UNIT - 3

* **Diode Applications**

→ Introduction

→ Load - line analysis

→ Series diode configurations

→ Parallel & series-parallel configuration

→ Half-wave rectification

→ Full- wave rectification

→ General filter considerations

→ Inductive

→ Capacitive

→ LC and CLC filters.

→ Zener diode as voltage regulator.

* **Special semiconductor devices**

→ Principle of operation

→ characteristics & applications of tunnel diode

→ Varactor diode

→ UJT

→ Photo diode

→ LED

→ LCR

→ SCR

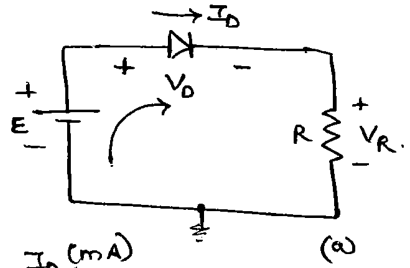
Diode Applications

* Load line Analysis

The applied load will normally have an important impact on the point of region of operation of the device. If the analysis is performed graphically, a line can be drawn on the characteristics of the device that represents the applied load. The intersection of load line with the characteristics will determine the point of operation of the device. Such an analysis is called Load-line Analysis.

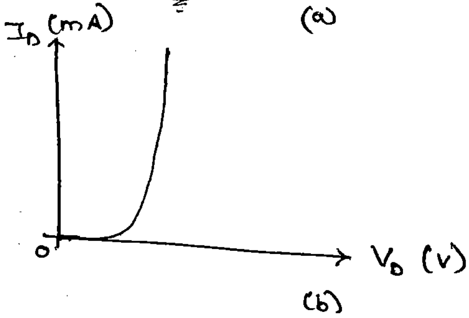
Note:- We normally do not use load-line approach for diode. But it is important for a transistor to define active region.

Consider a network employing a diode having the characteristics shown below.



Pressure established by the battery establishes a current through the series network in the clockwise direction.

Since this current is in the direction of conduction of diode, the diode is in "ON" state.



⇒ We are interested only in the V-I characteristics of forward bias.

Applying Kirchoff's law to the series circuit,

$$E - V_D - V_R = 0.$$

$$E = V_D + V_R$$

$$\boxed{E = V_D + I_D \cdot R.} \longrightarrow (3.1)$$

The intersection of load line on the characteristics can be easily determined by the fact that anywhere on the horizontal line $I_D = 0A$ and anywhere on the vertical axis $V_D = 0V$.

If we set $V_D = 0$ & solve for I_D in eq (3.1), we get

$$E = 0 + I_D \cdot R.$$

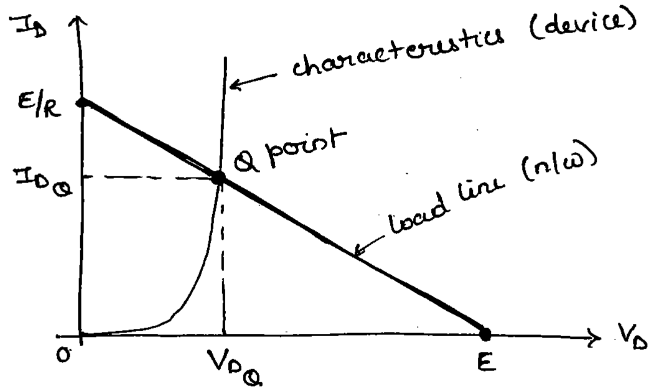
$$\boxed{I_D = \frac{E}{}} \longrightarrow (3.2)$$

If $I_D = 0$ and solve for V_D in eq (3.1), we get

$$E = V_D + 0 \cdot R.$$

$$\boxed{V_D = E \,\Big|_{I_D=0}} \longrightarrow (3.3)$$

A straight line drawn between these two points will define load line as shown below.



The point of intersection between the load line and characteristic curve is called point of operation of the circuit. It is called Quiescent point (or Q-point).

The Q-point reflects the circuits "still or unmoving" qualities as defined by the dc network.

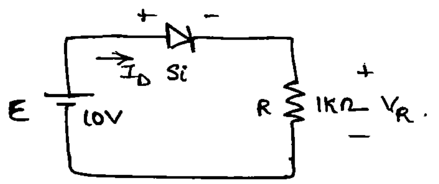
By drawing a line down to horizontal axis from point of intersection, the diode voltage V_{DQ} can be determined. Where as a horizontal line from point of intersection to vertical axis will defined I_{DQ}.

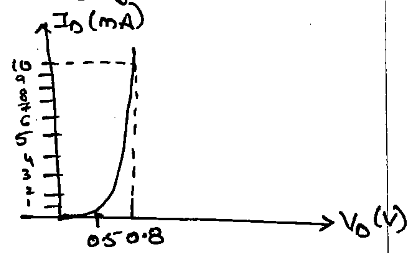
Note:- change the level of R (load) and intersection on vertical axis will change. The result is change in the slope of the load line and a different point of intersection between the load line & the device characteristics.

(Pb) For series diode configuration shown below employing the diode characteristics determine

a) V_{DQ} and I_{DQ}

b) V_R.

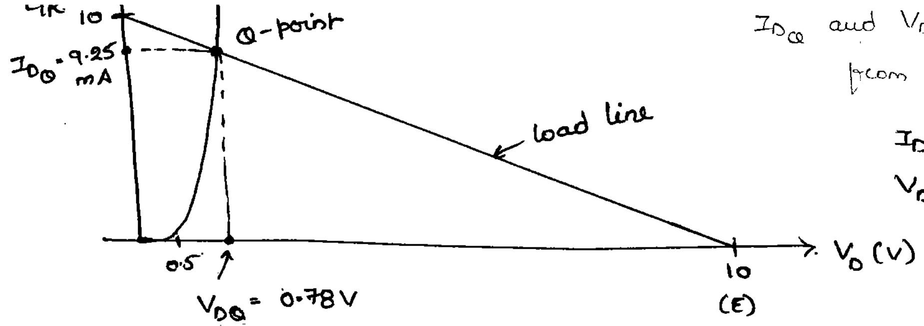




Sol: Load line is drawn from the 2 points

$$I_D = \frac{E}{R}\Big|_{V_D=0} = \frac{10}{1K\Omega} = 10\,mA.$$

$$V_D = E\,\Big|_{I_D=0} = 10V.$$



I_{DQ} and V_{DQ} are obtained from graph

$I_{DQ} = 9.25\,mA$

$V_{DQ} = 0.78\,V.$

b) $V_R = I_{DQ} \cdot R$ or $V_R = E - V_D = 10 - 0.78$

$= 9.25 \times 10^{-3} \times 1 \times 10^{3}$ $\qquad = \underline{\underline{9.22\,V}}$

$= \underline{\underline{9.25\,V}}$

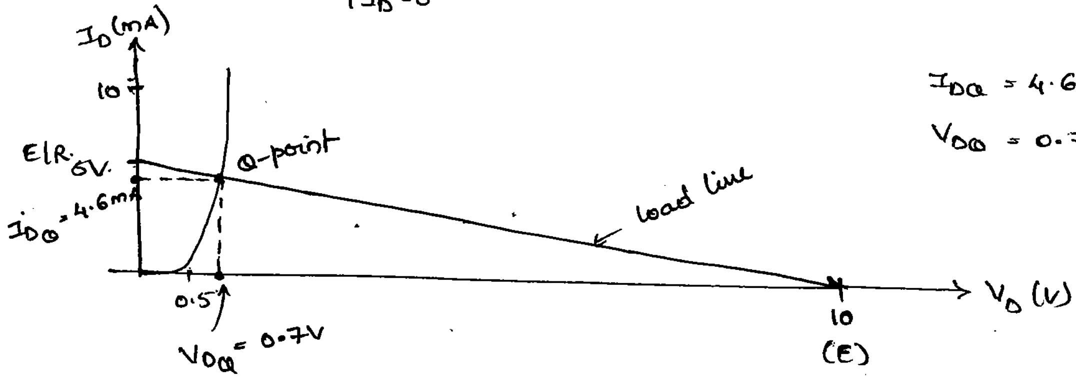
(difference in results is due to accuracy with which the graph is drawn).

(Pb) Repeat the same for $R = 2K\Omega$.

Sol: a) Load line is drawn b/w the points.

$$I_D = \frac{E}{R}\Big|_{V_D=0} = \frac{10}{2K} = 5\,mA.$$

$$V_D = E\,\Big|_{I_D=0} = 10\,V.$$



$I_{DQ} = 4.6\,mA$

$V_{DQ} = 0.7\,V.$

b) $V_R = I_{DQ} \cdot R$ (or) $V_R = E - V_D.$

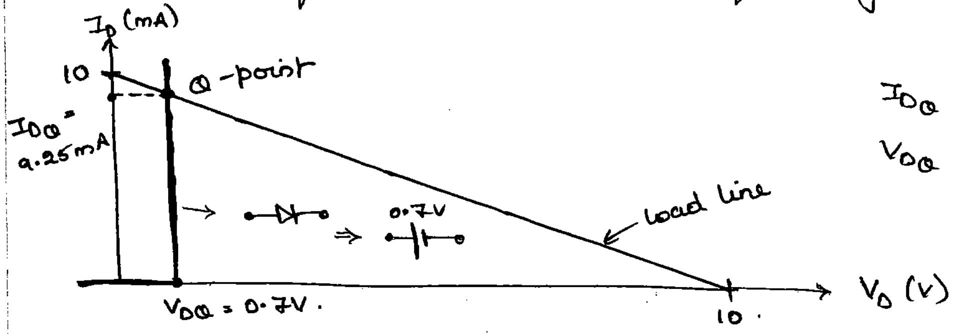
$= 4.6 \times 10^{-3} \times 5 \times 10^{+3}$ $\qquad = 10 - 0.7\,V$

$= \underline{\underline{9.2\,V}}$ $\qquad = \underline{\underline{9.3\,V}}$

As $R \uparrow$, slope of load line $\downarrow$, $I_D \downarrow$.

determine a) V_{DQ} and I_{DQ} b) V_R.

Sol: Approximate equivalent model has the following VI characteristics



$I_{DQ} = 9.25\,mA$

$V_{DQ} = 0.7V$.

$$I_D = \frac{E}{R}\Big|_{V_D=0} = \frac{10}{1K} = 10\,mA, \quad V_D = E\Big|_{I_D=0} = 10V.$$

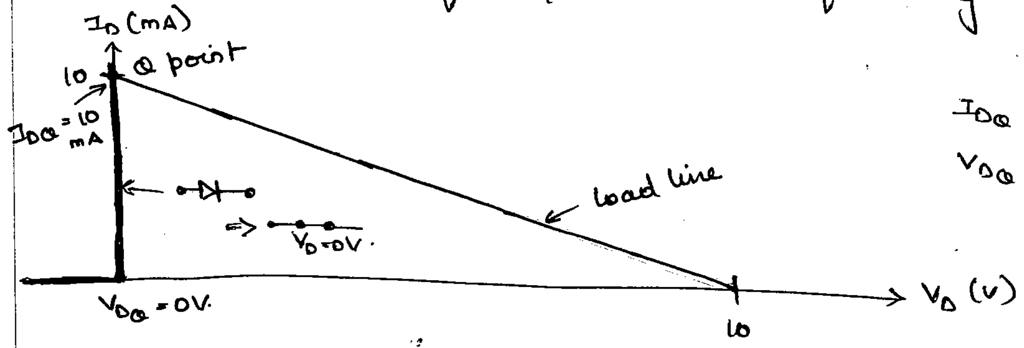
$\Rightarrow I_{DQ} = 9.25\,mA, \quad V_{DQ} = 0.7V$.

$\Rightarrow V_R = I_{DQ} \cdot R. = E - V_D$

$= \underline{\underline{9.25V}} \qquad = \underline{\underline{9.3V}}$

(Pb) Using ideal diode model for Si/Ge diode, with $R_L = 1K\Omega$ determine a) V_{DQ} and I_{DQ} b) V_R.

Sol: The ideal diode model for Si/Ge has the following VI characteristics



$I_{DQ} = 10\,mA$

$V_{DQ} = 0V$.

$$I_D = \frac{E}{R}\Big|_{V_D=0} = \frac{10}{1K} = 10\,mA, \quad V_D = E\Big|_{I_D=0} = 10V.$$

$\Rightarrow I_{DQ} = \cancel{9.25}\ 10\,mA, \quad V_{DQ} = 0V$.

$\Rightarrow V_R = I_{DQ} \cdot R \qquad V_R = E - V_D$

$= \underline{\underline{10V}} \qquad = \underline{\underline{10V}}$

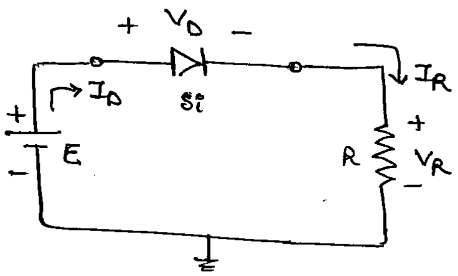
For each configuration,

1) Determine the state of diode, "ON" or "OFF"

2) Appropriate equivalent is substituted & n/w parameters are determined.

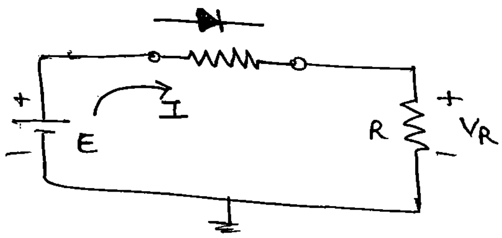
In general, diode is in "ON" state if the current established by the applied sources is such that its direction matches that of the arrow in the symbol, and $V_D = 0.7$ for Si and $V_D = 0.3$ for Ge.

Consider a series diode configuration,



forward biased.

① State of diode is determined by mentally replacing the diode with a resistor as shown below



① $V_D = V_\gamma$.

② $V_R = E - V_D$

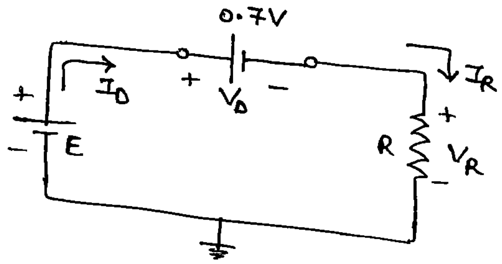
③ $I_D = I_R = \frac{V_R}{R}$.

→ (3.4)

Here, resulting direction of I is a match with the arrow of the diode symbol ⇒ Since $E > V_\gamma$

Diode is in "ON" state.

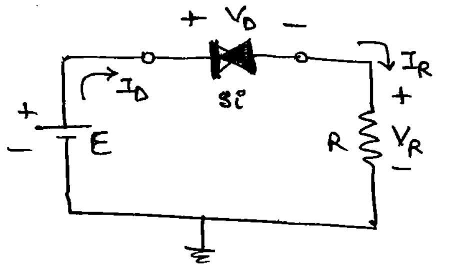
② Network is redrawn with appropriate equivalent of Si diode



Here, $V_D = V_\gamma = 0.7V$.

$V_R = E - V_\gamma$.

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



Reverse bias

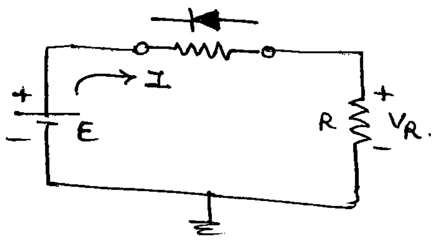
① $I_D = I_R = 0$.

② $V_R = 0V$.

③ $V_D = E$.

→ (3.5)

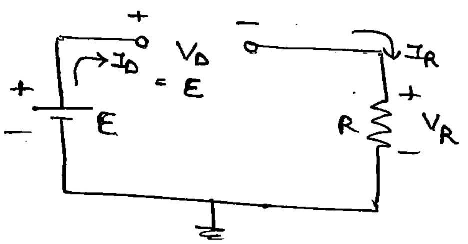
① State of the diode is determined by mentally replacing diode with a resistive element as shown



Here, the resulting current donot match with the direction of arrow in the diode symbol.

⇒ Diode is in "OFF" state.

② Diode is replaced by open circuit



Due to open circuit, diode current is 0

$$\Rightarrow I_D = \underline{\underline{0A}} = I_R$$

and voltage across resistor R is

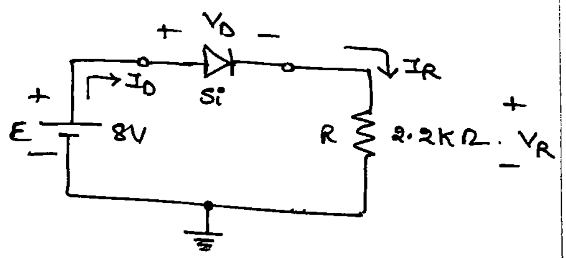
$$V_R = I_R \cdot R = 0 \cdot R = \underline{\underline{0V}}.$$

The fact That $V_R = 0$ will establish E volts across The open circuit as defined by kirchoff's voltage law.

$$V_D = E$$

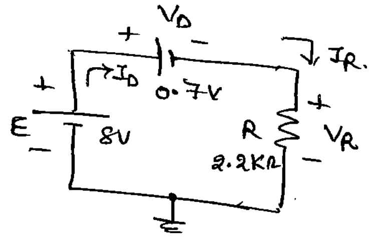
($\because$ $E - V_D - V_R = 0$. (from KVL).
since $V_R = 0 \Rightarrow E = V_D$).

Sol: Since, The applied voltage establishes a current in The clockwise direction to match the arrow of The symbol



$\Rightarrow$ Diode is in ON state.

$\Rightarrow$ $V_D = 0.7V$.



from Kirchoff's law

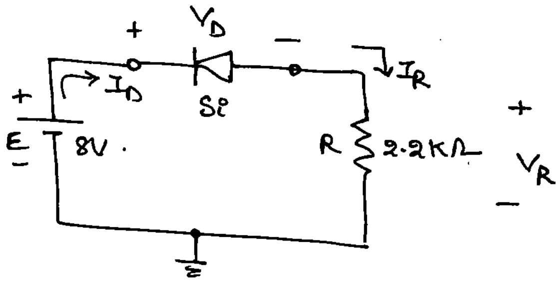
$$E - V_D - V_R = 0.$$

$$\Rightarrow V_R = E - V_D = 8 - 0.7 = 7.3V$$

Current in the series circuit.

$$I_D = I_R = \frac{V_R}{R} = \frac{7.3}{2.2 \times 10^3} = 3.32\ mA$$

(Pb) Repeat The above problem when diode is reversed!



Removing The diode we find the direction of I is opposite to The arrow in The diode symbol.

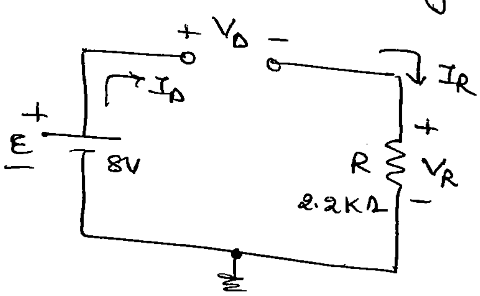
$\Rightarrow$ Diode is in OFF state.

$\Rightarrow$ replace diode by open circuit

Here, No current flows through The diode

$\Rightarrow$ $I_D = 0 = I_R$.

$\Rightarrow$ $V_R = I_R \cdot R = 0V$.



from Kirchoff's voltage law

$$E - V_D - V_R = 0.$$

$$E - V_D - 0 = 0.$$

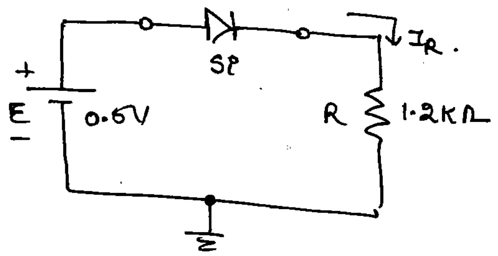
$$V_D = E = 8V$$

The current Through open circuit is 0 but The voltage across it is significant.

The current is always 0A.

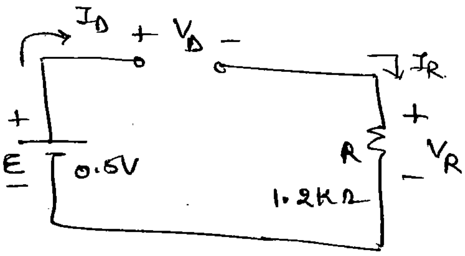
2) A short circuit has a 0-V drop across the terminals, but the current is limited only by the surrounding network.

(Pb) For the series diode configuration shown below determine I_D, V_D and V_R



Although the direction of current established matches with the arrow of the diode symbol, the level of applied voltage is insufficient to turn the diode "ON"

$\because E < V_\gamma = 0.7V$ for Si.



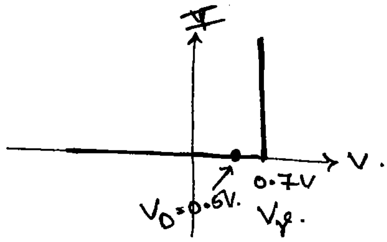
$\Rightarrow$ Diode is in "OFF" state & replaced by open circuit

here $I_D = 0A = I_R$.

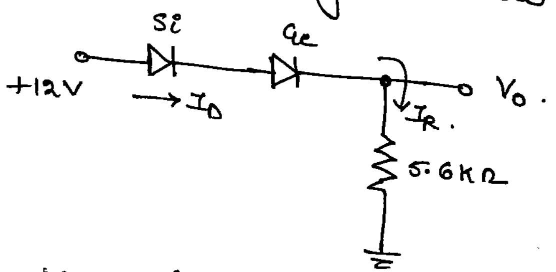
$\Rightarrow V_R = I_R \cdot R = 0V$

from KVL

$V_D = E = 0.6V$



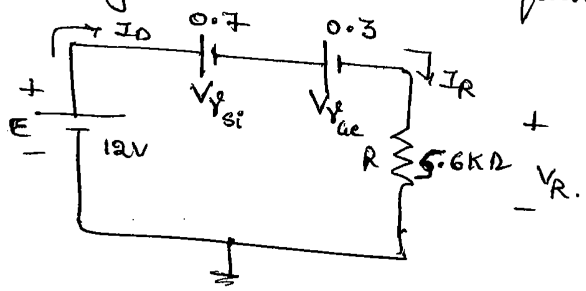
(Pb) Determine V_o and I_D for the series circuit given below.



Sol. The direction of current I matches with the arrow of diode symbols of both Si & Ge.

$\Rightarrow$ Both diodes in "ON" state $\because E > (V_{\gamma_{Si}} + V_{\gamma_{Ge}})$.

Replacing with approximate equivalent circuits



Applying KVL

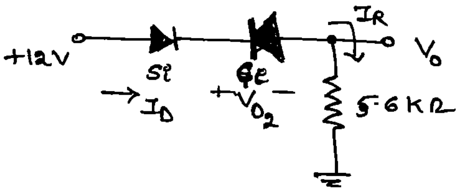
$E - V_{\gamma_{Si}} - V_{\gamma_{Ge}} - V_R = 0.$

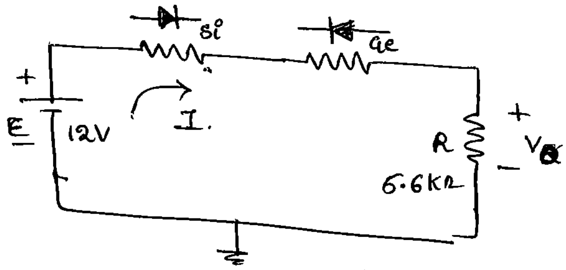
$\Rightarrow V_R = E - (V_{\gamma_{Si}} + V_{\gamma_{Ge}})$

$= 12 - (0.7 + 0.3)$

$I_D = I_R = V_R$ 11

Sol To determine the state of diodes mentally replace them by resistive elements.

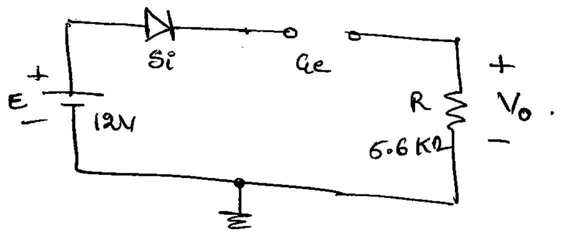




Direction of I matches arrow of Si diode symbol but not the Ge diode

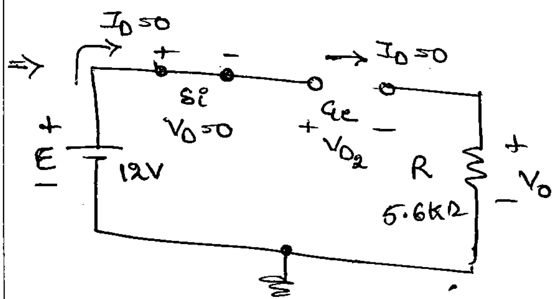
⇒ Si diode = ON ~~$V_D = 0.7V$~~

Ge diode = OFF ⇒ open circuit



The combination of a short circuit in series with open circuit always results in open circuit.

$$\Rightarrow I_D = 0.$$



For actual practical diode, when $I_D = 0 \Rightarrow V_D = 0$. (and vice-versa). indicating no bias situation.

$$\Rightarrow V_o = I_R \cdot R = I_D \cdot R = 0V$$

V_{D_2} = open circuit voltage

$V_{D_2} = E = 12V$.

(or)

Applying KVL,

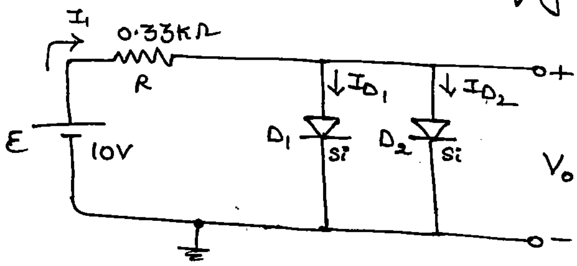
$$E - V_{D_1} - V_{D_2} = V_o.$$

$$\Rightarrow V_{D_2} = E - V_{D_1} - V_o$$

$$= 12V - 0 - 0$$

$$= 12V$$

(Pb) Determine V_o, I_{D_1}, I_{D_2} and I_1 for the parallel diode configuration shown below.



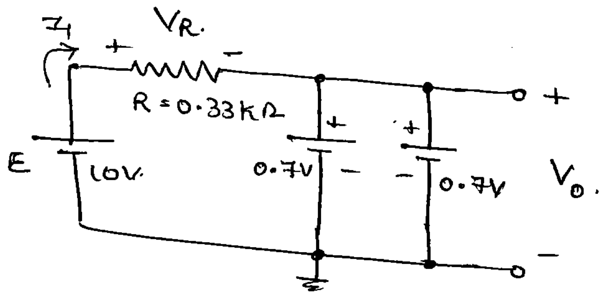
Sol: For the applied voltage, the pressure of the source is to establish a current through each diode in the same direction as I_1.

Since the resulting current direction matches that of the arrow in each diode symbol and applied voltage is greater than 0.7V, both diodes are forward biased & hence "ON".

Voltage across parallel elements is always same.

$$\Rightarrow V_o = 0.7V. \quad (\because D_1 \text{ \& } D_2 \text{ are Si diodes}).$$

The current $I_1 = \frac{V_R}{R}$.



But $V_R = E - V_D$

$= 10 - 0.7$

$= 9.3V$

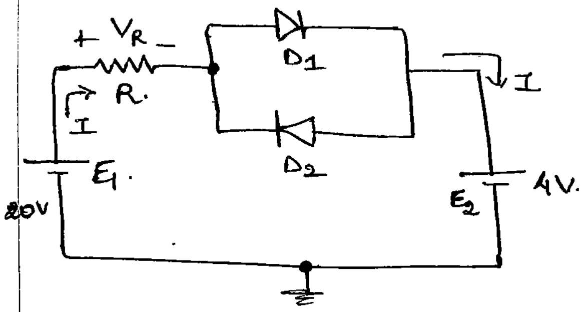
$$\Rightarrow I_1 = \frac{9.3}{0.33k\Omega} = 28.18\,mA$$

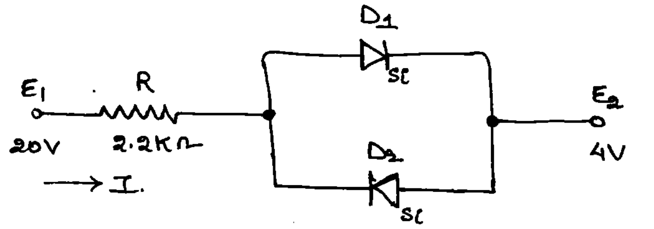
Assuming that diodes have similar characteristics,

$$I_{D_1} = I_{D_2} = \frac{I}{2} = \frac{28.18\,mA}{2} = 14.09\,mA.$$

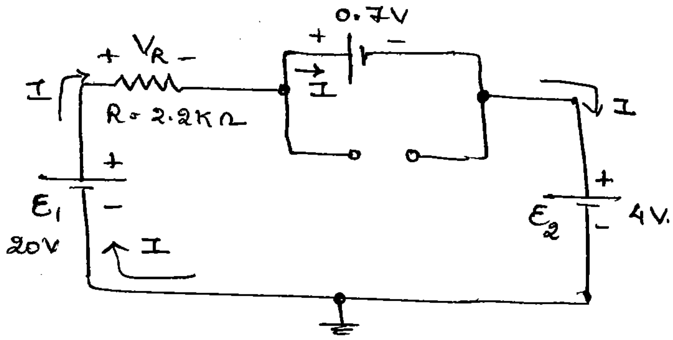
Note: If the current rating of diodes is only 20mA, a current of 28.18 mA would damage the device if it ~~is apparent~~ appeared alone across D_1. By placing two diodes in parallel, the current is limited to a safe value of 14.09mA with the same terminal voltage.

Sol. Redrawing the n/w





It is revealed that current direction is such that D_1 is ON. and D_2 is OFF.



⇒ Applying KVL

$$E_1 - V_R - 0.7 - E_2 = 0.$$

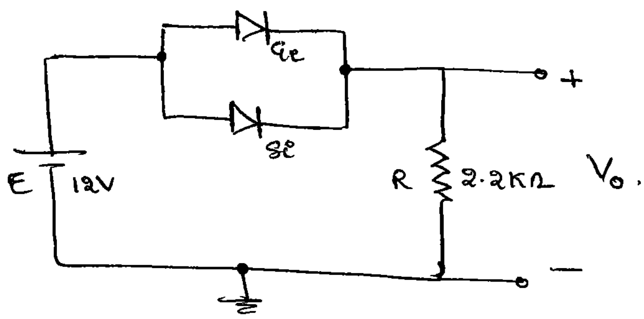
$$V_R = E_1 - E_2 - 0.7$$

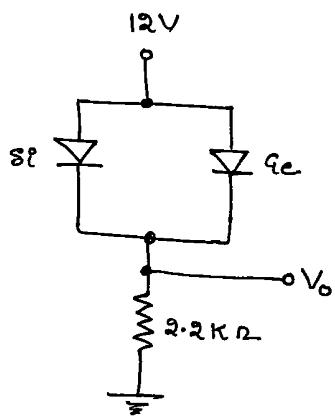
$$I_R \cdot R = E_1 - E_2 - 0.7.$$

$$I_R = I = \frac{E_1 - E_2 - 0.7}{R} = \frac{20 - 4 - 0.7}{2.2 \times 10^3} = \underline{6.95\,mA}$$

(Pb) Determine the voltage V_o for The network. shown

Sol: Redraw The n/w.

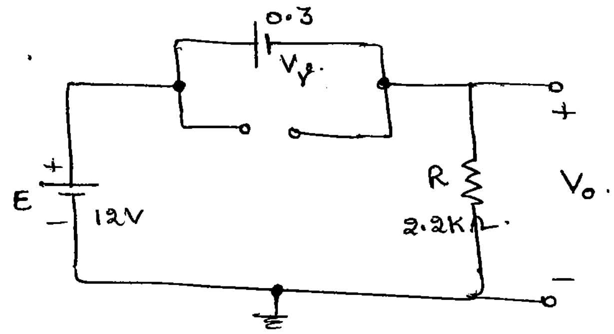




Initially, it appears as if both diodes are "ON" because. direction of current established by applied voltage matches The arrow symbol of diode.

However, if both were "ON", The 0.7V drop across Si diode will not match with 0.3V drop across Ge diode as required by The fact that The voltage across parallel elements must be same.

when supply is switched ON, it will increase from 0 to 12V over a period of time in mseconds. At the instant, when 0.3V appears across Ge diode it will turn "ON" and maintain a level of 0.3V ⇒ Si diode will never have the oppurtunity to capture its required voltage 0.7V ⇒ remains in its open-circuit state as shown below.

