction: when a p-type semiconductor material is suitably joined to n-type semiconductor the contact surface is called a p-n junction. The p-n junction is also called as semiconductor diode.





(a) p-n junction **(b) symbolic representation**

- The left side material is a p-type semiconductor having –ve acceptor ions and +vely charged holes. The right side material is n-type semiconductor having +ve donor ions and free electrons.
- Suppose the two pieces are suitably treated to form pn junction, then there is a tendency for the free electrons from n-type to diffuse over to the p-side and holes from p-type to the n-side. This process is called **diffusion.**
- As the free electrons move across the junction from n-type to p-type, +ve donor ions are uncovered. Hence a +ve charge is built on the n-side of the junction. At the same time, the free electrons cross the junction and uncover the –ve acceptor ions by filling in the holes. Therefore a net –ve charge is established on p-side of the junction.
- When a sufficient number of donor and acceptor ions is uncovered further diffusion is prevented, there is a +ve charge on n-side and –ve charge on p-side, This region is called depletion region or transition region or space charge region, which is depleted of free charge carriers.
- Thus a barrier is set up against further movement of charge carriers. This is called potential barrier or junction barrier Vo. The potential barrier is of the order of 0.3V for Ge and 0.7V for Si.

- Outside this barrier on each side of the junction, the material is still neutral. Only inside the barrier, there is a +ve charge on n-side and –ve charge on p-side. This region is called depletion layer.

Semiconductor diode: it is a pn junction with conductor for connecting the device in a circuit, it has an ability to permit substantial current flow when forward biased and block current when reverse biased and it can be used as a switch.

Biasing of a Diode

Connecting a p-n junction to an external d c. voltage source is called biasing.

1. Forward biasing
2. Reverse biasing

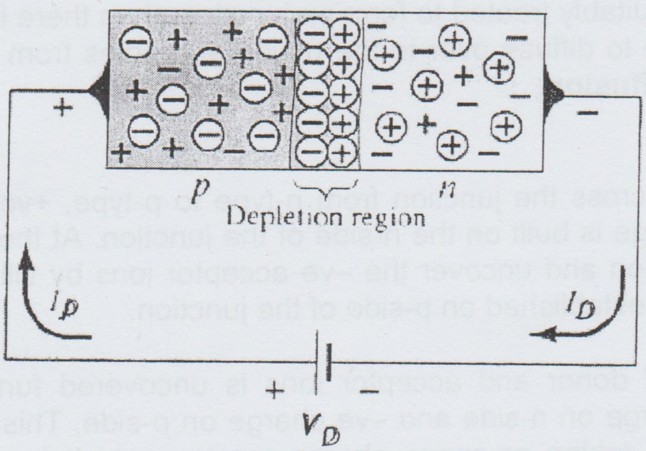
1. Forward biasing

- When external voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow is called forward biasing.

- To apply forward bias, connect +ve terminal of the battery to p-type and –ve terminal to n-type as shown in fig below.

- As a result holes in p-region will be repelled by the +ve terminal of the battery and moves towards junction and electrons in n-region will be repelled by the -ve terminal of the battery and moves towards junction and width of the depletion region narrows

- Since the potential barrier voltage is very small, a small forward voltage is sufficient to completely eliminate the barrier. Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore current flows in the circuit. This is called forward current.



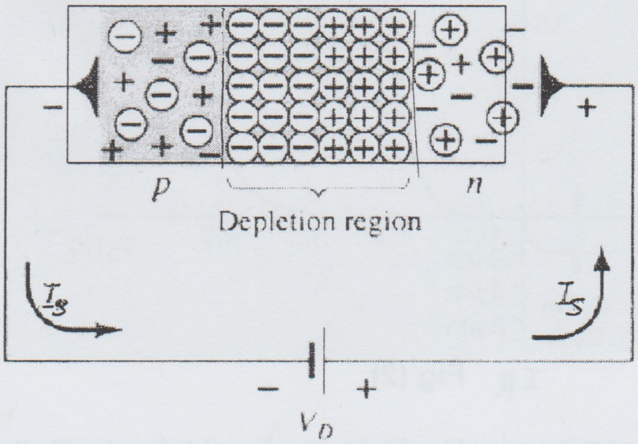
Forward biasing of p-n junction

2. Reverse biasing

- When the external voltage applied to the junction is in such a direction the potential barrier is increased it is called reverse biasing.

- To apply reverse bias, connect –ve terminal of the battery to p-type and +ve terminal to n-type as shown in figure below.

- The applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore the resultant field at the junction is strengthened and the barrier height is increased as shown in fig.2a. below
- The increased potential barrier prevents the flow of charge carriers across the junction. Thus a high resistance path is established for the entire circuit and hence current does not flow.



Reverse biasing of p-n junction

Volt- Ampere characteristics (V-I)

V-I characteristics of p-n junction diode.

(i) Circuit diagram
(ii) Characteristics

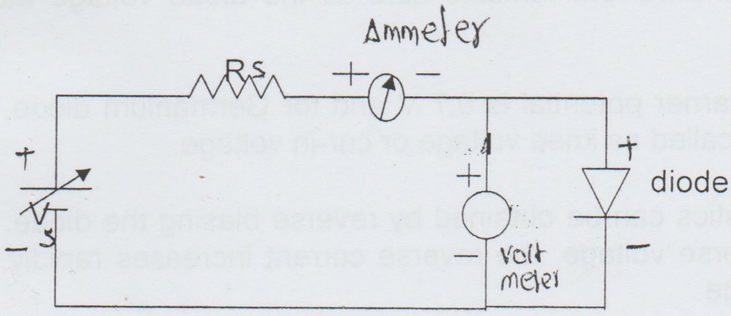
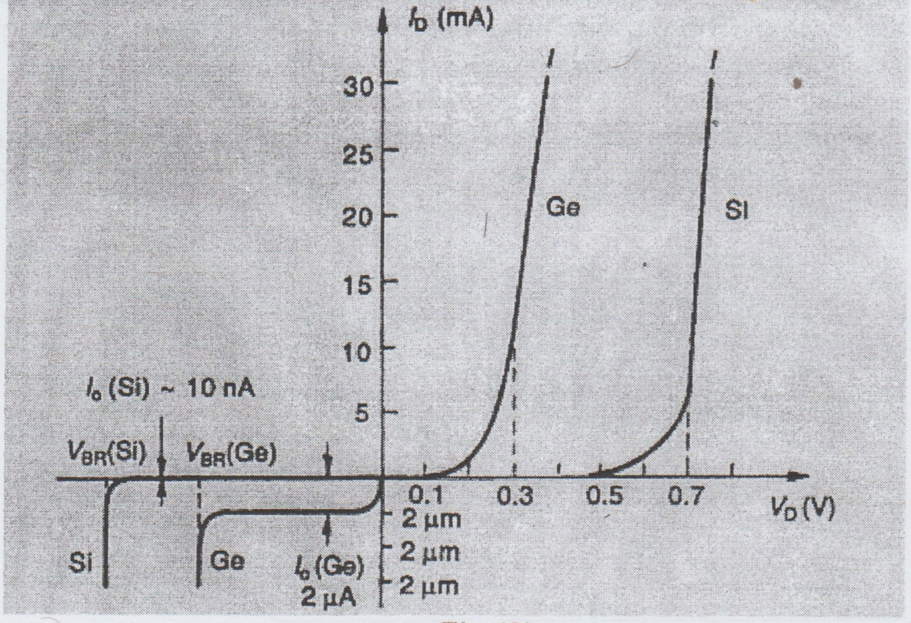


