Lecture Notes

On

Analog Electronics & OP-AMP

Handwritten

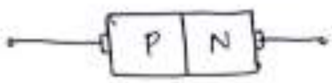
Prepared By

Tilu Behera

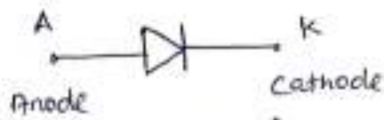
Lecturer in Electronics

PN Junction Diode

- A PN Junction diode consists of a PN junction formed either in Ge or Si crystal by joining an n-type & p-type material.
- The diode has two terminals namely anode & cathode. Anode refers to the p-type region & cathode refers to the n-type region.



(construction)



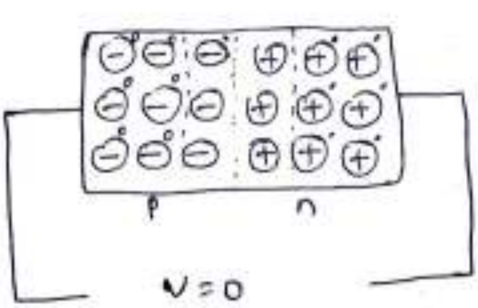
(symbol)

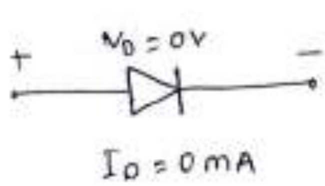
- It allows the electric current in only one direction while blocks the electric current in opposite or reverse direction.
- In n-type semiconductor free electrons are the majority charge carriers whereas in p-type semiconductors, holes are the majority charge carriers. When the n-type semiconductor is joined with the p-type semiconductor, a p-n junction is formed. The p-N junction which is formed when the p-type & n-type semiconductors are joined is called as p-N junction diode.

Working

(i) No Applied Bias (V=0V)

The bias refers to the application of a external voltage across the two terminals of the device to extract a response.



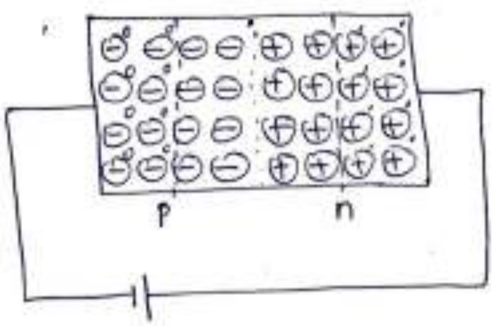


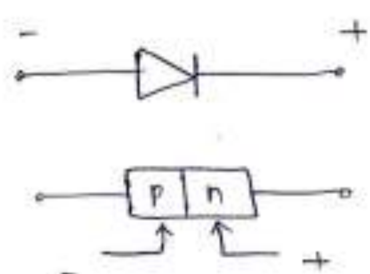
- Here the applied voltage is 0V & the resulting current is 0 A.

- With no voltage applied across the diode, majority change carriers i.e holes from p-side & electrons from n-side get combined with each other at the junction. These charge carriers on combining generate immobile ions that deplete across the junction.
- In absense of an applied bias across a semiconductor diode, the net flow of change in one direction is zero.
- The current under no-bias conditions is zero.

Reverse-Bias Condition

- If an external potential of V volts is applied across the p-n junction such that the positive terminal is connected to the n-type material & the negative terminal is connected to the p-type material.



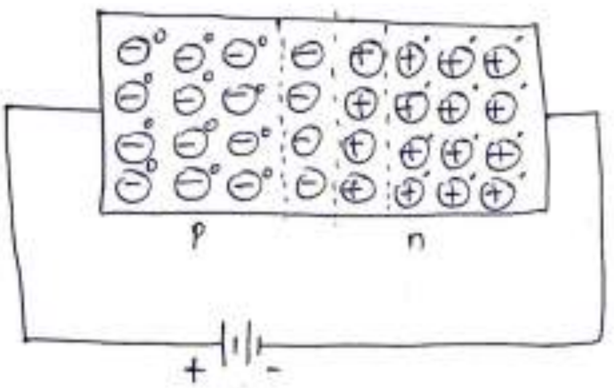


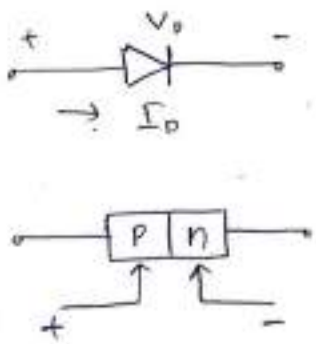
- The number of uncovered positive ions in the depletion region of the n-type material will increase due to the large number of free electrons drawn to the positive potential of the applied voltage.
- The number of uncovered negative ions will increase in the p-type material. Therefore, this result in widening of the depletion region.
- This widening of the depletion region will establish a barrier for the majority carriers to overcome, effectively reducing the majority carrier flow to zero.
- The minority carrier flow still continue.

- The current that exists under reverse-bias conditions is called reverse saturation current & is represented by I_s & it is of the order of μA.

Forward-Bias condition

A forward bias condition is established by applying the positive potential to the p-type material & the negative potential to the n-type material.





- The application of a forward bias potential V_D will pressure electrons in the n-type material & holes in the p-type material to recombine with the ions near the boundary & reduce the width of the depletion region.
- The reduction in the width of the depletion region has resulted in a heavy majority flow across the junction.
- As applied bias increases the depletion region will continue to decrease, resulting in an exponentially rise in current.

Shockley's Equation

$$I_D = I_s \left(e^{\frac{V_D}{nV_T}} - 1\right)$$

I_s : Reverse saturation current

I_D : Diode current

V_D : voltage across diode

V_T : Thermal voltage $\left(V_T = \frac{KT}{q}\right)$

n : Ideality factor (1 for Si)

$K = 1.38 \times 10^{-23}$ J/K

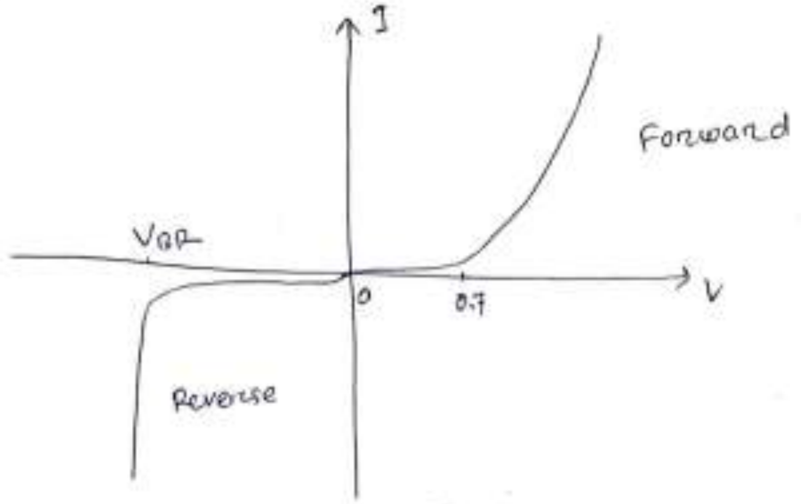
T = Temp in Kelvin

= (273 + Temp in Celsius)

$q = 1.6 \times 10^{-19}$ C

V-I Characteristics of PN Junction Diode

It is a graph between the voltage applied across the terminals of a device & the current that flows through it.



V-I characteristics can be divided into 2 parts namely forward characteristics & reverse characteristics.

Forward Characteristics

- In the forward region there is no diode current for smaller voltage i.e. for Ge it is below 0.3 V & 0.7 V for silicon. This value is usually refered to as the cut in voltage or break point (OFFset) or threshold or knee voltage V_r.

Knee voltage (V_r): It is defined as the minimum forward voltage required across the diode so that a current will flow into diode.

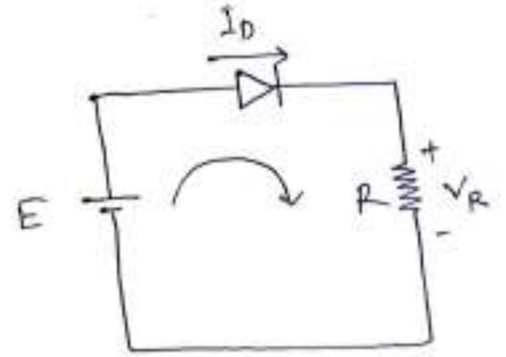
Reverse characteristics

- The reverse bias region of operation is entered when the diode voltage V is made negative.
- When the applied reverse voltage is below the breakdown V_{BR}, the diode current is small & remains constant. This value of current is called reverse saturation current I_0. It is of the order of nA for Si & µA for Ge.

Breakdown Voltage: When the reverse voltage is increased to a sufficiently large value the diode reverse current increases rapidly. The applied reverse voltage at which this happens is known as Breakdown voltage.

DC load line

A plot of the current I versus the voltage drop across the diode, V_D will yield a straight line, called the load line.