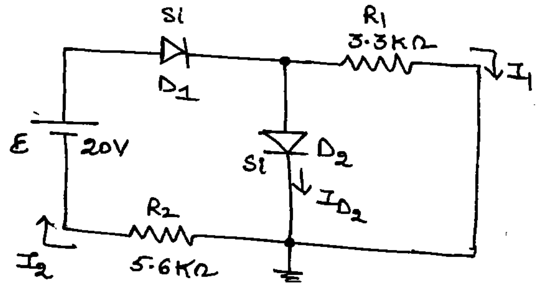


$$V_o = E - V_\gamma$$

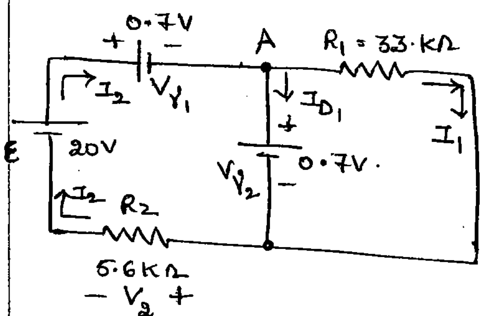
$$= 12 - 0.3$$

$$= \underline{\underline{11.7V}}$$

(Pb) Determine the currents I_1, I_2, I_{D_2} for the network shown.



Sol: The applied voltage is such that it turns on both the diodes



$$I_1 = \frac{V_{\gamma_2}}{R_1} \quad (\because R_1 \text{ is connected } ||\text{el to } V_{\gamma_2}).$$

$$= \frac{0.7}{3.3 \times 10^3}$$

$$= \underline{\underline{0.212 mA}}$$

Applying KVL

$$E - V_{\gamma_1} - V_{\gamma_2} - V_2 = 0.$$

$$V_2 = E - V_{\gamma_1} - V_{\gamma_2}$$

$$= 20 - 0.7 - 0.7$$

$$= 18.6V.$$

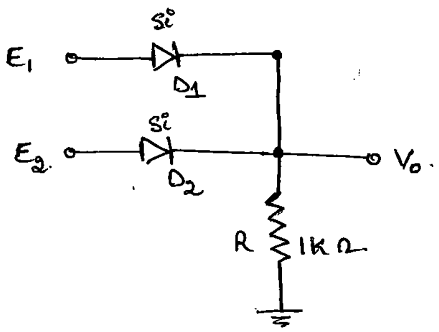
$$\Rightarrow I_2 = \frac{V_2}{R_2} = \frac{18.6V}{5.6 \times 10^3} = \underline{\underline{3.32mA}}$$

At node A, $I_2 = I_{D_1} + I_1 \Rightarrow I_{D_1} = I_2 - I_1 = (3.32 - 0.212) mA$

$$= \underline{\underline{3.108 mA}}$$

* Positive logic OR gate

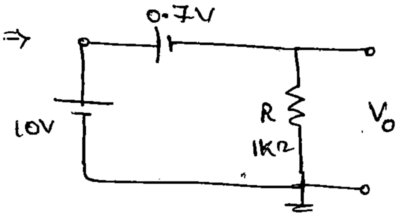
logic 1 = 10V , logic 0 = 0V.



① if $E_1 = 10V$ and $E_2 = 0V$.

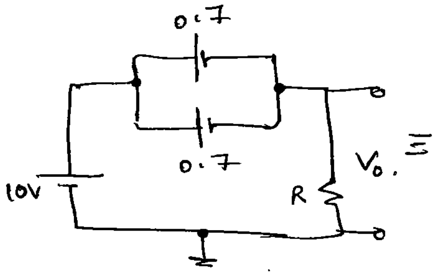
⇒ D_1 ON , D_2 = OFF.

⇒

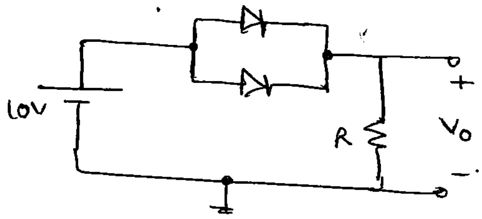


$V_o = 10 - 0.7$
$= 9.3V$
$=$ logic "1".

② if $E_1 = 10V$ and $E_2 = 10V$.



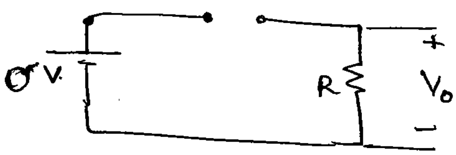
≡



D_1 + D_2 both ON.

⇒ $V_o = 10 - 0.7 = 9.3$ = logic 1.

③ If $E_1 = 0$, $E_2 = 0V$. both D_1 + D_2 are off ⇒ open circuited



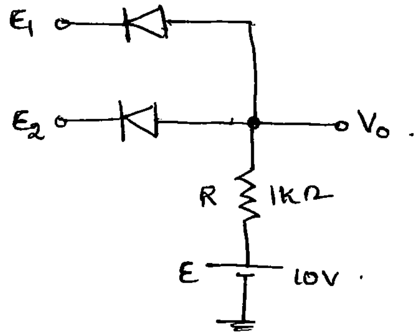
$= 0V$ = logic 0.

⇒

E_1	E_2	D_1	D_2	o/p
0	0	OFF	OFF	0
0	1	OFF	ON	1
1	0	ON	OFF	1
1	1	ON	ON	1

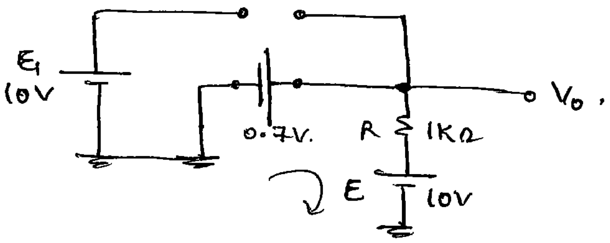
⇒ OR gate.

⇒ Positive logic AND gate



① If $E_1 = 10V$ and $E_2 = 0V$.

diode D_1 off, D_2 ON.



$$V_\gamma - V_R - E = 0$$

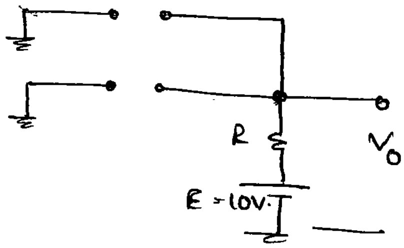
$$V_R = 0.7 - 10 = -9.3V.$$

$\Rightarrow V_o = 0.7 \Rightarrow$ logic "0".

② If $E_1 = 10V$ and $E_2 = 10V$.

D_1 and D_2 both are off.

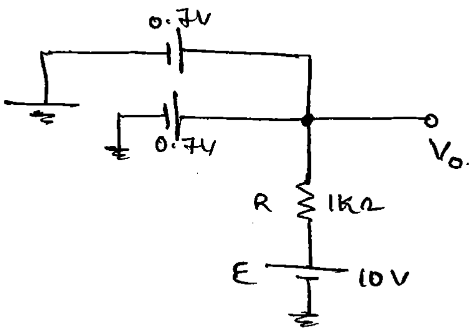
⇒



$V_o = 10V$ = logic "1".

③ If $E_1 = 0V$ and $E_2 = 0V$

D_1 & D_2 both are ON.



$V_o = 0.7V$ = logic "0".

⇒

E_1	E_2	D_1	D_2	o/p
0	0	ON	ON	0
0	1	ON	OFF	0
1	0	OFF	ON	0
1	1	OFF	OFF	1

→ AND gate.

* **Conversion of AC to DC**

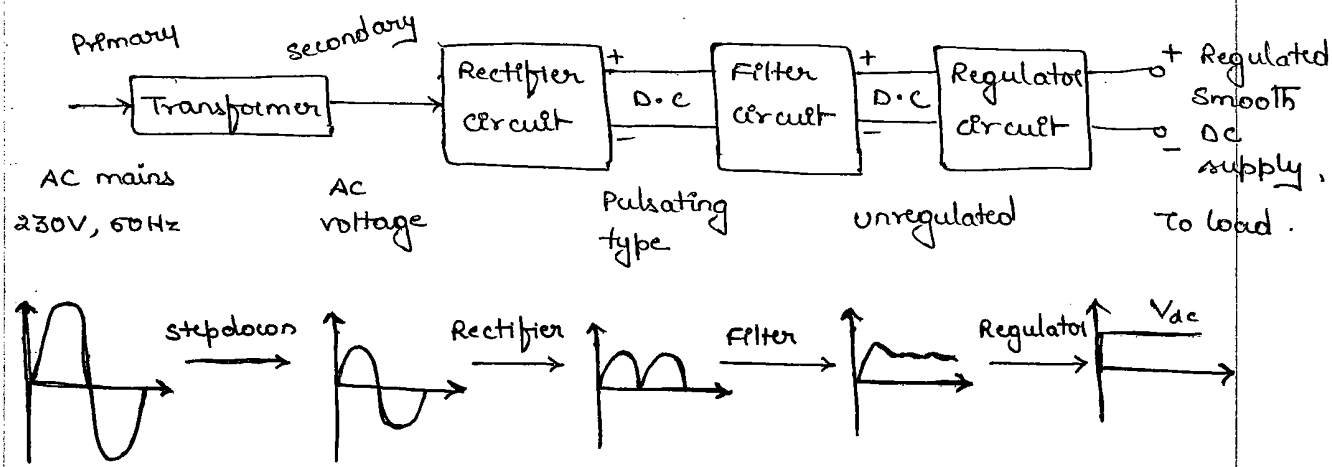
Almost all ~~ed~~ electronic circuits require a dc source of power. For portable low-power systems batteries may be used.

More frequently, however, electronic equipment is energized by a power supply, a piece of equipment which converts the alternating waveform from the power lines into an essential direct voltage.

This process of ac-to-dc conversion is called **Rectification**. This is achieved with

i) step-down transformer
ii) Rectifier
iii) Filter
iv) voltage regulator.

These elements constitute **d.c regulated power supply** as shown below:



An **ideal regulated power supply** is an electronic circuit designed to provide a predetermined d.c. voltage which is independent of the load current and variations in the i/p voltage and temperature.

If the o/p of a regulator circuit is an AC voltage then it is termed as **voltage stabilizer** whereas if the o/p is a DC voltage then it is termed as **voltage regulator**.

TRANSFORMER.

A transformer is a static device which transfers the energy from primary winding to secondary winding through the mutual induction principle, without changing the frequency.

The transformer winding to which the supply source is connected is called primary winding, while the winding connected to the load is called secondary.

If N_1, N_2 are the number of turns of the primary and secondary of the transformer then

$$\alpha = \frac{N_2}{N_1} = \text{turns ratio of the transformer.}$$

The different types of transformers are

1) step-up transformer.
2) step-down transformer
3) centre-tapped transformer.

Any device which offers a low resistance to the current in one direction but a high resistance to the current in the opposite direction is called a Rectifier.

Such a device is capable of converting a sinusoidal input waveform, whose average value is 0, into a uniform unidirectional waveform, with a nonzero average component.

The rectifying device is usually a semiconductor diode. The diode has infinite resistance in the reverse direction for a voltage V less than V_γ and a small constant resistance R_f in the forward direction for $V > V_\gamma$

i.e The current i in the diode or load resistance R_L is given by

$$i = I_m \sin \omega t \quad \text{for} \quad 0 \le \omega t \le \pi$$

$$i = 0 \quad \text{for} \quad \pi \le \omega t \le 2\pi .$$

where $V_i = V_m \sin \omega t$ and $I_m = \dfrac{V_m}{R_f + R_L}$.

* Important characteristics of a Rectifier circuit

1. Load currents

There are 2 types of o/p current. They are average or d.c. current and RMS current.

a) Average or DC current :

The average current of a periodic function is defined as the area of one cycle of the curve divided by the base. It is mathematically expressed as

$$\boxed{I_{dc} = \frac{1}{2\pi} \int_0^{2\pi} i \cdot d(\omega t)} \longrightarrow (3.6)$$

where $i = I_m \sin \omega t$.

b) Effective or R.M.S current:

The effective or rms value squared to a periodic function of time is given by the area of one cycle of the curve which represents the square of the function, divided by the base.

$$\boxed{I_{rms} = \left[\frac{1}{2\pi} \int^{2\pi} i^2 \cdot d(\omega t) \right]^{1/2}} \longrightarrow (3.7)$$

There are two types of o/p voltages. They are average or D.C. voltage and R.M.S voltage.

a) Average or DC voltage

The average voltage of a periodic function is defined as the area of one cycle of the curve divided by the base.

It is mathematically expressed as

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V \cdot d(\omega t) \qquad (or) \qquad \boxed{V_{dc} = I_{dc} \times R_L} \rightarrow (3.8)$$

where $V = V_m \sin \omega t$.

b) Effective or RMS voltage

The effective or RMS voltage squared of a periodic function of time is given by the area of one cycle of the curve which represents the square of the function divided by the base.

$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} V^2 \cdot d(\omega t)\right]^{1/2} \qquad (or) \qquad \boxed{V_{rms} = I_{rms} \times R_L} \rightarrow (3.9)$$

3. Ripple factor (γ)

It is defined as ratio of RMS value of ac component to the dc component in the output is known as Ripple Factor.

$$(3.10) \leftarrow \boxed{\gamma = \frac{V'_{rms}}{V_{dc}}} \rightarrow \text{with multimeter}$$

$$V_o = V_{ac} + V_{dc} \leftarrow V_{rms}$$

$V_{ac} \rightarrow V'_{rms}$, $V_{dc} \rightarrow V_{dc}$

$$\therefore V'_{rms} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

$$\Rightarrow \boxed{\gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}} \rightarrow (3.11)$$

$\rightarrow$ CRO.

V'_{rms} = obtained from multimeter

V_{rms} = obtained from CRO.

4. Efficiency (η):

It is the ratio of d.c output power to the a.c input power. It signifies, how efficiently the rectifier circuit converts ac power into dc power.

$$\boxed{\eta = \frac{P_{dc}}{P_{ac}} = \frac{\text{dc power delivered to load}}{\text{ac i/p power from transformer secondary}}} \rightarrow (3.12)$$

It is defined as the maximum reverse voltage that the diode can withstand without destroying the junction.

6. **Regulation**

The variation of dc o/p voltage as a function of d.c load current is called regulation.

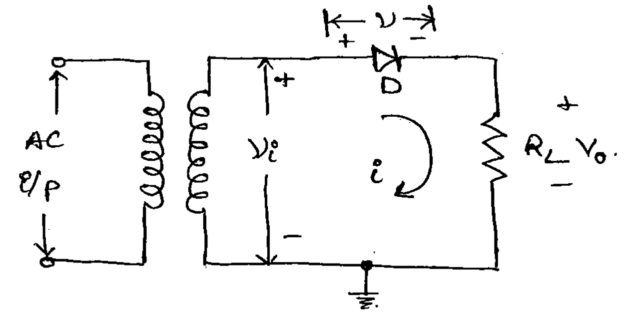
$$\boxed{\% \text{ Regulation} = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100\%} \rightarrow (3.13)$$

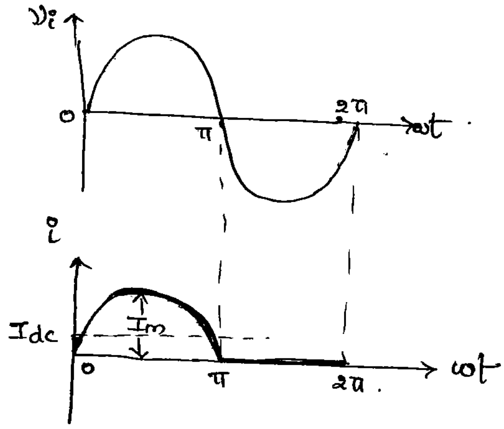
For an ideal power supply, % Regulation is 0.

* **Half-wave rectifier**

A half-wave rectifier is one which converts ac voltage into a pulsating voltage using one half cycle of the applied ac voltage.

The basic half wave rectifier circuit along with its i/p and o/p waveforms is shown below.





$\nu_i = V_m \sin \omega t$

where V_m = peak value of secondary a.c voltage

operation

For positive half cycle of input ac voltage, the diode is forward biased and hence it conducts.

⇒ current flows in the circuit & there is voltage drop across R_L

For negative half cycle of input, the diode D is reverse biased and hence it doesnot conduct.

⇒ No current flows in the circuit i.e $i = 0$ and hence $V_o = 0$.

⇒ for −ve half cycle no power is delivered to the load.

Analysis:

In the analysis of a HWR, the following parameters are to be analyzed.

i) DC output current
ii) DC output voltage
iii) RMS current
iv) RMS voltage
v) Rectifier efficiency (η)
vi) Ripple factor (γ)
vii) Regulation
viii) Transformer Utilization factor (TUF).
ix) Peak factor (P).
x) Form factor (F)
xi) Peak Inverse Voltage (PIV)

Let a sinusoidal voltage v_i be applied to the i/p of a rectifier.

$$\boxed{v_i = V_m \sin \omega t} \longrightarrow (3.14)$$

where V_m = max value of secondary voltage

Let the diode be idealized to piece-wise linear approximation with resistance R_f in the forward direction i.e, the ON state and R_r ($=\infty$) in the reverse direction i.e in OFF state.

Now, current i in the diode or in the load resistance R_L is given by.

$$i = I_m \sin \omega t \quad \text{for} \quad 0 \le \omega t \le \pi$$
$$= 0 \quad \text{for} \quad \pi \le \omega t \le 2\pi \longrightarrow (3.15)$$

$$\text{where} \quad I_m = \frac{V_m}{R_f + R_L} \longrightarrow (3.16)$$

i) Average or dc o/p current (I_{avg} or I_{dc})

The average dc current I_{dc} is given by

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

$$= \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin \omega t \cdot d(\omega t) + \int_{\pi}^{2\pi} 0 \cdot d(\omega t)\right]$$

$$= \frac{1}{2\pi}\left[I_m \left(-\cos \omega t\right)_0^{\pi}\right].$$

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

$$\boxed{I_{dc} = \frac{I_m}{\pi}} = 0.318\, I_m \,. = \frac{V_m}{\pi(R_f + R_L)}$$

The average or dc voltage is given by

$$V_{dc} = I_{dc} \times R_L$$

$$= \frac{I_m}{\pi} \times R_L. = \frac{V_m}{\pi(R_L+R_f)} \times R_L.$$

$$\boxed{V_{dc} = \frac{V_m \cdot R_L}{\pi(R_L+R_f)}}$$

If $R_L >> R_f$ $\Rightarrow$ $\boxed{V_{dc} = \frac{V_m}{\pi}.}$ $\longrightarrow$ (3.18)

iii) RMS output current (I_{rms})

The value of rms current is given by

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} i^2 \cdot d(\omega t)\right]^{1/2}$$

$$= \left[\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2\omega t \cdot d(\omega t) + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0 \cdot d(\omega t)\right]^{1/2}$$

$$= \left[\frac{I_m^2}{2\pi}\int_0^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right)\cdot d(\omega t)\right]^{1/2}$$

$$= \left[\frac{I_m^2}{4\pi}\left(\omega t - \frac{1}{2}\sin 2\omega t\right)_0^{\pi}\right]^{1/2}$$

$$= \left[\frac{I_m^2}{4\pi}\left(\pi - 0 - \frac{1}{2}\left(\sin 2\pi - \sin 0\right)\right)\right]^{1/2}.$$

$$= \left[\frac{I_m^2}{4\cancel{\pi}}(\cancel{\pi})\right]^{1/2}.$$

$$= \left[\frac{I_m^2}{4}.\right]^{1/2}$$

$\Rightarrow$ $\boxed{I_{rms} = \frac{I_m}{2}.}$ $\longrightarrow$ (3.19)

$$\therefore \; I_{rms} = \frac{I_m}{2} = \frac{V_m}{2(R_f+R_L)}.$$

(iv) Output RMS voltage

RMS voltage across load is given by $V_{rms} = I_{rms} \times R_L$.

$\boxed{V_{rms} = \frac{V_m \cdot R_L}{2(R_f+R_L)}}$. If $R_L >> R_f$ $\Rightarrow$ $\boxed{V_{rms} = \frac{V_m}{2}.}$

v) Rectifier efficiency (η):

The rectifier efficiency is defined as the ratio of dc o/p power to ac i/p power i.e.,

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

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

$I_{rms}^2 \cdot R_L$. Power dissipated across load

$$P_{ac} = I_{rms}^2 \cdot (R_L + R_f) = \frac{I_m^2}{4}(R_L + R_f) = P_d + P_L$$

Power dissipated across diode $I_{rms}^2 \cdot R_f$.

$$\Rightarrow \eta = \frac{P_{dc}}{P_{ac}} = \frac{\cancel{I_m^2} \cdot R_L}{\pi^2} \times \frac{4}{\cancel{I_m^2}(R_L + R_f)}$$

$$\eta = \frac{4}{\pi^2}\left(\frac{R_L}{R_L + R_f}\right) = \frac{0.406 \cdot R_L}{R_L + R_f}.$$

$$\boxed{\eta = \frac{4}{\pi^2}\left(\frac{1}{1 + R_f/R_L}\right)} \Rightarrow \boxed{\% \eta = \frac{40.6}{(1 + R_f/R_L)}} \rightarrow (3.21)$$

Theoretically, maximum value of rectifier efficiency of a half wave rectifier is 40.6 when $\frac{R_f}{R_L} = 0$.

vi) Ripple factor (γ):

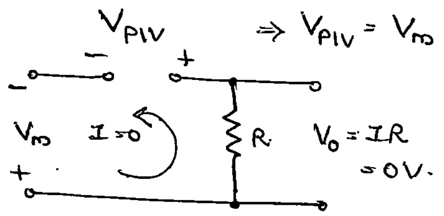
The ripple factor is given by

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} \quad \text{(or)} \quad \gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

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

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

$$\boxed{\gamma = 1.21} \longrightarrow (3.22)$$



vii) Peak Inverse Voltage (PIV)

It is defined as the maximum reverse voltage that a diode can withstand without destroying the junction.

PIV = peak of −ve half cycle.

for HWR, $\boxed{PIV = V_m.} \longrightarrow (3.23)$

The variation of dc o/p voltage as a function of dc load current is called regulation.

The variation of V_{dc} with I_{dc} for a half-wave rectifier is obtained as follows:

$$I_{dc} = \frac{I_m}{\pi} = \frac{V_m/\pi}{R_f + R_L}$$

But $V_{dc} = I_{dc} \times R_L$

$$= \frac{V_m}{\pi}\left(\frac{R_L}{R_f + R_L}\right) = \frac{V_m}{\pi}\left(1 - \frac{R_f}{R_f + R_L}\right)$$

$$= \frac{V_m}{\pi} - I_{dc} \cdot R_f.$$

$$\Rightarrow \boxed{V_{dc} = \frac{V_m}{\pi} - I_{dc} R_f.} \longrightarrow (3.24)$$

This result shows that V_{dc} equals $\frac{V_m}{\pi}$ at no load and that the dc voltage decreases linearly with an increase in dc output current. The larger the magnitude of the diode forward resistance, the greater is this decrease for a given current change.

ix) Transformer Utilization Factor (TUF):

The dc power to be delivered to the load in a rectifier circuit decides the rating of the transformer used in the circuit.

⇒ Transformer Utilization Factor is defined as

$$TUF = \frac{\text{dc power to be delivered to the load}}{\text{ac rating of the transformer secondary}}$$

$$= \frac{P_{dc}}{P_{ac\,(rated)}}$$

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

The ac power ~~to~~ rating of transformer = $V_{rms} \cdot I_{rms}$. (rated voltage of transformer secondary.)

The secondary voltage is purely sinusoidal hence its rms value is $\frac{1}{\sqrt{2}}$ times maximum while the current is half sinusoidal hence its rms value is 1/2 of the maximum.

$$\therefore \quad P_{ac\,(rated)} = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{2} = \frac{V_m I_m}{2\sqrt{2}}.$$

The dc power delevered to the load $= I_{dc}^2 \cdot R_L.$

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

$$\therefore \quad TUF = \frac{P_{dc}}{P_{ac\,(rated)}} \longrightarrow 3.25$$

$$= \left(\frac{I_m}{\pi}\right)^2 \cdot R_L \times \frac{2\sqrt{2}}{V_m I_m}$$

$$= \frac{I_m^2 \cdot R_L \cdot 2\sqrt{2}}{\pi^2 \cdot I_m^2 \cdot R_L} \qquad (\because V_m \approx I_m R_L)$$

$$= 0.287$$

$$\Rightarrow \boxed{TUF = 0.287} \longrightarrow 3.26$$

The value of TUF is low which shows that in half wave circuit, the transformer is not fully utilezed.

If the transformer rating is 1KVA (1000 VA) then the half-wave rectifier can deliver $1000 \times 0.287 = 287$ watts to resistance load.

x) Form factor. (F)

The form factor F is defined as

$$F = \frac{\text{rms value}}{\text{average value}} = \frac{I_m/2}{I_m/\pi}.$$

$$F = \frac{0.5\, I_m}{0.318\, I_m} = 1.57.$$

$$\boxed{F = 1.57} \longrightarrow 3.27$$

xi) Peak Factor (P)

The peak factor P is defined as

$$P = \frac{\text{Peak value}}{\text{rms value}} = \frac{V_m}{V_m/2} = 2.$$

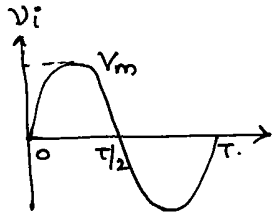
$$\boxed{P = 2} \longrightarrow 3.28$$

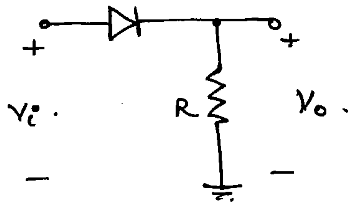
Disadvantages with Half-wave Rectifier :

1. Ripple factor is high.
2. Efficiency is low
3. TUF is low

Because of all these disadvantages, the half-wave rectifier circuit is normally not used as a power rectifier circuit.

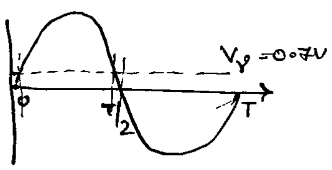
(Pb) For the given circuit obtain the o/p and V_{dc} value if a Si diode with $V_\gamma = 0.7$ V. is used.

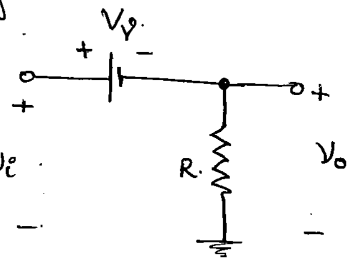


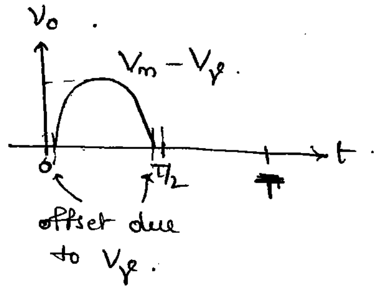


Sol: when cutin voltage of diode $V_\gamma = 0.7$V.

for positive half cycle diode is ON and can be replaced by its cutin voltage.







$$\Rightarrow V_{dc} = \frac{V_m - V_\gamma}{\pi} \simeq 0.318\,(V_m - V_\gamma).$$

The applied signal must now be atleast 0.7V before the diode can turn ~~off~~ "ON".

for $\nu_i < V_\gamma$, $\nu_o = 0$ since diode is still open circuit.

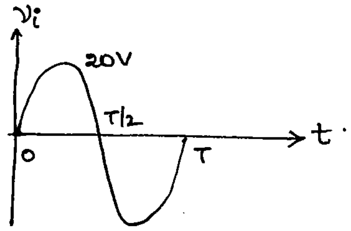
when turned "ON",

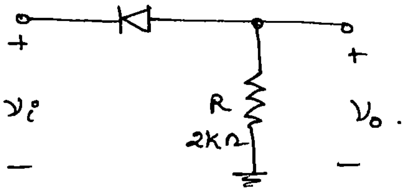
$$\nu_o = \nu_i - V_\gamma.$$

⇒ The net effect is a reduction in area above the axis, which naturally reduces the resulting dc voltage level.

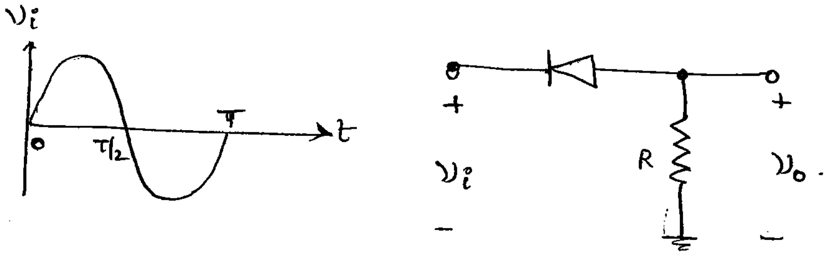
⇒ for $V_i \gg V_\gamma$, $V_{dc} = 0.318\,(V_m - V_\gamma)$.

(10) a) Sketch the output V_o and determine the dc level of the o/p for the network.
b) Repeat (a) if the ideal diode is replaced by Si diode with $V_\gamma = 0.7V$
c) Repeat (a) and (b) if V_m is increased to 200V and compare the solutions.

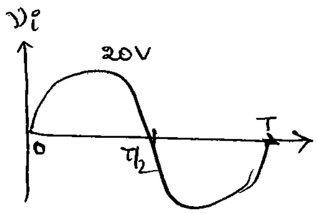


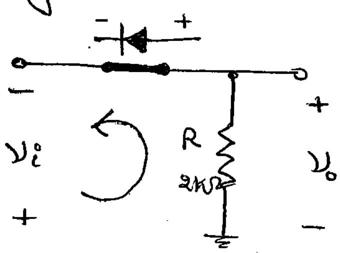


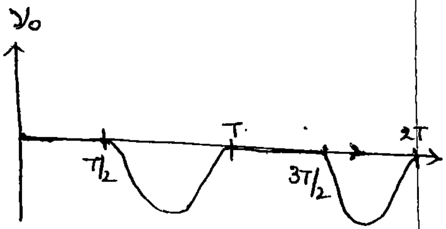
Sol: a)



here diode conducts only during negative half cycle.
⇒ can be replaced by short circuit.







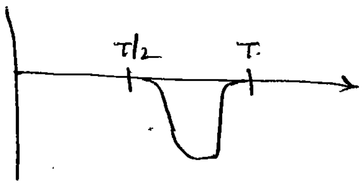
$$\Rightarrow V_{dc} = \frac{-V_m}{\pi} = \frac{-20V}{\pi} = -0.318 \times 20 = -6.36V$$

Here, negative sign indicates that the polarity of o/p is opposite to the defined polarity.

b) when a silicon diode with $V_\gamma = 0.7V$ is used.

for negative half cycle, diode conducts and is replaced by its cutin voltage. V_γ.

$$V_{dc} = -0.318\,(V_m - V_\gamma)$$
$$= -0.318\,(20 - 0.7)V$$
$$= -6.14V$$



c) If $V_m = 200V$, $V_{dc} = -0.318 \times 200 = -63.6V$ (ideal)

(10) A diode whose internal resistance is 20Ω is to supply power to a 100Ω load from 110V (rms) source of supply. Calculate

a) peak load current

b) dc load current

c) ac load current

d) % regulation from no load to full load.