Fig1: Circuit diagram



IR Fig (2)

The V-I characteristics of a semiconductor diode can be obtained with the help of the circuit shown in fig (2)

- The supply voltage V is a regulated power supply, the diode is forward biased in the circuit shown. The resistor R is a current limiting resistor. The voltage across the diode is measured with the help of voltmeter and the current is recorded using an ammeter.

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

- For silicon diode, the barrier potential is 0.7 V and for Germanium diode, it is 0.3 V. The barrier potential is also called as knee voltage or cur-in voltage.

- The reverse characteristics can be obtained by reverse biasing the diode. It can be noted that at a particular reverse voltage, the reverse current increases rapidly. This voltage is called breakdown voltage.

Diode current equation

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

$$I = I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

Where:
I = the net current flowing through the diode;
I_0 = reverse saturation current
V=applied voltage across the terminals of the diode;
q=absolute value of electron charge=1.610^{-19}c
k=Boltzmann's constant and=8.61710^{-15}evk^{-1}=1.3810^{-23}J/k
T = absolute temperature (K).
n = ideality factor which is 1 for Ge and 2 for Si

At 293 K, $V_T = kT/q = 0.025V$, where V_T is thermal voltage.

The breakdown in the diode may be due to any of the following mechanisms.

Zener breakdown: [Ionization due to electric field]

- In a heavily doped PN junction when an electric field is applied at the junction, covalent bond breaks, As a result new e-hole pair is created and reverse current increases.
- Due to heavy doping the depletion region width becomes very small, even for a less applied reverse bias voltage break the covalent bonds. This is called **zener break down**
- It is found in the diodes having $V_{BR} < 5v$

Avalanche breakdown: [Ionization by collision]

- This type of breakdown occurs in wider depletion region, where electric field is not strong enough to produce zener break down
- When the reverse bias voltage is increased, the velocity of minority charge carriers will also increase and consequently their energy content will also increase.
- When these high energy charge carriers collide with the atom within the depletion region they cause other charge carriers to break away from their atoms and join the flow of current across the junction.
- The additional charge carriers generated in this way collide with other atoms and generate new carriers by making them to break away from their atoms.
- This cumulative process is referred to as avalanche multiplication which results in the flow of large reverse current and this breakdown of the diode is called **avalanche breakdown.**
- It is found in the diodes having $V_{BR} > 7v$

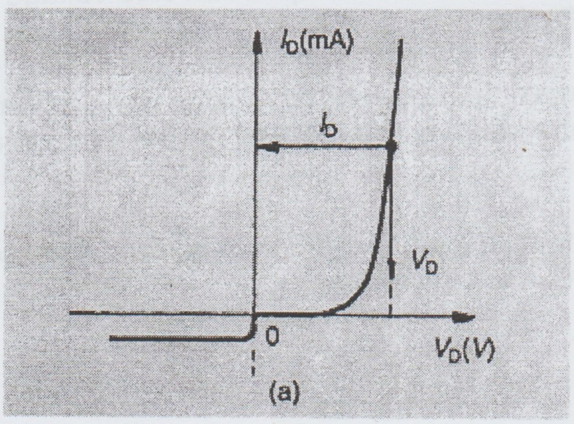
Diode Resistance:

Semiconductors react differently to DC and AC currents.
There are two types of resistance:
• DC (static) resistance
• AC (dynamic) resistance

DC (static) resistance

For a specific applied DC voltage V_D, the diode has a specific current I_D, and a specific resistance R_D.

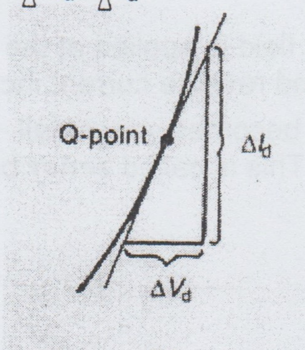
$$R_D = V_D / I_D$$



AC (dynamic) resistance

This resistance of a diode is resistance offered to changing levels of forward voltage

$$r_d = \Delta V_d / \Delta I_d$$



(b)

$r_d = 26mv/I_f$ by equation

Diode Parameters

The manufacturer of the diode provides the detail information about the diode, in the form of the **datasheet**. The various diode parameters are specified in the datasheet which help us to select the diode for an application circuit.

1. **Reverse saturation current:** The constant current flowing through the diode, when it is reverse biased is called Reverse Saturation Current of the diode denoted as I_s. It is constant at constant temperature, it increases when reverse voltage increases until breakdown of diode occurs.

2. **Reverse Breakdown Voltage:** When the reverse voltage is increased, at a certain value a breakdown occurs and reverse current increases very rapidly. This voltage is called reverse breakdown voltage and denoted as V_{BR}. The diode gets damaged due to the breakdown.

3. **Knee voltage:** A small forward voltage applied to the diode at which the current starts increasing is called Knee voltage of a diode.

4. **Maximum Forward current:** the maximum current that a forward biased diode can Withstand before burning out or damaged due high junction temperature is called Maximum forward current. It is denoted by I_F (max).

5. **Peak Inverse Voltage:** The maximum voltage applied to the diode in the reverse Direction without breakdown of the diode is called peak inverse voltage of a diode. It is also called PIV rating of a Diode.

6. **Maximum Power rating:** The maximum power that a diode can dissipate safely, without increasing the junction temperature above its initial limit is called maximum power rating of the diode.it is measured in watts.

7. **Forward Voltage Drop:** It is the maximum forward voltage drop specified at certain forward current and temperature. It is denoted by V_F.