Applying KVL : $E = V_D + I_D R$ ——— ①

If $V_D = 0$ in eq①, $E = 0 + I_D R$

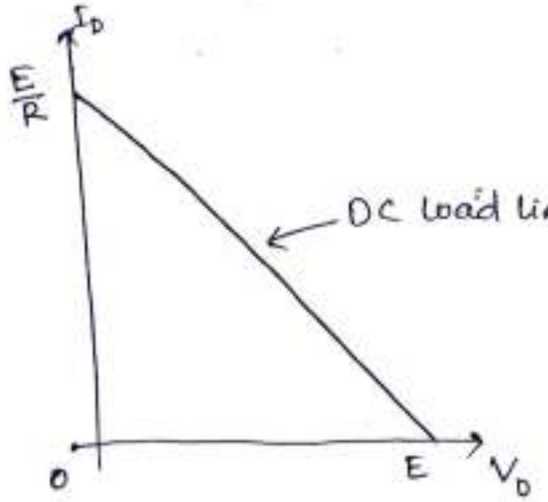
$$\Rightarrow I_D = \frac{E}{R}\Big/_{V_D = 0V}$$

- Here the value of I_D lies on the vertical axis.

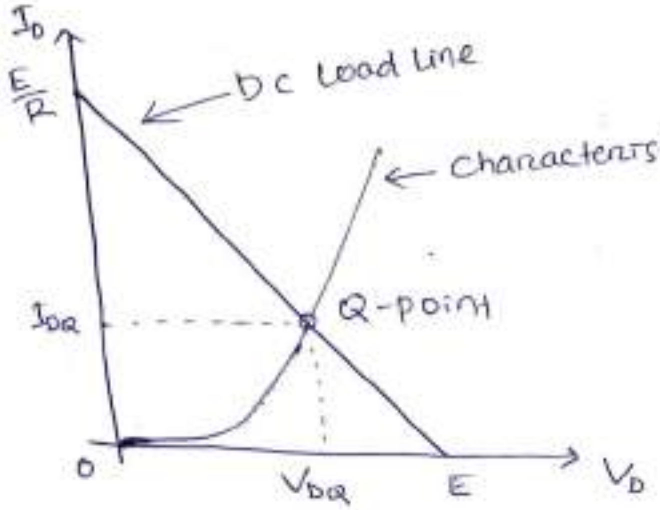
If $I_D = 0$, eq① becomes, $E = V_D + 0 \times R$

$$V_D = E \Big/_{I_D = 0\,A}$$

- Here the magnitude of the V_D lies on the horizontal axis.
- A straight line drawn between the two points will define the load line.



- The intersection of the load line with the V-I Characteristics curve of the diode determines the operating point or the quiescent point or the Q-point of the circuit.

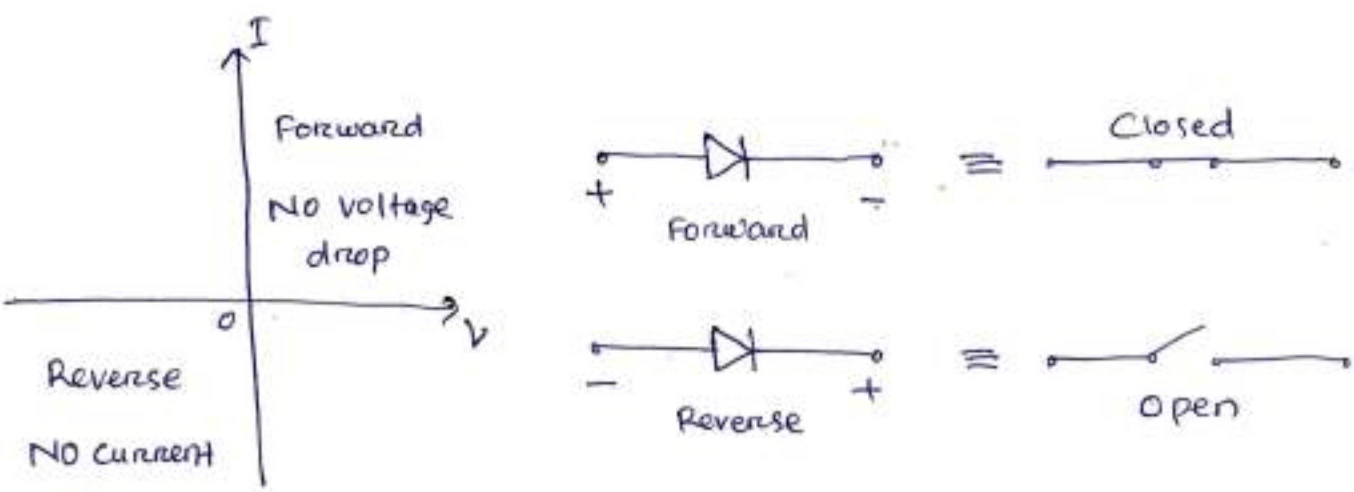


- The operating point for the circuit is (V_{DQ}, I_{DQ}).

Ideal Diode

- If the diode acts as a perfect conductor having no voltage drop across it, when forward biased & as a perfect insulator having no current through it, when reverse biased.

- An ideal diode acts like an automatic switch. The switch is closed when the diode is forward biased & is open switch when it is reverse biased.



Junction Breakdown

① Zener Breakdown

- Zener breakdown occurs in junctions, which are heavily doped. The heavily doped junctions have a narrow depletion layer.
- When reverse voltage is increased, the electric field at the junction also increases. A strong electric field causes a covalent bond to break from the crystal structure.
- As a result of this, a large number of minority carriers are generated & a large current flows through the junction.

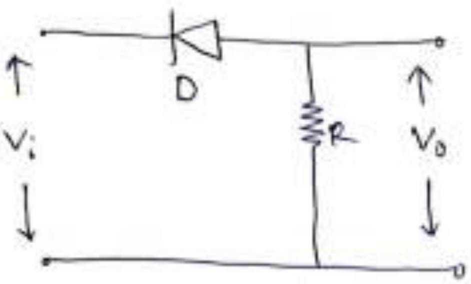
② Avalanche Breakdown

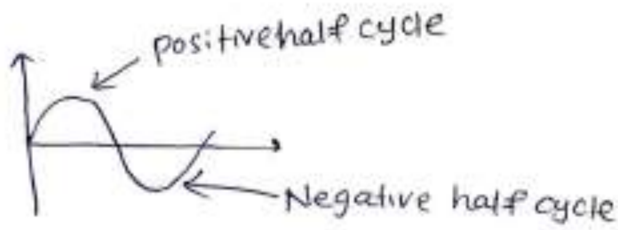
- Here the increased reverse voltage increases the amount of energy pass on to minority carriers.
- As the reverse voltage is increased, further, the minority carriers acquire a large amount of energy. When these carriers collide with silicon atoms, they give sufficient energy to break a covalent bond & generate additional carriers.
- These additional carriers pick up energy from the applied voltage & generate still more carriers.
- As a result of this the reverse current increases rapidly. This cummulative process of carrier generation is known as Avalanche Breakdown or Avalanche multiplication.

PN Diode clipping Circuit

The circuit that employ diodes to clip away a portion of an input signal without distorting the remaining part of the applied waveform is called a clipping circuit or clipper.

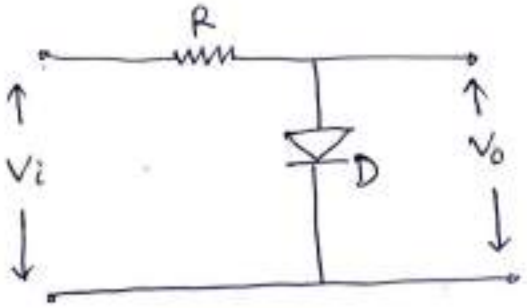
① Positive Clipper

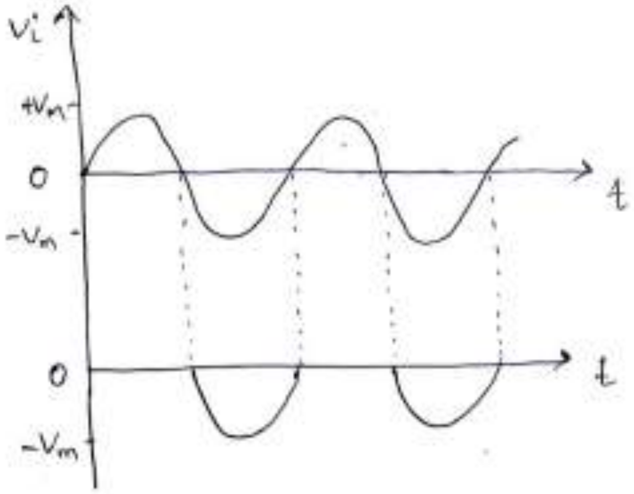




- It consists of a diode & a resistor.
- During the positive half cycle of the input voltage, the diode becomes reverse bias & it acts as an open switch. Therefore voltage drop across the resistor is zero.
- During the negative half cycle of the input voltage, the diode becomes forward biased & it acts as a closed switch. Therefore all the input voltage is dropped across the resistor.
- The positive clipper allows to pass the negative half cycle of the input & clipped the positive half cycle completely. Hence it is called a positive clipper.
- The diode acts as a series switch between the source & load. So the circuit is called series positive clipper.