Sol Given a half-wave rectifier circuit

$$R_f = 20\Omega \quad , \quad R_L = 100\Omega.$$

Given an ac source with rms voltage of 110V, Therefore The maximum amplitude of sinusoidal i/p is given by

$$V_m = \sqrt{2} \times V_{rms} = \sqrt{2} \times 110 = \underline{\underline{155.56\,V.}}$$

a) Peak load current $I_m = \dfrac{V_m}{R_f + R_L}$

$$\Rightarrow I_m = \frac{155.56}{120} = \underline{\underline{1.29\,A}}$$

b) DC load current $I_{dc} = \dfrac{I_m}{\pi} = \underline{\underline{0.41A}}$.

c) AC load current $I_{rms} = \dfrac{I_m}{2} = \underline{\underline{0.645\,A}}$

d) $V_{no\,load} = \dfrac{V_m}{\pi} = \dfrac{155.56}{\pi} = \underline{\underline{49.51\,V}}$

$$V_{full\,load} = \frac{V_m}{\pi} - I_{dc} R_f = \underline{\underline{41.26\,V}}.$$

$$\%\ \text{Regulation} = \frac{V_{no\,load} - V_{full\,load}}{V_{full\,load}} \times 100$$

$$= \underline{\underline{19.97\,\%}}.$$

(Pb) A diode has an internal resistance of 20Ω and 1000Ω load from a 110 V (rms) source of supply. Calculate
a) Efficiency of regulation rectification
b) % regulation from no load to full load

Sol: Given a half wave rectifier

$$R_f = 20\Omega, \quad R_L = 1000\Omega$$

Given an ac source with rms voltage of 110V, Therefore the maximum amplitude of sinusoidal input is given by

$$V_m = \sqrt{2} \times V_{rms} = \sqrt{2} \times 110 = \underline{\underline{155.56\,V}}$$

a) $$\%\eta = \frac{40.6}{1+\frac{R_f}{R_L}} = \frac{40.6}{1+\frac{20}{1000}} = \frac{40.6}{1.02} = \underline{\underline{39.8\,\%}}$$

b) $$I_m = \frac{V_m}{R_f + R_L} = \frac{155.56}{1020} = \underline{\underline{0.1625\,A}} = \underline{\underline{152.5\,mA}}$$

$$I_{dc} = \frac{I_m}{\pi} = \frac{152.5}{\pi} = \underline{\underline{48.54\,mA}}$$

$$V_{no\ load} = \frac{V_m}{\pi} = \frac{155.56}{\pi} = \underline{\underline{49.51\,V}}$$

$$V_{full\ load} = \frac{V_m}{\pi} - I_{dc} \cdot R_f = 49.51 - (48.54 \times 10^{-3} \times 20)$$
$$= \underline{\underline{48.54\,V}}$$

$$\%\ Regulation = \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \times 100$$

$$= \frac{49.51 - 48.54}{48.54} \times 100$$

$$= \underline{\underline{1.94\,\%}}$$

(10) An ac supply of 230V is applied to a half-wave rectifier circuit through transformer of turns ratio 5:1. Assume the diode is an ideal one. The load resistance is ~~300Ω~~ 300Ω. Find

a) dc o/p voltage

b) PIV

c) Maximum value of ~~load current~~ power delivered to the load.

d) Average value of power delivered to the load.

Sol: a) The transformer secondary voltage $= \frac{230}{5} = 46\,V$.

Maximum value of secondary voltage, $V_m = \sqrt{2} \times 46 = \underline{\underline{65V}}$

$\Rightarrow$ dc o/p voltage, $V_{dc} = \frac{V_m}{\pi} = \frac{65}{\pi} = \underline{\underline{20.7\,V}}$

b) PIV of diode $= V_m = \underline{\underline{65V}}$.

c) Maximum value of load current, $I_m = \frac{V_m}{R_L} = \frac{65}{300} = 0.217\,A$

$\Rightarrow$ maximum value of power delivered to the load,

$$P_m = I_m^2 \times R_L$$

$$= (0.217)^2 \times 300 = \underline{\underline{14.1\,W}}$$

d) Average value of load current, $I_{dc} = \frac{V_{dc}}{R_L} = \frac{20.7}{300} = 0.069\,A$.

$\Rightarrow$ Average value of power delivered to the load

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

$$= (0.069)^2 \times 300 = \underline{\underline{1.43\,W}}$$

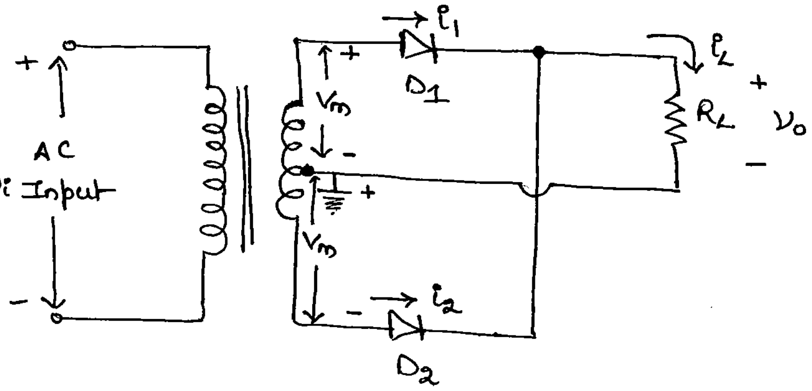
* Full wave Rectifier

A full wave rectifier converts an ac voltage into a pulsating dc voltage using both half cycles of the applied ac voltage.

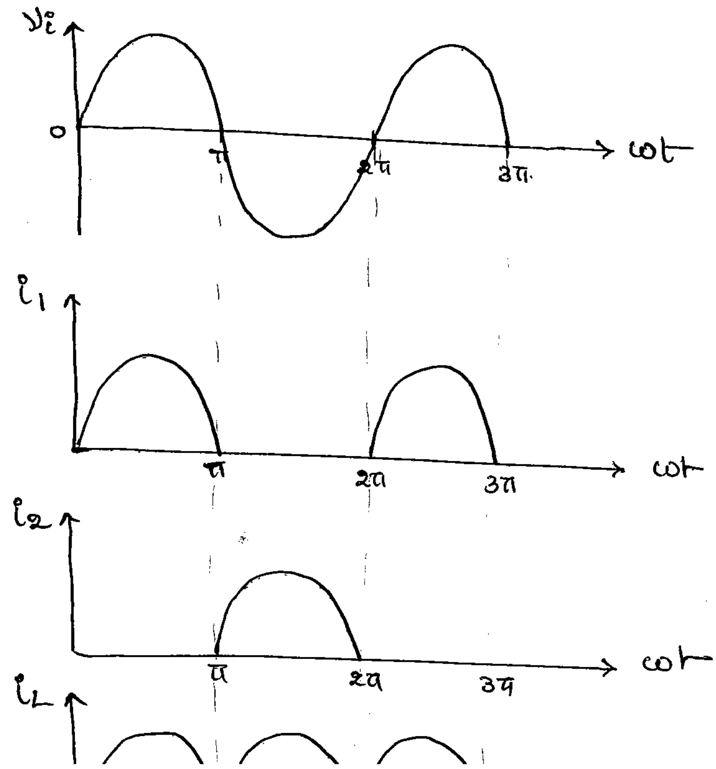
In order to rectify both the half cycles of ac input, two diodes are used in this circuit. The diodes feed a common load R_L with the help of a center tap transformer.

A center tap transformer is the one which produces two sinusoidal waveforms of same magnitude and frequency but out of phase wrt the ground in the secondary winding of the transformer.

The full wave rectifier is shown below:



The individual diode currents and the load current waveforms are shown below:



i/p voltage

current through diode D_1

current through diode D_2

current through R_L (load)

Operation:

During positive half of the i/p signal, anode of diode D_1 becomes positive and at the same time anode of diode D_2 becomes negative. $\Rightarrow$ D_1 conducts and D_2 doesnot conduct. The load current flows through D_1 and the voltage across R_L will be equal to the i/p voltage.

During negative half cycle of the i/p signal, the anode of D_1 becomes negative and the anode of D_2 becomes positive. Hence, D_1 doesnot conduct and D_2 conducts. The load current flows through D_2 and the voltage drop across R_L will be equal to the i/p voltage.

Here, the load current flows in both the half cycles of ac voltage and in the same direction through the load resistance.

Analysis:

Let a sinusoidal voltage v_i be applied to the input of a rectifier.

$$v_i = V_m \sin \omega t$$

The current i_1 through diode D_1 and load R_L is given by.

$$\begin{aligned} i_1 &= I_m \sin \omega t && \text{for } 0 \le \omega t \le \pi \\ &= 0 && \text{for } \pi \le \omega t \le 2\pi. \end{aligned} \quad \rightarrow (3.29)$$

where $I_m = \dfrac{V_m}{R_f + R_L}$

Illy, the current i_2 through diode D_2 and load R_L is given by.

$$\begin{aligned} i_2 &= 0 && \text{for } 0 \le \omega t \le \pi \\ &= -I_m \sin \omega t && \text{for } \pi \le \omega t \le 2\pi \end{aligned} \quad \rightarrow (3.30)$$

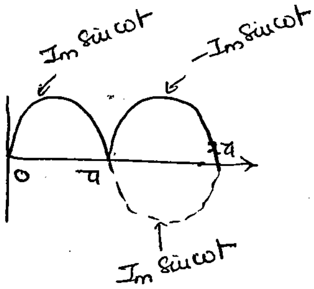
$\Rightarrow$ total current flowing through R_L is the sum of the two currents i_1 and i_2.

i.e, $i_L = i_1 + i_2$. $\rightarrow$ (3.31)

i) Average or dc output current (I_{dc}) :

The average dc current I_{dc} is given by

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_1 \, d(\omega t) + \frac{1}{2\pi}\int_0^{2\pi} i_2 \cdot d(\omega t)$$



$$= \frac{1}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\cdot d(\omega t) + 0 + 0 + \frac{1}{2\pi}\int_{\pi}^{2\pi} I_m \sin(\omega t)\cdot d(\omega t)$$

$$= \frac{I_m}{\pi} + \frac{I_m}{\pi}.$$

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

$$\Rightarrow \boxed{I_{dc} = \frac{2I_m}{\pi}.} \longrightarrow (3.32)$$

periodic over 0 to π.

(or) $I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_m \sin\omega t \cdot d(\omega t)$

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

Substituting the value of I_m, we get

$$I_{dc} = \frac{2}{\pi}\cdot\frac{V_m}{R_f + R_L}.$$

This is double that of Half wave Rectifier.

ii) Average or dc output voltage (V_{dc})

The dc voltage across the load is given by

$$V_{dc} = I_{dc} \times R_L$$

$$= \frac{2I_m \cdot R_L}{\pi}$$

$$\Rightarrow V_{dc} = \frac{2}{\pi}\cdot\frac{V_m \cdot R_L}{R_f + R_L}$$

If $R_L >> R_f$ Then $\boxed{V_{dc} = \frac{2V_m}{\pi}} \longrightarrow (3.33)$

iii) RMS output current (I_{rms})

The RMS value of current can be obtained as follows

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} i_L^2 \cdot d(\omega t)\right]^{1/2}$$

$$= \left[\frac{1}{2\pi}\int_0^{\pi} i_1^2 \cdot d(\omega t) + \frac{1}{2\pi}\int^{2\pi} i_2^2 \cdot d(\omega t)\right]^{1/2}$$

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

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

$$= \left\{ \frac{I_m^2}{4\pi} \left[\omega t - \frac{\sin 2\omega t}{\omega t} \right]_0^{\pi} + \frac{I_m^2}{4\pi} \left[\omega t - \frac{\sin 2\omega t}{\omega t} \right]_{\pi}^{2\pi} \right\}^{1/2}$$

$$= \left\{ \frac{I_m^2}{4\pi} \left[(\pi - 0) - (0) \right] + \frac{I_m^2}{4\pi} \left[(2\pi - 0) - (\pi - 0) \right] \right\}^{1/2}.$$

$$= \left[\frac{I_m^2}{4\pi} \times \pi + \frac{I_m^2}{4\pi} \times \pi \right]^{1/2}$$

$$= \left(2 \times \frac{I_m^2}{4} \right)^{1/2} = \frac{I_m}{\sqrt{2}}.$$

$$\Rightarrow \boxed{I_{rms} = \frac{I_m}{\sqrt{2}}} \rightarrow (3.34)$$

(or) $I_{rms} = \left[\frac{1}{2\pi} \int_0^{2\pi} i_L^2 \cdot d(\omega t) \right]^{1/2}$

$$= \left[\frac{2}{2\pi} \int_0^{\pi} I_m^2 \sin^2 \omega t \cdot d(\omega t) \right]^{1/2}$$

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

(or) $I_{rms} = \dfrac{V_m}{\sqrt{2}\,(R_f + R_L)}.$

iv) RMS o/p voltage (V_{rms})

RMS voltage across the load is given by

$$V_{rms} = I_{rms} \times R_L$$

$$= \frac{V_m}{\sqrt{2}\,(R_f + R_L)} \times R_L.$$

$$\Rightarrow V_{rms} = \frac{V_m}{\sqrt{2} \left[1 + \frac{R_f}{R_L} \right]}$$

If $R_L >> R_f$, then $\boxed{V_{rms} = \frac{V_m}{\sqrt{2}}} \rightarrow (3.35)$

v) Rectifier efficiency (η):

The rectifier efficiency is defined as

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

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

$$P_{ac} = I_{rms}^2 \cdot (R_L + R_f) = \frac{I_m^2}{2} (R_L + R_f).$$

$$\Rightarrow \eta = \frac{P_{dc}}{P_{ac}} = \frac{4 I_m^2 R_L}{\pi^2} \times \frac{2}{I_m^2 (R_L + R_f)}$$

$$= \frac{8}{\pi^2} \left(\frac{R_L}{R_L + R_f} \right)$$

$$= \frac{8}{\pi^2 \left[1 + R_f/R_L\right]} = \frac{0.812}{1 + \frac{R_f}{R_L}}$$

$$\Rightarrow \boxed{\% \eta = \frac{81.2}{1 + \frac{R_f}{R_L}}} \rightarrow (3.36)$$

Theoretically, the maximum value of rectifier efficiency of a full wave rectifier is 81.2 % when $\frac{R_f}{R_L} = 0$

$\Rightarrow$ FWR has efficiency twice that of half wave rectifier

vi) Ripple factor (γ)

The ripple factor γ is given by

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} \quad \text{(or)} \quad \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

$$\Rightarrow \gamma = \sqrt{\left(\frac{I_m}{\sqrt{2}} \times \frac{\pi}{2 I_m}\right)^2 - 1}$$

$$= \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1} = 0.48$$

$$\Rightarrow \boxed{\gamma = 0.48} \rightarrow (3.37)$$

vii) Regulation:

The variation of V_{dc} with I_{dc} for a FWR is

$$V_{dc} = I_{dc} \times R_L$$

$$= \frac{2I_m}{\pi} \times R_L \qquad \left(\because I_{dc} = \frac{2I_m}{\pi}\right)$$

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

$$= \frac{2V_m}{\pi} \left[1 - \frac{R_f}{R_L + R_f}\right]$$

$$= \frac{2V_m}{\pi} - I_{dc} R_f .$$

$$\Rightarrow \boxed{V_{dc} = \frac{2V_m}{\pi} - I_{dc} R_f} \rightarrow (3.38)$$

The percentage regulation of the FWR is given by

$$\%\ \text{Regulation} = \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \times 100$$

$$= \frac{\frac{2V_m}{\pi} - \left(\frac{2V_m}{\pi} - I_{dc} \cdot R_f\right)}{\frac{2V_m}{\pi} - I_{dc} R_f} \times 100 .$$

$$= \frac{I_{dc} \cdot R_f}{I_{dc} \cdot R_L} \times 100 .$$

$$\boxed{\%\ \text{Regulation} = \frac{R_f}{R_L} \times 100} \rightarrow (3.39)$$

viii) Form factor (F)

$$F = \frac{\text{rms value}}{\text{average value}} = \frac{I_m / \sqrt{2}}{2I_m / \pi} = 1.12 .$$

$$\boxed{F = 1.12 .} \rightarrow (3.40)$$

(iii) Transformer utilization factor (TUF)

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

$$\text{Secondary TUF} = \frac{\text{DC power to the load}}{\text{AC power rating of secondary}}$$

$$\Rightarrow (TUF)_s = \frac{I_{dc}^2 \times R_L}{\frac{I_m}{\sqrt{2}} \times \frac{V_m}{\sqrt{2}}} = \frac{(2I_m/\pi)^2 \times R_L}{\frac{V_m \cdot I_m}{2}}$$

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

$$= \frac{8}{\pi^2} \left(\frac{1}{1 + R_f/R_L} \right)$$

If $R_f \ll R_L$, then $(TUF)_s = \frac{8}{\pi^2} = \underline{\underline{0.812}}$

The primary of the transformer is feeding two half-wave rectifiers seperately. These two halfe-wave rectifiers work endependently of each other but feed the same common load. We have already derived the TUF for half-wave rectifier circuit to be equal to 0.287. Hence,

$$\text{TUF for primary winding} = 2 \times \text{TUF for half wave circuit}$$

$$\Rightarrow (TUF)_p = 2 \times 0.287 = \underline{\underline{0.574}}$$

The average TUF for full wave rectifier is

$$(TUF)_{avg} = \frac{(TUF)_s + (TUF)_p}{2}$$

$$= \frac{0.812 + 0.574}{2}$$

$$\boxed{(TUF)_{avg} = 0.693} \rightarrow (3.41)$$

x) Peak factor (P)

$$P = \frac{\text{peak value}}{\text{rms value}} = \frac{I_m}{I_m/\sqrt{2}}$$

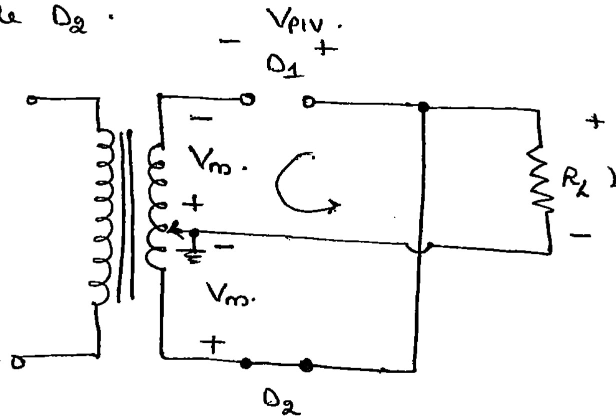
$$= \sqrt{2} = 1.414.$$

$$\Rightarrow \boxed{P = 1.414.} \rightarrow (3.42)$$

xi) Peak Inverse Voltage (PIV)

Peak inverse voltage is the maximum voltage across a diode when it is reverse biased.

consider diode D_2 is in forward bias i.e conducting and D_1 is reverse biased i.e nonconducting. In this case, V_m is developed across load R_L because of the conducting diode D_2.



because of conducting diode D_2.

Now applying KVL, .

$$V_{PIV} = \text{Voltage across } R_L + \text{Voltage of Secondary}$$

$$= V_m + V_m$$

$$V_{PIV} = 2V_m$$

Now, voltage across the diode is sum of voltages across load resistor R_L and voltage across the ~~lower~~ upper half of transformer secondary.

$$\Rightarrow \boxed{\text{PIV of diode } D_1 = 2V_m.} \rightarrow (3.43)$$

$$\boxed{\text{Illy PIV of diode } D_2 = 2V_m.}$$

a center-trapped secondary winding. The rms voltage from either end of secondary to center tap is 30V. If the diode forward resistance is 5Ω and that of the secondary is 10Ω for a load of 900Ω, calculate:

i) power delivered to load

ii) % regulation at full load

iii) Efficiency at full load.

iv) TUF of secondary.

Sol: Given $V_{rms} = 30V$,

$R_f = 5\Omega$,

$R_s = 10\Omega$,

$R_L = 900\Omega$.

But $V_{rms} = \frac{V_m}{\sqrt{2}} \Rightarrow V_m = 30 \times \sqrt{2} = 42.426\ V$

$$I_m = \frac{V_m}{R_f + R_s + R_L} = \frac{30\sqrt{2}}{5+10+900} = 46.36\ mA$$

$$I_{dc} = \frac{2I_m}{\pi} = \frac{2 \times 46.36}{\pi} = 29.5\ mA.$$

i) Power delivered to load $= I_{dc}^2 \cdot R_L$.

$$= (29.5 \times 10^{-3})^2 \times 900$$

$$= \underline{0.783\ W}.$$

ii) % Regulation of full load $= \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \times 100$

$$V_{no\ load} = \frac{2V_m}{\pi} = \frac{2 \times 42.426}{\pi} = 27.02\ V$$

$$V_{full\ load} = I_{dc} \cdot R_L = 29.5 \times 10^{-3} \times 900 = 26.5\ V.$$

$\therefore$ % Regulation $= \frac{27.02 - 26.5}{26.5} \times 100$

$$= \underline{1.96\ \%}$$

iii) efficiency at full load $= \dfrac{81.2}{1 + \dfrac{R_f + R_s}{R_L}} = \dfrac{81.2}{1 + \dfrac{15}{900}} = \underline{\underline{79.8\%}}$

iv) TUF of Secondary $= \dfrac{\text{DC power output}}{\text{Secondary ac rating}}$

Transformer secondary rating $= V_{rms} \cdot I_{rms}$.

$$= 30 \times \frac{46.36}{\sqrt{2}} \times 10^{-3} \text{ W}.$$

$P_{dc} = I_{dc}^2 \cdot R_L = 0.783 \text{ W}$.

$$\Rightarrow \text{TUF} = \frac{0.783}{30 \times \frac{46.36}{\sqrt{2}} \times 10^{-3}} = \underline{\underline{0.796}}$$

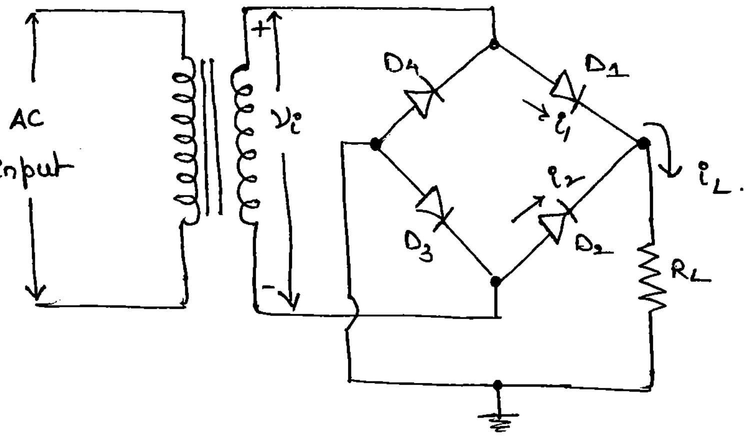
The full-wave rectifier circuit requires a center tapped transformer where only one half of the total ac voltage of the transformer secondary winding is utilized to convert into dc o/p.

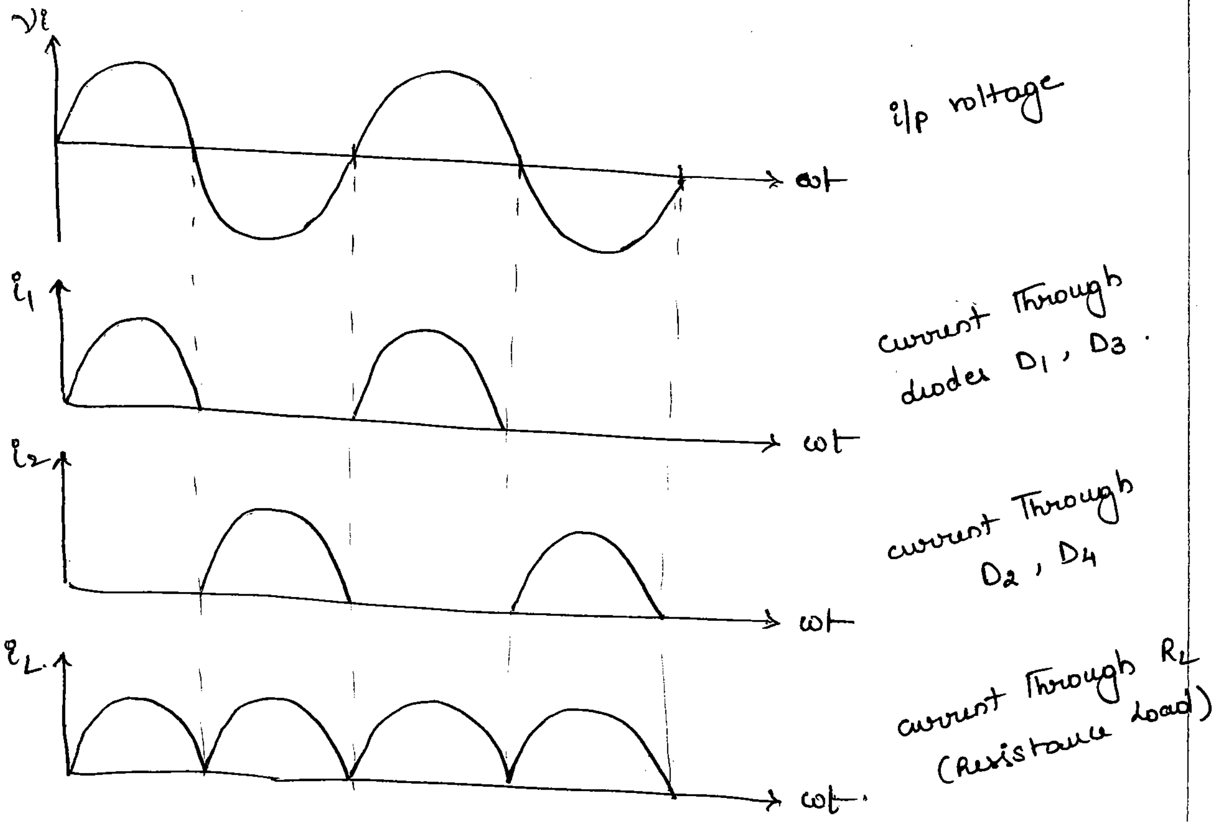
The need of the center tapped transformer in a full wave rectifier is eliminated in the bridge rectifier.

The bridge rectifier circuit has four diodes connected to form a bridge.

The ac input voltage is applied to diagonally opposite ends of the bridge. The load resistance is connected between the other two ends of the bridge.

The bridge rectifier circuit and its waveforms are shown below:





Operation:-

For the positive half cycle of the i/p ac voltage, diodes D_1 and D_3 conducts, whereas diodes D_2 and D_4 donot conduct. The conducting diodes will be in series through the load resistance R_L, so the load current flows through the R_L.

During negative half cycle of the i/p ac voltage, diodes D_2 and D_4 conducts, whereas diodes D_1 and D_3 donot conduct. The conducting diodes D_2 and D_4 are in series through the load resistance, R_L and the current flows through the R_L, in the same direction as in the previous half cycle.

Thus, a bidirectional wave is converted into a unidirectional wave.

Analysis:

The average values of output voltage and load current, the rms values of voltage and current, the ripple factor and rectifier efficiency are the same as for a center-tapped fullwave rectifier,

Hence,

$$V_{dc} = \frac{2V_m}{\pi} \qquad \gamma = 0.48$$

$$I_{dc} = \frac{2I_m}{\pi} \qquad \eta = \frac{81.2}{1+\frac{2R_f}{R_L}}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}} \qquad I_m = \frac{V_m}{2R_f + R_L} \rightarrow (3.44)$$

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

Since in each ~~cyc~~ half cycle two diodes conduct simultaneously.

The transformer utilization factor (TUF) of primary & secondary will be the same as there is always through primary and secondary.

$$\text{TUF of secondary} = \frac{P_{dc}}{\text{V-A rating of secondary}}$$

$$= \frac{I_{dc}^2 \cdot R_L}{V_{rms} \cdot I_{rms}}$$

$$= \frac{\left(\frac{2I_m}{\pi}\right)^2 \cdot R_L}{\left(\frac{V_m}{\sqrt{2}}\right)\left(\frac{I_m}{\sqrt{2}}\right)} = 0.812 \rightarrow (3.45)$$

$$\therefore (TUF)_{av} = \frac{(TUF)_p + (TUF)_s}{2}$$

$$= \frac{0.812 + 0.812}{2} = \underline{\underline{0.812}}$$

$$\boxed{TUF = 0.812} \rightarrow (3.46)$$

The reverse voltage appearing across the reverse biased diodes is $2V_m$, but two diodes are sharing it, Therefore the PIV rating of diode is V_m.

Advantages of Bridge Rectifier Circuit

1. No center tapped transformer is required.
2. TUF is considerably high.
3. PIV is reduced across the diode

Disadvantage of Bridge Rectifier Circuit

The only disadvantage of bridge rectifier is the use of four diodes as compared to 2 diodes for center-tapped FWR. This reduces o/p voltage.

* Disadvantages of half wave rectifier circuit

1. Ripple factor of half wave rectifier circuit is 1.21, which is quite high. The output contains lot of varying components.
2. The maximum theoretical rectification efficiency is found to be 40%. The practical value will be less than this. This indicates that half-wave rectifier is quite inefficient.
3. The circuit has low transformer utilization factor, showing that transformer is not fully utilized.
4. The dc current is flowing through the secondary winding of the transformer which may cause dc saturation of the core of the transformer. To minimize the saturation, transformer size have to be increased accordingly. Thus increases cost.

Because of all these drawbacks, the half-wave rectifier circuit is normally not used as a power rectifier circuit.

* Comparison of full wave and half wave circuit

1. The dc load current in case of full wave circuit is twice to that of half-wave circuit. Illy, the dc voltage in full wave circuit is twice that in half wave circuit.
2. The lowest ripple frequency in full wave circuit is twice that in half wave circuit. Now to remove ripple, the additional circuits called filter circuits are used along with rectifier circuits. But as frequency is more in full wave, circuit the capacitor values required in capacitance filter are much less hence smaller elements are sufficient in filter circuits used with full wave circuit to reduce ripple.
3. Because there is no net dc current through windings of the transformer used in full wave circuit, the losses are less as compared to losses in transformer used in half wave circuit.
4. Full wave connection gives dc power output four times as large, when compared with half-wave connection.

4. The efficiency of rectification gives ac power output four times as large, when compared with half wave connection

5. The efficiency of rectification in a full wave connection is twice that for half wave connection

6. The ripple factor is less for full-wave, i.e rectification is more nearly complete for full wave as compared to half-wave.

* Advantages of Bridge Rectifier Circuit

1. The current in both the primary and secondary of the power transformer flows for the entire cycle and hence for a given power output, power transformer of small size and less cost may be used.
2. No center tapped transformer is required. Hence, wherever required ac voltage can be directly applied to the bridge
3. The current in the secondary of the transformer is in opposite direction in 2 half cycles. Hence, net dc component flowing is zero which reduces the losses and danger of saturation
4. Due to pure ac in secondary of transformer, the transformer gets utilized effectively & hence the circuit is suitable for applications where large powers are required.
5. As two diodes conduct in series in each half cycle, inverse voltage appearing across diodes get shared. Hence, the circuit can be used for high voltage applications. Such a peak inverse voltage appearing across diode is called PIV of a diode

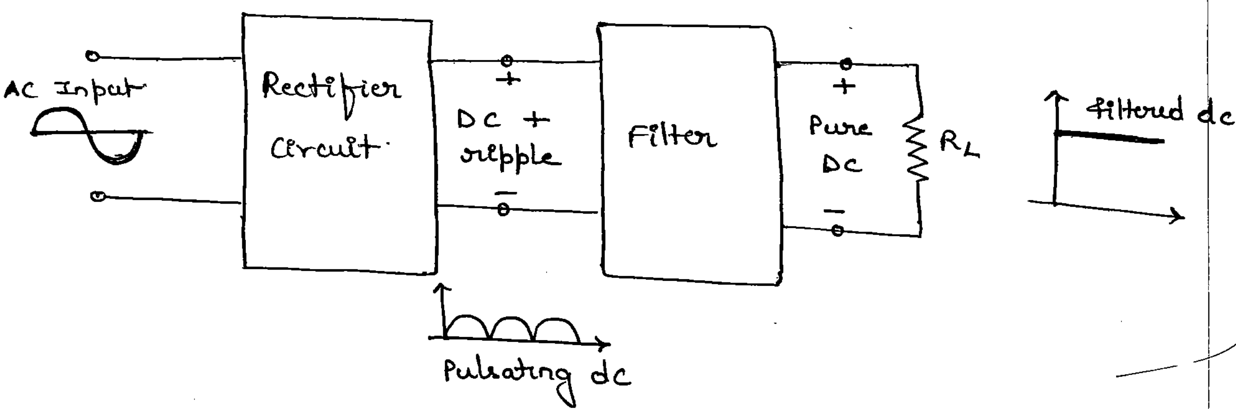
* Disadvantage of Bridge Rectifier Circuit

only disadvantage is it uses 4 diodes as compared to 2 diodes in normal full wave rectifier. This causes additional voltage drop as indicated by term $2R_f$ present in expression of I_m instead of R_f. This reduces o/p voltage

* Comparison of Rectifier circuits

	Parameter	HWR	FWR	Bridge
1	No. of diodes	1	2	4
2.	Average DC current, I_{dc}	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
3.	Average DC voltage V_{dc}	$\frac{V_m}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2V_m}{\pi}$
4.	RMS current I_{rms}	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
5.	RMS Voltage V_{rms}	I_m^2		
6.	AC Power Input P_{ac}	$\frac{I_m^2(R_L+R_f+R_s)}{4}$	$\frac{I_m^2(R_f+R_s+R_L)}{2}$	$\frac{I_m^2(R_f+R_s+R_L)}{2}$.
7.	DC Power Output P_{dc}	$\frac{I_m^2 R_L}{\pi^2}$	$\frac{4I_m^2 R_L}{\pi^2}$	$\frac{4I_m^2 R_L}{\pi^2}$
8.	Max. Rectifier Efficiency η	40.6 %	81.2 %	81.2 %
9.	Ripple factor γ	1.21	0.482	0.482
10.	Peak Inverse Voltage PIV	V_m	$2V_m$	V_m
11	Transformer Utilization factor, TUF	0.287	0.693	0.812
12.	Max. Load current I_m	$\frac{V_m}{R_s+R_f+R_L}$	$\frac{V_m}{R_s+R_f+R_L}$	$\frac{V_m}{R_s+2R_f+R_L}$

The output of a ~~fa~~ half-wave or full wave rectifier circuit is not pure dc, but it contains fluctuations or ripples, which are undesired. To minimize the ripple content in the output, filter circuits are used. These circuits are connected between the rectifier & load. as shown.