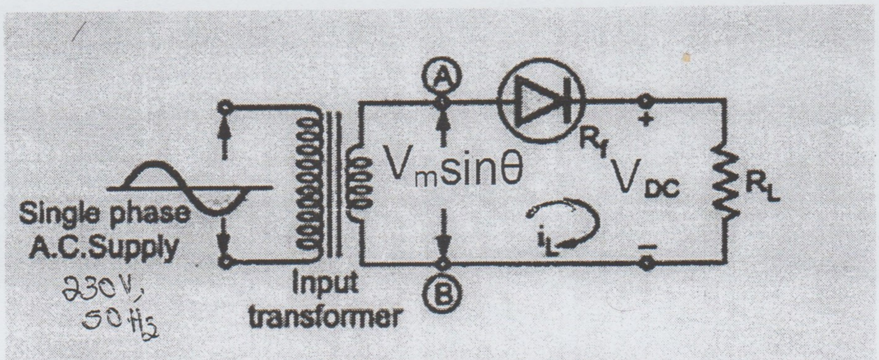
RECTIFIERS

"Rectifiers are the circuit which converts ac to pulsating dc" using one or more p-n junction diodes.

Rectifiers are grouped into two categories depending on the period of conductions.

1. Half-wave rectifier
2. Full- wave rectifier.

Half wave rectifier



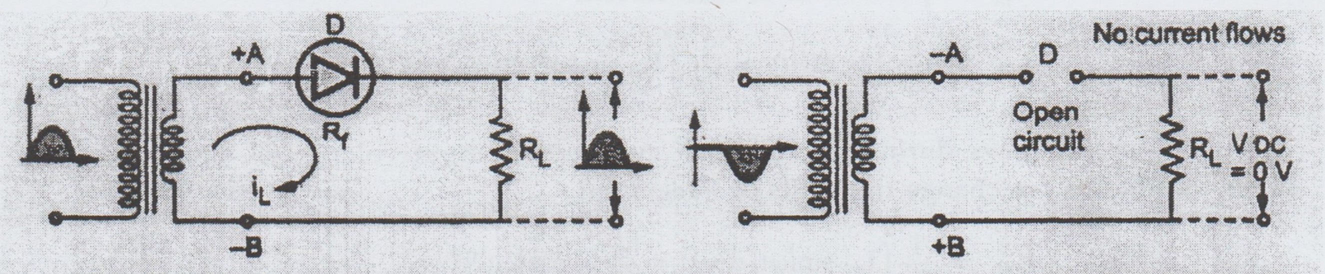
Half wave rectifier

The above fig shows the circuit diagram of half wave rectifier. It consists of the resistive load, rectifying element, i.e., P-N junction diode and the AC voltage source ,all are connected in series. Usually, the rectifier circuit operated from ac mains supply. To obtain the desired dc voltage across the load, the ac voltage is applied to rectifier circuit using suitable transformer.

The input voltage to half-wave rectifier circuit is a sinusoidal ac voltage, having a frequency which is supply frequency,50 Hz.

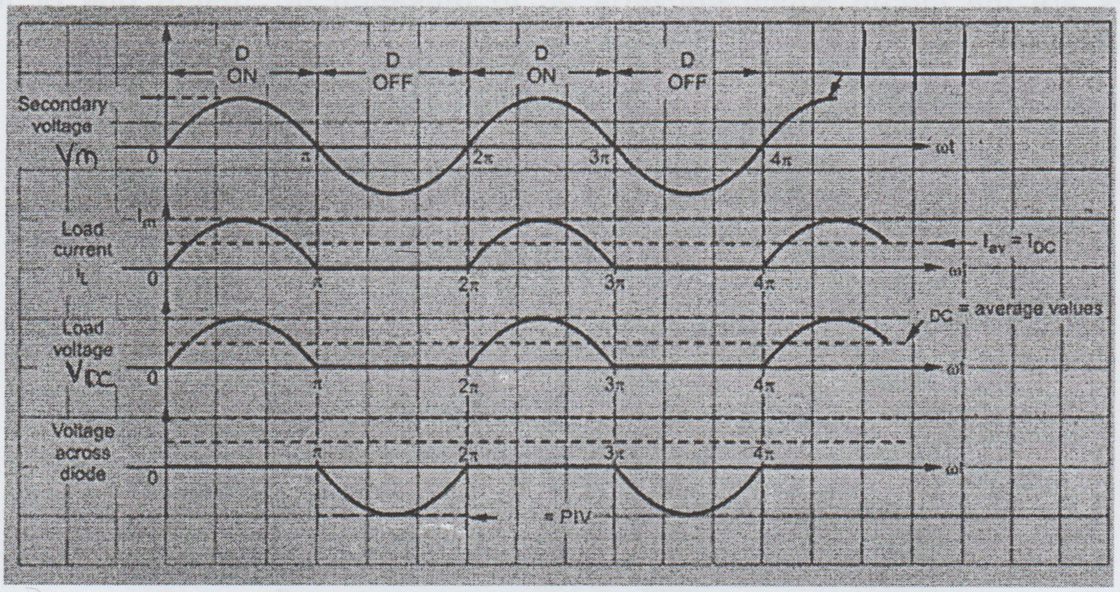
Operation: During the positive half cycle of secondary ac voltage, terminal A becomes positive wrt to terminal B. The diode is forward biased and the current flows in the circuit in the clockwise direction, as shown in below fig (a). The current will flow for almost full positive half cycle. This current is also flowing through load resistance R_L hence denoted as I_L, the load current.

During the negative half cycle of secondary ac voltage, terminal A becomes negative wrt to terminal B. The diode is reverse biased. Hence no current flows in the circuit as shown in fig (b). Thus, the circuit current, which is also the load current, is in the form of half sinusoidal pulses.



(a) Diode forward biased (b) Diode reverse biased

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 the below fig



Efficiency of Half wave rectifier

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

I = $I_m \sin\theta$ be the current flowing in secondary circuit

r_d = diode resistance

R_L = load resistance

i_L = load current

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 i.e. 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 = peak value of load current

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

As no current flows during negative half cycle of a.c. input voltage, i.e. between $\omega t = \pi$ to $\omega t = 2\pi$, we change the limits of integration.

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

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

$$\therefore \quad \boxed{I_{DC} = \frac{I_m}{\pi} = \text{average value}}$$

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. If R_s is not given it should be neglected while calculating I_m.

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

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

$$V_{dc} = E_{DC} = I_{DC} R_L \qquad E_{sm} = V_m$$

Substituting value of I_{DC}, $\quad E_{DC} = \frac{I_m}{\pi} R_L = \frac{E_{sm}}{(R_f + R_L + R_s)\,\pi} R_L$

The winding resistance R_s and forward diode resistance R_f are practically very small compared to R_L.

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

But as R_f and R_s are small compared to R_L, $(R_f + R_s)/R_L$ is negligibly small compared to 1. So neglecting it we get,

$$\therefore \quad \boxed{E_{DC} \approx \frac{E_{sm}}{\pi}} \quad \text{or } V_{dc} = \frac{V_m}{\pi}$$

Note : When R_f and R_s are finite, calculate I_m, then I_{DC} and from that calculate E_{DC} as $I_{DC}R_L$.