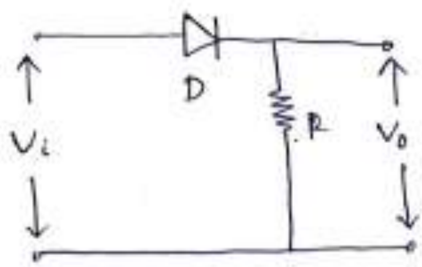
Shunt Positive Clipper





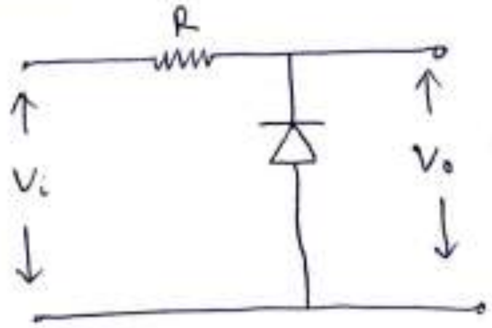
(Input & Output waveform)

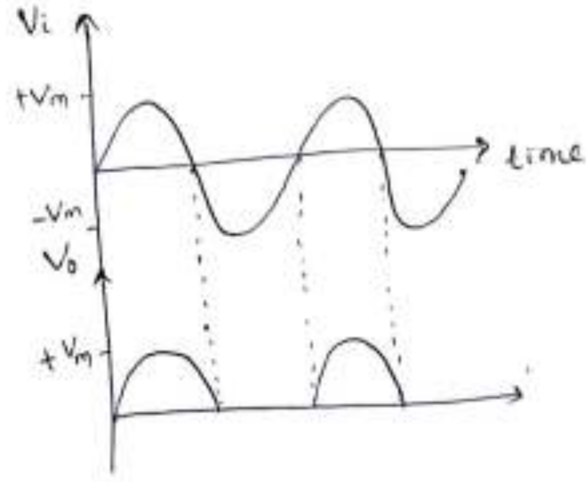
(ii) Negative Clipper



- During the positive half cycle of the input, the diode becomes forward biased & it acts as a closed switch. As a result, all the input voltage appears across the resistor R.
- During the negative half cycle of the input voltage, the diode becomes reverse biased & it acts as an open switch. Thus there is no voltage drop across the resistor during the negative half cycle.
- The negative clipper allows to pass the positive half cycle of the input voltage & clipped the negative half cycle completely.

Shunt Negative clipper



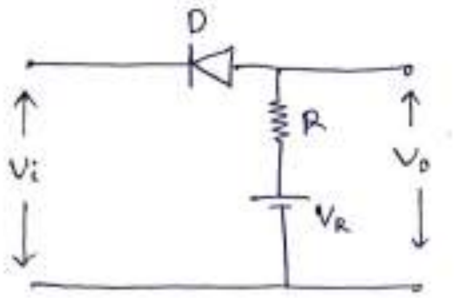


(Input & output waveform)

Biased Clipper

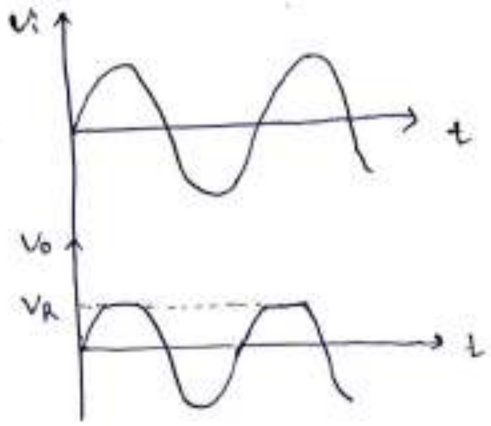
A clipping circuit which has a provision for the adjustment of a clipping level is called a Biased clipper. The name bias designated because the adjustment of clipping level is achieved by adding a bias voltage in series with the diode or resistor.

Biased Positive Clipper

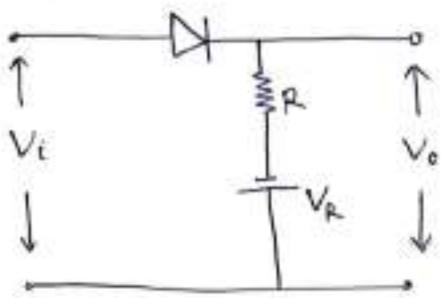


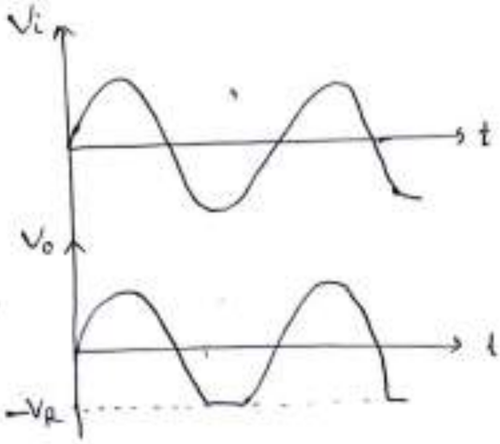
Case-I : when $V_i > V_R$, Diode becomes reverse biased & it acts as an open switch. Therefore output voltage equal to V_R.

Case-II : when $V_i < V_R$, Diode becomes forward biased & it acts as a closed switch. So the output voltage is equal to input voltage.



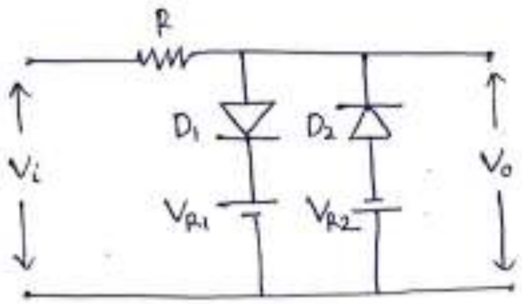
Biased Negative clipper





Combination clipper

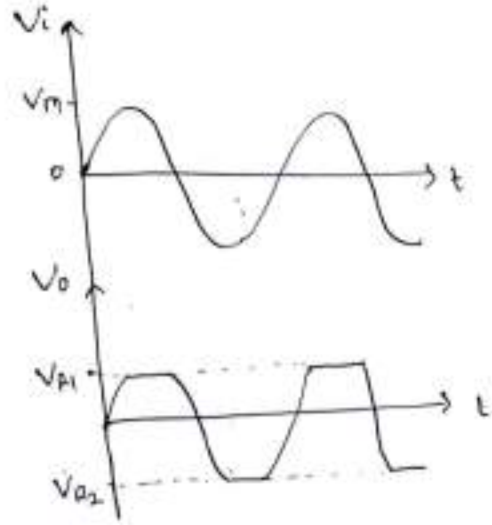
The combination of a biased positive clipper & a biased negative clipper is called combinational clipper.



Case-I: When input voltage $V_i > V_{R1}$, diode D_1 becomes forward bias & it acts as a closed switch and diode D_2 becomes reverse biased & it acts as an open switch. Therefore output voltage is equal to V_{R1}.

Case-II: when V_i lies between V_{R1} & V_{R2}, both diode D_1 & D_2 becomes reverse biased & they act as open switch. So output voltage equal to input voltage.

Case-III: when $V_i < V_{R2}$, diode D_1 becomes reverse biased & it acts as an open switch and diode D_2 becomes forward biased & it acts as a closed switch. Therefore output voltage equal to reference voltage V_{R2}.



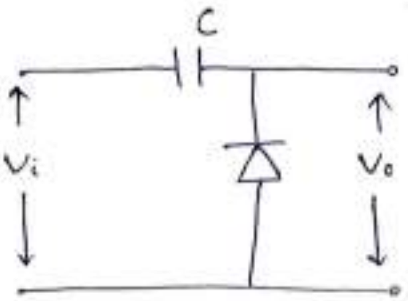
(Input & output waveform)

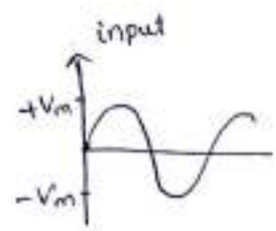
Clamping circuit

A clamper is a network, constructed of a diode, resistor & capacitor, that shifts a waveform to a different DC level without changing the appearance of the applied signal.

- A clamping circuit is also known as DC restorer.

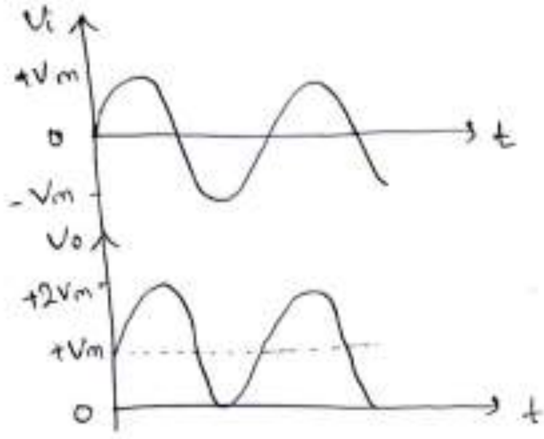
Positive clamper





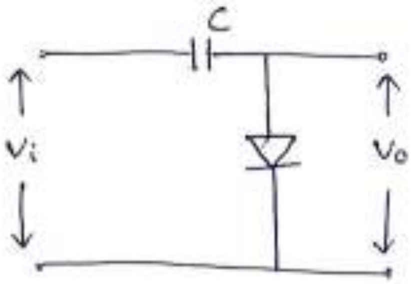
- During negative half cycle of the input voltage V_i, the diode is forward biased & current flows through the circuit.
- Hence the capacitor is charged to a voltage equal to the negative peak value of input voltage, $-V_m$. It means the capacitor acts as a battery of $-V_m$.
- The polarity of this voltage is such that it add to the input signal. Therefore the output voltage is equal to the sum of the ac input signal & the capacitor voltage V_m.

$$\boxed{V_o = V_i + V_m}$$



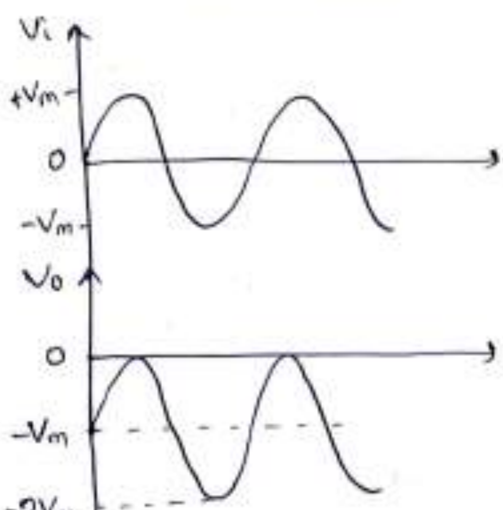
(Input & output waveform)

Negative clamper



- During the positive half cycle of the input voltage V_i, the diode is forward biased & current flows through the circuit.
- Therefore the capacitor is charged to a voltage equal to the positive peak of the input voltage, V_m.
- The polarity of this voltage is such that it is subtracted from the input signal. Hence the output voltage is equal to the difference between AC input signal & the capacitor voltage V_m.