An a.c input is applied to the rectifier. At the output of the rectifier, there will be dc and ripple voltage present, which is the input to the filter.

Ideally o/p of the filter should be pure dc. Practically, the filter circuit will try to minimize the ripple at the o/p, as far as possible.

Basically, the ripple is ac component (varies w.r.t time), while dc is a constant w.r.t time ⇒ in order to seperate dc from ripple, the filter circuit should use components which have widely different impedance for a.c and d.c. Two such components are
1) Inductors
2) Capacitors.

Inductance acts as short circuit for dc, but it has a large impedance for ac. Since, it acts as short circuit for dc, it cannot be placed in the shunt arm across the load, otherwise dc will be shorted.

⇒ In a filter circuit, **Inductance** is always connected in **series with a load.**

capacitor act as open circuit for d.c, and almost short circuit for ac, if value of capacitance is sufficiently large. Since, capacitance is open for d.c i.e it blocks dc, hence it ~~at~~ cannot be connected in series with the load.

⇒ **Capacitance** is always connected in **shunt arm**, parallel to the load.

∴ Filter is an electronic device composed of capacitor, inductor or combination of both & connected between rectifier and load so as to convert pulsating dc to pure dc.

There are basically two types of filter circuits

1. Capacitor Input filter
2. Choke Input filter.

Looking from rectifier side, if the first element in the filter circuit is capacitor then the filter circuit is called capacitor Input filter.

If the first element is an inductor, it is called choke input filter. The choke input filters are not use now a days as inductors are bulky, expensive and consume more power.

* Fourier series expansion for half-wave rectifier o/p

In general,

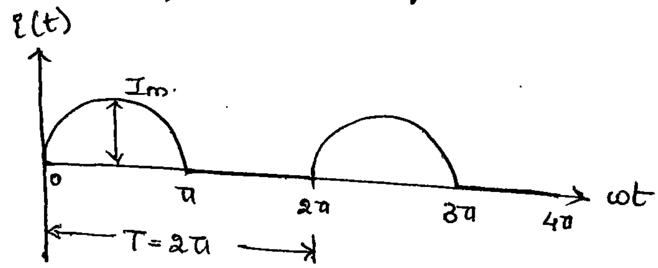
$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega_0 t) + \sum_{n=1}^{\infty} b_n \sin(n\omega_0 t)$$

where $a_0 = \frac{1}{T}\int_0^T f(t)\cdot dt$

$$a_n = \frac{2}{T}\int_0^T f(t)\cos(n\omega_0 t)\cdot dt$$

$$b_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega_0 t)\cdot dt$$

o/p of half wave rectifier is



$\omega = \frac{2\pi}{T}$.

$$i(t) = I_m \sin(\omega t), \quad 0 \le \omega t \le \pi.$$

$$= 0 \quad , \quad \pi \le \omega t \le 2\pi$$

$$\Rightarrow i(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + \sum_{n=1}^{\infty} b_n \sin(n\omega t).$$

where $a_0 = \frac{1}{2\pi}\int_0^{2\pi} i(t)\cdot d(\omega t)$

$$= \frac{1}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\cdot d(\omega t).$$

$$= \frac{I_m}{2\pi}\Big[-\cos(\omega t)\Big]_0^{\pi}.$$

$$= \frac{I_m}{2\pi}\Big[-(-1)+1\Big] = \frac{I_m}{\pi}.$$

$$\Rightarrow a_0 = \frac{I_m}{\pi}.$$

$$a_n = \frac{2}{2\pi}\int_0 i(t)\cdot \cos(n\omega t)\cdot d(\omega t).$$

$$= \frac{2}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\cdot \cos(n\omega t)\cdot d(\omega t).$$

$$= \frac{I_m}{\pi}\int_0^{\pi}\left[\frac{\sin(\omega t[1+n]) + \sin(\omega t[1-n])}{2}\right]\cdot d(\omega t).$$

$$\left[\because \sin\theta\cos\phi = \frac{\sin(\theta+\phi)+\sin(\theta-\phi)}{2}\right].$$

$$= \frac{I_m}{2\pi}\left[\frac{-\cos(\omega t[1+n])}{1+n} + \frac{-\cos(\omega t[1-n])}{1-n}\right]_0^{\pi}.$$

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

for $n = \text{odd}$, $\cos(\pi[1+n]) = \cos(\pi[1-n]) = 1$.

for $n = \text{even}$, $\cos[\pi[1+n]] = \cos[\pi(1-n)] = -1$.

$\Rightarrow a_n = 0$ for $n = \text{odd}$.

~~a_n = 2Im~~ for $n = \text{even}$.

$$a_n = \frac{-I_m}{2\pi}\left[\frac{-2}{1+n} + \frac{-2}{1-n}\right] = \frac{2I_m}{2\pi}\left[\frac{1\cancel{-n}+1\cancel{+n}}{(1-n^2)}\right]$$

$$= \frac{2I_m}{\pi(1-n^2)}.$$

$$\Rightarrow a_n = \frac{2I_m}{\pi(1-n^2)},\ \text{for } n = \text{even}.$$

So, $a_1 = 0$, $a_3 = 0$, $a_5 = 0$, ... for $n = \text{odd}$

$$a_2 = \frac{2I_m}{\pi(1-4)} = \frac{-2I_m}{3\pi},\quad a_4 = \frac{2I_m}{\pi(1-16)} = \frac{-2I_m}{15\pi},$$

--- for $n = \text{even}$

$$b_n = \frac{2}{2\pi}\int_0 i(t) \cdot \sin(n\omega t) \cdot d(\omega t)$$

$$= \frac{2}{2\pi}\int_0^{\pi} I_m \sin\omega t \cdot \sin(n\omega t) \cdot d(\omega t).$$

$$= \frac{I_m}{\pi}\int_0^{\pi} \left[\frac{\cos(\omega t[1-n]) - \cos(\omega t[1+n])}{2}\right] \cdot d(\omega t)$$

$$\left[\because \sin\theta \sin\phi = \frac{\cos(\theta-\phi) - \cos(\theta+\phi)}{2}\right].$$

$$= \frac{I_m}{2\pi}\left[\frac{\sin(\omega t[1-n])}{1-n} - \frac{\sin(\omega t[1+n])}{1+n}\right]_0^{\pi}$$

$$= \frac{I_m}{2\pi}\left[\frac{\sin(\pi[1-n]) - 0}{1-n} - \frac{\sin(\pi[1+n]) - 0}{1+n}\right].$$

$$= \frac{I_m}{2\pi}\left[\frac{\sin(\pi[1-n])}{1-n} - \frac{\sin(\pi[1+n])}{1+n}\right].$$

for all except $n=1$,

$$\sin(\pi[1-n]) = \sin(\pi[1+n]) = 0$$

$\Rightarrow$ $b_n = 0$ except for $n=1$.

$\Rightarrow$ for $n=1$,

$$b_1 = \frac{I_m}{\pi}\int_0^{\pi} \sin(\omega t) \cdot \sin(\omega t) \cdot d(\omega t)$$

$$= \frac{I_m}{\pi}\int_0^{\pi} \sin^2(\omega t) \cdot d(\omega t)$$

$$= \frac{I_m}{\pi}\int_0^{\pi} \left[\frac{1-\cos 2\omega t}{2}\right] \cdot d(\omega t)$$

$$= \frac{I_m}{2\pi}\left[\omega t - \frac{\cos 2\omega t}{2}\right]_0^{\pi}$$

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

⇒ fourier series expansion for half wave rectifier is

$$i(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + \sum_{n=1}^{\infty} b_n \sin(n\omega t).$$

$$= \frac{I_m}{\pi} + \sum_{\substack{n=1 \\ n=\text{even}}}^{\infty} \frac{2I_m}{\pi(1+n)(1-n)} \cdot \cos(n\omega t) + \frac{I_m}{2} \sin \omega t$$

$$= \frac{I_m}{\pi} + \frac{I_m}{2} - \frac{2I_m}{3\pi}\sin(2\omega t) - \frac{2I_m}{15\pi}\sin(4\omega t) + \cdots$$

⇒ fourier series expansion for half wave rectifier is

$$i(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + \sum_{n=1}^{\infty} b_n \sin(n\omega t)$$

where $a_0 = I_m/\pi$

$a_n = 0$ for $n =$ odd

$= \dfrac{2I_m}{\pi(1-n^2)}$ for $n =$ even

$b_n = \dfrac{I_m}{2}$ for $n = 1$

$= 0$ for $n \neq 1$.

$$\Rightarrow i(t) = \frac{I_m}{\pi} + \sum_{\substack{n=1 \\ n=\text{even}}}^{\infty} \frac{2I_m}{\pi(1-n^2)} \cos(n\omega t) + \frac{I_m}{2} \sin \omega t$$

$$i(t) = \frac{I_m}{\pi} + \frac{I_m}{2}\sin \omega t - \frac{2I_m}{3\pi}\cos(2\omega t) - \frac{2I_m}{15\pi}\cos(4\omega t) + \cdots$$

Note :-

$$\cos\theta \cos\phi = \frac{\cos(\theta-\phi) + \cos(\theta+\phi)}{2}$$

$$\sin\theta \sin\phi = \frac{\cos(\theta-\phi) - \cos(\theta+\phi)}{2}$$

$$\sin\theta \cos\phi = \frac{\sin(\theta+\phi) + \sin(\theta-\phi)}{2}$$

$$\sin\phi \cos\theta = \sin(\theta+\phi) - \sin(\theta-\phi)$$

inductor or combination of both and connected between the rectifier and the load so as to convert pulsating dc to pure dc.

The different types of filters are:

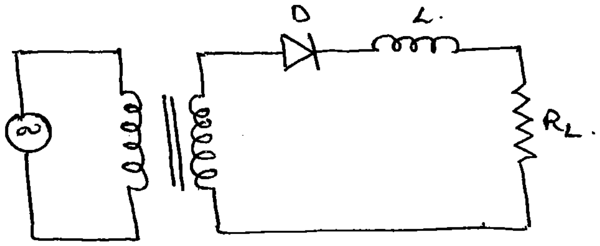
1. Inductor filter
2. Capacitor filter.
3. LC or L-section filter
4. CLC or π-section filter.

* Inductor Filter

a) Half-wave Rectifier with series inductor filter

The inductor filter for half-wave rectifier is shown in figure below.

In this filter the inductor (choke) is connected in series with the load.



Series Inductor filter for HWR.

The operation of the inductor filter depends upon the property of the inductance to oppose any change of current that may flow through it.

Expression for ripple factor

For a half-wave rectifier, the output current is given by

$$i = I_m \left[\frac{1}{\pi} + \frac{1}{2} \sin\omega t - \frac{2}{\pi} \sum_{\substack{K = \text{even} \\ K \neq 0}} \frac{\cos K\omega t}{(K+1)(K-1)} \right]$$

$$\Rightarrow i = \frac{I_m}{\pi} + \frac{I_m}{2} \sin\omega t - \frac{2 I_m}{\pi} \left[\frac{\cos 2\omega t}{3} + \frac{\cos 4\omega t}{15} + \cdots \right] \rightarrow (3.47)$$

Neglecting the higher-order terms, we have

$$I_{dc} = \frac{I_m}{\pi} = \frac{V_m}{\pi \cdot R_L} \rightarrow (3.48)$$

If I_1 be the rms value of fundamental component of current, Then

$$I_1 = \frac{I_m}{2\sqrt{2}} = \frac{V_m}{2\sqrt{2}\,(R_L + j\omega L)} = \frac{V_m}{2\sqrt{2}\,[R_L^2 + \omega^2 L^2]^{1/2}}$$

At operating frequency, the reactance offered by inductance L is very large compared to R_L (i.e, $\omega L >> R_L$) and hence R_L can be neglected.

$$I_1 = \frac{V_m}{2\sqrt{2} \cdot \omega L.} \rightarrow (3.49)$$

If I_2 be rms value of second harmonic,

Then $$I_2 = \frac{2 I_m}{3\sqrt{2}\,\pi} = \frac{2 V_m}{3\sqrt{2}\,\pi\,[R_L^2 + 4\omega^2 L^2]^{1/2}} = \frac{V_m}{3\sqrt{2}\,\pi\,\omega L} \quad (\because R_L << \omega L)$$

$$\rightarrow (3.50)$$

If I_{ac} be the rms value of all current components

Then, $$I_{ac} = \sqrt{I_1^2 + I_2^2} \rightarrow (3.51)$$

Now, $$\gamma = \frac{V_{ac}}{V_{dc}} \approx \frac{I_{ac} \cdot R_L}{I_{dc} \cdot R_L} = \frac{I_{ac}}{I_{dc}.}$$

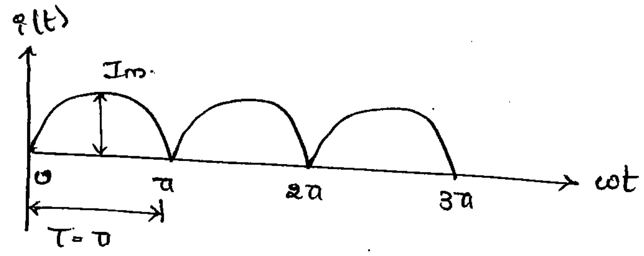
$$\gamma = \frac{\sqrt{\left(\frac{V_m}{2\sqrt{2} \cdot \omega L}\right)^2 + \left(\frac{V_m}{3\sqrt{2}\,\pi\,\omega L}\right)^2.}}{\frac{V_m}{\pi \cdot R_L.}}$$

$$= \frac{\frac{V_m}{\omega L}\sqrt{1/8 + 1/18\pi^2}}{\frac{V_m}{\pi R_L.}} = \frac{\pi \cdot R_L}{\omega L}\sqrt{\frac{1}{8} + \frac{1}{18\pi^2}}$$

$$\boxed{\gamma = \frac{1.13 R_L}{\omega L.}} \rightarrow (3.52)$$

* Fourier Series expansion for full wave rectifier o/p

for full wave, o/p is



Here, signal is periodic over $T = \pi$.

$\Rightarrow$ frequency of the o/p doubles as time period is 1/2.

as $\omega_0 = \dfrac{2\pi}{T}$.

for half wave rectifier, $\omega_0 = \dfrac{2\pi}{2\pi} = 1$.

for full wave rectifier, $\omega_0 = \dfrac{2\pi}{\pi} = 2$.

$$\Rightarrow i(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(2n\omega t) + \sum_{n=1}^{\infty} b_n \sin(2n\omega t),$$

$$\Rightarrow a_0 = \frac{1}{\pi}\int_0^{\pi} i(t) \cdot d(\omega t).$$

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

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

$$\Rightarrow a_0 = \frac{2I_m}{\pi}.$$

$$a_n = \frac{2}{\pi}\int_0^{\pi} I_m \sin(\omega t) \cdot \cos(2n\omega t) \cdot d(\omega t)$$

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

$$= \frac{-I_m}{\pi}\left[\frac{\cos[\omega t(1+2n)]}{(1+2n)} + \frac{\cos[\omega t(1-2n)]}{(1-2n)}\right]_0^{\pi}.$$

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

for n = odd or even, $2n$ = even $\Rightarrow$ $(1+2n)$ = odd = $(1-2n)$

$$\Rightarrow \cos[\pi(1+2n)] = \cos[\pi(1-2n)] = -1.$$

$$\Rightarrow a_n = \frac{-I_m}{\pi}\left[\frac{-1-1}{(1+2n)} + \frac{-1-1}{(1-2n)}\right].$$

$$= \frac{-I_m}{\pi}\left[\frac{-2}{(1+2n)} + \frac{-2}{(1-2n)}\right] = \frac{2I_m}{\pi}\left[\frac{1-\cancel{2n}+1+\cancel{2n}}{(1-4n^2)}\right]$$

$$a_n = \frac{4I_m}{\pi(1-4n^2)}.$$

Then, $b_n = \frac{2}{\pi}\int_0^{\pi} I_m \sin\omega t \cdot \sin(2n\omega t)\cdot dt$

$$= \frac{2I_m}{\pi}\int_0^{\pi}\left[\frac{\cos(\omega t[1-2n]) - \cos(\omega t[1+2n])}{2}\right]\cdot d(\omega t).$$

$$= \frac{I_m}{\pi}\left[\frac{\sin[\omega t(1-2n)]}{(1-2n)} - \frac{\sin[\omega t(1+2n)]}{(1+2n)}\right]_0^{\pi}.$$

here, we will not get $\frac{0}{0}$ value.

$\Rightarrow$ $b_n = 0$ for n = odd values.

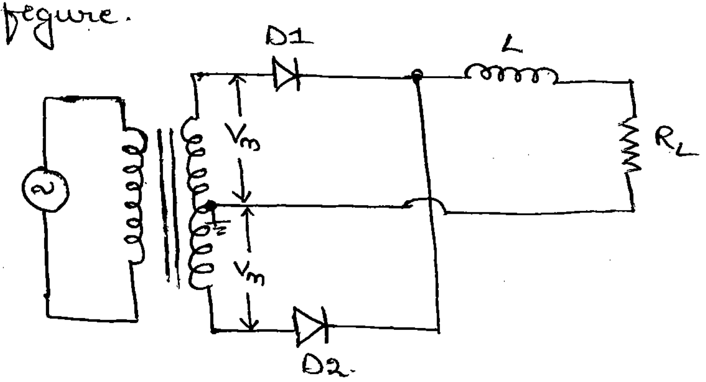
$$\Rightarrow i(t) = \frac{2I_m}{\pi} + \sum_{n=1}^{\infty}\frac{4I_m}{\pi(1-4n^2)}\cdot \cos(2n\omega_0 t) + 0.$$

$$i(t) = \frac{2I_m}{\pi} - \frac{4I_m}{\pi}\left[\frac{\cos(2\omega t)}{3} + \frac{\cos(4\omega t)}{15} + \frac{\cos(6\omega t)}{35} + \cdots\right]$$

Hly $v_0(t) = \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\left[\frac{\cos(2\omega t)}{3} + \frac{\cos(4\omega t)}{15} + \frac{\cos(6\omega t)}{35} + \cdots\right]$

b) Full-wave rectifier with series inductor filter

A full-wave rectifier with series inductor is shown in figure.



FWR with series inductor filter

The inductor offers high impedance to ac variations. The inductor blocks the ac component and allows only the dc component to reach the load.

To analyse the inductor filter for a FWR, the fourier series can be written as

$$V_o = \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\left[\frac{1}{3}\cos 2\omega t + \frac{1}{15}\cos 4\omega t + \frac{1}{35}\cos 6\omega t + \cdots\right] \rightarrow (3.53)$$

The dc component is $\frac{2V_m}{\pi}$.

Assuming the 3rd and higher terms contribute little output, the output voltage is

$$V_o = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t \rightarrow (3.54)$$

For the sake of simplicity, the diode drop and diode resistance are neglected because they introduce a little error. Thus, for dc component, the current $I_m = \frac{V_m}{R_L}$

For ac component, the impedance of L and R_L will be in series and is given by.

for dc L acts as se

$$Z = \sqrt{R_L^2 + (2\omega L)^2}, \quad \text{frequency of ac component} = 2\omega$$

$$= \sqrt{R_L^2 + 4\omega^2 L^2} \angle\phi \quad \text{where } \phi = \tan^{-1}\frac{2\omega L}{R}$$

Thus for ac component

$$I_m = \frac{V_m}{\sqrt{R_L^2 + 4\omega^2 L^2}}$$

The current flowing in a FWR is given by..

$$i = \frac{2 I_m}{\pi} - \frac{4 I_m}{3\pi} \cos 2\omega t \rightarrow (3.56)$$

Substituting the value of I_m for dc and ac in equation (3.56), we get.

$$i = \frac{2 V_m}{\pi R_L} - \frac{4 V_m}{3\pi \sqrt{R_L^2 + 4\omega^2 L^2}} \cos(2\omega t - \phi). \rightarrow (3.57)$$

where ϕ is the angle by which the load current lags behind the voltage. This is given by.

$$\phi = \tan^{-1}\left(\frac{2\omega L}{R_L}\right) \rightarrow (3.58)$$

Expression for ripple factor

$$\gamma = \frac{I_{r,rms}}{I_{dc}}$$

from eq

$$I_{dc} = \frac{2 V_m}{\pi R_L}, \quad I_{r,rms} = \frac{4 V_m}{3\pi\sqrt{2}\left(\sqrt{R_L^2 + 4\omega^2 L^2}\right)}$$

$$\gamma = \frac{\frac{4V_m}{3\pi\sqrt{2}} \cdot \frac{1}{\sqrt{R_L^2 + 4\omega^2 L^2}}}{\frac{2V_m}{\pi R_L}} = \frac{2}{3\sqrt{2}} \frac{1}{\sqrt{1 + \left(\frac{4\omega^2 L^2}{R_L^2}\right)}}$$

(2) If $\frac{4\omega^2 L^2}{R_L^2} \gg 1$, Thus $\gamma = \frac{1}{3\sqrt{2}} \cdot \frac{R_L}{\omega L} = 0.236 \cdot \frac{R_L}{\omega L}$

$$\boxed{\gamma = \frac{R_L}{3\sqrt{2} \cdot \omega L}} \rightarrow (3.59)$$

This expression shows that ripple factor varies inversely as the magnitude of the inductance.

Also, the ripple is smaller for smaller values of R_L, i.e for high currents.

when $R_L \to \infty$, The value of γ is given by $\gamma = \frac{2}{3\sqrt{2}}$.

$\Rightarrow \gamma = 0.471$ (close to the value 0.482 of rectifier)

Thus, The inductor filter should be used when R_L is consistently small.

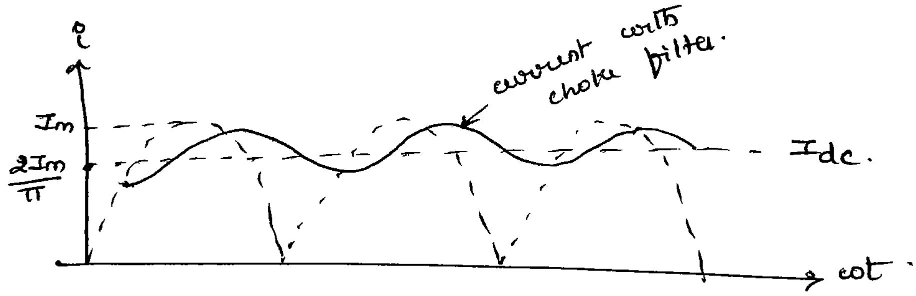
(1) for no load condition, $R_L \to \infty$ and hence $\frac{4\omega^2 L^2}{R_L^2} \to 0$

$\Rightarrow$ ripple factor $\gamma = \frac{2}{3\sqrt{2}} = 0.472$

This is very close to normal full wave rectifier without filtering.

Note :- Smaller The value of R_L smaller is The ripple hence The filter is suitable for low load resistances i.e for high load current applications

choke filters are not used now-a-days as inductors are bulky, costlier and more power consuming.

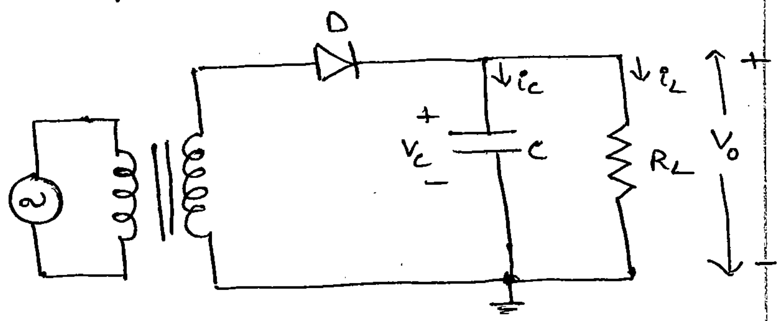


** when The i/p is greater Than average or dc value, it stores energy in the form of magnetic field. when i/p is less Than average value it releases energy.

* Capacitor filter

a) Half-wave rectifier with capacitor filter

The half-wave rectifier with capacitor input filter is shown below



HWR with capacitor filter.

The filter uses a single capacitor connected in parallel to the load R_L.

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.

The operation of capacitor filter depends upon the fact that the capacitor stores energy during the conduction period and delivers this energy to the load during non-conduction period.

Operation:

During the positive ~~half~~ quater cycle of the ac input signal, the diode D is forward biased and hence it conducts. This quickly charges capacitor "C" to the peak value of input voltage "V_m".

Practically, diode forward voltage drop is considered then, capacitor charges to $(V_m - V_\gamma)$.

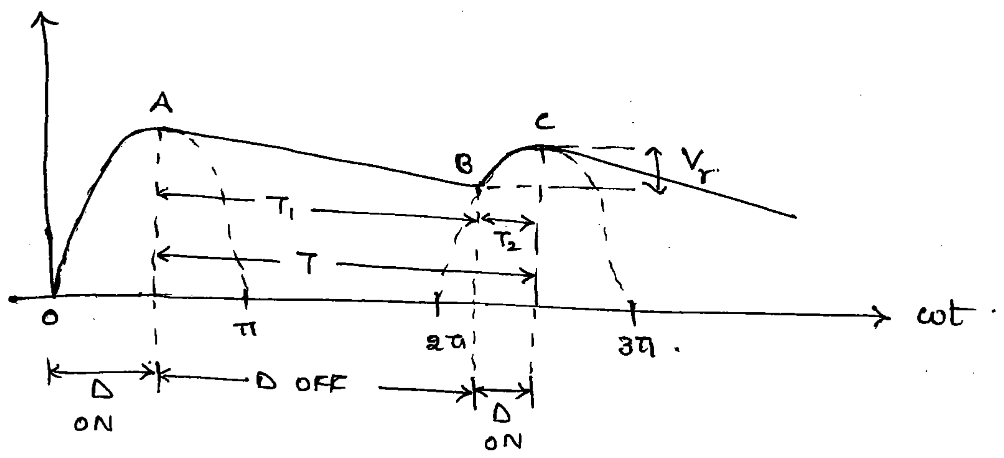
When the i/p starts decreasing below its peak value, the capacitor remains charged at V_m and ideal diode gets reverse biased. This is because the capacitor voltage which is cathode voltage of diode becomes more positive than anode.

Therefore, during the entire negative half cycle and some part of the next positive half cycle, capacitor discharges through R_L.

The discharging of capacitor is decided by $R_L C$, time constant which is very large and hence capacitor discharges very little from V_m.

· In the next positive half cycle, when the i/p signal becomes more than the capacitor voltage, the diode becomes forward biased and charges the capacitor "C" back to "V_m"

The output waveform is shown below:



The discharging of capacitor is from A to B, the diode remains nonconducting. The diode conducts only from B to C and the capacitor charges.

<u>Expression for ripple factor</u>

Let T = time period of the ac input voltage.

T_1 = time for which diode is non conducting

T_2 = time for which diode is conducting

Let V_r be the peak to peak value of ripple voltage which is assumed to be triangular waveform.

It is known mathematically that the rms value of such a triangular waveform is

$$V'_{rms} = \frac{V_r}{2\sqrt{3}} \longrightarrow (3.60)$$

During the time interval T_1, the capacitor C is discharging through the load resistance R_L. Therefore, the charge lost is

$$Q = C \cdot V_r$$

But $$i = \frac{dQ}{dt}.$$

$$\therefore Q = \int_0^{T_1} i \cdot dt = I_{dc} \cdot T_1.$$

As integration gives average or dc value hence

$$I_{dc} \cdot T_1 = C \cdot V_r.$$

$$\therefore V_r = \frac{I_{dc} \cdot T_1}{C}$$

But $T_1 + T_2 = T.$

Normally, $T_1 \gg T_2$.

$$\therefore T_1 + T_2 \approx T_1 \Rightarrow T_1 = T.$$

$$\Rightarrow V_r = \frac{I_{dc} \cdot T}{C} = \frac{I_{dc}}{f \cdot C} \quad (\because T = 1/f).$$

But $$I_{dc} = \frac{V_{dc}}{R_L}$$

$$\Rightarrow V_r = \frac{V_{dc}}{f \cdot C \cdot R_L}$$

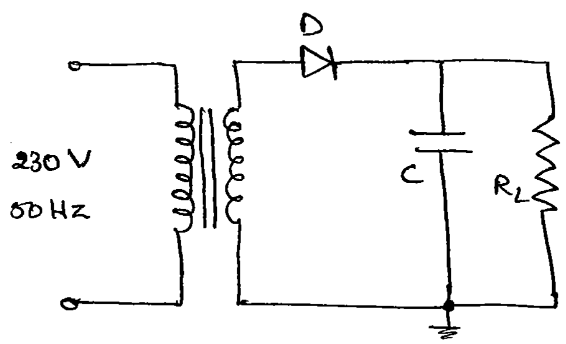
Ripple factor, $$\gamma = \frac{V'_{rms}}{V_{dc}} = \frac{V_r}{2\sqrt{3} \cdot V_{dc}}.$$

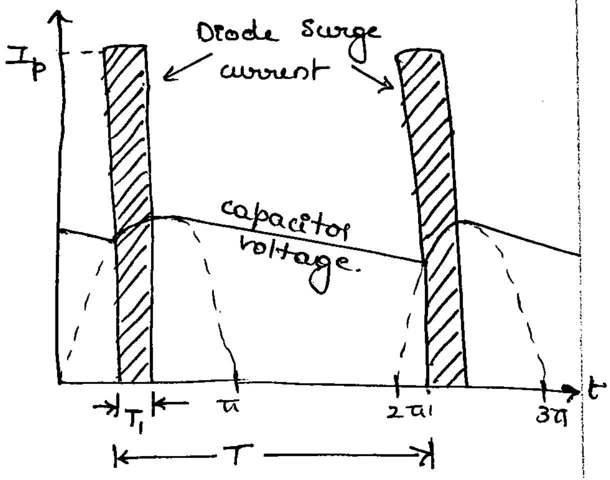
$$= \frac{V_{dc}}{2\sqrt{3} \cdot f \cdot C \cdot R_L \, V_{dc}}$$

$$\Rightarrow \boxed{\gamma = \frac{1}{2\sqrt{3} \cdot fC R_L}} \longrightarrow (3.61)$$

The product $C \cdot R_L$ is the time constant of the filter circuit.

Surge current in HWR using capacitor filter:





In a half wave rectifier, the diode is forward biased only for short period of time & conducts only during this time interval to charge the filter capacitance.

The instant at which the diode gets forward biased, the capacitor instantaneously acts as a short circuit and a surge current flows through a diode.

When diode is non conducting, the capacitor discharges through load resistance R_L.

Thus, the total amount of charge that flows through conducting diode or diodes to recharge the capacitor must be equal to the amount of charge lost during the period when the diode or diodes are non conducting and capacitor is discharging through load resistance R_L.

It can be seen that conducting period T_1 is very small compared to time period T, for the diode

let I_{dc} = average dc current

$I_{p(surge)}$ = peak value of surge current.

Assume the current pulse to be rectangular assuming peak surge current flows for the entire conduction period of diode which is T_1.

Then, Q (discharge) = Q (charge)

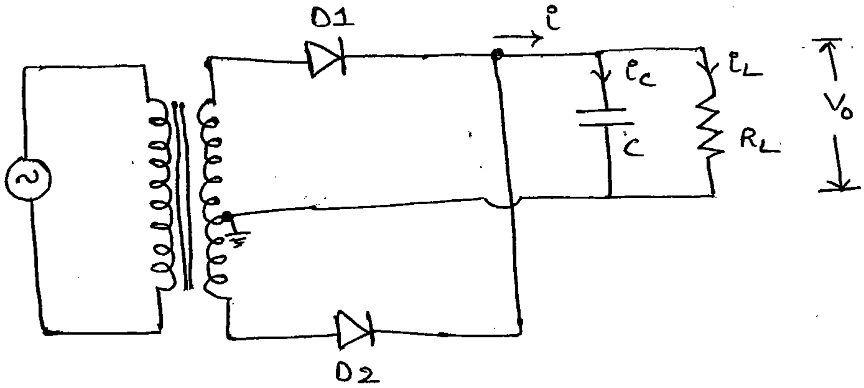
$$I_{dc} \cdot T = I_{p(surge)} \cdot T_1.$$

$$\boxed{I_{p(surge)} = I_{dc}\left(\frac{T}{T_1}\right)} \rightarrow (3.62)$$

As $T_1 << T$, it can be seen that $I_{p(surge)}$ can be many times larger than the average dc current supplied to the load.

b) Full-wave Rectifier with capacitor filter

The full-wave rectifier with capacitor filter is shown below



operation:

During the positive quater cycle of an ac input signal, The diode D1 is forward biased, the capacitor "C" gets charged Through forward bias diode D_1 to The peak value of input voltage V_m.