Key Point : *Do not calculate E_{DC} as E_{sm}/π directly for finite R_f and R_s. Calculate I_m then I_{DC} and then $E_{DC} = I_{DC} R_L$.*

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,

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

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

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

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

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

Note : Students must remember that this R.M.S. value is for half wave rectified waveform hence it is $I_m/2$. For full sine wave it is $I_m/\sqrt{2}$, which is derived later.

R.M.S. Value of the Load Voltage

The r.m.s. value of the load voltage is the r.m.s. value of the total output voltage which includes d.c. output and the a.c. ripples. As the load is resistive, the r.m.s. value of the load voltage is given by,

$$V_{rms} = \boxed{E_{L\,(RMS)} = I_{RMS}\, R_L = \frac{I_m}{2} R_L}$$

$$\therefore \quad E_{L\,(RMS)} = \frac{E_{sm}}{2\,(R_f + R_L + R_s)} \times R_L = \frac{E_{sm}}{2\left[1 + \frac{R_f + R_s}{R_L}\right]}$$

Now $\quad R_L >> R_f + R_s$ hence $\frac{R_f + R_s}{R_L} << 1$

$$\therefore \quad V_{rms} = E_{L\,(RMS)} \approx \frac{E_{sm}}{2} = \frac{V_m}{2}$$

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

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

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

$$\text{D.C. Power output} = I_{DC}^2 R_L = \left[\frac{I_m}{\pi}\right]^2 R_L = \frac{I_m^{\,2}}{\pi^2} R_L$$

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

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

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

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

The power input taken from the secondary of transformer is the power supplied to three resistances namely load resistance R_L, the diode resistance R_f and winding resistance R_s. The a.c. power is given by,

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

but $$I_{RMS} = \frac{I_m}{2} \quad \text{for half wave,}$$

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

Rectifier Efficiency (η)

The rectifier efficiency is defined as the ratio of output d.c. power to input a.c. power.

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

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

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

If $(R_f + R_s) << R_L$ as mentioned earlier, we get the maximum theoretical efficiency of half wave rectifier as,

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

Thus in half wave rectifier, maximum 40.6% a.c. power gets converted to d.c. power in the load. If the efficiency of rectifier is 40% then what happens to the remaining 60% power. It is present interms of ripples in the output which is fluctuating component present in the output.

Ripple Factor (γ)

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**. Ideally there should not be any ripples in the rectifier output. The measure of such ripples present in the output is with the help of a factor called **ripple factor** denoted by γ. It tells how smooth is the output.

Key Point : *Smaller the ripple factor closer is the output to a pure d.c.*

The ripple factor expresses how much successful the circuit is, in obtaining pure d.c. from a.c. input.

Definition :

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.

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

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

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

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

Now

$$\text{Ripple factor} = \frac{I_{ac}}{I_{DC}} \qquad \text{as per definition}$$

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

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

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

Now for a half wave circuit,

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

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

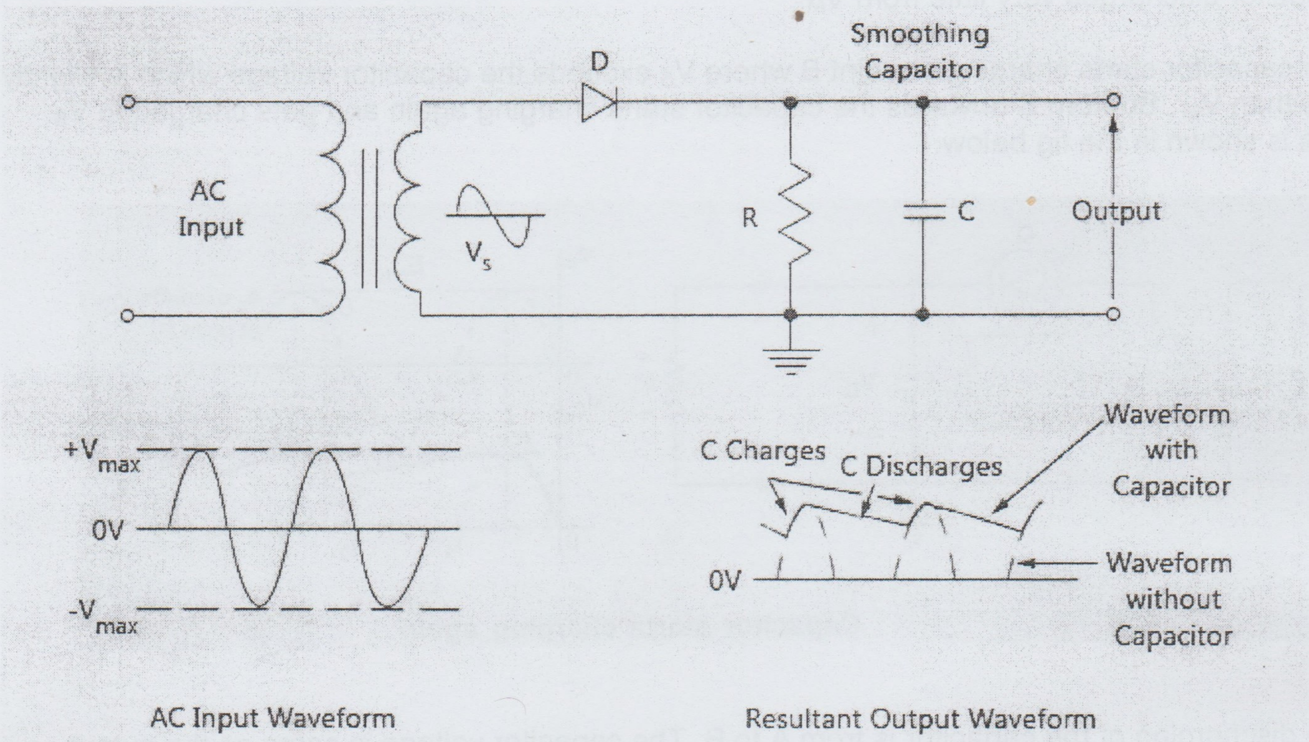
$$\therefore \quad \gamma = 1.211 \qquad \text{.. Half wave}$$

This indicates that the ripple contents in the output are 1.211 times the d.c. component i.e. 121.1 % of d.c. component.

Key Point : *The ripple factor for half wave is very high which indicates that the half wave circuit is a poor converter of a.c. to d.c.*

The ripple factor is minimised using filter circuits along with the rectifiers.