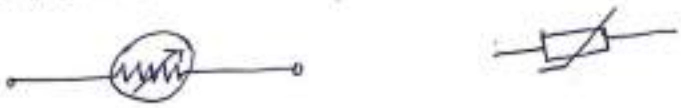
$$\boxed{V_o = V_i - V_m}$$



(Input & output waveform)

Thermistors

- The thermistor is a temperature sensitive resistor, i.e its terminal resistance is related to its body temperature.
- It is not a junction divice & is constructed of Ge, Si or a mixture of oxides of cobalt, Nickel or manganese. The compound employed determines whether the device has a positive or a negative temperature coefficient.
- Symbol :-

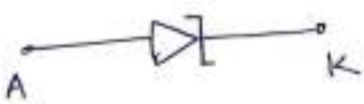


- positive temperature coefficient means, if the temperature increases then resistance increases & negative temperature coefficient means if the temperature increases then resistance decreases.

Zener Diode

A zener diode is also called a voltage reference, voltage regulator or breakdown diode.

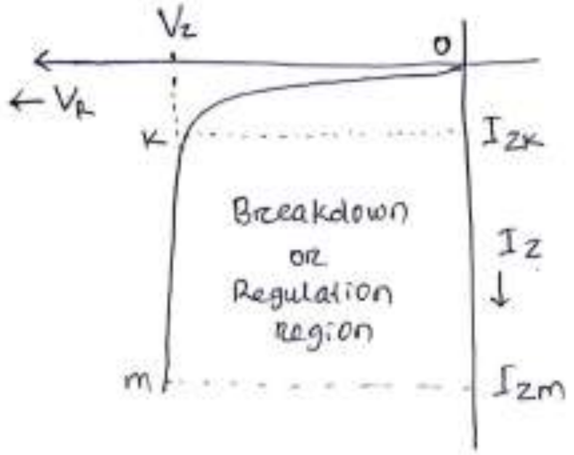
- Symbol :



- Zener diode operates in the reverse breakdown region.
- The reverse breakdown of a PN junction may occur either due to avalanche or zener effect.
- The zener diodes with breakdown voltages of less than 6V, operate in zener breakdown. Those with breakdown voltages greater than 6V operate in avalanche breakdown.

Reverse Characteristics

- As the reverse voltage is increased, the reverse current remains negligibly small up to the knee of the curve.
- From the bottom of knee, the breakdown voltage remains constant. This ability of a diode is called regulating ability & is an important feature of a zener diode.



(Reverse V-I characteristics)

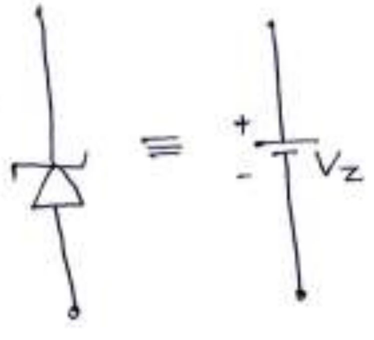
Specification

- The zener diodes are generally specified in terms of 4 factors namely zener voltage (V_Z), maximum power dissipation (P_{Dmax}) Breakdown Current (I_{ZK}) & zener resistance (R_Z).
- The power dissipation of a zener diode is the product of breakdown voltage (V_Z) & reverse current (I_Z).

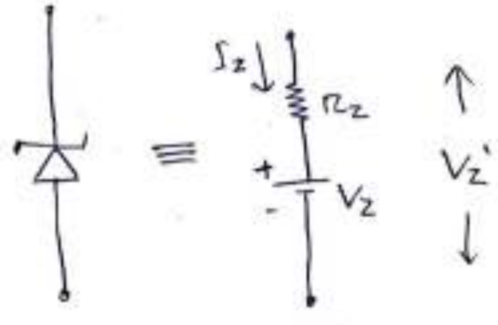
$$\boxed{P_Z = V_Z \times I_Z}$$

- The maximum value of power dissipation, which a zener can dissipate, without failure is called power rating & is designated by P_{Zm}.

Zener diode equivalent circuit



(Ideal)



(Practical)

$$\boxed{V_Z' = V_Z + I_Z R_Z}$$

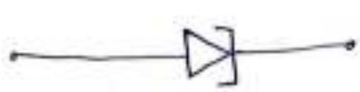
Tunnel Diode

- If the concentration of impurity atoms is greatly increased in a normal PN junction i.e. by 1000 times or more, its characteristics are completely changed. This gives rise to a new type of diode known as tunnel diode or Esaki diode.

- when impurity concentration is increased i.e about one part in 10^3 atoms, the width of depletion layer reduces to about 10 nanometer. Under such conditions the charge carriers will penetrate through the junction at the speed of light, even though they do not have enough energy to overcome the potential barrier. As a result of this a large forward current is produced even if the applied forward voltage is much less than 0.3V.

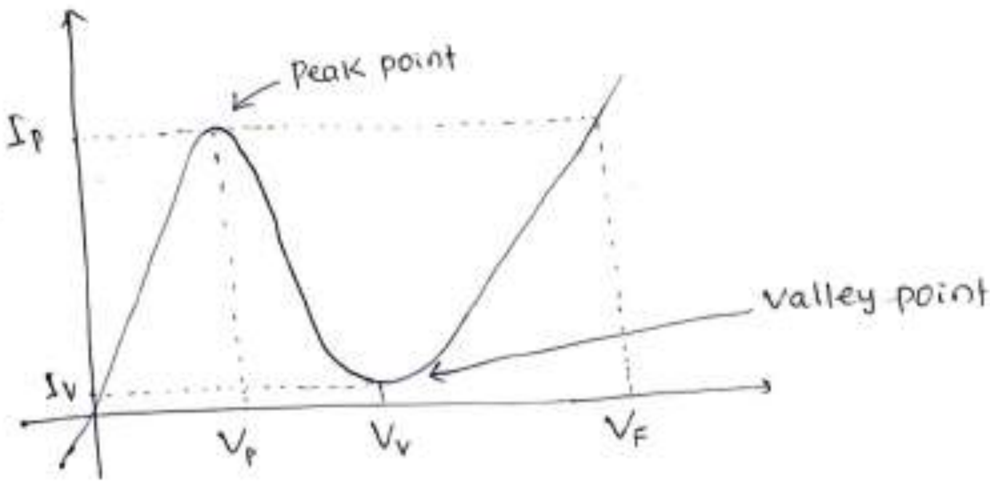
- The phenomenon of penetrating the charge carriers directly through the potential barrier instead of climbing over it, is called tunnelling. So highly doped PN junction devices are called tunnel diodes.

- These diodes are usually made of Ge or gallium arsenide (GaAs)

- Symbol :- 

V-I characteristics of Tunnel diode

- As the applied forward voltage is increased from zero, the current increases very rapidly, till it reaches its maximum value known as peak current I_P & the corresponding value of the forward voltage is indicated by peak voltage V_P.



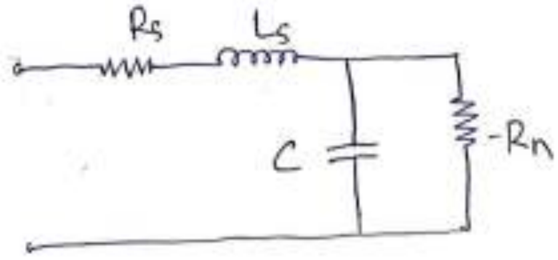
- If the forward voltage is further increased the current decreases till it reaches its minimum value known as valley current I_V.

- As the voltage further increased, the current increases in a usual manner as in a normal PN junction diode. The current again reaches its peak value I_P & the corresponding voltage is indicated by V_F.

- The tunnel diode exhibits a negative resistance characteristics between the peak current I_P & the minimum value I_V.

- For currents whose values are between I_V & I_P the curve is triple valued. It means that each current can be obtained at three different applied voltages.

- Tunnel diode equivalent circuit:



<u>Application</u>

- As an ultra high speed switching device.
- As a logic memory storage device.
- As a microwave oscillator at frequency in the order of 10 GHz.
- In relaxation oscillator.