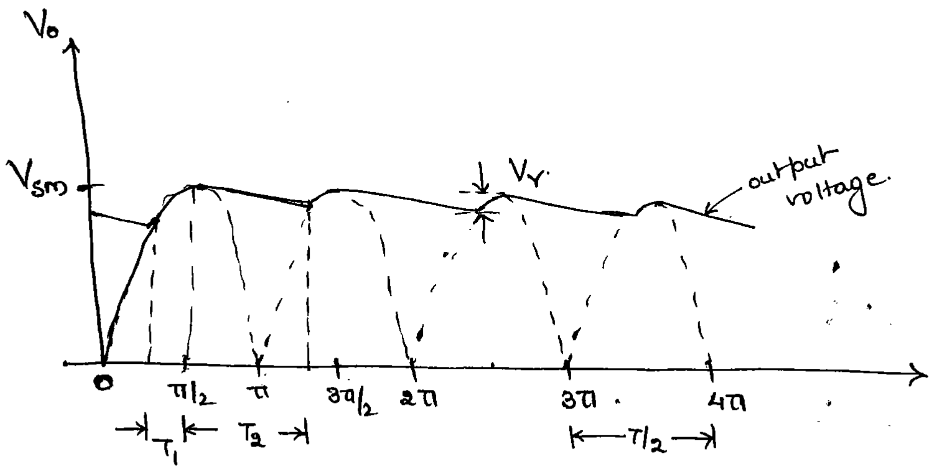
In The next quater cycle from $\frac{\pi}{2}$ to π, The capacitor starts discharging Through R_L, because once The capacitor gets charged to V_m, the diode D_1 gets reversed biased and stops conducting, so during The period from $\frac{\pi}{2}$ to π, The capacitor C supplies The load current.

In The next quarter half cycle, That is, π to $\frac{3\pi}{2}$ of The rectified output voltage, if the input voltage exceeds the capacitor voltage, making D_2 forward biased, This charges capacitor back to V_m.

In the next quarter half cycle, that is, from $\frac{\pi}{2}$ to 2π, the diode D_2 gets reverse biased and the capacitor supplies the load current.

In FWR, as the time required by the capacitor to charge is very small and it discharges very little due to large time constant, hence ripple in the output gets reduced considerably.

The output waveform is shown below.



Expression for ripple factor.

Let T = time period of the ac input voltage

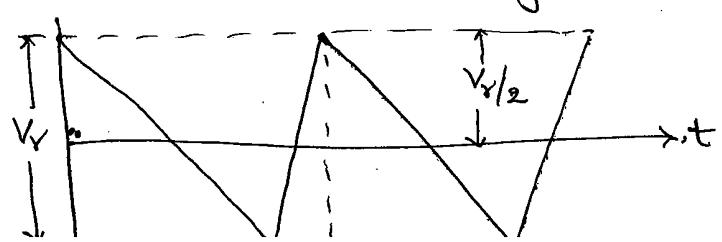
$\frac{T}{2}$ = Half of the time period

T_1 = Time for which diode is conducting

T_2 = Time for which diode is nonconducting

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 $T_2 \gg T_1$

Let V_r be the peak to peak value of ripple voltage, which is assumed to be triangular as shown in figure below



It is known mathematically that the rms value of such a triangular waveform is

$$V_{rms} = \frac{V_r}{2\sqrt{3}}$$

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

$$Q = C V_r.$$

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

$$\therefore \quad Q = \int_0^{T_2} i \cdot dt = I_{DC} \cdot T_2$$

As integration gives average or dc value

Hence, $I_{DC} \cdot T_2 = C V_r.$

$$\therefore \quad V_r = \frac{I_{DC} \cdot T_2}{C}$$

Now, $T_1 + T_2 = \frac{T}{2}$; Normally, $T_2 \gg T_1$

$$\therefore \quad T_1 + T_2 \simeq T_2 = \frac{T}{2} \quad \text{where } T = \frac{1}{f}.$$

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

But $I_{DC} = \frac{V_{DC}}{R_L}.$

$$\therefore \quad V_r = \frac{V_{DC}}{2fC\,R_L} \text{ - peak to peak ripple voltage}$$

$$\text{Ripple factor} = \frac{V_{rms}}{V_{dc}} = \frac{\frac{V_{dc}}{2fC\,R_L}}{2\sqrt{3}} \times \frac{1}{V_{dc}} \qquad \left(\because V_{rms} = \frac{V_r}{2\sqrt{3}}\right)$$

$$\boxed{\text{Ripple factor} = \frac{1}{4\sqrt{3}\,fC\,R_L}} \longrightarrow (3.63)$$

here CR_L = time constant of filter

From the expression of the ripple factor, it is clear 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.

However, very large value of capacitor cannot be used because larger the value of capacitor, larger the initial surge charging surge current. This may exceed the current rating of the diodes in the rectifier. Otherwise, the diodes must be of higher current rating which increases the cost.

Why capacitor filters are not suitable for variable loads?

The other factor controlling the ripple factor is load resistance R_L. As the load current drawn increases, for the same dc voltage, the load resistance decreases. This increases the ripple contents in the o/p. Hence, the filter is not suitable for variable loads.

The desirable feature of the filter is high voltage and less ripple at the o/p for small load currents.

Advantages of "C" filter

1) Less no. of components
2) Low ripple factor.
3) Suitable for high voltage at low loads.

Disadvantages of "C" filter

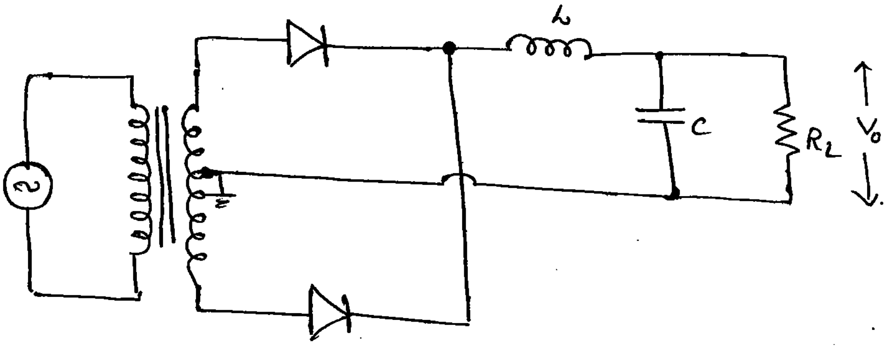
1) Ripple factor depends on load resistance
2) Not suitable for variable loads as ripple content increases as R_L decreases.
3) Regulation is poor.
4) Diodes are subjected to high surge currents hence must be selected accordingly.

The series inductor filter and shunt capacitor filter are not much efficient to provide low ripple at all loads.

** The capacitor filter has low ripple at heavy loads while inductor filter at small loads.

A combination of these two filters may be selected to make the ripple independent of load resistance. The resulting filter is called L-section filter or LC-filter or choke input filter. This name is due to the fact that the inductor and capacitor are connected as an inverted L.

The full-wave rectifier with choke input filter is shown below.



The action of a choke filter is like a "low pass filter". The capacitor shunting the load bypasses the harmonic currents because it offers very low reactance to ac ripple current while it appears as an open circuit to dc current. On the other hand, the inductor offers a high impedance to the harmonic terms. In this way, most of the ripple voltage is eliminated from the load voltage.

a) Regulation:

The output voltage of the rectifier is given by

$$v = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t$$

The dc voltage at no load condition is

$$V_{dc} = \frac{2V_m}{\pi}.$$

The ac voltage on load is

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

where $R = R_f + R_c + R_s$.

where R_f = diode forward resistance

R_c = choke resistance

R_s = resistance of secondary winding

b) Ripple factor.

The main aim of filter is suppress the harmonic components. So, the reactance of the choke must be large as compared to the combined parallel impedance of capacitor & resistor.

The parallel impedance of capacitor & resistor can be made small by making the reactance of capacitor much smaller than the resistance of the load.

Now, the ripple factor current which has passed through L will not develop much ripple voltage across R_L because the reactance of C at ripple frequency is very small as compared with R_L.

⇒ for LC filter.

$$X_L \gg X_C \text{ at } 2\omega = 4\pi f \quad \text{and} \quad R_L \gg X_C.$$

Under these conditions, the ac current through L is determined primarily by $X_L = 2\omega L$ (the reactance of the inductor at second harmonic frequency).

The rms value of ripple current is (from L filter)

$$(I_r)_{rms} = \frac{4V_m}{3\pi\sqrt{2}} \cdot \frac{1}{X_L} = \frac{2}{3\sqrt{2}X_L}\left(\frac{2V_m}{\pi}\right)$$

$$= \frac{\sqrt{2}}{3X_L} \cdot (V_{dc}).$$

with R_L, but it is not zero.

The ac voltage across the load (The ripple voltage) is the voltage across the capacitor.

$$\Rightarrow (V_r)_{rms} = (I_r)_{rms} \times X_c$$

$$= \left\{ \frac{\sqrt{2}}{3 X_L} \cdot V_{dc} \right\} X_c .$$

We know that ripple factor γ is given by.

$$\gamma = \frac{(V_r)_{rms}}{V_{dc}} = \frac{\sqrt{2}\, X_c}{3\, X_L}.$$

But $X_c = \frac{1}{2\omega C}$ and $X_L = 2\omega L$.

$$\Rightarrow \gamma = \frac{\sqrt{2}}{3(2\omega L)} \cdot \frac{1}{2\omega C}$$

$$\Rightarrow \boxed{\gamma = \frac{1}{6\sqrt{2}\ \omega^2 LC.}} \rightarrow (3.64)$$

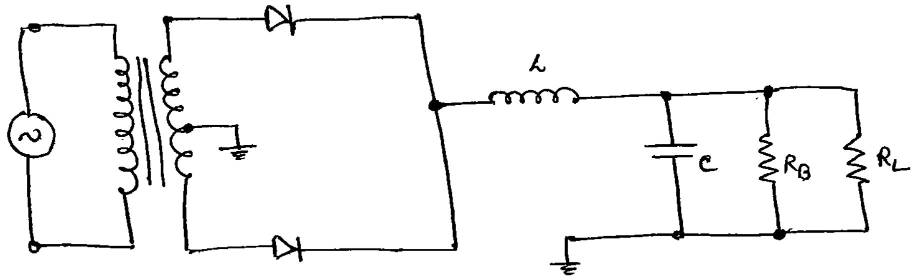
This shows that ω is independent of R_L.

The necessity of Bleeder Resistance R_B

The basic requirement of this filter circuit is that the current through the choke must be continuous and not interrupted. An interrupted current through the choke may develop a large back emf which may be in excess of PIV rating of the diodes and/or maximum voltage rating of the capacitor C. Thus, this back emf is harmful to both diodes & capacitor.

To eliminate back emf developed across the choke, the current through it must be maintained continuous. This is assured by connecting a bleeder resistance, R_B across the output terminals.

The full wave rectifier with a [illegible] and bleeder resistor is shown in the figure

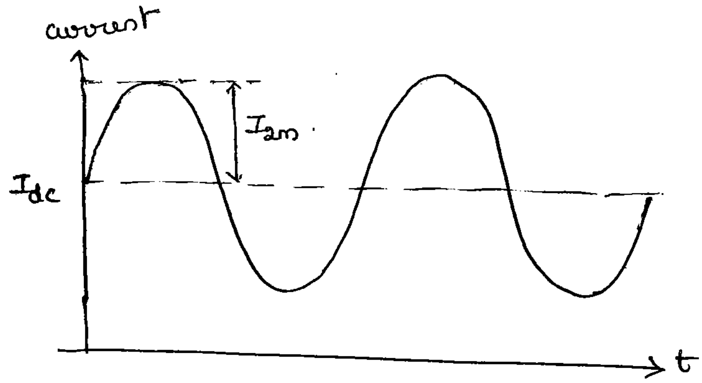


We know, $I_{dc} = \frac{2}{\pi} \frac{V_m}{R_c + R}$

where R_c = choke internal resistance

$R = R_B \parallel R_L$

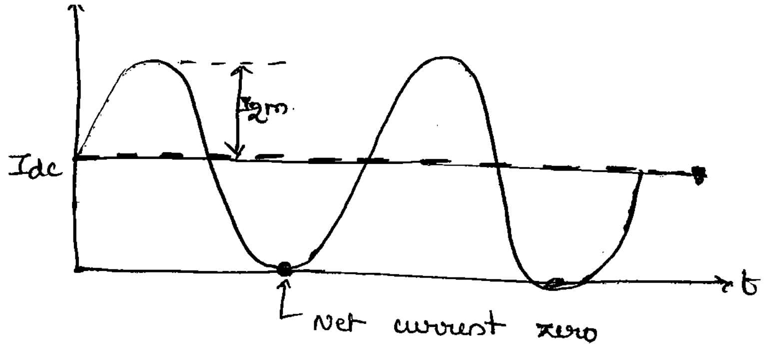
and $I_{2m} = \frac{4}{3\pi} \cdot \frac{V_m}{2\omega L}$



Thus, I_{dc} is seen to depend on load resistance $[R = R_B \parallel R_L]$ while I_{2m} does not. I_{2m} is constant, independent of R_L.

The second harmonic current I_{2m} is superimposed on I_{dc}, as shown in the above figure.

If the load resistance is increased, I_{dc} will decrease, but I_{2m} will not. If the load resistance is still further increased, a stage may come where I_{dc} may become less than I_{2m}. In such situation, for a certain period of time in each cycle, the net current in the circuit will be zero, as shown below.



In other words, The current will be interrupted and not continuous. This interruption of current, producing large back emf is harmful to both diodes & filter capacitor C.

To avoid such situations some minimum load current has to be drawn. For This purpose, the bleeder resistance R_B is connected. The bleeder resistance R_B is so selected That it draws, a minimum current Through choke.

The condition is $I_{dc} \geq I_{2m}$.

$$\Rightarrow \frac{\cancel{2}}{\cancel{\pi}} \cdot \frac{V_m}{R_c + R} \geq \frac{\cancel{4}}{3\cancel{\pi}} \frac{V_m}{\cancel{2}\omega L}$$

$$\Rightarrow R_c + R \geq 3\omega L$$

Usually, $R_c << R$ then $R \geq 3\omega L$.

Since, $R = R_B \| R_L$, considering the worst case That the load resistance R_L is not connected, Then $R = R_B$

$$\Rightarrow R_B \geq 3\omega L.$$

$$\Rightarrow R_B \geq 6\pi f L \quad (\because \omega = 2\pi f).$$

If $f = 50\,Hz$, Then $\boxed{R_B \geq 943\, L.}$ $\longrightarrow$ (3.65)

Practically, R_B is selected to be equal to $900\,L$.

We have assumed that the current flows through the circuit all the times. For this, the value of inductance L must be kept above certain minimum value which is called critical inductance. This value of inductance depends on load resistance R_L and supply frequency ω.

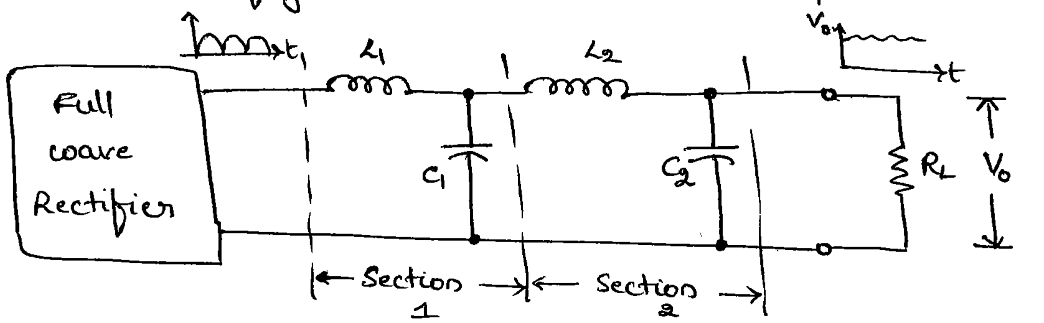
The required value of critical inductance for 50 Hz supply frequency is

$$\boxed{L_c \geqslant \frac{R_L}{943}} \qquad L_c \geqslant \frac{R_L}{3\omega}\ \text{in general.} \rightarrow (3.66)$$

Multiple L-Section filter

The number of L-sections i.e., LC circuits can be connected one after another to obtain multiple L-section filter. It gives excellent filtering and smooth dc output voltage.

The figure below shows multiple L-section filter.



For two section LC filter, the ripple factor is given by.

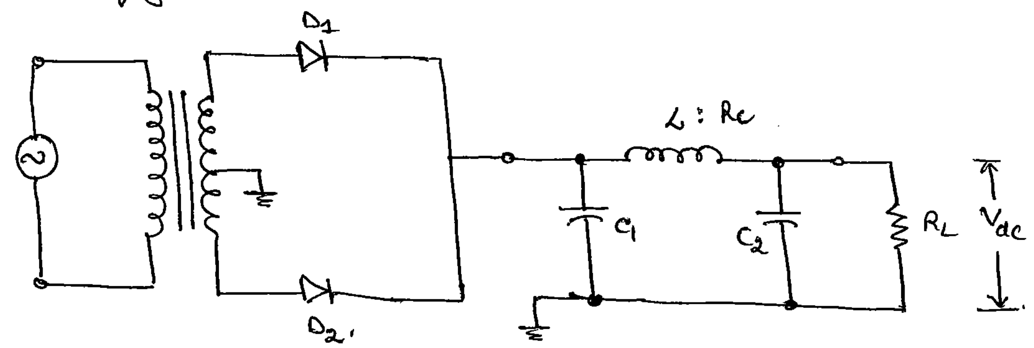
$$\boxed{\gamma = \frac{\sqrt{2}}{3} \cdot \frac{X_{C_1}}{X_{L_1}} \cdot \frac{X_{C_2}}{X_{L_2}}} \rightarrow (3.67)$$

for n stages, $\gamma = \frac{\sqrt{2}}{3}\left(\frac{X_C}{X_L}\right)^n$

where n = no. of stages

Thus is a capacitor input filter followed by a L-section filter. The ripple rejection capability of a π-section filter is very good.

The full wave rectifier with π-section filter is shown in the figure



It consists of an inductance L with a dc winding resistance as R_c and two capacitors C_1 and C_2. The filter circuit is fed from full wave rectifier. Generally, two capacitors are selected equal.

The rectifier output is given to the capacitor C_1. This capacitor offers very low reactance to the ac component but blocks dc component. Hence, capacitor C_1 bypasses most of the ac component. The dc component then reaches to the choke L. The choke L offers very high reactance to ac component & low reactance to dc.

So, it blocks ac component and does not allow it to reach to load while it allows dc component to pass through it. The capacitor C_2 now allows to pass remaining ac component and almost pure dc component reaches to the load. The circuit looks like a π, hence called π-filter.

The fourier analysis of a Δ^{lar} wave is given by.

$$v = V_{dc} - \frac{V_r}{\pi}\left(\sin 2\omega t - \frac{\sin 4\omega t}{2} + \frac{\sin 6\omega t}{3} + \cdots\right). \quad \rightarrow (3.68)$$

In case of full wave rectifier with capacitor filter, we have proved that

$$V_{r} = \frac{I_{dc}}{2fC} = \frac{I_{dc}}{2fC_1} \quad (\because C = C_1 \text{ here}).$$

The rms second harmonic voltage is

$$(V_r)_{rms} = \frac{V_r}{\pi\sqrt{2}}.$$

Substituting the value of V_r

$$(V_r)_{rms} = \frac{I_{dc}}{2\pi f C_1 \sqrt{2}} = \sqrt{2}\, I_{dc} \cdot X_{C_1}.$$

where $X_{C_1} = \frac{1}{2\omega C_1} = \frac{1}{4\pi f C_1}$ = reactance of C_1 at second harmonic freq.

The voltage $(V_r)_{rms}$ is impressed on L-section. Now, the ripple voltage $(V_r')_{rms}$ can be obtained by multiplying $(V_r)_{rms}$ by X_{C_2}/X_L i.e.,

$$(V_r')_{rms} = (V_r)_{rms} \times \left(\frac{X_{C_2}}{X_L}\right)$$

or $$(V_r')_{rms} = \sqrt{2}\, I_{dc}\, X_{C_1} \cdot \frac{X_{C_2}}{X_L}$$

$$\therefore \quad r = \frac{(V_r')_{rms}}{V_{dc}} = \frac{\sqrt{2}\, I_{dc} \cdot X_{C_1} \cdot \frac{X_{C_2}}{X_L}}{V_{dc}}$$

$$= \frac{\sqrt{2}\, X_{C_1} \cdot X_{C_2}}{R_L \cdot X_L} \quad \left(\because \frac{I_{dc}}{V_{dc}} = \frac{1}{R_L}\right).$$

$$\boxed{r = \frac{\sqrt{2}\, X_{C_1} \cdot X_{C_2}}{X_L \cdot R_L}} \rightarrow (3.69)$$

Here, all reactances are calculated at second harmonic frequency. Substituting the values, we get

$$\boxed{r = \frac{\sqrt{2}}{8\omega^3 C_1 C_2 L \cdot R_L}} \rightarrow (3.70)$$

At $f = 50Hz$,

$$\boxed{\gamma = \frac{5700}{L \cdot C_1 \cdot C_2 \cdot R_L}} \rightarrow (3.71)$$

where C_1 and C_2 are in μF.

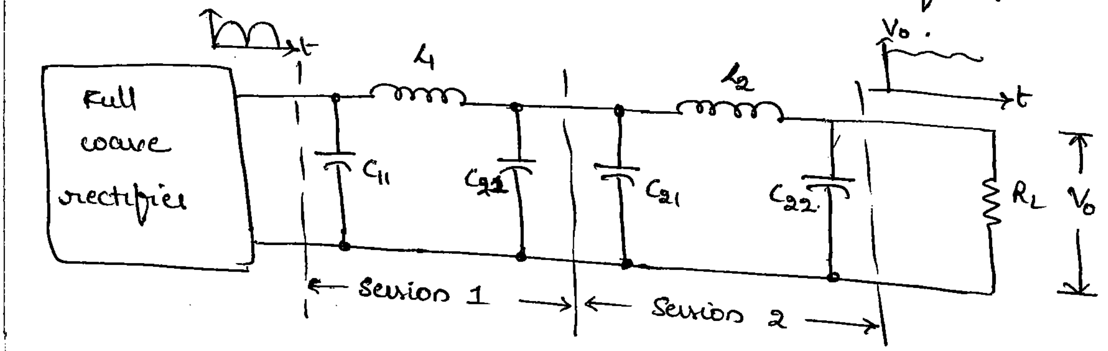
L is in henrys.

R_L in ohms.

Multiple π - section filter.

To obtain almost pure dc to the load, more π sections may be used one after another. Such a filter using more than one π - section is called multiple - π section filter.

The figure shows multiple - π - section filter.



The ripple factor of two section π - filter is given by.

$$\boxed{\gamma = \sqrt{2} \cdot \frac{X_{C_{11}}}{R_L} \cdot \frac{X_{C_{21}}}{X_{L_1}} \cdot \frac{X_{C_{22}}}{X_{L_2}}} \rightarrow (3.72)$$

(Pb) Calculate the ripple factor for a π filter, employing 10H choke and two equal capacitors of 16μF each and fed from a full wave rectifier and 50 Hz mains. The load resistance is 4KΩ.

Sol Given that

$C_1 = C_2 = 16\mu F$, $R_L = 4K\Omega$

$L = 10H$, $f = 50Hz$.

$$\gamma = \frac{\sqrt{2}}{8\omega^3 L C_1 C_2 R_L} = \frac{\sqrt{2}}{8(2\pi f)^3 L C_1 C_2 R_L}$$

$$= \frac{\sqrt{2}}{8(2\pi \times 50)^3 \times 10 \times 16 \times 10^{-6} \times 16 \times 10^{-6} \times 4000}$$

$\gamma = 0.055\%$

(P5) Design a CLC or π - section filter for $V_{dc} = 10V$, $I_L = 200mA$ and $\gamma = 2\%$.

Sol:

$$R_L = \frac{V_{dc}}{I_L} = \frac{10}{200 \times 10^{-3}} = 50\,\Omega$$

$$\gamma = \frac{5700}{L C_1 C_2 R_L}$$

$$\Rightarrow 0.02 = \frac{5700}{L C_1 C_2 \times 50} = \frac{114}{L C_1 C_2}.$$

If we assume, $L = 10\,H$ and $C_1 = C_2 = C$, we have

$$0.02 = \frac{114}{LC^2} = \frac{11.4}{C^2}.$$

$$C^2 = 570 \Rightarrow C = \sqrt{570} = \underline{\underline{24\,\mu F}}$$

(P6) In a full wave rectifier using an LC filter $L = 10H$, $C = 100\mu F$ and $R_L = 500\,\Omega$. Calculate I_{dc}, V_{dc} and ripple factor for an input of $V_i = 30 \sin(100\pi t)\,V$.

Sol

$$V_i = V_m \sin \omega t = 30 \sin(100\pi t)\ V$$

$$V_m = 30V$$

$$V_{dc} = \frac{2V_m}{\pi} = \frac{2 \times 30}{\pi} = \underline{\underline{19.0985\ V}}$$

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{19.0985}{500} = \underline{\underline{38.19\,mA}}$$

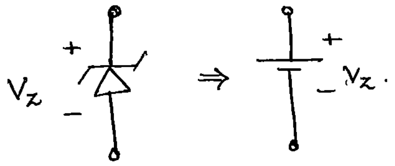
Ripple factor,
$$\gamma = \frac{1}{6\sqrt{2}\,\omega^2 LC}$$

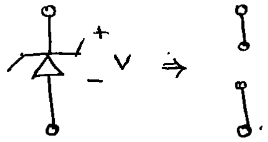
$$= \frac{1}{6\sqrt{2}\,(2\pi f)^2 LC}$$

$$= \frac{1}{6\sqrt{2}\,(200\pi)^2 \times 10 \times 100 \times 10^{-6}}$$

$$= \underline{\underline{1.194 \times 10^{-3}}}$$

* Zener diode as voltage regulator.



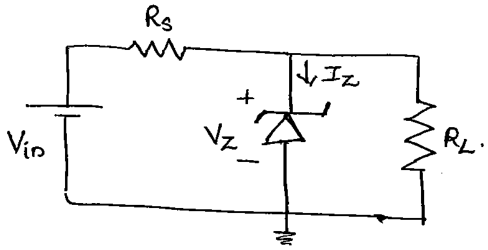


(a) "ON" state.
($V \geq V_Z$).

(b) "OFF" state.
($0 < V < V_Z$).

a) V_{in} and R_L fixed

The simplest zener diode networks appears as shown

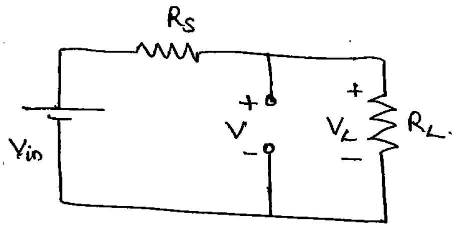


Here, applied dc voltage is fixed, as is the load resistor.

The analysis is broken into 2 steps:

1. Determine the state of zener diode (ON or OFF) by removing it from the network & calculating the voltage across the resulting open circuit.

Applying step 1 to the above network, we get



Applying, voltage divider circuit rule. we get.

$$\boxed{V = V_L = \frac{R_L \cdot V_{in}}{R_S + R_L}} \longrightarrow (3.73)$$

If $V \geq V_Z$ ⇒ Zener diode is "ON".

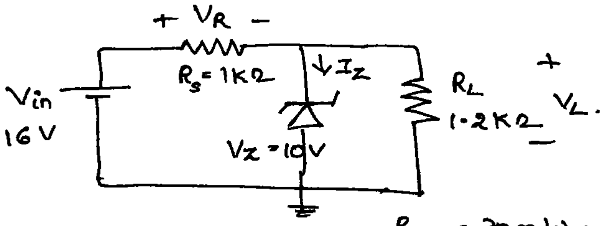
If $V < V_Z$ ⇒ zener diode is "OFF".

2. Substitute appropriate equivalent circuit & solve for the desired unknowns.

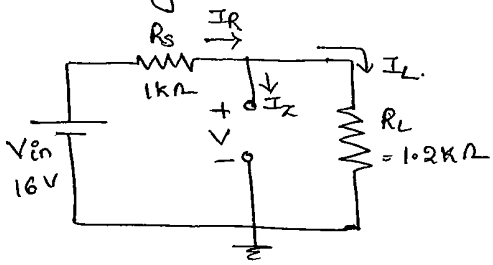
If zener diode is "ON" replace it by a voltage source of V_Z.
If zener diode is "OFF" replace it by an open circuit.

V_L, V_R, I_Z and P_Z. Repeat the same with $R_L = 3k\Omega$.

Sol: **Step 1**:- Determine voltage V across zener diode by removing it.



$P_{ZM} = 30mW$.



$$V = \frac{R_L \cdot V_{in}}{R_S + R_L} = \frac{1.2 \times 10^3 \times 16}{1 \times 10^3 + 1.2 \times 10^3}$$

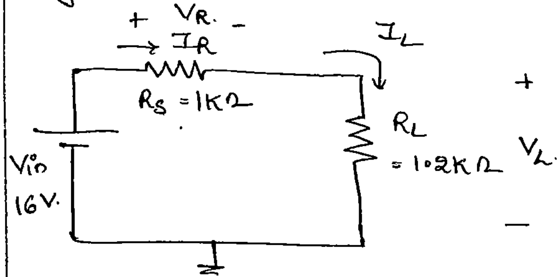
$$V = V_L = \underline{8.727\,V}$$

Given That $V_Z = 10V \Rightarrow V < V_Z$

$\Rightarrow$ zener diode is "OFF".

$\Rightarrow$ replace zener diode by open circuit

Step 2:- Determine V_L, V_R, I_Z and P_Z by replacing zener diode by open circuit.



$V_L = 8.727V$.

$I_Z = 0$ (since open circuited).

$V_{in} = V_R + V_L$.

$16 = V_R + 8.727$

$\Rightarrow V_R = 16 - 8.727$

$= 7.273$.

Thus,

$V_L = 8.727V$.

$V_R = 7.273V$.

$I_Z = 0A$.

$P_Z = 0W$.

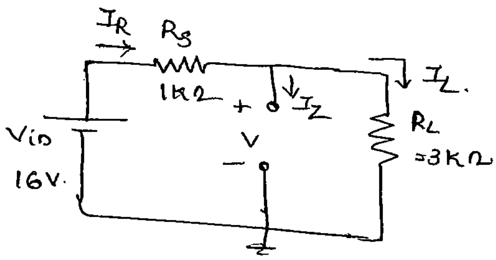
$P_Z = V_Z \cdot I_Z = V_L \cdot I_Z$

$= (8.727)(0)$.

$= 0W$.

Now, if $R_L = 3k\Omega$.

Step 1:- Determine V.



$$V = V_L = \frac{V_{in} \cdot R_L}{R_L + R_S}$$

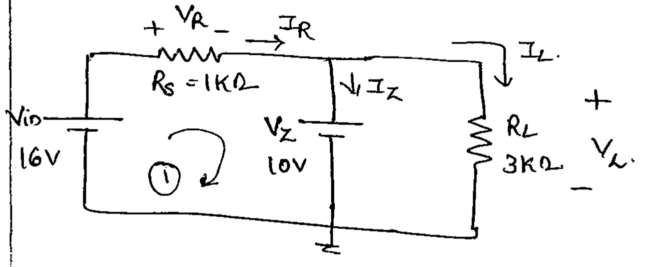
$$= \frac{16 \times 3 \times 10^3}{\ldots} = 12V$$

Step 2 :- Given $V_Z = 10V$.

since $V = 12V > V_Z$

zener diode is replaced by a voltage source of 10V because voltages across $\parallel^{el}$ connection should be same.

$\Rightarrow V_L = V_Z. = 10V$



In loop 1.

$V_{in} = V_R + V_Z.$

$16 = V_R + 10.$

$\Rightarrow V_R = \underline{6V}.$

$V_L = I_L \cdot R_L \Rightarrow I_L = \frac{V_L}{R_L} = \frac{10}{3K} = \underline{3.3mA}$

$I_R = \frac{V_R}{R_S} = \frac{6}{1K} = \underline{6mA}.$

$\Rightarrow I_Z = I_R - I_L = 6mA - 3.3mA.$

$= \underline{2.7mA}$

Thus,

$V_L = V_Z = 10V.$

$V_R = 6V$

$I_R = 6mA$

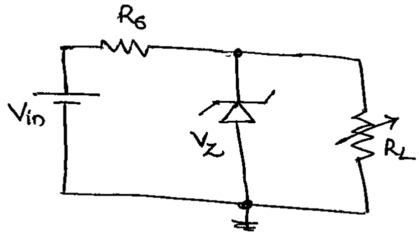
$I_Z = 2.7mA.$

$I_L = 3.3mA.$

b) Fixed V_{in}, Variable R_L

Due to the offset voltage V_Z, there is a specific range of resistor values ($\Rightarrow$ load current) which will ensure that the zener is in the "on" state. Too small load resistance R_L, will result a in a voltage V_L across the load resistor less than V_Z and the zener device will be in the "off" state.