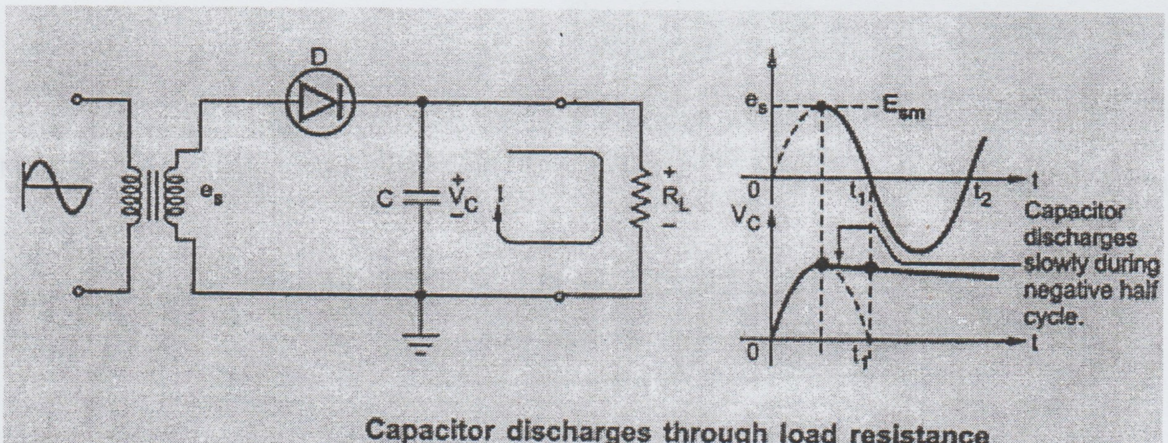
Half wave rectifier with shunt capacitor filter



The fig above shows a half wave rectifier with a capacitor input filter. In order to minimize the ripple in the output, the capacitor C used in the filter circuit is quite large, of the order of tens of microfarads.

During the positive quarter cycle of the input signal V_s, the diode is forward biased. This charges the capacitor C to peak value of input i.e. V_M. This initial charging happens only once, immediately when the power is turned on.

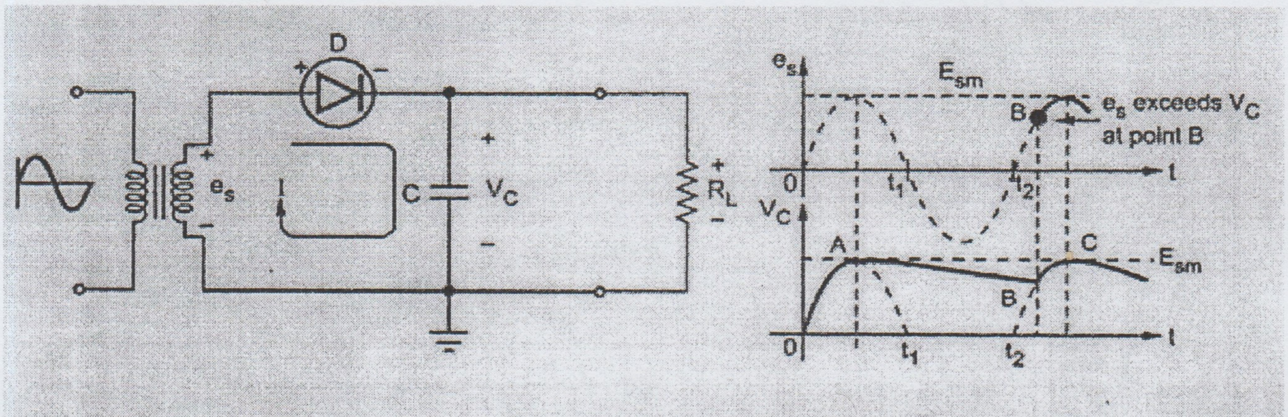
When the input starts decreasing below its peak value, the capacitor remains charged at V_M and the ideal diode gets reverse biased. This is because the capacitor voltage which is cathode voltage of diode becomes more positive than anode.so during the entire negative half cycle and some part of the next positive half cycle, capacitor discharges through R_L as shown in fig below.



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 V_M.

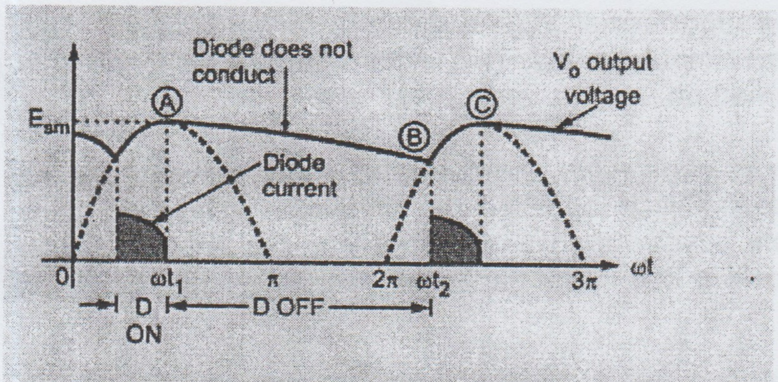
The capacitor starts charging at point B where V_S exceeds the capacitor voltage which is slightly less than V_M . So from B onwards the capacitor starts charging again and gets charged to V_S. This is shown in the fig below.



Capacitor starts charging again

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. From point A to B, the diode remains non conducting and conducts only for the period from B to C.

This is as shown in fig below.



Diode conducts only for part of positive cycle

When diode is nonconducting the capacitor supplies the load current. As time required by the capacitor is very small to charge while it's discharging time constant is very large, the ripple in the output gets reduced considerably.

For half wave rectifier with capacitor input filter the ripple factor is,

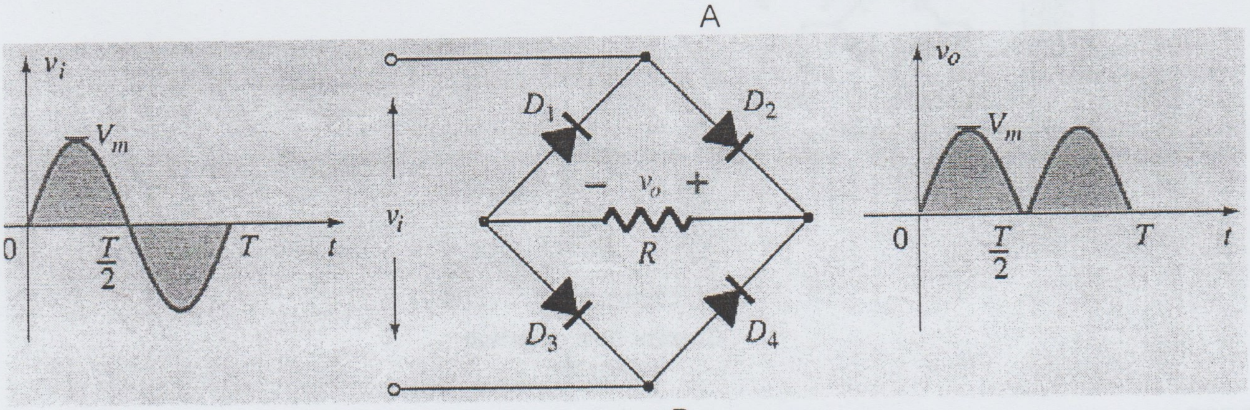
$$\text{Ripple factor} = \frac{1}{2\sqrt{3}\, f C R_L} \quad \text{for half wave}$$