PIN Diode

- A PIN diode is made up of 3 semiconductor materials. One heavily doped P-type & one N-type material separated by an intrinsic semiconductor.
- The intrinsic region offers high resistance to the current flowing through it.
- The capacitance between the P & N region decreases because of the increased separation between P & N region. This allows the PIN diode to have fast response time. Hence useful at very high frequency.
- There is a greater electron-hole pair generation because of the increased electric field between the P & N.
- When the PIN diode is forward biased, the width of depletion layers decreases. As a result of this, more carriers are injected into the I-region. This reduces the resistance of the I-region. Thus when a PIN diode is forward bias, it acts like a variable resistance.
- When the PIN diode is reverse biased, the depletion layer become thicker. As the reverse bias is increased, the thickness of the depletion layer increases till the I-region becomes free of mobile carriers. The reverse bias, at which this happens is called swept out voltage. At this stage the PIN diode acts like an almost constant capacitance.
- Equivalent circuit of a PIN Diode :-

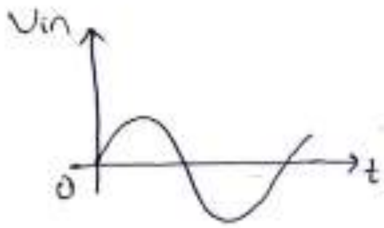
(Forward biased) (Reverse biased)

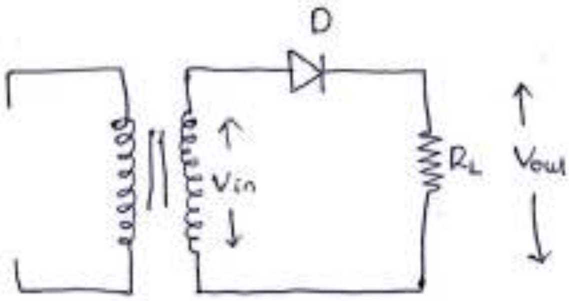
Rectifier

- low voltage rectifier (provide low dc output)
  - Formed by using diodes
    - Half wave Rectifier
    - Full wave Rectifier
      - Centre tapped
      - Bridge
- High voltage rectifier (provide large dc output)
  - Formed by using SCR

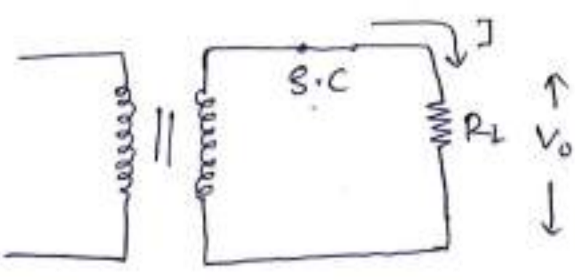
Rectifier : The process of conversion of AC into pulsating DC is called Rectification & the device performing rectification is a Rectifier.

Half Wave Rectifier (HWR)

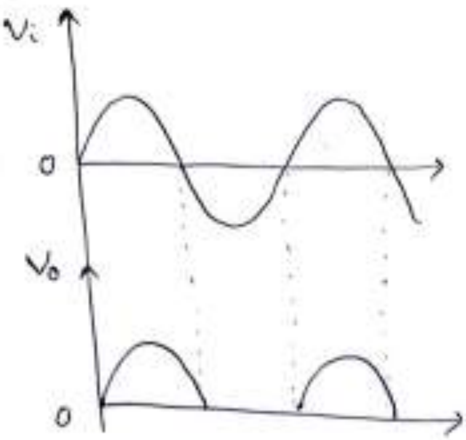




Case-I : During the positive half cycle of the input ac voltage, the diode D is forward biased biased & hence conduct. While conducting, the diode acts as a short circuit so that circuit current flows & hence positive half cycle of the input ac voltage is dropped across R_L. It constitutes the output voltage V_0.



Case-II : During the negative half cycle the diode is reverse-biased and hence does not conduct i.e there is no current flow. Hence there is no voltage drop across R_L i.e $I_D = 0$ & $V_{out} = 0$.



DC output Current

DC or Average value :- $I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i \, d\theta$

$$i = \begin{cases} I_m \sin\theta \; ; & \text{where } 0 \le \theta \le \pi \\ 0 \; ; & \text{where } \pi < \theta < 2\pi \end{cases}$$

$$I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin\theta \, d\theta + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0 \, d\theta$$

$$= \frac{1}{2\pi} I_m \left[-\cos\theta\right]_0^{\pi} + 0$$

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

$$\boxed{I_{DC} = \frac{I_m}{\pi}} \qquad V_{ave} \text{ or } V_{DC} = \frac{V_m}{\pi}$$

RMS output Current

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

$$\left[\begin{array}{l} \cos 2\theta = 1 - 2\sin^2\theta \\ (1-\cos 2\theta)\frac{1}{2} = \sin^2\theta \end{array}\right]$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2\theta \, d\theta}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \frac{1}{2}(1-\cos 2\theta)\, d\theta}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\left[(\theta)_0^{\pi} - \frac{1}{2}(\sin 2\theta)_0^{\pi}\right]}$$

$$I_{RMS} = \sqrt{\frac{I_m^2}{4\pi}[\pi]} = \frac{I_m}{2}$$

$$\boxed{I_{RMS} = \frac{I_m}{2}} \qquad \boxed{V_{RMS} = \frac{V_m}{2}}$$

Ripple factor (r)

A measure of the fluctuating components is given by the ripple factor. It is defined as :-

$$r = \frac{\text{RMS value of AC component}}{\text{Average value}}$$

$$= \frac{I'_{RMS}}{I_{dc}} = \frac{\sqrt{I_{RMS}^2 - I_{dc}^2}}{I_{dc}}$$

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

$$= \sqrt{\frac{\pi^2}{4} - 1} = 1.21$$

$$\boxed{r = 1.21}$$

Efficiency (η)

It is a measure of the ability of a rectifier to convert input AC power into dc power.

mathematically, $\eta = \frac{\text{dc output power}}{\text{Input power}}$

$$\%\eta = \frac{P_{dc}}{P_i} \times 100\% = \frac{I_{dc}^2 R_L}{I_{RMS}^2 R_L} \times 100\%$$

$$= \frac{(I_m/\pi)^2}{(I_m/2)^2} \times 100\% = \frac{400}{\pi^2}$$

$$\boxed{\%\eta = 40.5\%}$$

Regulation

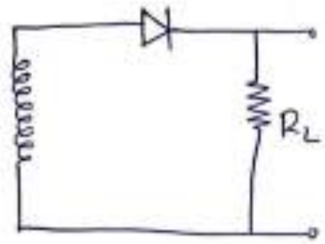
The variation of DC output voltage as a function of DC load current is called regulation.

% of regulation is defined as, $\%\ \text{Regulation} = \frac{V_{no\ load} - V_{Full\ load}}{V_{Full\ load}} \times 100\%$

$$\%\ \text{Regulation} = \frac{V_m/\pi - (V_m/\pi - I_{DC}R)}{I_{DC}R_L} \times 100\%$$

$$\%\ \text{Regulation} = \frac{R}{R_L} \times 100\% \qquad (R = R_{secondary} + R_f)$$

Note



$$V_{DCNL} = \frac{I_m}{\pi} R_L = \frac{V_m}{\pi} \quad \text{(No load voltage)}$$

$$V_{DCFL} = \frac{V_m}{\pi} - I_{DC}R \quad \text{(Full load voltage)}$$

$$= I_{DC}R_L$$

No Load :- $I_{DC} = 0$

Full Load :- $I_{DC} \neq 0$

Transformer Utilization Factor (TUF)

- TUF is the ratio of dc output power & AC rating of transformer secondary winding.
- AC rating is the product of rms voltage across the winding & the rms current through the winding.

$$TUF = \frac{P_{DC}}{\text{AC rating of Secondary}}$$

$$= \frac{I_{DC}^2 R_L}{V_m/\sqrt{2} \cdot I_m/\sqrt{2}} = \frac{(I_m^2/\pi^2) \cdot R_L}{I_m^2 R_L / 2\sqrt{2}} = \frac{2\sqrt{2}}{\pi^2}$$

$$\boxed{TUF = 0.286}$$

Peak Inverse Voltage (PIV)

For each rectifier circuit there is a maximum voltage to which the diode is subjected. This potential is called the peak Inverse voltage.

$$PIV = |V_{diode}|_{max} \quad \text{in reverse bias Condition}$$

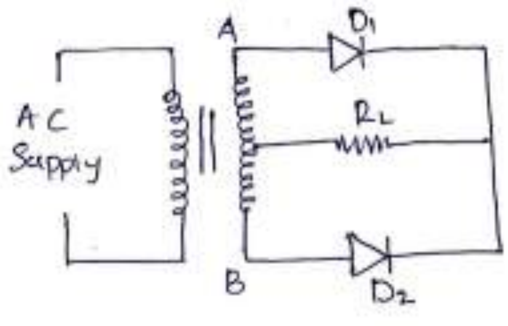
$$PIV = |V_m \sin\theta|_{max}$$

$$\boxed{PIV = V_m}$$

Disadvantages of Half wave Rectifier

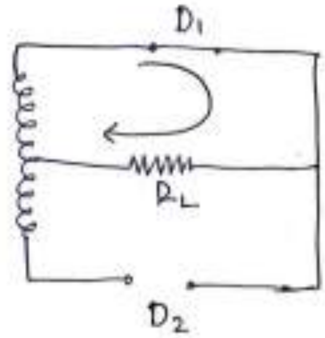
(i) The pulsating current in the load contains alternating component whose basic frequency is equal to the supply frequency. Therefore the output is low.