To determine the minimum load resistance that will turn the zener diode on, simply calculate the value of R_L that will result in a load voltage $V_L = V_Z$



i.e, $V_L = V_Z = \frac{R_L V_{in}}{R_L + R_S}.$

$V_Z (R_L + R_S) = R_L V_{in}$

$R_L (V_{in} - V_Z) = V_Z R_S.$

$\boxed{R_{L_{min}} = \frac{V_Z R_S}{\quad}}$ — (2.71)

Any load resistance value greater than R_{Lmin} will ensure that the zener diode is in "ON" state & diode can be replaced by its V_Z source equivalent.

when R_L is minimum, I_L is maximum

$$\Rightarrow \boxed{I_{Lmax} = \frac{V_Z}{R_{Lmin}}} \longrightarrow (3.75)$$

once the diode is in the "ON" state, the voltage across R remains fixed at

$$\boxed{V_R = V_i - V_Z} \longrightarrow (3.76)$$

and I_R remains fixed at $\boxed{I_R = \frac{V_R}{R_S}} \longrightarrow (3.77)$

The zener current $I_Z = I_R - I_L$

$$\left.\begin{array}{l} \text{when } I_{Lmax} \Rightarrow I_{Zmin} \text{ is obtained} \\ \text{when } I_{Lmin} \Rightarrow I_{Zmax} \text{ is obtained} \end{array}\right\} \text{Since } I_R = \text{constant}$$

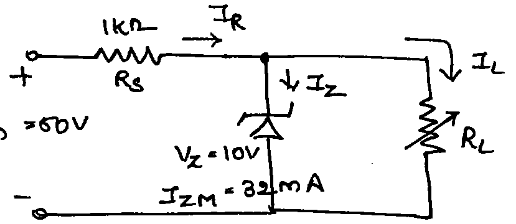
Since I_{Zmax} is limited to I_{ZM} as provided in data sheet

$$\Rightarrow \boxed{I_{Lmin} = I_R - I_{ZM}} \longrightarrow (3.78)$$

and maximum load resistance is

$$\boxed{R_{Lmax} = \frac{V_Z}{I_{Lmin}}} \longrightarrow (3.79)$$

(Pb) For the network shown below, determine the range of R_L and I_L that will result in V_L being maintained at 10V. Determine the maximum wattage rating of the diode.



Sol: To determine the value of R_L that turns the zener diode "on" is

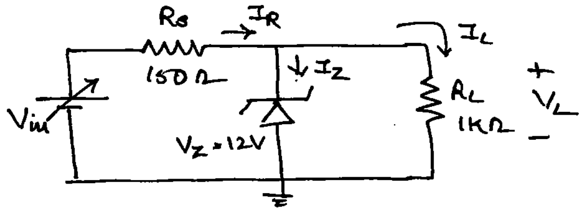
$$R_{Lmin} = \frac{V_Z \cdot R_S}{V_{in} - V_Z}$$

$$= \frac{10 \times 1 \times 10^3}{50 - 10} = \frac{10^4}{40} = 250\,\Omega$$

$$I_{Lmax} = \frac{V_Z}{R_{Lmin}} = \frac{10V}{250\,\Omega} = 40\,mA$$

currents are 0 and 25mA. Calculate the range of i/p voltage assuming zener diode is in breakdown condition

Sol: Given That



$I_{Zmin} = 0\ A$

$I_{Zmax} = 25mA$.

$V_Z = 12V$, $R_S = 160\Omega$, $R_L = 1K\Omega$.

Range of i/p voltage = $V_{in\,min} = ?$

$V_{in\,max} = ?$

To operate the zener diode in ON state

$$V_{in\,min} = \frac{(R_S + R_L) V_Z}{R_L} = \frac{(160 + 1K) \times 12}{1K}$$

$$= \underline{13.8V}$$

$$I_L = \frac{V_Z}{R_L} = \frac{12}{1K} = 12mA.$$

we have $I_{R_{max}} = I_{Z_{max}} + I_L$.

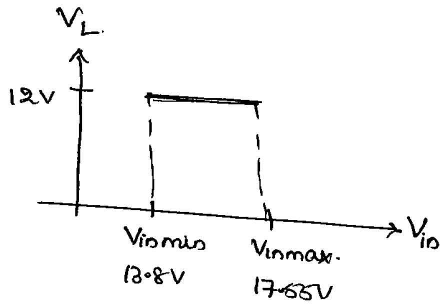
$= 25mA + 12mA$

$= \underline{37mA}$

$V_{in\,max} = I_{Rmax} \cdot R_S + V_Z$

$= 37m \times 160 + 12.$

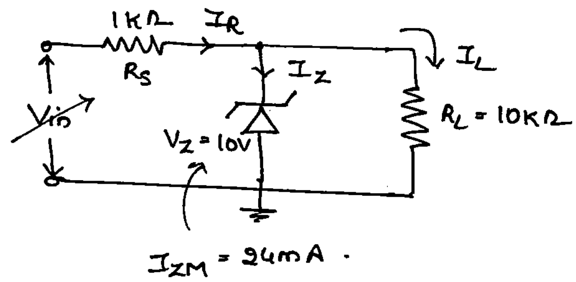
$= \underline{17.55\ V}$



$\underline{13.8V < V_{in} < 17.55V.}$

(Pb) Determine the range of i/p voltage that maintains the o/p voltage of 10V, for the regulator shown below

Sol: To turn zener diode into ON state.



$$V_{in\,min} = \frac{(R_S + R_L) V_Z}{R_L}$$

$$= \frac{(1K + 10K)\,10}{10K}$$

$$= \underline{11V}$$

$I_L = \frac{V}{R_L} = \frac{10V}{10K} = 1mA.$

$I_{Rmax} = I_{Zmax} + I_L.$

$= I_{ZM} + I_L$

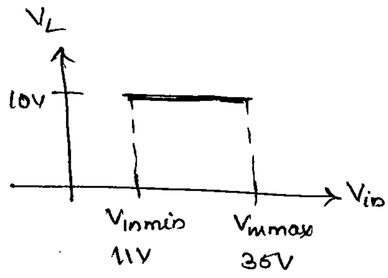
$= 24mA + 1mA$

$= 25mA$

$V_{in\,max} = I_{Rmax} \cdot R_S + V_Z$

$= 25m \times 1K + 10$

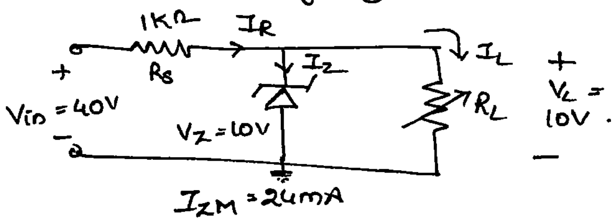
$= \underline{35V}$



$\underline{11V < V_{in} < 35V}$

(Pb) For the zener voltage regulation shown, determine the range of R_L and I_L that gives the stabilizer voltage of 10V.

Sol: Calculate value of R_L that will turn the zener diode "on".



$R_{Lmin} = \frac{V_Z \cdot R_S}{V_{in} - V_Z}$

$= \frac{10 \times 1K}{40 - 10} = \underline{333.33\,\Omega}$

$333.33\,\Omega < R_L < 1.67K\Omega$

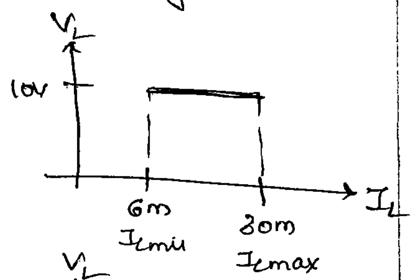
$6mA < I_L < 30mA$

$\Rightarrow I_{Lmax} = \frac{V_Z}{R_{Lmin}} = \frac{10}{333.33} = \underline{30mA}$

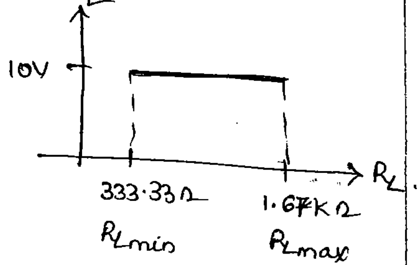
once diode is in ON state, it is replaced by V_Z and V_R = constant

$V_R = V_{in} - V_Z$

$= 40 - 10 = 30V.$



$\Rightarrow I_R = \frac{V_R}{R_S} = \frac{30}{1K} = 30mA.$

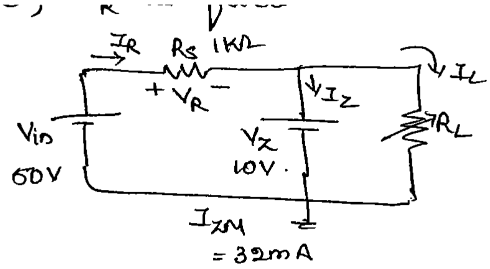


$I_{Lmin} = I_R - I_{ZM}$

$= 30mA - 24mA = \underline{6mA}$

$R_{Lmax} = \frac{V_Z}{I_{Lmin}} = \frac{10}{6m} = \underline{1.67K\Omega}$

once the ... R ...



$$V_{in} = V_R + V_Z$$

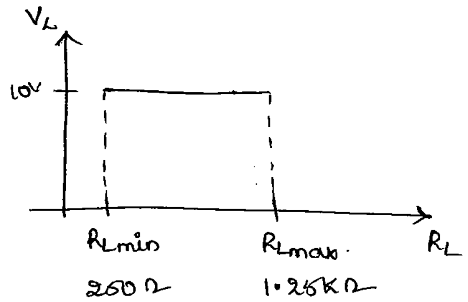
$$V_R = V_{in} - V_Z$$
$$= 60V - 10V$$
$$= 40V$$

Then $I_R = \frac{V_R}{R_S} = \frac{40}{1K} = 40mA$

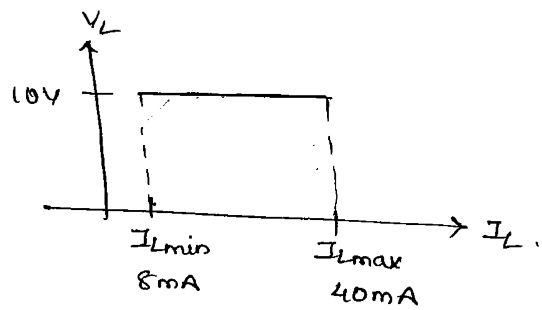
Thus, $I_{Lmin} = I_R - I_{ZM}$.
$$= 40mA - 32mA$$
$$= 8mA$$

Now, $R_{Lmax} = \frac{V_Z}{I_{Lmin}} = \frac{10\,V}{8\,mA} = 1.25\,K\Omega$

Power Rating $P_{max} = V_Z \cdot I_{Zmax} = V_Z I_{ZM}$.
$$= (10V) \cdot (32mA).$$
$$= 320mW$$

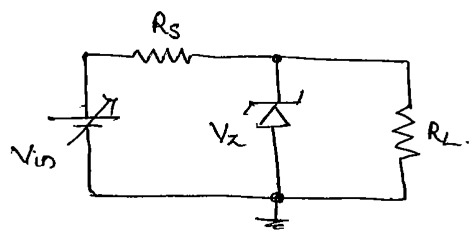


V_L Verses R_L for voltage regulation



V_L Verses I_L for voltage regulation

c) Variable V_{in} and fixed R_L



For fixed value of R_L, The voltage V_{in} must be sufficiently large to turn "on" the zener diode

The minimum turn "ON" voltage $V_{in} = V_{in\,min}$ is determined by.

$$V_L = V_Z = \frac{R_L \cdot V_{in}}{R_L + R_S}.$$

$$\boxed{V_{in\,min} = \frac{(R_L + R_S)\,V_Z}{R_L}} \longrightarrow (3.80)$$

The maximum value of V_i is limited by the maximum zener current $I_{ZM} = I_R - I_L$.

$$\Rightarrow \boxed{I_{R_{max}} = I_{ZM} + I_L} \rightarrow (3.81)$$

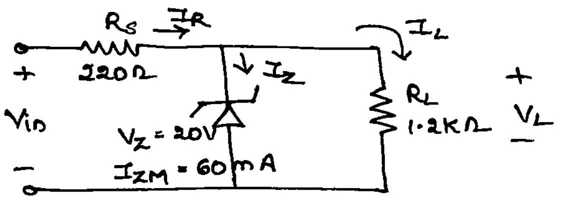
Since I_L is fixed at $\frac{V_Z}{R_L}$ and I_{ZM} is I_{Zmax},

the maximum V_{in} defined is

$$V_{i_{max}} = V_{R_{max}} + V_Z.$$

$$\boxed{V_{in\,max} = I_{R_{max}} R_s + V_Z.} \rightarrow (3.82)$$

(Pb) Determine the range of values of V_{in} that will maintain the zener diode of the figure in the ON state.



Sol: $V_{in\,min}$ required to turn ON zener diode is

$$V_{in\,min} = \frac{(R_S + R_L) V_Z}{R_L}$$

$$= \frac{(220 + 1.2K)\, 20}{1.2K} = 23.67\,V$$

$$I_L = \frac{V_Z}{R_L} = \frac{20}{1.2K} = 16.67\,mA.$$

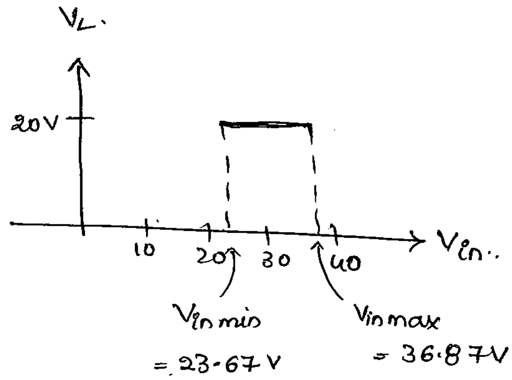
$$I_{R_{max}} = I_{ZM} + I_L$$

$$= 60m + 16.67m = 76.67\,mA$$

$$V_{in\,max} = I_{R_{max}} R_s + V_Z.$$

$$= 76.67m \times 220 + 20$$

$$= 36.87V$$



V_L verses V_{in} for voltage regulation

Special Semiconductor Devices

* Tunnel Diode

A pn-junction-diode has an impurity concentration of about 1 part in 10^8. With this amount of doping, the width of the depletion layer, which constitutes a barrier ~~barrier~~ potential at the junction, is of 5 microns (5×10^{-4} cm). This potential barrier restrains the flow of carriers from the side of the junction where they constitute majority carriers to the side where they constitute minority carriers.

If the concentration of impurity atoms is greatly increased, say to 1 part in 10^3, the device characteristics are completely changed. This new diode was announced by Esaki in 1958.

→ Tunneling Phenomenon

The width of the junction barrier varies inversely as the square root of impurity concentration

$$\boxed{V_B = \frac{q N_A}{2\epsilon} \cdot \omega^2}$$

$$\Rightarrow \omega = \left[\frac{V_B \cdot 2\epsilon}{q \cdot N_A}\right]^{1/2} \Rightarrow \boxed{\omega \propto \frac{1}{\sqrt{N_A}}}$$

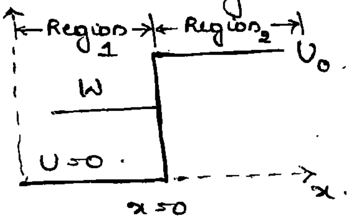
$\Rightarrow \omega$ is reduced to less than 100 A° (10^{-6} cm).

This thickness is only one-fiftieth of the wavelength of visible light.

Classically, a particle must have an energy atleast equal to the height of a potential-energy barrier if it is moved from one side of the barrier to the other.

However, for barriers as thin as those estimated for Esaki diode, the Schrodinger equation estimates that there is a large probability that an electron will penetrate through the barrier. This quantum mechanical behavior is referred to as tunneling and hence these high-impurity-density pn junction diodes are called Tunnel diodes.

Consider an electron of total energy W joules, ...
region 1, where there is potential barrier energy of height $U_0 > W$ and the potential energy remains constant in region 2 for $x > 0$ as shown below.



Region 1:

Schrodinger Equation is given as.

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2} W\psi = 0$$

solution is given by.

$$\psi = C \cdot e^{\pm j(8\pi^2 mW/h^2)^{1/2}x}$$

where C = Constant

The electronic wave function $\phi = e^{j\omega t} \cdot \psi$ represents a travelling wave.

The product of ψ and its complex conjugate ψ^* gives the probability of finding an electron between x and $x + dx$.

$$\psi \cdot \psi^* = |\psi|^2 = C^2 = \text{Constant}$$

$\Rightarrow$ electron has equal probability of being found anywhere in region 1. $\Rightarrow$ electron is free to move in the region of zero potential energy.

Region 2

Schrondinger Equation is given by (for $x > 0$).

$$\frac{d^2\psi}{dx^2} - \frac{8\pi^2 m}{h^2}(U_0 - W)\psi = 0$$

Since $U_0 > W$, this equation has a solution of the form

$$\psi = A e^{-[(8\pi^2 m/h^2)(U_0 - W)]^{1/2}x} = A e^{-x/2d_0}$$

where A is constant and

$$d_0 = \frac{1}{2}\left[\frac{h^2}{8\pi^2 m(U_0 - W)}\right]^{1/2} = \frac{h}{4\pi}\left[\frac{1}{2m(U_0 - W)}\right]^{1/2}$$

the solution of Schrodinger equation in region 2 is of the form

$\psi = A e^{-x/2d_0} + B e^{x/2d_0}$

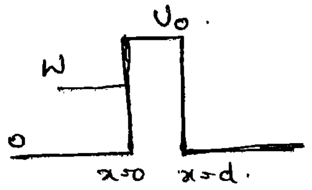
however, $B = 0$, since it is required that ψ be finite everywhere in region 2.

The probability of finding the electron between x and $x+dx$ in region 2 is

$$\psi \cdot \psi^* = A^2 \cdot e^{-x/d_0}$$

from this equation we see that an electron can penetrate a potential energy barrier and that the probability decreases exponentially with distance into the barrier region.

If the potential-barrier hill has a finite thickness d, then there is a nonzero probability $A^2 \cdot e^{-d/d_0}$ that the electron will penetrate (tunnel) through the barrier.



If the depth of the hill d is very much larger than d_0, then the probability that the electron will tunnel through the barrier is virtually zero.

→ <u>Energy band structure for open circuited condition</u>

The condition that "d" be the same as "d_0" in magnitude is a necessary condition but not sufficient condition for tunneling. It is also required that occupied energy states exist on the other side into which electrons penetrate at the same energy level.

⇒ Energy band structure for high-impurity concentration has to be considered

In the energy band structure for the lightly dopped pn-diode, the fermi level E_F lies inside the forbidden energy gap. In the heavily dopped pn diode E_F lies outside the forbidden band.

We know that, $E_F = E_C - kT \ln\left(\frac{N_C}{N_D}\right)$

For a lightly doped ~~diode~~ semiconductor, $N_D < N_C \Rightarrow \ln\left(\frac{N_C}{N_D}\right) = +ve$

⇒ $E_F < E_C$ and fermi level lies inside the forbidden band.

For heavily doped ~~diode~~ semiconductor, $N_D > N_C$ and $\ln\left(\frac{N_C}{N_D}\right) = -ve$

⇒ $E_F > E_C$ and fermi level lies outside the forbidden band.

$\text{llly}, \quad E_F = E_V + KT \ln\left(N_A\right)$

for heavily doped p-region, $N_A > N_V$ and $E_F < E_V$

⇒ fermilevel lies in the valance band.

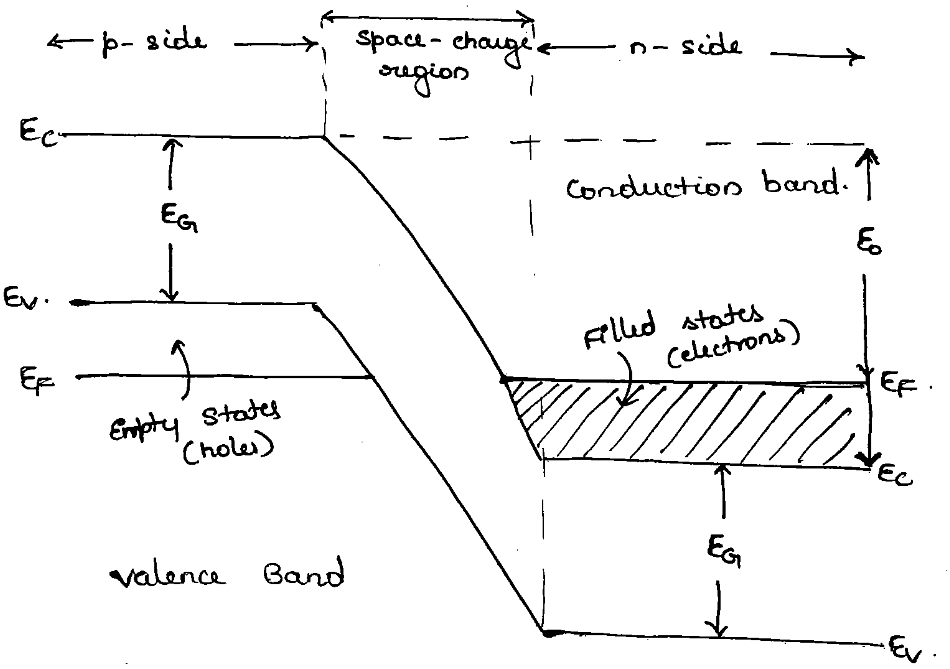
The energy-band structure in a heavily doped pn-diode under open circuited condition is shown below.

we have,

$$E_G = KT \ln\left(\frac{N_C \cdot N_V}{n_i^2}\right)$$

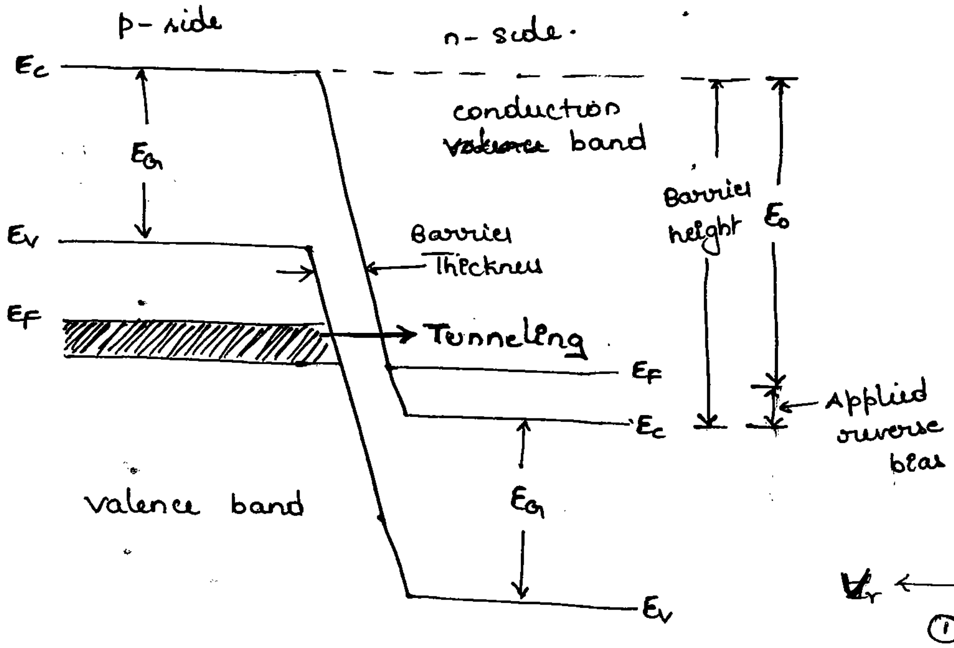
$$E_o = KT \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right)$$

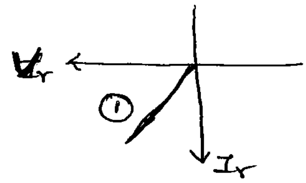
Comparing the above equations for heavily doped pn-diode, we find that $E_o > E_G$. Therefore, the contact difference of potential energy E_o excede the forbidden gap voltage E_G.



The fermi level E_F in the p-side is at the same energy as the fermi level E_F in the n-side. Note that there are no filled states on one side of the junction which are at the same energy as empty allowed states on the other side. Hence, there can be no flow of charge in either direction across the junction, and the current is zero for an open circuited diode.

① If a reverse bias voltage is applied to the tunnel diode, the height of the barrier is increased above the open-circuit value E_0. Hence, the n-side levels must shift downwards wrt p-side levels as shown below.



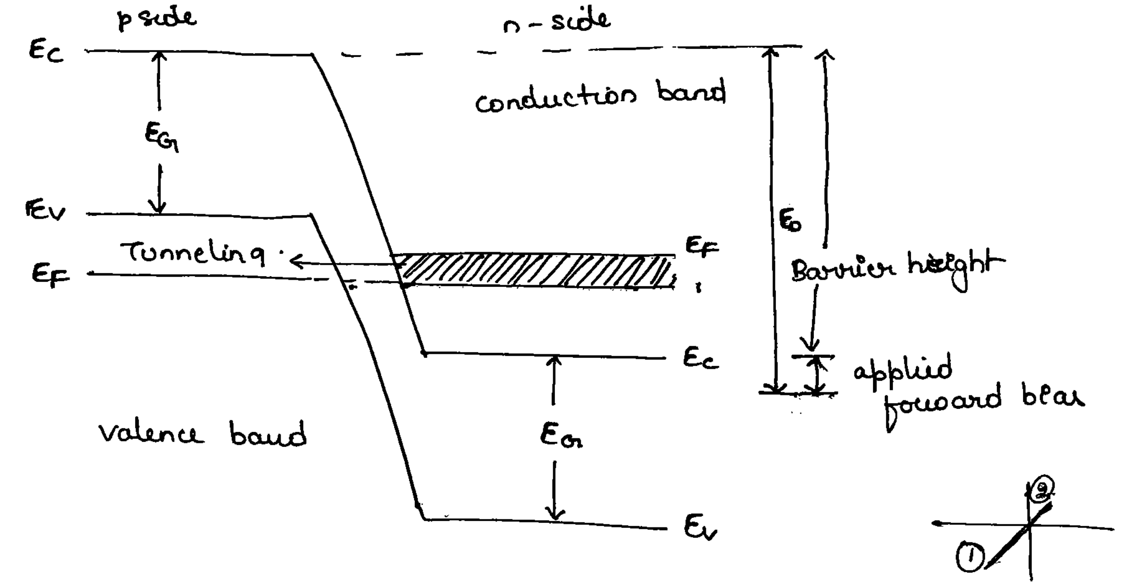


We now observe that there are some energy states in the valence band of the p-side which lie at the same level as allowed empty states in the conduction band of the n-side. Hence, these electrons will tunnel from p-side to n-side, giving rise to reverse diode current.

As magnitude of reverse bias increases, reverse current also increases.

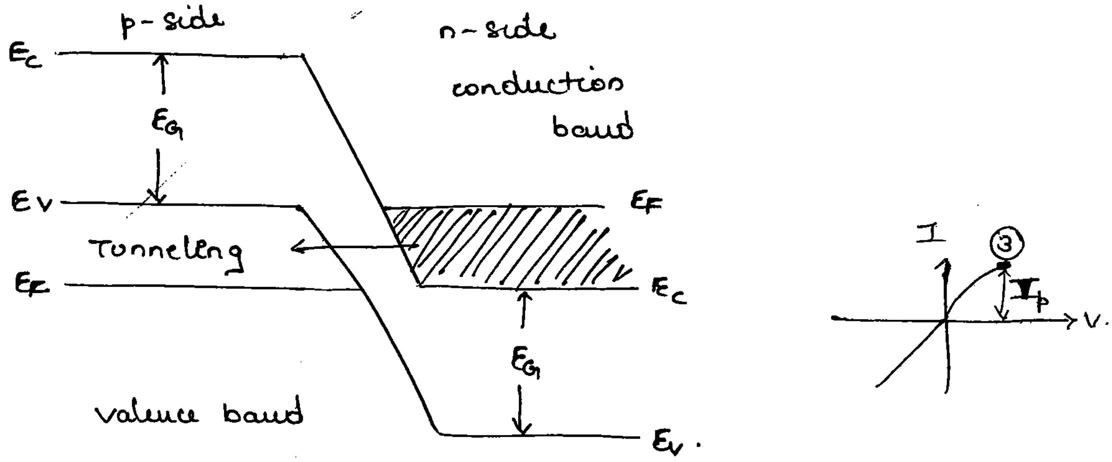
② Consider, if a forward bias is applied to the diode so that the potential barrier is decreased below E_0. Hence, n-side levels should shift upwards wrt those on p-side.

The energy band diagram for a heavily doped diode under forward bias conditions are shown below.

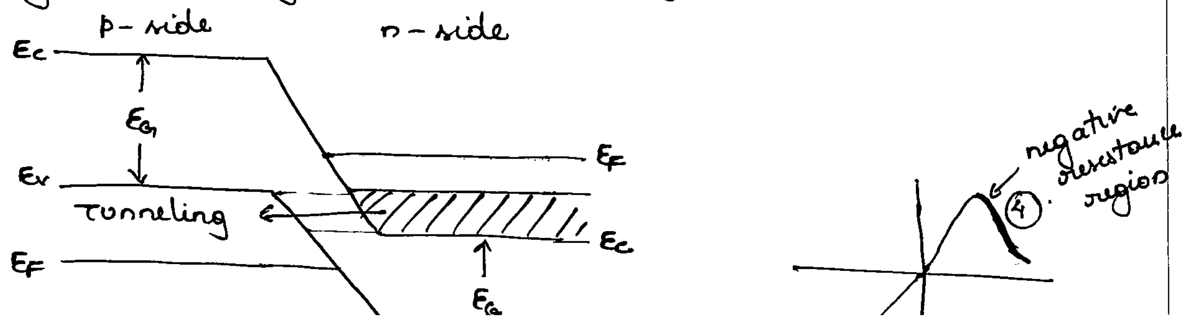


We observe that the electrons will tunnel from the n side to p side giving rise to forward current.

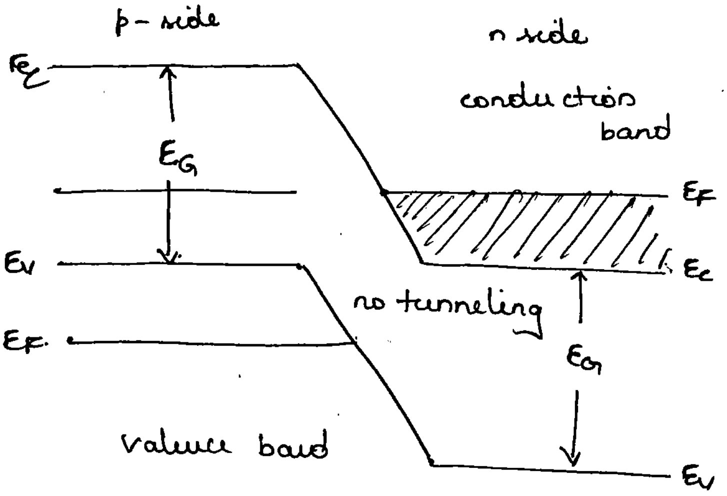
(3) As the forward bias is increased further, the maximum number of electrons can leave from occupied states on the right side of the junction, and tunnel through the barrier to empty states on the left side of the junction giving rise to the peak current I_p.

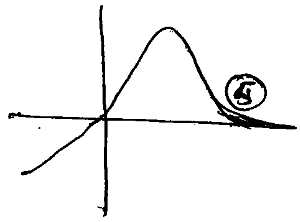


(4) If still more forward bias is applied, the following band structure is obtained and tunneling current decreases giving rise to negative resistance region.

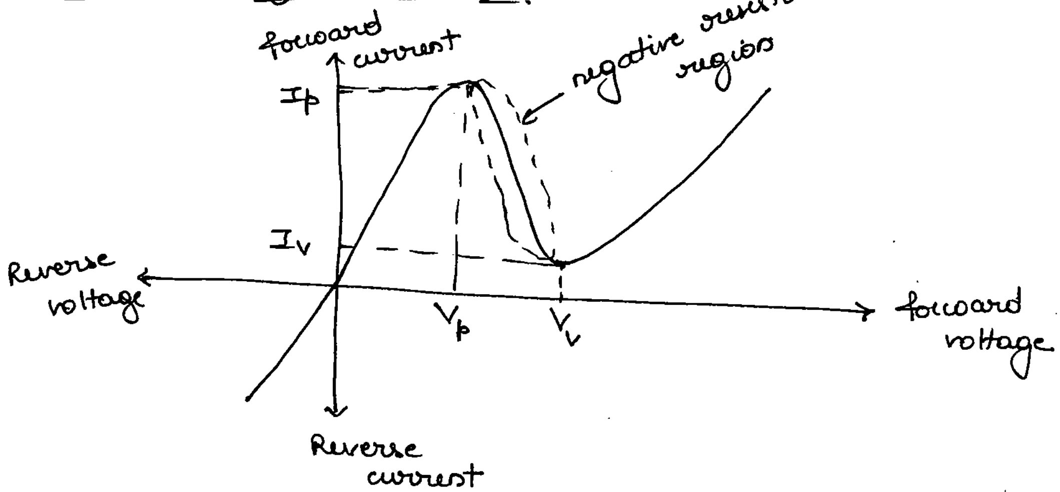


(5) Finally if the forward bias is still larger, there are no empty allowed states on one side of the junction at the same energy as occupied states on other side & tunneling current must drop to zero.