Full-wave rectifier

Full-wave rectifier is of two types

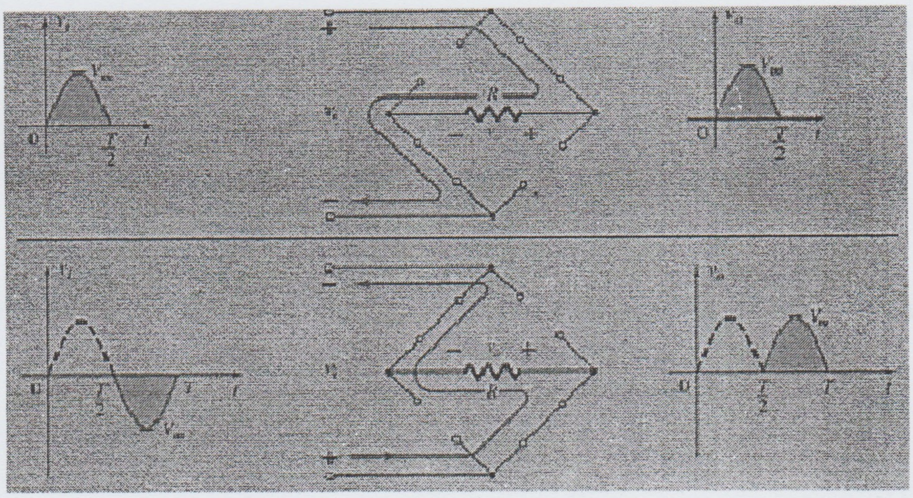
1. Centre tapped full-wave rectifier
2. Bridge rectifier

Bridge rectifier

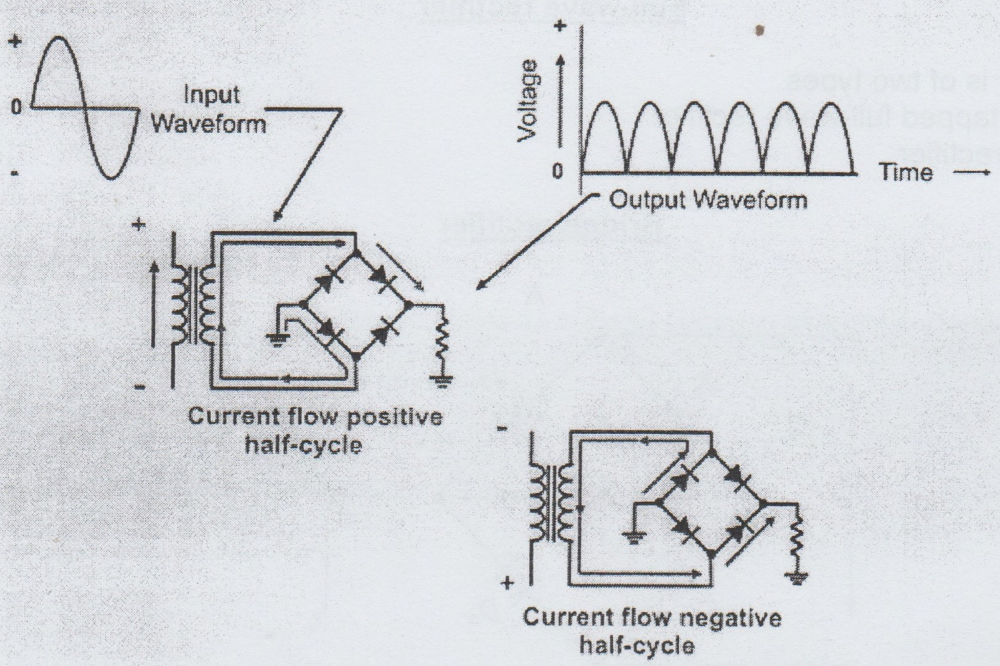


Full wave bridge wave rectifier

- The circuit diagram of a bridge rectifier is shown above. It uses four diodes and a transformer.
- During the +ve half-cycle, end A is +ve and end B is –ve thus diodes D2 and D3 are forward bias while diodes D1 and D4 are reverse biased thus a current flows through diode D2, load R_L and diode D_3.
- During the –ve half-cycle, end B is +ve and end A is –ve thus diodes D1 and D4 are forward biased while the diodes D2 and D_3 are reverse biased. Now the flow of current is through diode D1 load R_L and diode D4. Thus, the waveform is same as in the case of center-tapped full wave rectifier.



DC Bridge Rectifiers (Full Wave)



Advantages

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

Disadvantages

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

Efficiency of bridge rectifier

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

Average or dc value of current. This is obtained as:

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

or

$$I_{dc} = \frac{I_m}{2\pi}(2+2) = \frac{2 I_m}{\pi}$$

R.M.S. value of current. We have

$$I_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi} I_{d1}^2(\omega t) + \int_{\pi}^{2\pi} I_{d2}^2\, d(\omega t)\right]}$$

or,

$$I_{rms}^2 = \frac{I_m^2}{2\pi}\left[\int_0^{\pi} \sin^2(\omega t)\, d(\omega t) + \int_{\pi}^{2\pi} \sin^2(\omega t)\, d(\omega t)\right] = \frac{I_m^2}{2\pi}\left(\frac{\pi}{2}+\frac{\pi}{2}\right) = \frac{I_m^2}{2\pi}\,\frac{2\pi}{2}$$

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

Rectifier efficiency. It is obtained as

$$\eta = \frac{P_{dc}}{P_{ac}}$$

where

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

and

$$P_{ac} = I_{rms}^2 (r_d + R_S + R_L) = \frac{I_m^2 (r_d + R_S + R_L)}{2}$$

Thus

$$\eta = \frac{4 I_m^2}{\pi^2}\,\frac{2}{I_m^2}\,\frac{R_L}{r_d + R_S + R_L} = \frac{8}{\pi^2}\,\frac{R_L}{r_d + R_S + R_L} \times 100\%$$

or

$$\eta = 81\% \qquad \text{if } (r_d + R_S) << R_L$$

The efficiency will be maximum if r_f is negligible as compared to R_L.