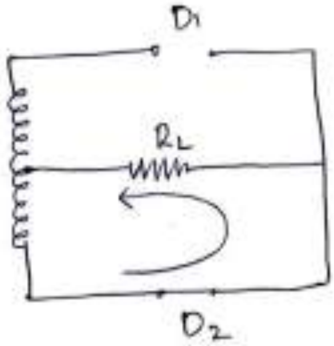
Centre tapped Fullwave Rectifier



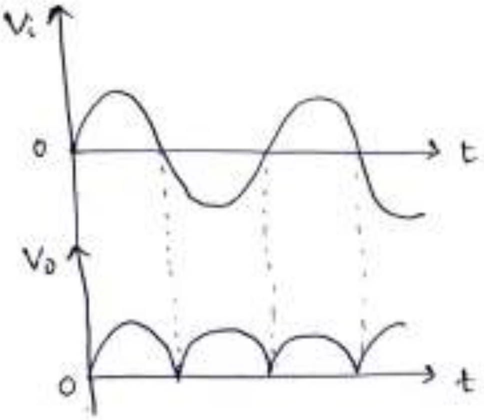
Case-I: During the positive half cycle of secondary voltage, the end A of the secondary winding becomes positive & end B negative. This makes the diode D_1 forward biased & diode D_2 reverse biased. Therefore, diode D_1 conducts while diode D_2 does not. Current flow is through diode D_1, load resistor R_L.

Case-II: During the negative half cycle, end A of the secondary winding becomes negative & end B positive. Therefore diode D_2 conducts while diode D_1 does not. The current flow is through diode D_2, load R_L & lower half winding.





- Current in the load R_L is in the same direction for both half cycle of the input ac voltage. Therefore dc is obtained across the load R_L.



$$i = \begin{cases} I_m \sin\theta \ ; & \text{where } 0 \leq \theta \leq \pi \\ -I_m \sin\theta \ ; & \text{where } \pi \leq \theta \leq 2\pi \end{cases}$$

DC output current

$$I_{DC} / I_{Avg} = \frac{1}{2\pi} \int_0^{2\pi} i \, d\theta$$

$$= \frac{1}{2\pi} \left[\int_0^{\pi} I_m \sin\theta \, d\theta - \int_{\pi}^{2\pi} I_m \sin\theta \, d\theta \right]$$

$$= \frac{1}{2\pi} \left[-I_m (\cos\theta)_0^{\pi} + I_m (\cos\theta)_{\pi}^{2\pi} \right]$$

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

$$= \frac{I_m}{2\pi} \times 4 = \frac{2I_m}{\pi}$$

$$\boxed{V_{DC} = \frac{2V_m}{\pi}} \qquad \boxed{I_{DC} = \frac{2I_m}{\pi}}$$

Rms output current

$$I_{Rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} i^2 d\theta} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2\theta \, d\theta}$$

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

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

$$\boxed{I_{Rms} = \frac{I_m}{\sqrt{2}}} \qquad \boxed{V_{Rms} = \frac{V_m}{\sqrt{2}}}$$

Ripple Factor

$$r = \frac{\text{Rms value of AC component}}{\text{Average value}}$$

$$= \frac{I'_{Rms}}{I_{dc}} = \frac{\sqrt{I_{Rms}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\left(\frac{I_{Rms}}{I_{dc}}\right)^2 - 1}$$

$$= \sqrt{\frac{(I_m/\sqrt{2})^2}{(2I_m/\pi)^2} - 1} = \sqrt{\frac{\pi^2}{8} - 1} = 0.483$$

$$\boxed{r = 0.483}$$

Efficiency

$$\%\eta = \frac{P_{dc}}{P_{ac}} \times 100\% = \frac{I_{dc}^2 R_L}{I_{Rms}^2 (R_f + R_L)} \times 100\%$$

$$= \frac{4I_m^2 R_L/\pi^2}{I_m^2 (R_f+R_L)/2} \times 100\%$$

$$= \frac{8}{\pi^2}\left(\frac{R_L}{R_f+R_L}\right) \times 100\%$$

$$= \frac{800}{\pi^2}\left(\frac{R_L}{R_f+R_L}\right)\% = 81\left(\frac{R_L}{R_f+R_L}\right)\%$$

$$\%\eta = 81\left(\frac{R_L}{R_f+R_L}\right)\%$$

For ideal diode $R_f = 0$, then $\boxed{\%\eta = 81\%}$

Regulation

$$V_{DCNL} = \frac{2V_m}{\pi} \quad , \quad V_{DCFL} = \frac{2V_m}{\pi} - I_{DC}R = I_{DC}R_L$$

(No load Dc voltage) (Full Load DC voltage)

$$\%\,\text{Regulation} = \frac{V_{DCNL} - V_{DCFL}}{V_{DCFL}} \times 100\,\%$$

$$\%\,\text{Regulation} = \frac{\frac{2V_m}{\pi} - \left(\frac{2V_m}{\pi} - I_{DC}R\right)}{I_{DC}R_L} \times 100\,\%$$

$$\%\,\text{Regulation} = \frac{R}{R_L} \times 100\,\% \qquad \left[\begin{array}{l} R = \frac{R_S}{2} + R_f \\ R_S \rightarrow R_{secondary} \end{array}\right]$$

Transformer Utilization Factor (TUF)

As centre tapped is a combination of 2 half wave rectifier, so TUF with respect to secondary winding is :-

$$TUF_{SW} = 2 \times 0.286 = 0.572$$

TUF w.r.t primary winding, $TUF_{PW} = \dfrac{\text{DC output power}}{\text{AC rating of primary winding}}$

$$TUF_{PW} = \frac{I_{DC}^2 R_L}{V_m/\sqrt{2} \cdot I_m/\sqrt{2}} = \frac{I_{DC}^2 R_L}{I_m^2 R_L/2}$$

$$TUF_{PW} = \frac{4\, I_m^2 \cdot 2}{I_m^2 \cdot \pi^2} = 0.81$$

$$\text{Average TUF} = \frac{TUF_{PW} + TUF_{SW}}{2} = 0.69$$

$$\boxed{TUF = 0.69}$$

Peak Inverse Voltage

$PIV = |V_{diode}|_{max}$ in reverse bias condition

$$PIV = |2V_m \sin\theta|_{max}$$

$$\boxed{PIV = 2V_m}$$

Advantage of Full wave Rectifier

(i) Smaller ripple factor.

(ii) Greater efficiency

(iii) Greater dc output voltage & current.

(iv) Greater transformer utilization factor.

Disadvantage of centre tapped Rectifier

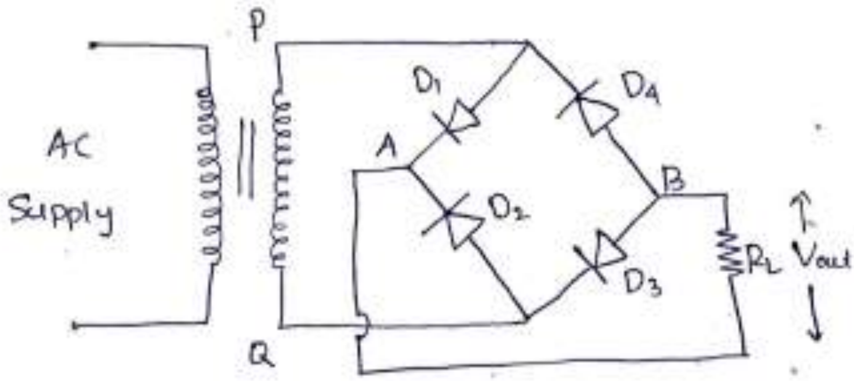
(i) It is difficult to locate the centre tap on the secondary winding.

(ii) The dc output is small as each diode utilizes only one half of the transformer secondary voltage.

(iii) The diodes used must have high peak inverse voltage.

Full wave Bridge Rectifier

It consists of four diodes D_1, D_2, D_3 & D_4

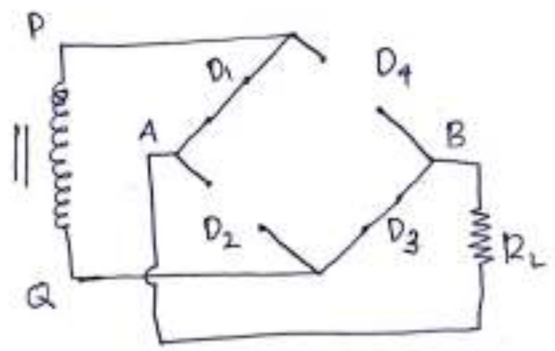


Case-I:

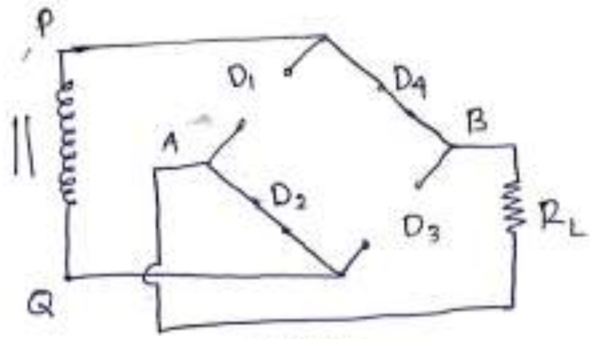
During the positive half cycle of secondary voltage, the end P of the secondary winding becomes positive & end Q negative. This makes diode D_1 & D_3 forward biased while diodes D_2 and D_4 are reverse biased. Therefore only diodes D_1 and D_3 conducts. It may be seen that current flows from A to B through the Load R_L.