→ <u>characteristics of tunnel diode</u>.



The tunnel diode exhibits a negative resistance characteristics between peak current I_p and valley current I_V.

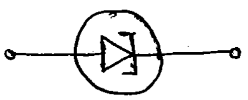
The tunnel diode is excellent conductor in reverse bias conditions.

By applying small forward bias voltage to the tunnel diode the current increases and reaches to maximum level. The maximum current for small forward bias voltage is called as a "peak current" (I_p). The corresponding voltage to the peak current is called "peak voltage" (V_p)

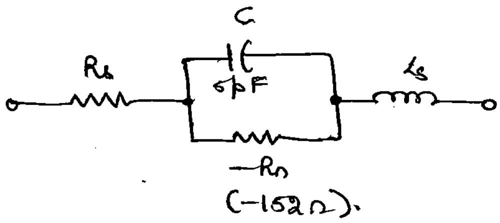
→ If the forward bias voltage is increased beyond the peak voltage the current starts decreasing and reaches to minimum level. This minimum value of current is called as "valley current" (I_V). The corresponding voltage to valley current is called as "valley voltage" (V_V).

If forward bias voltage is increased beyond valley voltage it exhibits the same characteristics as ordinary diode.

The symbol and equivalent circuit of tunnel diode is shown below:



a) Symbol



b) Equivalent Circuit.

→ Advantages.

1. Environmental immunity i.e The peak point (V_p, I_p) is not a sensitive function of temperature.
2. Low Cost.
3. Simplicity i.e a tunnel diode can be used along with dc supply and few passive elements to obtain various application circuits.
4. Low noise
5. High speed i.e The tunelling takes place at the speed of light hence the switching times of the order of a nanosecond are easily obtained + switching times as low as 50psec also can be obtained
6. Low power consumption

→ Disadvantage

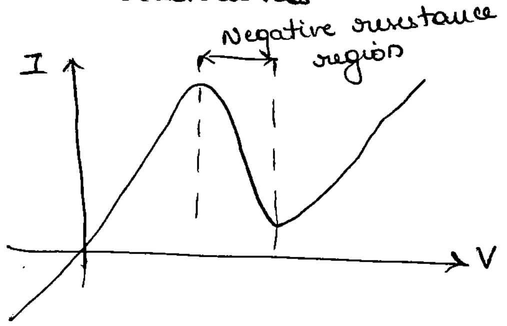
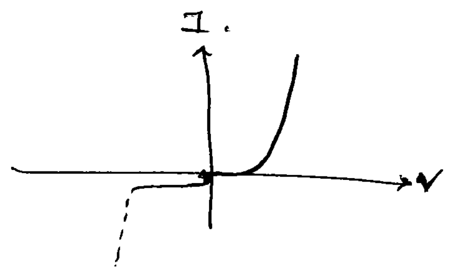
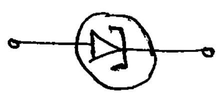
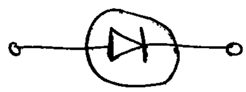
The only disadvantage are is its low o/p voltage swing and it is a two terminal device. ⇒ There is no isolation between i/p and o/p.

⇒ Txr is used along with tunnel diode for frequencies below 1 GHz

II

1. As a high speed switch.
2. In pulse & digital circuits
3. In negative resistance and high frequency oscillator.
4. In switching networks.
5. In timing & computer logic circuitry.
6. Design of pulse generators & amplifiers.

Comparison of Tunnel diode & pn junction diode

Tunnel Diode	pn-junction diode
1. Impurity concentration is high about 1 part in 10^3 atoms.	1. Impurity concentration is low about 1 part in 10^8 atoms.
2. Depletion region width is about 5 microns, which is 1/100th the width of pn junction diode	2. Depletion region width is high compared to tunnel diode
3. Carrier velocities are very high at low forward bias, hence can punch through the depletion region.	3. Carrier velocities are low at low forward bias, hence can not penetrate the depletion region.
4. VI characteristics show negative resistance region	4. VI characteristics does not show negative resistance region
5. VI characteristics 	5. VI characteristics 
6. Materials used for construction are Ge and GaAs	6. Si is most popularly used.
7. Symbol is 	7. Symbol is 
8. Switching time is very low in nano or picoseconds.	8. Switching time is high

9. Applications	9. Applications
— Used for high frequency oscillators.	— Rectifiers
— switching networks.	— clippers
— pulse & digital circuits.	— clampers,
	— logic gates design etc.

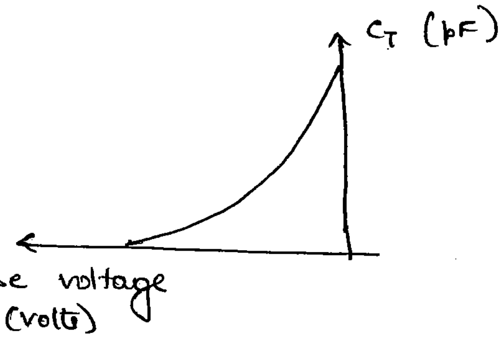
Varactor Diode

We know that the transition capacitance C_T is given by $C_T = \frac{\epsilon A}{W}$.

In both alloy junction diode & grown junction diode as the magnitude of the reverse bias increases, the width "W" of the transition region increases, and the junction capacitance C_T reduces.

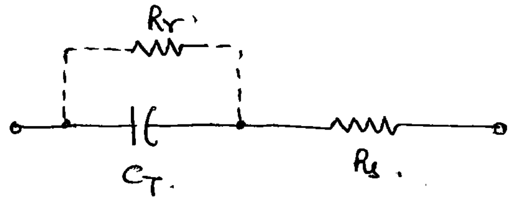
As transition capacitance varies with the applied voltage, it can be used as voltage variable capacitance in many applications. In practice, special type of diodes are manufactured which shows the transition capacitance property more predominantly compared to normal diodes. Such diodes are called varactor diodes, varicap, VVC (voltage variable capacitance) or tuning diodes.

C_T verses reverse voltage is shown below.



Symbol of varactor diode & its equivalent circuit is shown below

a) symbol.



b) Equivalent circuit

where R_s = Body (ohmic) series resistance

C_T = Barrier capacitance

R_r = Reverse diode resistance.

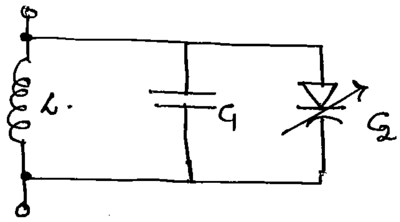
Typically, at a reverse bias of 4V,

C_T = 20pF, R_s = 8.5Ω, R_r > 1MΩ (usually neglected)

Applications

The main application of varactor diodes is LC tuned circuits.

Figure below shows how varactor diode can be connected in a LC tuned circuit.



The resonant frequency for a parallel LC tuned circuit is given by.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

As varactor diode is connected in parallel, The resultant capacitance becomes $C_1 + C_2$. Hence, the resonance frequency becomes.

$$f_r = \frac{1}{2\pi\sqrt{L(C_1+C_2)}}$$

where C_2 = transition capacitance of varactor diode

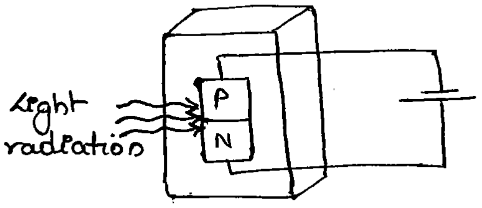
Value of C_2 can be changed by controlling the voltage applied to The circuit. Hence, the circuit can be tuned by changing voltage applied at a resonance frequency, This is called electrical tuning.

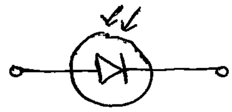
Other Applications

1. Self-balancing bridge circuits.
2. In parametric amplifiers.
3. FM radio & TV receivers, AFC circuits (Automatic frequency Control circuits).
4. Used in adjustable band pass filter.

Photodiode

The photodiode is a device that operates in reverse diode. The photodiode has a small transparent window that allows light to strike one surface of the pn junction, keeping the remaining sides unilluminated.

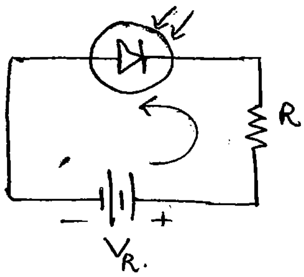




Symbol of photodiode

→ Principle of operation

The photodiode is connected in reverse biased condition. The depletion width is large. Under normal condition, it carries small reverse current due to minority carriers.



When light is incident through glass window on the pn junction, photons in the light bombard the pn junction & some energy is imparted to valence electrons.

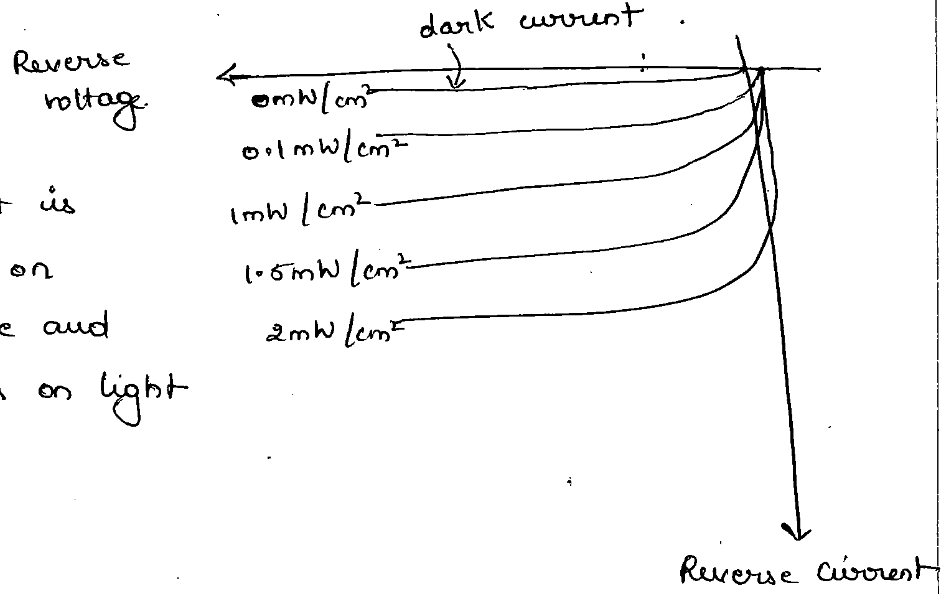
Due to this, valence electrons are dislodged from the covalent bonds and become free electrons. Thus more electron-hole pairs are generated. Hence, total no. of minority carriers increase and the reverse current increases. This is the basic principle of operation of photodiode.

→ Photodiode characteristics

A photodiode differs from a rectifier diode in that when its pn junction is exposed to light, the reverse current increases with light intensity.

When there is no incident light the reverse current, I_λ is almost negligible and is called the dark current. An increase in the amount of light intensity expressed as Irradiance (mW/cm²) produces an increase in the reverse current as shown below

The VI characteristics of photodiode are shown below.



*** Reverse current is not dependent on reverse voltage and totally depends on light intensity.

→ Photodiode as Variable Resistance Device.

Typically, the reverse current is approximately $1.4\mu A$ at a reverse bias voltage of 10V with an irradiance of $0.5 mW/cm^2$

$$\Rightarrow R_R = \frac{V_R}{I_\lambda} = \frac{10V}{1.4\mu A} = 7.14 M\Omega.$$

At $20 mW/cm^2$, the current is approximately $55\mu A$ at $V_R = 10V$

$$\Rightarrow R_R = \frac{V_R}{I_\lambda} = \frac{10V}{55\mu A} = 182 k\Omega.$$

This shows that the photodiode can be used as a variable resistance device controlled by light intensity. It is also called as photoconductive devices.

Since response of photodiode is very fast hence change in resistance from high to low or otherwise, is very fast as well. Hence, can be used in a variety of applications

The reverse current without light in diode is in the range of μA. The change in the current due to the light is also in the range of μA. Thus, such a change can be significantly observed in reverse current because forward current is in mA.

→ Photodiode as photovoltaic cell

When photodiode is illuminated without any biasing, there is increase in the no. of holes in the p-side and the number of electrons in the n-side. Due to this, minority carriers are swept across the junction. We know that, the barrier potential is negative on the p-side and positive on the n-side. The barrier potential tends to reduce because of the flow of minority carriers. When an external circuit is connected across the diode terminals, the minority carriers will return to the original side via the external circuit. The electrons which crossed the junction from p to n will now flow out through the n terminal and into the p-terminal.

This means that the diode is behaving as a voltage cell with n-side being the negative terminal and the p-side the positive terminal. Thus, the photodiode is a photovoltaic device as well as a photoconductive cell.

→ Advantages-

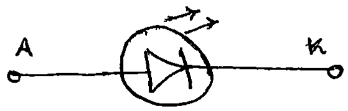
1. Can be used as a variable resistance device.
2. Highly sensitive to light
3. Speed of operation is very high. The switching of current and hence the resistance value from high to low or otherwise is very fast.

→ Disadvantages.

1. Dark current I_λ is temperature dependent.
2. overall photodiode characteristics are temperature dependent hence have poor temperature stability.
3. Current & change in current is in range of μA which not be sufficient to drive other circuits. Hence, amplification is necessary.

* Light Emitting Diode (LED)

The LED is an optical diode which emits light when forward biased, by a phenomenon called Electroluminescence. The symbol of LED is shown below.



It is similar to pn junction diode apart from the 2 arrows indicating that the device emits the light energy.

The LEDs use the materials like Gallium Arsenide (GaAs), Gallium Arsenide Phosphide (GaAsP) or Gallium Phosphide (GaP). These are mixtures of the elements Ga, As, P.

→ Basic operation

When the LED is forward biased, the electrons and holes move towards the junction and recombination takes places. As a result of recombination, the electrons lying in conduction bands of n-region fall into the holes lying in the valence band of a p-region

The difference of energy between the conduction band and the valence band is radiated in the form of light energy. The energy released in the form of light depends on the energy corresponding to the forbidden gap. This determines the wavelength of the emitted light.

The wavelength determines the color of the light and also determines whether the light is visible or invisible (infrared).

The color of the emitted light depends on the type of material used:

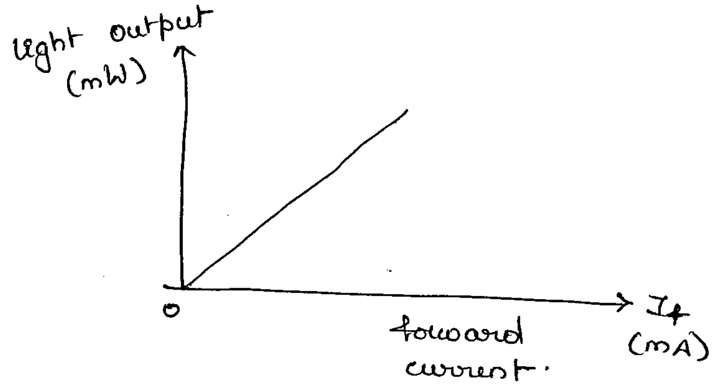
1) Gallium Arsenide (GaAs) → Infrared radiation (Invisible)
2) Gallium Phosphide (GaP) → Red or Green
3) Gallium Arsenide Phosphide (GaAsP) → Red or Yellow

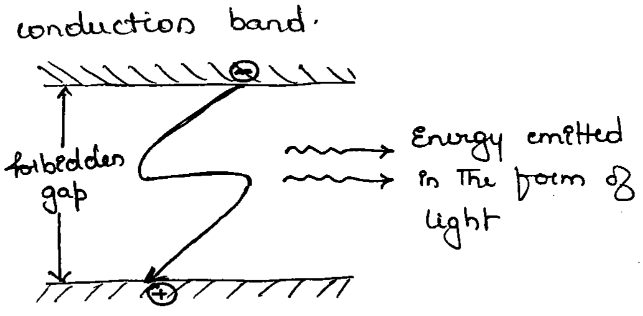
The brightness of the emitted light is directly proportional to the forward bias current.

→ Output characteristics of LED

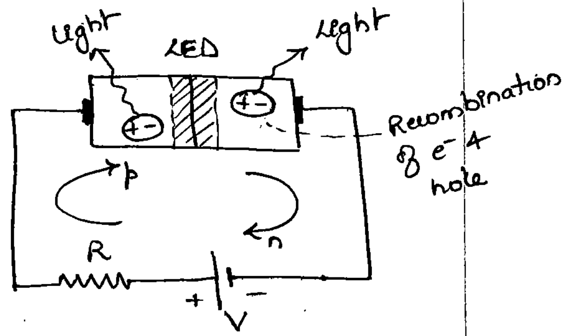
The amount of power output translated into light is directly proportional to the forward current I_f. More the forward current I_f, the greater is the output light.

The graph of forward current and output light in mW is shown in the figure below. This is called output characteristics of LED.





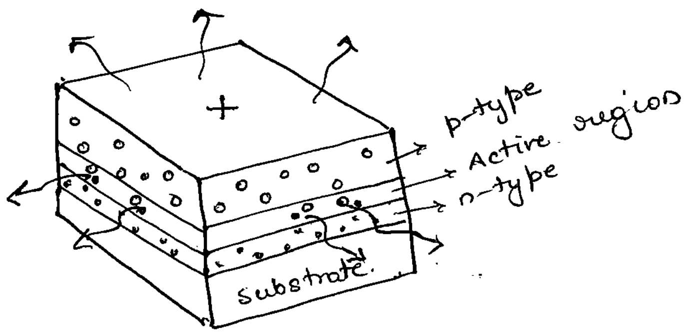
a) process of electroluminescence

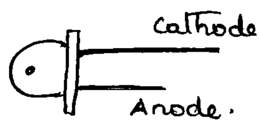


b) LED forward biased

→ Construction of LED

One of the methods used to construct LED is to deposit three semiconductor layers on the substrate as shown below





LED.

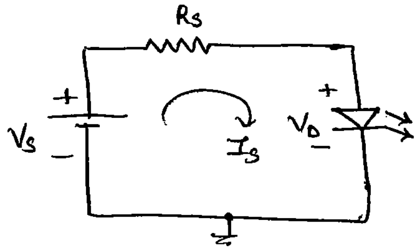
In between p-type and n-type, there exists an active region. This active region emits light, when an electron and hole recombine.

and electrons from n-type, both are driven into active region. And when they recombine, the light is emitted.

In this particular structure, LED emits light all the way around the layered structure. Thus the basic layered structure is placed in a tiny reflective cup so that the light from the active layer will be reflected towards the desired exit direction.

→ LED : voltage & current

Consider a source and a resistor connected to LED as shown below:



The resistor R_s is the current limiting resistor. Due to this resistor, the current through the circuit is limited & prevented from exceeding the maximum current rating of the diode

Let V_s = Supply Voltage

V_D = Drop across LED

Applying KVL, $V_s = I_s \cdot R_s + V_D$

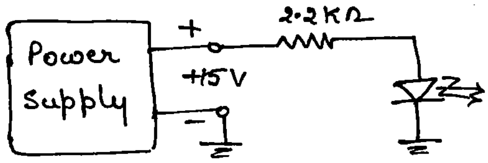
$$\Rightarrow \boxed{I_s = \frac{V_s - V_D}{R_s}}$$

During forward bias, the voltage drop across conducting LED is about 2 to 3V which is considerably greater than that across a normal silicon or germanium diode. The current range of commercially available LEDs is 10 to 80 mA.

Unless and otherwise specified, while analysing the LED circuits, the drop across LED is considered as $V_D = 2V$.

The reverse breakdown voltage of LED is much less than the normal diode, which is about 3V to 10V.

(10) What is the current through LED used in a circuit shown below?



Sol. Assume the drop across LED = 2V.

$V_D = 2V$

Given $R_S = 2.2\,K\Omega$ and $V_S = 15\,V$

$$\Rightarrow I_S = \frac{V_S - V_D}{R_S} = \frac{15-2}{2.2 \times 10^3} = \underline{5.91\,mA}$$

→ Advantages of LED

1. LEDs are small in size, and hence can be regarded as point source of light. Because of their small size, thousands of LEDs can be packed in one square meter area.
2. The brightness of light emitted by LED depends on the current flowing through the LED. Hence, brightness of light can be smoothly controlled by varying current. This makes possible to operate LED displays under different ambient lighting conditions.
3. LEDs are fast operating devices. They can be ~~too~~ turned on and off in ~~less~~ less than 1 microsecond.
4. LEDs are light in weight.
5. LEDs are available in various colors
6. LEDs have long life.
7. LEDs are cheaper and readily available
8. LEDs are easy to interface with various electronic circuits.

→ Disadvantages.

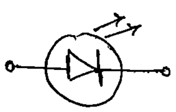
1. It draws considerable current requiring frequent replacement of battery in low power battery operated devices.
2. Luminous efficiency of LED is low which is 1.5 lumens/watt.
3. Characteristics are affected by temperature
4. Need large power for the operation compared to normal

→ Applications

Due to the advantages like low voltage, long life, cheap, reliable, fast on-off switch etc, LEDs are used in many applications like

1. All kinds of visual displays i.e seven segment displays and alpha numeric displays. Such displays are commonly used in watches and calculators.
2. In optical devices such as optocouplers.
3. As on-off indicator in various types of electronic circuits.
4. Some LEDs radiate infrared light which is invisible. But such LEDs are used in remote controls and applications like bulgar alarms.

→ Comparison of LED and pn junction diode

	LED	pn - Junction diode
1	Emits light when forward biased.	Doesnot emit light
2.	Uses material like GaAs, GaP, GaAsP	Uses material like Si & Ge.
3.	Drop across forward biased LED is 2V.	Drop across forward biased pn diode is 0.7V, much less than LED.
4.	Reverse breakdown voltage is 3V to 10V, which is very low	Reverse breakdown voltage is high about 50V and more
5.	Need large power for operation	Needs less power for operation.
6.	Draws considerable power from battery.	Draws less current.
7.	Symbol: 	Symbol: 
8.	Applications: Seven segment displays, alpha numeric displays,	Applications: Rectifiers, clippers, clampers, voltage multipliers

A liquid crystal is a material that will flow like a liquid but whose molecular structure has some properties normally associated with solids. ⇒ liquid crystals have been called the "fourth state of matter" after solids, liquids & gases.

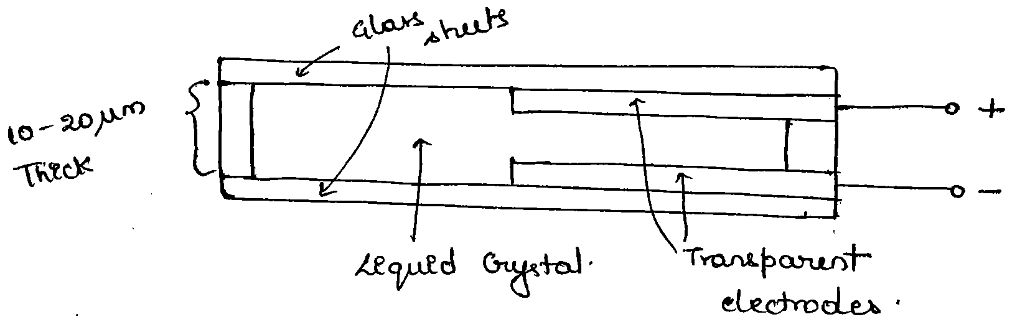
Unlike LEDs and other electroluminescent devices, LCDs do not generate light energy but simply alter or control the existing light to make selected areas appear bright or dark.

There are two major types of LCDs:

1. Dynamic Scattering LCDs
2. Field effect LCDs.

a) Dynamic Scattering LCDs.

Figure below shows the construction of a typical LCD ~~cell~~.

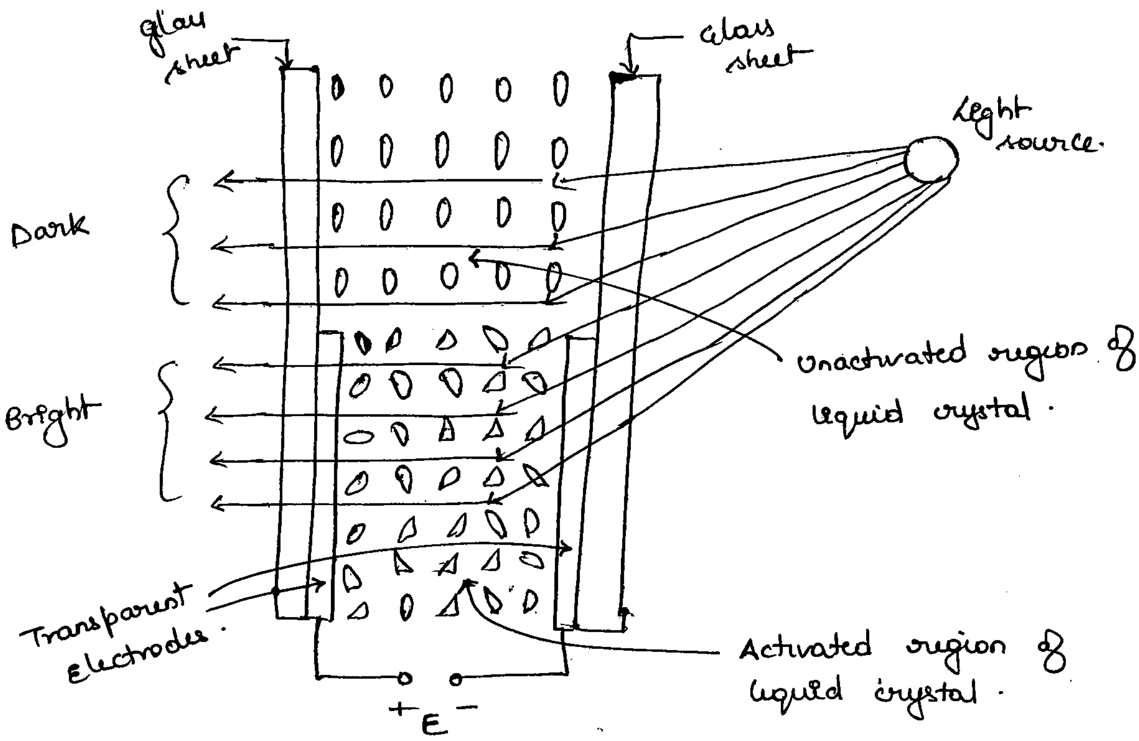


It consists of a layer of liquid crystal material sandwiched between glass sheets with transparent metal film electrodes. Usually, an optically thin (about 50nm) layer of Indium Tin Oxide (ITO) on each surface acts as an electrode to allow a voltage to be held across the cell. Then alignment treatment is applied on top of ITO.

In dynamic scattering method, the molecules of the liquid crystal acquire a random orientation by virtue of an externally applied electric potential. As a result, light passing through the material is reflected in many different directions & has a bright, frosty appearance as it emerges.

The dynamic scattering type LCD operates in "transmissive mode". In this mode, the light is allowed to fall on one side glass sheet & the rays passes through the liquid crystals and

The dynamic scattering is shown below.



b) Field Effect LCDs

In field effect LCDs, The molecules are oriented in such a way that they alter the polarization of the light passing through the material.

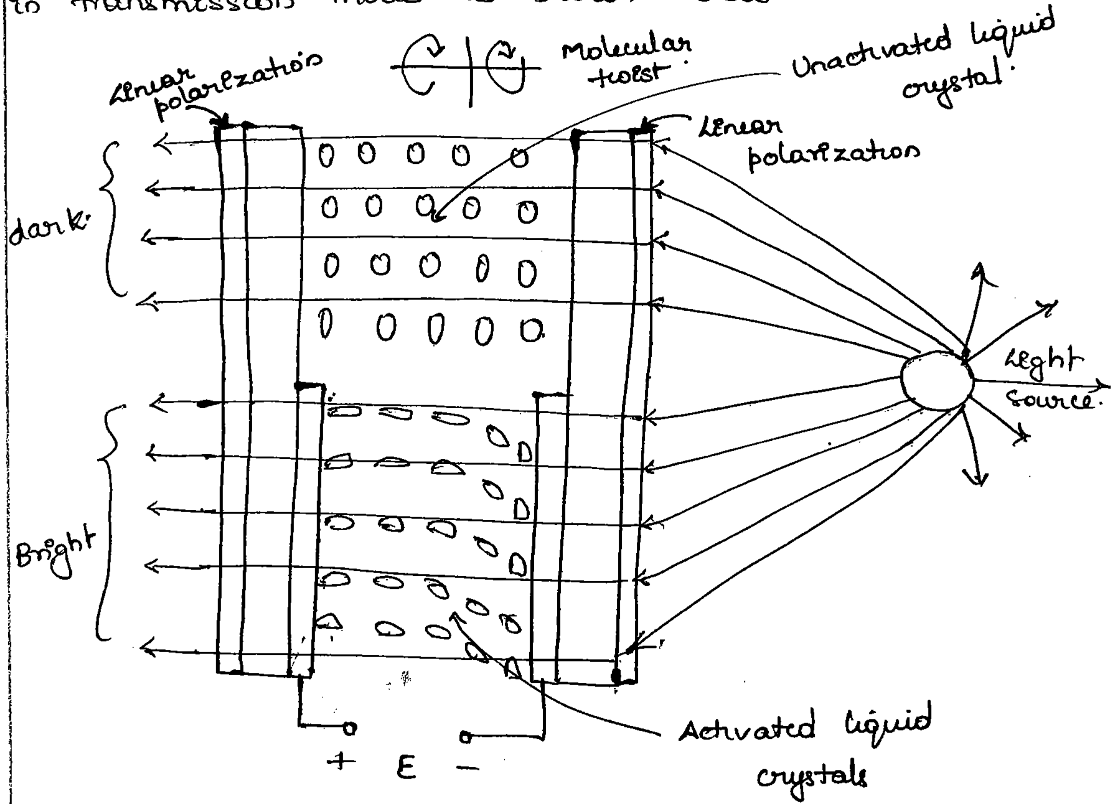
Polarization filters are used to absorb or pass the light depending on the polarization it has been given, so light is visible only in those regions where it can emerge from the filter.

The field effect LCDs operate in both "transmissive" and "reflective" modes. To operate in reflecting mode, a reflecting mirror is placed on one side of the glass sheet.

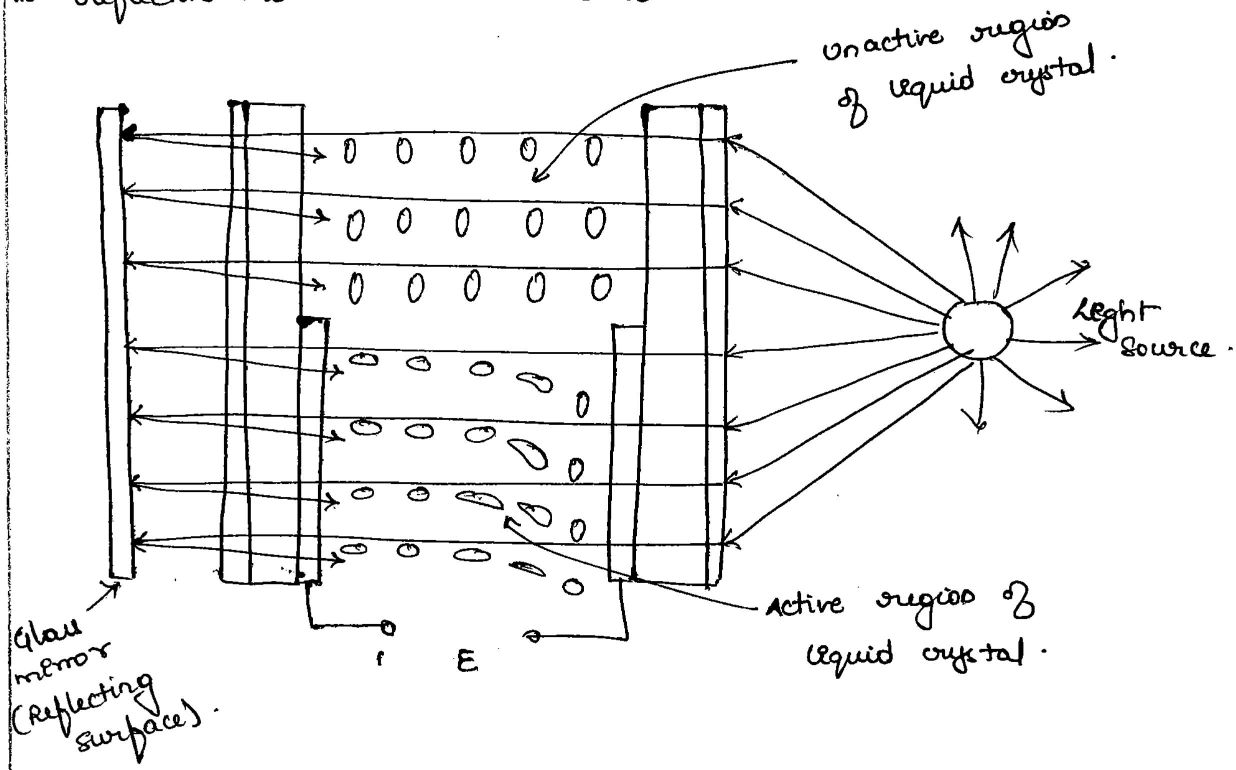
Materials used to form the electrodes are

1) Stannic oxide (SnO_2)
2) Indium Oxide (In_2O_3).

in transmission mode is shown below.