Maximum efficiency = 81.2 %

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

Ripple factor

The pulsating output of a rectifier consists of d.c. component and a.c. component (also known as ripple). The a.c. component is undesirable and account for the pulsations in the rectifier output. The effectiveness of a rectifier depends upon the magnitude of a.c. component in the output : the smaller this component, the more effective is the rectifier.

" The ratio of rms value of a.c. component to the d.c. component in the rectifier output is known as ripple factor"

$$r = \frac{I_{ac}}{I_{dc}} = \sqrt{\left[I_{rms} / I_{dc}\right]^2 - 1}$$

Ripple factor. It is obtained by the formula

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1} = 0.482$$

where

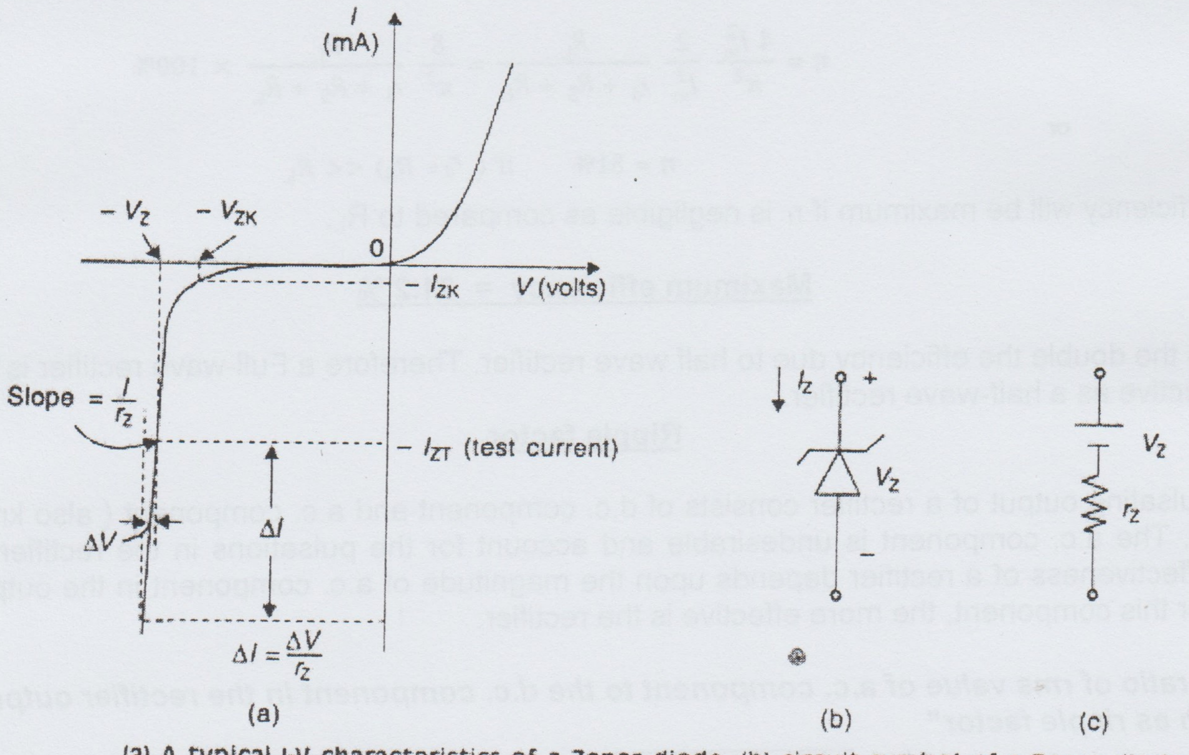
$$\frac{I_{rms}}{I_{dc}} = \frac{I_m}{\sqrt{2}}\,\frac{\pi}{2\,I_m} = \frac{\pi}{2\sqrt{2}}$$

Ripple factor r = 0.48

This shows that in the output of Full-wave rectifier, the D.C. component is more than the a.c. component

Zener Diode

- A zener diode is a special kind of diode which allows current to flow in the forward direction in the same manner as an ideal diode, but will also permit it to f low in the reverse direction. when the voltage is above a certain value known as the breakdown voltage, "zener knee voltage" or "zener voltage."
- Zener diodes are heavily doped silicon diodes that, unlike normal diodes, exhibit an abrupt Reverse break-down at relatively low voltages.
- The Zener diode is designed to operate in reverse breakdown region.
- Zener diode is used for voltage regulation purpose.
- Zener diodes are designed for specific reverse breakdown voltage called Zener breakdown voltage (Vz). The value of Vz depends on amount of doping.



(a) A typical I-V characteristics of a Zener diode, (b) circuit symbol of a Zener diode and (c) equivalent circuit of a Zener diode.

A typical I-V characteristics of a Zener diode is shown in Fig. (a). The steep I-V curve and almost constant voltage drop in the breakdown region suggest that Zener diode operating in the breakdown region can be used in the design of a voltage regulator. The reverse current is small for small reverse voltages. The I-V characteristics is almost straight for currents greater than the *knee current* (I_{ZK}) and in the breakdown region. As the reverse voltage is brought back to zero, the reverse I-V characteristics is retraced and thus this breakdown is called ***reversible breakdown***.

Large breakdown current may destroy the diode because of excessive heating. To prevent destruction of the diode, the current should be limited to external circuit and proper heat dissipation capability should be provided. The manufacturer usually specifies the voltage across the Zener diode V_Z at a specified test current, I_{ZT}. As the current through the Zener diode deviates from I_{ZT}, the voltage across it will change, though slightly. Figure (a) shows that corresponding to current change ΔI the Zener voltage changes by ΔV, which is related to ΔI as

$$\Delta V = r_Z \Delta I$$

where r_Z is the inverse of the slope of the almost-linear I–V curve at point Q. Resistance r_Z is the *incremental resistance* of the Zener diode at operating point Q. It is also known as the *dynamic resistance* of the Zener, and its value is specified on the device data sheet. Typically, r_Z is in the range of a few ohms to a few tens of ohms. Obviously, the lower the value of r_Z is, the more constant the Zener voltage remains as its current varies and thus the more ideal its performance becomes. In this regard, it is noted from Fig. (a) that while r_Z remains low and almost constant over a wide range of current, its value increases considerably in the vicinity of the knee. Therefore, as a general design guideline one should avoid operating the Zener in this low-current region.

Zener diodes are fabricated with voltages V_Z in the range of a few volts to a few hundred volts. In addition to specifying V_Z at a particular current I_{ZT}, r_Z, and I_{ZK}, the manufacturer also specifies the maximum power that the device can safely dissipate. Thus a 0.5-W, 6-V Zener diode can operate safely at currents up to a maximum of about 80 mA. Figure (b) shows the circuit symbol of the Zener diode. In normal applications of Zener diodes, current flows into the cathode, and the cathode is positive with respect to the anode; thus I_Z and V_Z in Fig. (b) have positive values.