Case-II

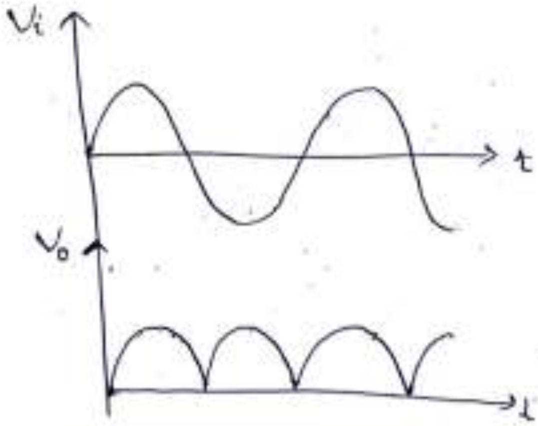
During the negative half cycle of secondary voltage, end P becomes negative & end Q positive. This makes diodes D_2 and D_4 forward biased where as diodes D_1 & D_3 are reverse biased. Therefore only diodes D_2 and D_4 conduct. It may be seen that, as case-I, here also current flows from A to B through the load i.e in the same direction as case-I or positive half cycle.



case-I



case-II



(Input & output waveform)

Transformer Utilization Factor (TUF)

$$TUF = \frac{\text{DC output Power}}{\text{AC rating of Secondary}}$$

$$= \frac{I_{DC}^2 R_L}{V_m/\sqrt{2} \; I_m/\sqrt{2}} = \frac{(2I_m)^2 R_L/\pi^2}{I_m^2 R_L/2}$$

$$= \frac{8}{\pi^2} = 0.81$$

$$\boxed{TUF = 0.81}$$

Peak Inverse Voltage (PIV)

$PIV = |V_{diode}|_{max}$ in reverse bias condition

$PIV = |V_m \sin\theta|_{max}$

$$\boxed{PIV = V_m}$$

Advantage of Bridge Rectifier

(i) The need for centre tapped transformer is eliminated.

(ii) Lower peak inverse voltage is required.

(iii) It provides greater TUF.

Disadvantage

(i) It requires 4 diodes.

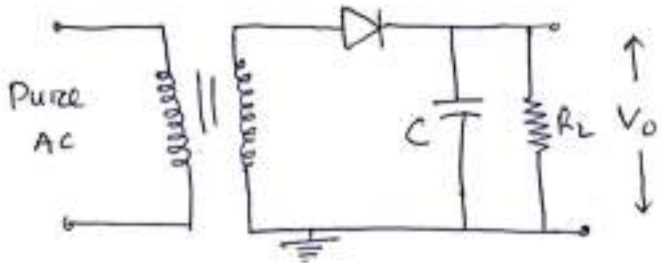
(ii) As during each half cycle of ac input two diodes are in series, therefore voltage drop in the internal resistance also twice that of centre tap.

	RMS	DC or Average	Ripple Factor	Efficiency	PIV	TUF
HWR	$V_m/2$	V_m/π	1.21	40.5%	V_m	0.286
Centre tap	$V_m/\sqrt{2}$	$2V_m/\pi$	0.48	81 %	$2V_m$	0.69
Bridge Rectifier	$V_m/\sqrt{2}$	$2V_m/\pi$	0.48	81%	V_m	0.81

Filter

Filter circuit is defined as a circuit which removes the unwanted AC component of the rectifier output & allows only the dc component to reach the load.

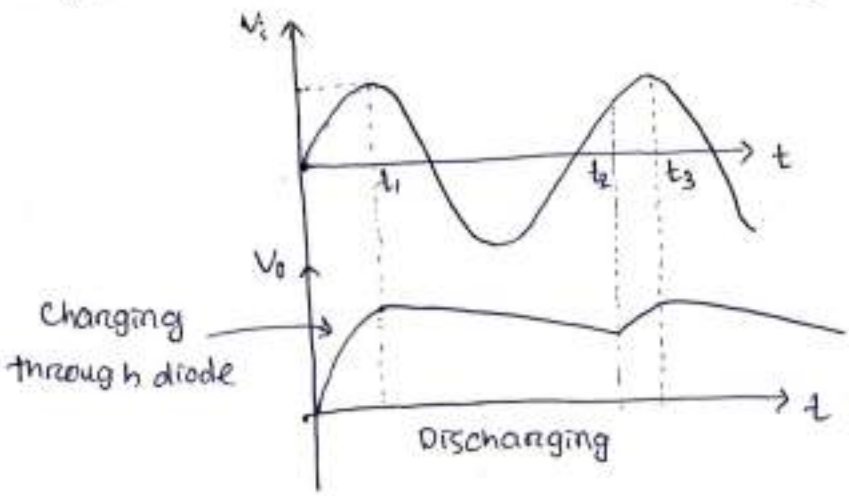
① <u>Capacitor Filter</u> (Shunt Capacitor Filter)



<u>For $t > 0$</u>: V_i becomes positive & diode begins conduction as a result capacitor starts charging through diode. If diode is ideal it behaves as a short circuit in forward bias therefore capacitor voltage increases at the same rate as rate of increase of input voltage. Charging of capacitor is continued till $t = t_1$.

<u>For $t > t_1$</u>: V_i starts decreasing hence capacitor should discharge & voltage across capacitor should decrease. So, capacitor will discharge slowly through R_L as R_L is very large, as time constant $\tau = R_L C$. Capacitor voltage decreases till $t = t_2$ & diode remains in off condition from t_1 to t_2.

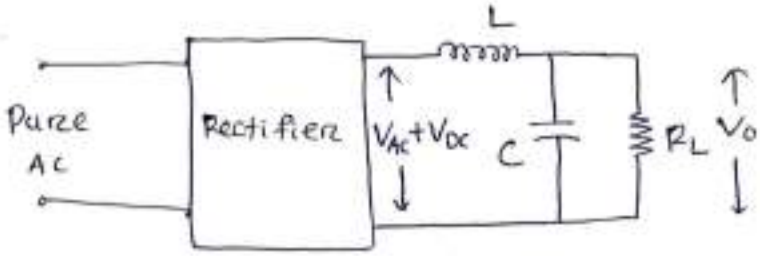
<u>For $t > t_2$</u>: Diode gets forward bias & capacitor begins to charge which is continued till $t = t_3$.



Due to charging & discharging of a capacitor, there is a ripple present in the output voltage of a capacitor filter. Smaller the value of this ripple, better will be the filtering action. The ripple factor of a capacitor filter is given by :-

$$\boxed{r = \frac{1}{4\sqrt{3}\, fCR_L}}$$

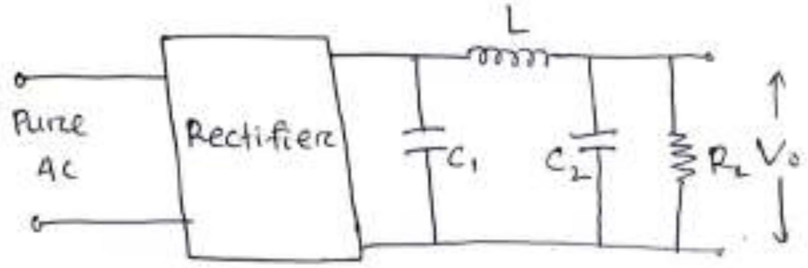
② LC Filter (choke input filter)



- The LC filter is also known as choke input filter.
- It consists of a choke L connected in series with the rectifier output and a filter capacitor C across the load.
- The pulsating output of rectifier is applied across inductor. pulsating output of rectifier contains AC & DC components. The choke offers high opposition to the passage of AC component but negligible opposition to the DC component.
- Before capacitor, the rectifier output contains dc component & the remaining part of AC component which has managed to pass through the choke. Now the capacitor bypasses the AC component but prevents the DC component to flow through it. Therefore only DC component reaches the load.
- The ripple factor of a LC filter is ;-

$$\boxed{r = \frac{\sqrt{2}}{12\omega^2 LC}}$$

③ π - Filter



- It consists of two capacitors C_1 & C_2 and an inductor L Connected in the form of a π.
- The pulsating output from the rectifier is applied at the input terminals of the π- filter

(i) Capacitor C_1 :

It offers a low reactance to AC component of rectifier output. But it offers infinite resistance to the dc component. Therefore the capacitor C_1 bypasses an appreciable amount of AC component to the ground, while DC component moves towards inductor L.

(ii) Inductor L :

It offers a high reactance to the AC component of rectifier output but zero resistance to the DC component. Therefore it allows the DC component to pass through it & blocks the AC component, which can't pass by the capacitor C_1.

(iii) capacitor C_2 :

Its behaviour is similar to the capacitor C_1. It bypasses the AC component of rectifier output, which can not block by inductor L. As a result, only the DC component is available at the output

- The ripple Factor of a π Filter is :-

$$\boxed{r = \frac{1}{4\sqrt{2}\omega^3 C_1 C_2 L R_L}}$$

Transistor (BJT)

A bipolar junction transistor is a three terminal semiconductor device that consists of two p-n junctions which are able to amplify a signal.