Field effect LCD based on light absorption operating in reflective mode is shown below



→ Advantages

1. voltages required are small.
2. They have a low power consumption
3. They are economical (cheaper).

→ Disadvantages

1. LCDs are very slow devices, The turn-on and off times are quite large. (few mseconds).
2. Lifetime is limited to 50,000 hrs due to chemical degradation
3. They occupy large space

→ Applications

1. Used for display of numeric and alphanumeric character in dot matrix and segment display.
2. Used in pocket calculators, wrist watches and other portable digital devices.

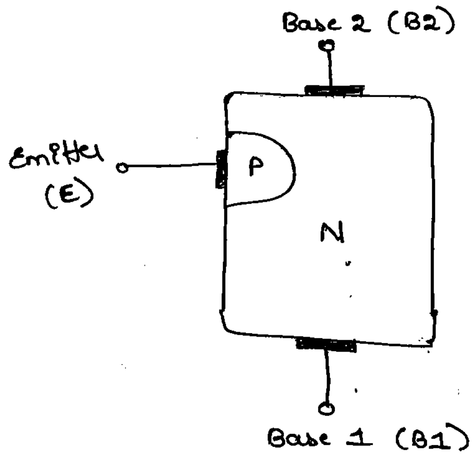
J6, L8, 9, M1, 05, 8, P3, 4

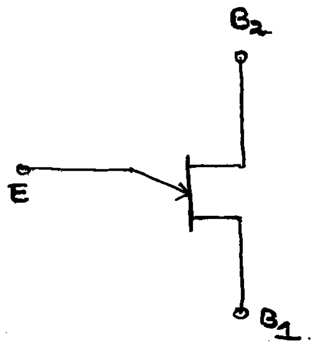
UJT (Uni Junction Transistor)

A Unijunction transistor (UJT) is a Three terminal semiconductor switching device. As it has only one PN junction and Three leads, it is commonly called as UJT. The Three terminals are Emitter (E), Base 1 (B1) and Base 2 (B2)

→ Construction + Symbol

The basic structure and symbol of UJT is shown





b) Circuit Symbol

a) Basic Symbol.

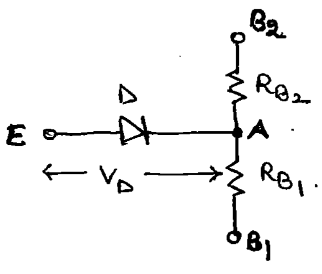
It consists of a slab of lightly dopped n-type silicon material. The two base contacts are attached to both The ends of this n-type surface. These are denoted by B_1 and B_2.

A p-type material which is heavily doped is alloyed to lightly doped n-type material on one side closer to B2 for producing single PN junction

Here, emitter leg is drawn at an angle to the vertical and The arrow indicates The direction of The conventional ~~circuit~~ current.

→ Equivalent Circuit of UJT.

The equivalent circuit of UJT is shown below:



Internal resistances of The two bases are represented as R_{B_1} and R_{B_2}.

In actual construction, terminal E is closer to B_2 as compared to B_1.

$\Rightarrow R_{B_1} > R_{B_2}$

The pn junction is represented by a normal diode with V_D as the drop across it.

when emitter diode is not conducting (i.e O.C) Then the resistance between the two bases B_1 and B_2 is called **Interbase Resistance** denoted by R_{BB}.

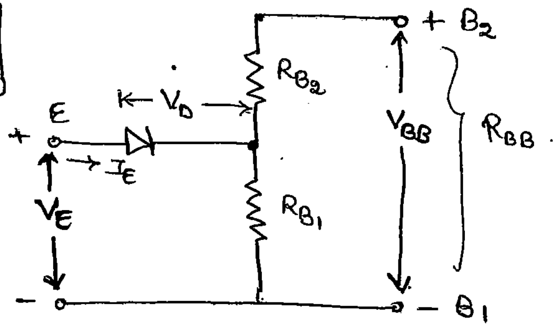
$$\Rightarrow R_{BB} = R_{B_1} + R_{B_2}.$$

Its value ranges from 4KΩ to 12KΩ.

→ **Intrinsic Stand off Ratio** (η)

Consider UJT as shown below to which supply V_{BB} is connected. with $I_E = 0$ i.e emitter diode is not conducting

$$\boxed{R_{BB} = R_{B_1} + R_{B_2}. \Big|_{I_E=0}}$$



Then voltage drop across R_{B_1} can be obtained by using potential divider rule

$$V_{R_{B_1}} = \frac{R_{B_1} \cdot V_{BB}}{R_{B_1} + R_{B_2}} \quad \text{when } I_E = 0.$$

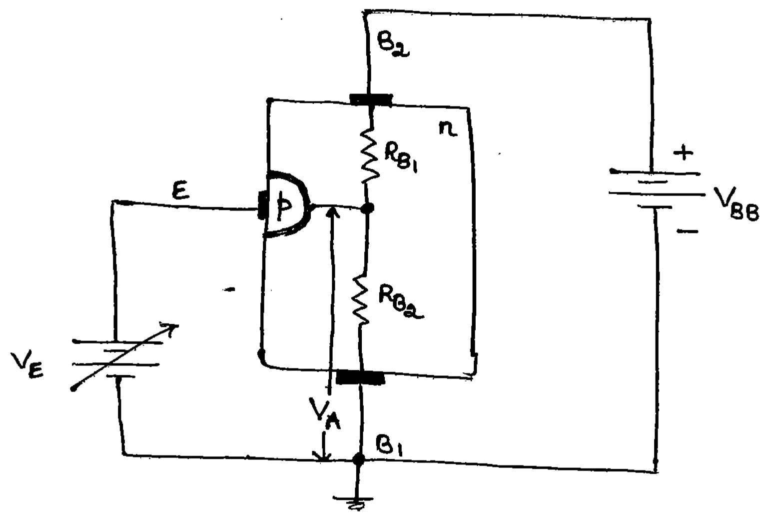
$$= \eta \cdot V_{BB} \quad \text{when } I_E = 0$$

Then, intrinsic stand off ratio $= \eta = \dfrac{R_{B_1}}{R_{B_1} + R_{B_2}}\Big|_{I_E=0}$.

$$\boxed{\eta = \frac{R_{B_1}}{R_{BB}}\Big|_{I_E=0}.}$$

The typical range of η is from 0.5 to 0.8. The voltage $V_{R_{B_1}}$ is called intrinsic stand off voltage because it keeps the emitter diode reverse biased for all the emitter voltage Than $V_{R_{B_1}}$.

while operating an UJT, The supply V_{BB} is applied between B_2 and B_1 while the variable emitter voltage V_E is applied across the emitter terminals. This arrangement is shown below:



potential at A = $V_A = \eta V_{BB}$.

case 1:- $V_E < V_A$

As long as V_E is less Than V_A, the p-n junction is reverse biased. Hence, emitter current I_E will not flow.

⇒ UJT is said to be OFF.

case 2:- $V_E > V_P$

The drop V_D is generally between 0.3V to 0.7V. Hence, we have.

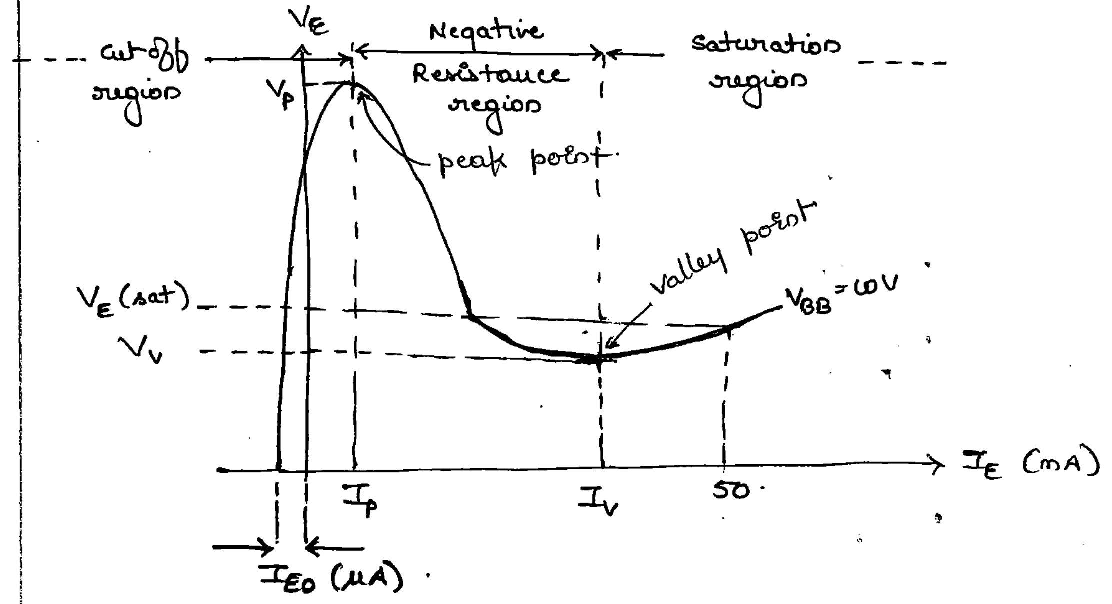
$$V_P = V_A + V_D$$

$$\boxed{V_P = \eta V_{BB} + V_D}$$

when V_E becomes equal to or greater Than V_P The pn junction becomes forward biased & current I_E flows. The UJT is said to be ON.

→ UJT characteristics

The characteristic curve between



Here, upto the peak point (V_p), the diode is reverse biased and hence, the region to the left of the peak point is called **cut-off region**.

At peak point, the peak voltage

$$V_p = \eta V_{BB} + V_D,$$

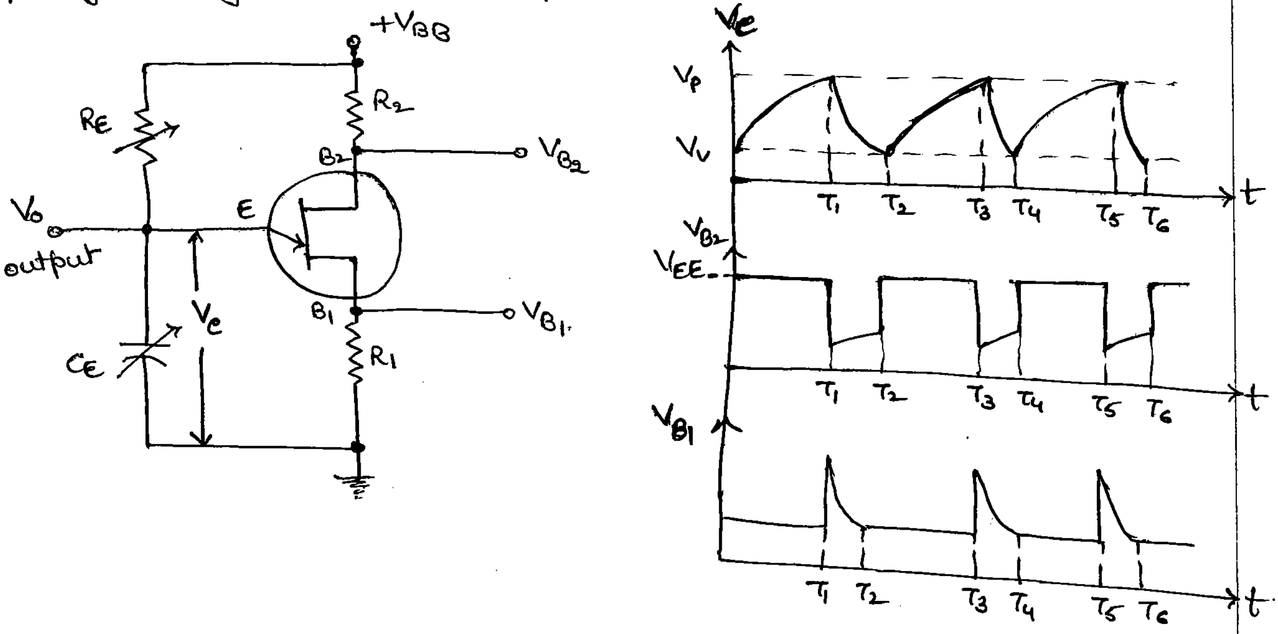
The diode starts conduction & holes are injected into n-layer. Hence, resistance decreases thereby decreasing V_E for the increase in I_E. So, there is a **negative ~~reg.~~ resistance region** from peak point V_p to valley point V_v.

After the valley point, the device is driven into saturation and behaves like a conventional forward biased pn junction diode. The region to the right of the valley point is called **Saturation Region**.

In the valley point, the resistance changes from negative to positive and it remains positive in saturation region.

Due to the negative resistance property, a UJT can be employed in a variety of applications, viz a sawtooth wave generator, pulse generator etc.

The relaxation oscillator using UJT which is meant for generating sawtooth waveform is shown



The voltage across the capacitor increases exponentially and when the capacitor voltage reaches the peak point voltage (V_p), the UJT starts conducting and the capacitor voltage is discharged rapidly through E, B_1 and R_1.

After the peak point voltage of UJT is reached, it provides negative resistance to discharge path which is useful in the working of the ~~relation~~ relaxation oscillator. As the capacitor voltage reaches zero, the device then cutoffs and capacitor C_E starts to charge again.

This cycle is repeated continuously generating a sawtooth waveform across C_E.

The inclusion of external resistances R_1 and R_2 in series with B_1 and B_2 provides spike waveform.

When the UJT fires, the sudden surge of current through B_1 causes drop across R_1, which provides positive going spikes. Also, at the same time of firing, fall of V_{EB_1} causes I_2 to increase rapidly which generates negative going spikes across R_2.

By changing the values of capacitor C_E or resistance R_E frequency of the output waveform can be changed as desired.

The time period and hence the frequency of the sawtooth wave can be calculated as follows

Assuming that the capacitor is initially uncharged, the voltage V_c across the capacitor prior to breakdown is given by

$$V_c = V_{BB}\left(1 - e^{-t/R_E C_E}\right)$$

where $R_E C_E$ = charging time constant of RC circuit

t = time from commencement of waveform

The discharge of the capacitor occurs when V_c is equal to the peak-point voltage V_p, i.e.,

$$V_p = \eta V_{BB} = V_{BB}\left(1 - e^{-t/R_E C_E}\right).$$

$$\Rightarrow \eta = 1 - e^{-t/R_E C_E}$$

$$e^{-t/R_E C_E} = 1 - \eta.$$

$$\Rightarrow t = R_E C_E \cdot \log_e\left(\frac{1}{1-\eta}\right)$$

$$= 2.303\, R_E C_E \log_{10}\left(\frac{1}{1-\eta}\right)$$

If discharge period of capacitor is neglected, then

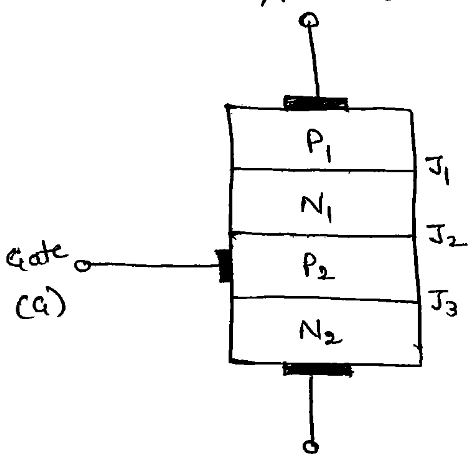
$t = T$ = period of wave

$\Rightarrow$ frequency of oscillation of sawtooth wave,

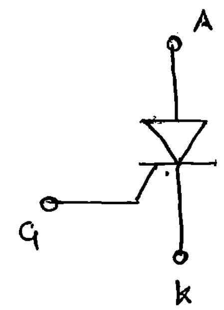
$$\boxed{f = \frac{1}{T} = \frac{1}{2.3\, R_E C_E \log_{10}\left(\frac{1}{1-\eta}\right)}}$$

* Silicon Controlled Rectifier (SCR)

The basic structure and symbol of SCR is shown below



(a) Basic structure



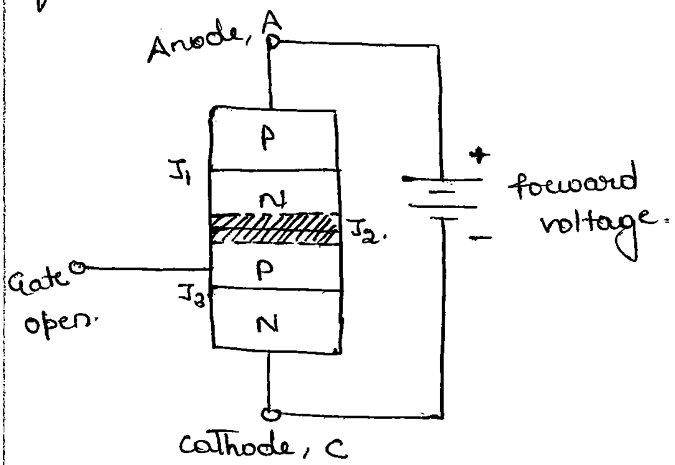
(b) Circuit symbol.

→ operation of SCR

The operation of SCR is divided into two categories.

a) when gate is open

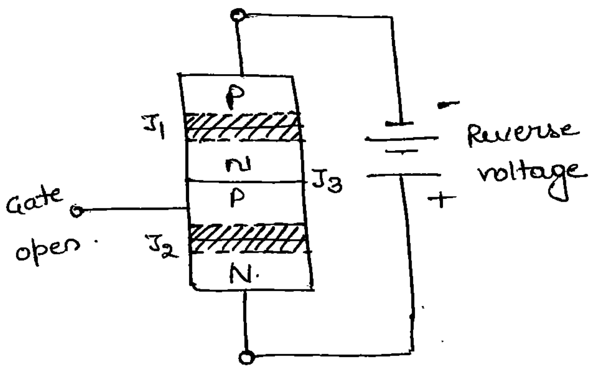
Consider that the anode is positive with respect to cathode and gate as open. The junctions J_1 and J_3 are forward biased and J_2 is reverse biased.



There is a depletion region around J_2 and only leakage current flows which is negligibly small.

Practically, SCR is said to be OFF. This is called forward blocking state of SCR and voltage applied to anode and cathode, with anode positive is called forward voltage.

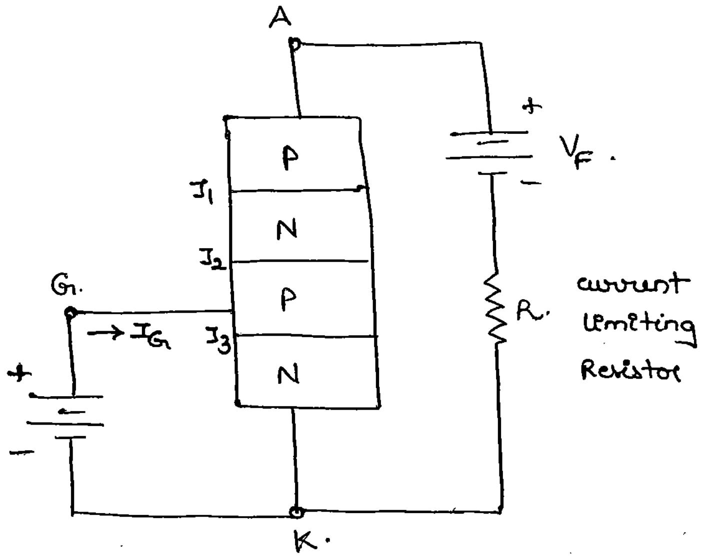
with gate open, if cathode is made positive with respect to anode, the junctions J_1, J_3 become reverse biased and J_2 forward biased. still the current flowing is leakage current, which can be neglected as it is very small.



The voltage applied to make cathode positive is called reverse voltage and SCR is said to be in reverse blocking state.

b) when gate is closed.

Consider that the voltage is applied between gate + cathode when the SCR is in forward blocking state as shown below



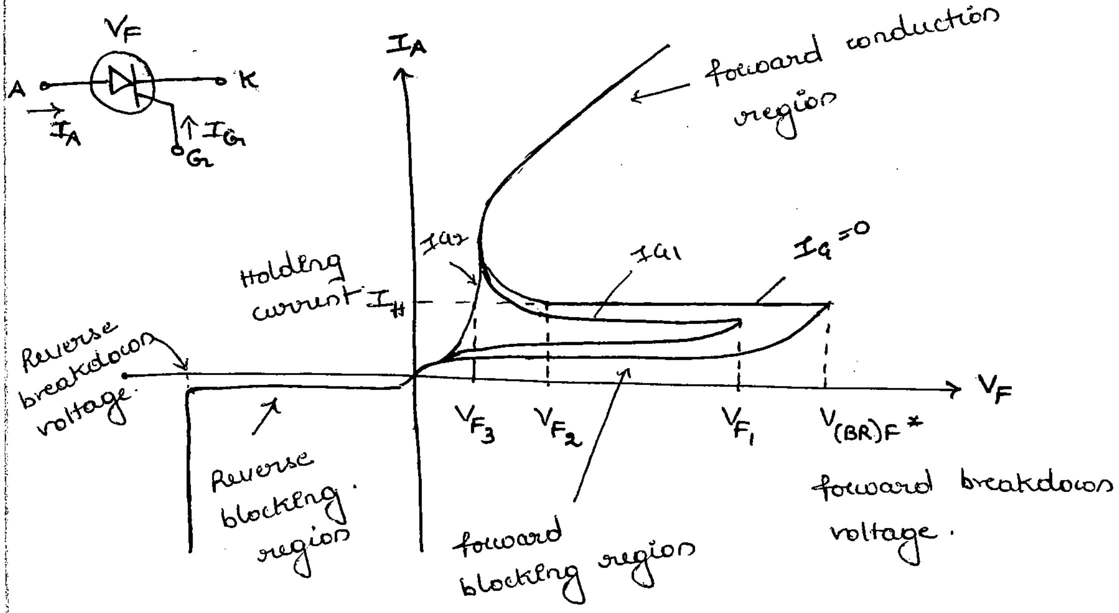
The gate is made positive wrt cathode. The electrons from n-type cathode which are majority in number, cross the junction J_3 to reach to positive of battery.

while holes from p-type move towards the negative of battery, it constitutes the gate current (I_G). This current increases the anode current as some of the electrons cross junction J_2. As anode current increases, more electrons cross the junction J_2 and the anode current further increases.

Due to regenerative action, within short time, the junction J_2 breaks and SCR conducts heavily. ~~The connections are shown in~~ The resistance R is required to limit the current. once the SCR conducts, the gate loses its control.

→ SCR characteristics:

The characteristics of an SCR are shown for various values of current.



1. Forward breakdown voltage. $V_{(BR)F^*}$.

It is that voltage above which the SCR enters the conduction region.

The asterisk (*) is a letter that is to be added that is dependent on the condition of the gate terminal as follows:

O = open circuit from G to K

S = Short circuit from G to K

R = resistor from G to K

V = fixed bias-voltage from G to K.

2. Holding current, I_H.

It is that current value below ~~the~~ which the SCR switches from the conduction state to forward blocking region under stated conditions.

3. Forward & Reverse blocking regions

These are the regions corresponding to the open circuit condition for the controller rectifier which block the flow of charge (current) from anode to cathode.

4. Reverse breakdown voltage.

It is equivalent to the zener or avalanche region of the fundamental two-layer semiconductor diode.

SCR characteristics are very similar to those of the basic 2-layer semiconductor diode except for the horizontal offshoot before entering the conduction region. It is this horizontal jutting region that gives the gate control over the response of SCR.

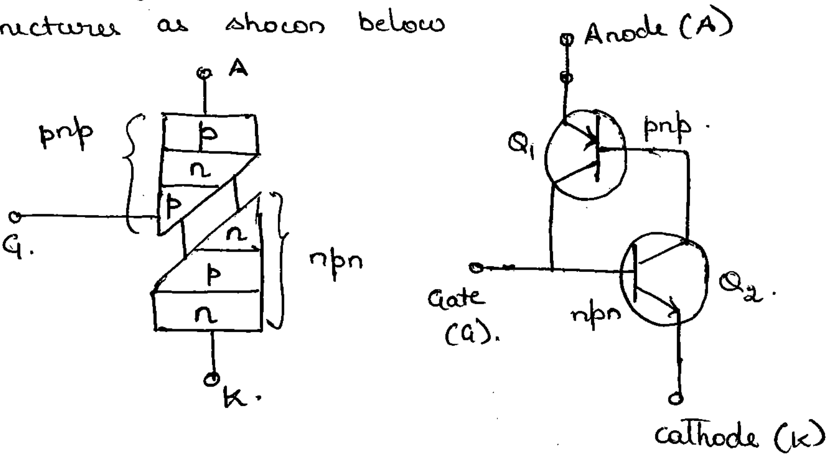
For $I_G = 0$, V_F must reach the largest required breakdown voltage ($V_{(BR)F*}$) before the "collapsing" effect will result and the SCR can enter the conduction region corresponding to the "on" state.

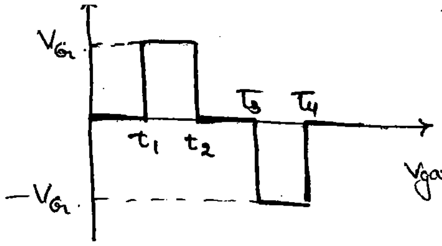
If the gate current is increased to I_{G_1}, by applying a bias voltage to the gate terminal, the value of V_F required for the conduction (V_{F_1}) is considerably less. The holding current I_H also drops with increase in I_G.

If ~~the~~ gate current is further increased to I_{G_2}, the SCR will fire at very low values of voltages (V_{F_3}) and the characteristics begin to approach those of the basic pn junction diode.

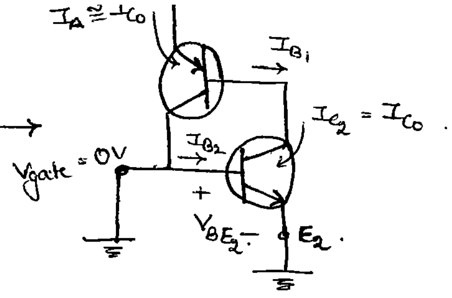
→ SCR two-transistor equivalent circuit.

The basic operation of SCR is best effected by splitting the 4-layer pnpn structure into two 3-layer transistor structures as shown below

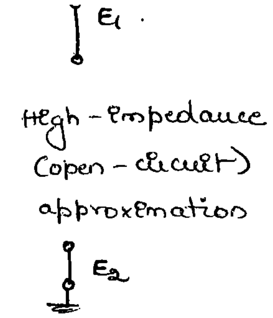




(a)



(b)



(c)

"off" state

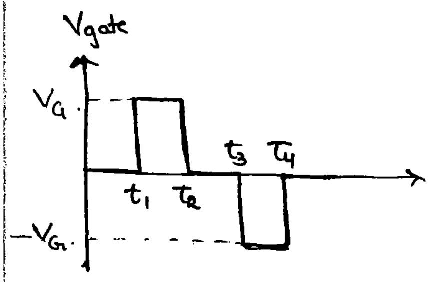
During the interval $0 \rightarrow t_1$, $V_{gate} = 0V$, the circuit appears as shown in figure (b).

for $V_{BE_2} = V_{gate} = 0V$,

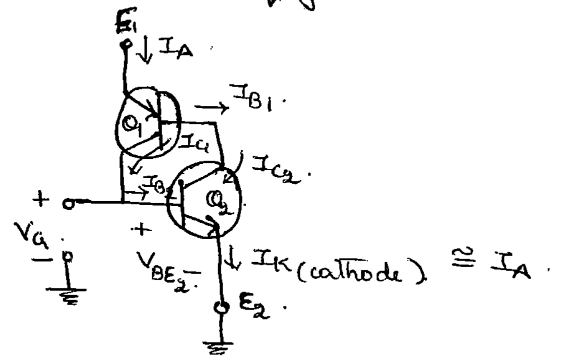
base current $I_{B_2} = 0$,

collector current $I_{C_2} \cong I_{C0}$.

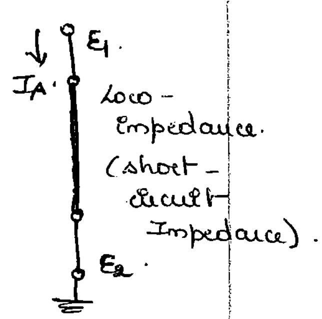
The base current of Q_1, $I_{B_1} = I_{C_2} = I_{C0}$ = very small to turn Q_1 into ON state ⇒ both transistors are therefore in the "off" state, resulting in high impedance between the collector 4 emitter of each transistor and the open circuit representation for the controlled rectifier as shown in figure (c).



(a)



(b)



(c)

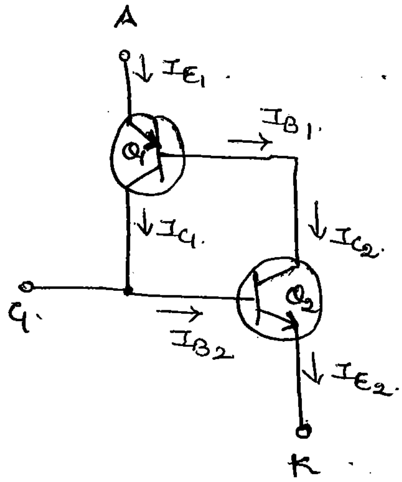
"ON" state

At $t = t_1$, a pulse of V_G volts will appear at SCR gate. The circuit conditions established with this input are shown in fig (b). The potential V_G was chosen sufficiently large to turn Q_2 on ($V_{BE_2} = V_G$). The collector current of Q_2 will then rise to a value sufficiently large to turn Q_1 on ($I_{B_1} = I_{C_2}$).

As Q_1 turns on, I_{C_1} will increase, resulting in a corresponding increase in I_{B_2}. The increase in base current for Q_2 will result in further increase in I_{C_2}. The net result is a regenerative increase in the collector current of each transistor.

The resulting anode-to-cathode resistance $\left(R_{SCR} = \frac{V}{I_A}\right)$ is very small because I_A is large, resulting in a short-circuit representation for the SCR.

Mathematical Analysis



Let I_{E_1}, I_{E_2} = emitter currents

I_{C_1}, I_{C_2} = collector currents

I_{B_1}, I_{B_2} = base currents

Let both the txors are operating in active region

From transistor analysis, we can write,

$$I_{C_1} = \alpha_1 I_{E_1} + I_{CO_1}.$$

$$I_{C_2} = \alpha_2 I_{E_2} + I_{CO_2}.$$

where I_{CO} = reverse saturation current

and $\alpha = \frac{\beta}{1+\beta}$.

Now, $I_{E_2} = I_{C_2} + I_{B_2}$.

I_A = anode current = I_{E_1}.

I_K = cathode current = I_{E_2}.

I_G = gate current

Now, $I_K = I_A + I_G$.

$$\therefore I_{E_2} = I_A + I_G = I_{C_2} + I_{B_2}.$$

But, $I_{B_2} = I_{C_1} + I_G$.

$$\therefore I_A + I_G = I_{C_2} + I_{C_1} + I_G.$$

Substituting I_{C_1} and I_{C_2}

$$I_A = \alpha_1 I_{E_1} + I_{CO_1} + \alpha_2 I_{E_2} + I_{CO_2}.$$

$$I_A = \alpha_2 (I_A + I_G) + \alpha_1 I_A + I_{CO_1} + I_{CO_2}.$$

$$\therefore I_A - \alpha_2 I_A - \alpha_1 I_A = \alpha_2 I_G + I_{CO_1} + I_{CO_2}$$

$$\therefore I_A = \frac{\alpha_2 I_G + I_{CO_1} + I_{CO_2}}{1-(\alpha_1+\alpha_2)}.$$

In blocking state α_1 and α_2 are small $\Rightarrow I_A = \text{small}$. As $\alpha_1 + \alpha_2$ approaches unity, SCR is ready to enter into conduction. Thus, due to positive gate current, the regenerative action takes place and SCR conducts.

[illegible], F4, G4, H9,