Zener shunt regulator

The function of the regulator is to provide an output voltage V_0 that is as constant as possible in spite of the ripple in source voltage, V_s and the variations in the load current, I_L. Two parameters- the line regulation and the load regulation-can be used to measure how well the regulator is performing its function.

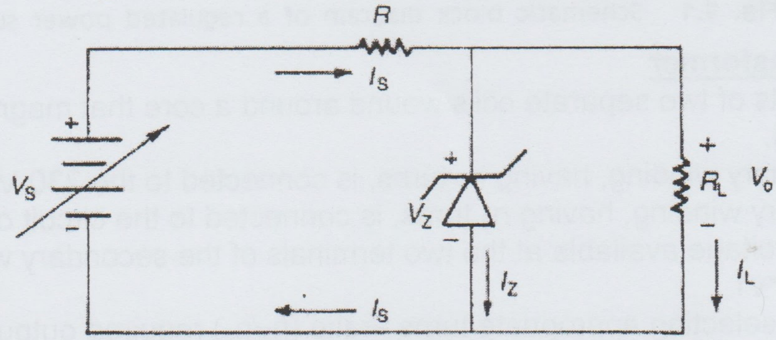
The line regulation is defined as the change in V_0 corresponding to a 1-V change in V_s

Line regulation= $\Delta V_o / \Delta V_s$, It is expressed in mV/V.

The load regulation is defined as the change in V_0 corresponding to a 1-mA change in I_L

Load regulation= $\Delta V_o / \Delta I_L$

A voltage regulator circuit using a zener diode is as shown in the figure.



This circuit is known as a shunt regulator because the zener diode is connected in parallel with the load R_L.

- The regulator is fed with a supply voltage (V_s) which is not constant and may include a large ripple component.
- *Such a dc supply voltage along with ripple component is obtained as the output of a rectifier* circuit even after inclusion of filter circuit.

- The load can be a simple resistor or a complex electronic circuit.
- The function of the zener diode is to keep the output voltage constant over a wide variation of load current. This is accomplished by operating the zener in the breakdown region, when its voltage varies only slightly with changes in zener current.
- The resistance Rs is provided to keep the zener current limited to its maximum value even load R_L is shorted and this resistance is called current limiting resistance of zener regulator circuit.
- The zener diode has to be kept operating in its breakdown region with Iz>Izmin in order to keep the load voltage relatively constant.in practice Iz should be kept much greater than Izmin.
- The source voltage Vs delivers a total current Is, which is called source current and it divides between zener current I_z and load current I_L i.e. **Is=Iz+IL**. So as long as zener remains in breakdown region, Vz will be constant and Is is given by

$$Is = \frac{Vs-Vz}{Rz}$$

When RL is large, IL is small and most of input current flow through Zener

When RL is small, IL is large and most of input current flow through load and IZ decreases

If IZ falls below IZK, Zener will not be operating in breakdown region and VZ gradually reduces and cause output load voltage to come out of regulation.

Block diagram of DC power supply

- One of the most important applications of diodes is in design of DC power supply
- In the dc power supply, ac voltage from supply mains is stepped down, rectified, filtered and regulated to give the required dc voltage

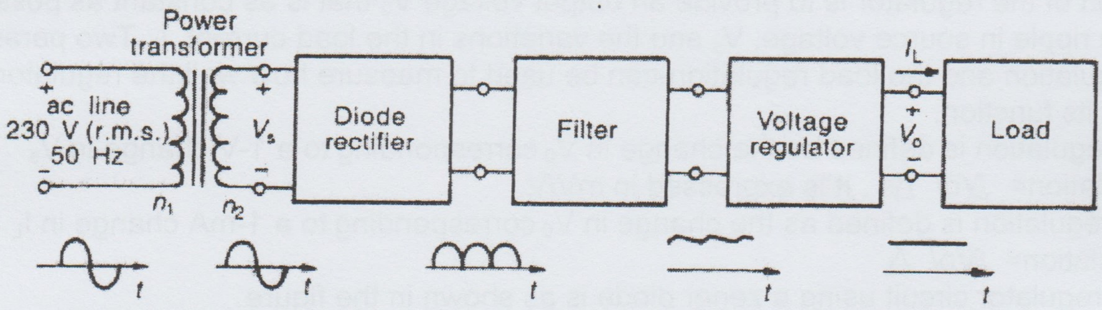


Fig. 3.1 Schematic block diagram of a regulated power supply.

Power Transformer

- It consists of two separate coils wound around a core that magnetically couples the two windings.
- The primary winding, having n_1 turns, is connected to the 230-V ac supply; and the secondary winding, having n_2 turns, is connected to the circuit of the dc power supply.
- The ac voltage available at the two terminals of the secondary windings is given by $V_2=n_2/n_1*v1$
- Thus by selecting appropriate turns –ratio (n_2/n_1) required output voltage can be obtained.
- It steps down 230V AC mains to required low AC voltage.

Rectifier

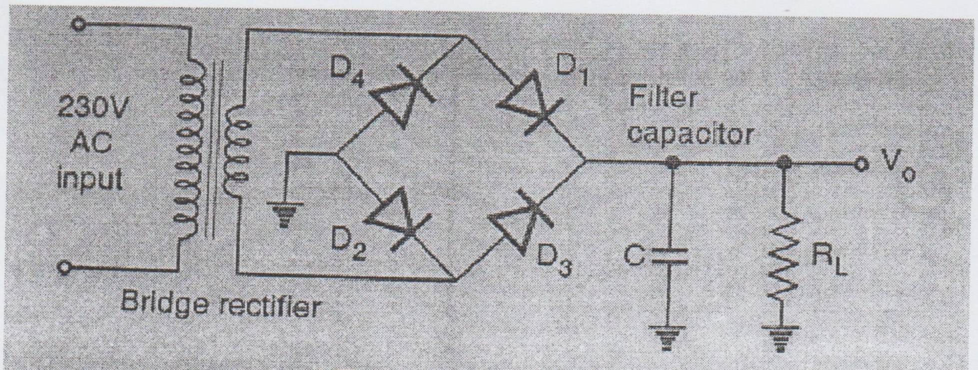
- Converts AC voltage from transformer secondary to DC voltage, but the DC voltage output is pulsating.
- It employ 1,2or 4 diodes to provide various degrees of rectifying ettectiveness.

Filter

- Filter circuit is required to reduce the variations in the magnitude of the rectified output.
- They use the energy storage capabilities of capacitors and inductors to smooth out the pulsation and to provide a steady output current. Filters out the ac component from the rectified output.

Voltage Regulator

- Eliminates ripple by setting DC output to a fixed voltage.



: Bridge rectifier with capacitor filter