- It is a current controlled device.

construction

A BJT has essentially three regions known as emitter, base and collector.

Emitter :- Denoted as E. It is a region situated in one side of transistor which supplies charge carriers to the other two regions.

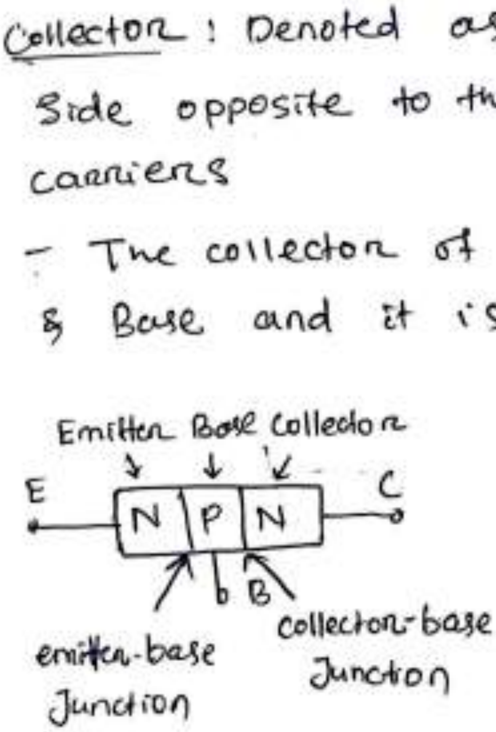
- The emitter is a heavily doped region.

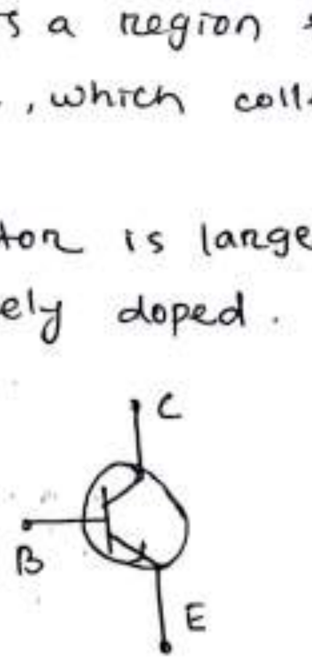
Base :- Denoted as B. It is the middle region that forms two PN junction in the transistor.

- The base of transistor is thin & is a lightly doped region.

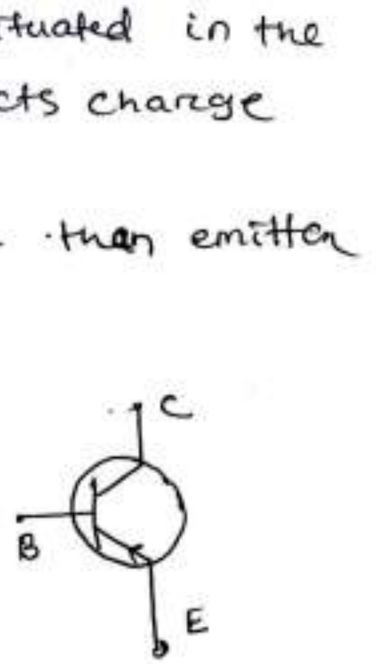
Collector : Denoted as C. It is a region situated in the side opposite to the emitter, which collects charge carriers

- The collector of a transistor is larger than emitter & Base and it is moderately doped.



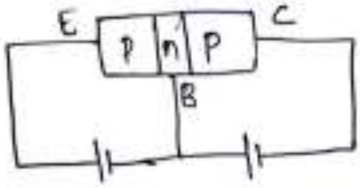


(Symbol of NPN.)

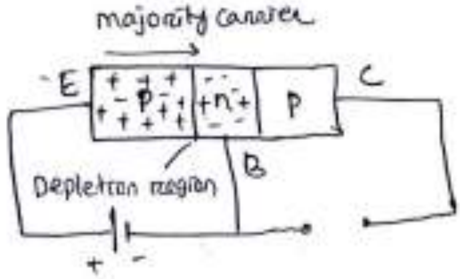


(Symbol of PNP)

Transistor Operation

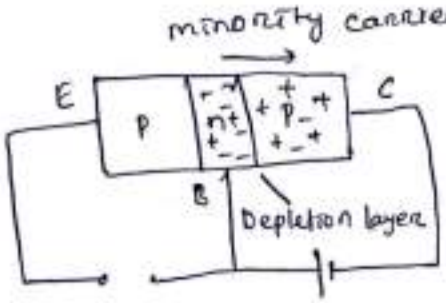


case-I If only Emitter to base bias is consider.



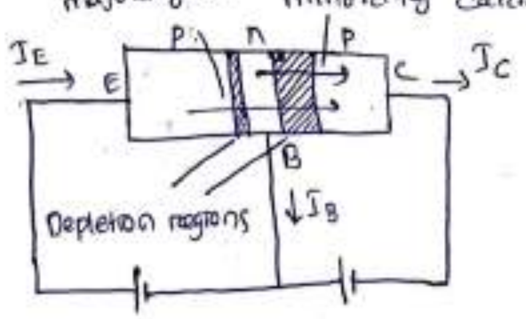
- The depletion region has been reduced in width due to the applied bias, resulting in a heavy flow of majority carriers from the p- to the n-type material.

case-II let us now consider only base-collector bias.



- It is now similar to a reverse biased diode. So the flow of majority carriers is zero, resulting in only a minority carrier flow.

case-III let us now consider both Emitter-Base & Base-collector Bias.

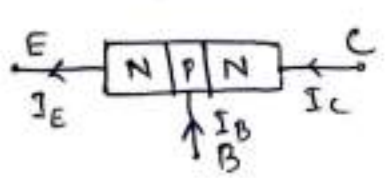


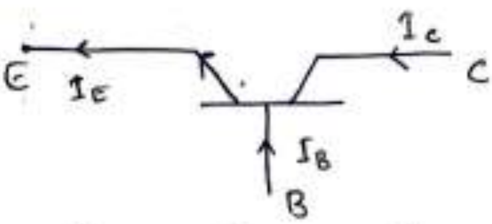
- A large number of majority carriers will diffuse across the forward biased p-n junction into the n-type material. Since n-type material is very thin & has a low conductivity, a very small number of these carriers will take this path of high resistance to the base terminal. The magnitude of the base current is typically on the order of microampere.

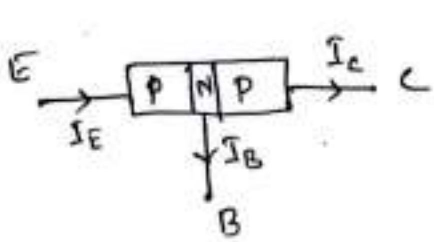
- The larger no. of majority carriers will diffuse across the reverse biased junction into the collector. It is because the majority carrier in P region appear as minority carrier in n-region & hence crosses the reverse-biased junction. This constitute collector current.

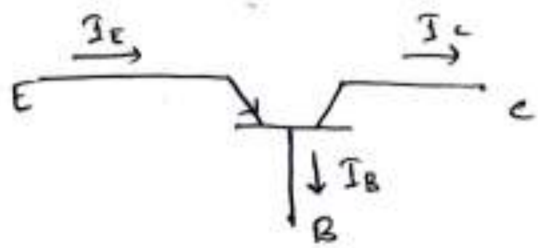
Current components in Transistor

- The direction of conventional current is always opposite to the electron current.









Applying KCL considering it to a single node :-

$$\boxed{I_E = I_B + I_C}$$

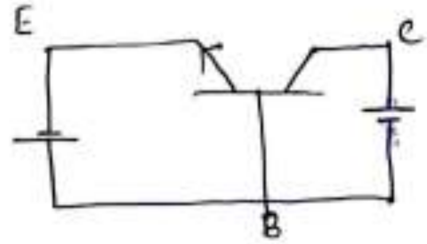
Since base current is very small, Therefore

$$\boxed{I_E \approx I_C}$$

Different modes of Operation

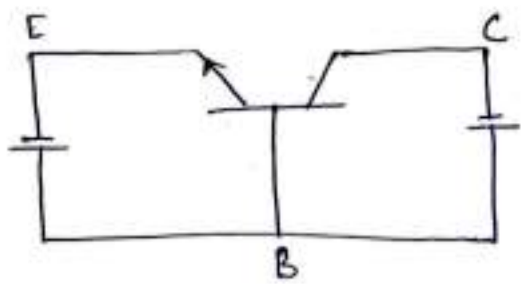
- Each Junction of a transistor may be forward biased or reverse biased. There are 3 different ways of biasing a transistor, which are known as modes of transistor operation.

① Active mode / Active region



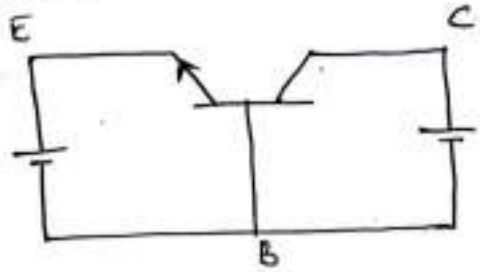
In this mode the emitter-base junction of a transistor is forward biased and the collector base junction is reverse biased.

② Saturation region



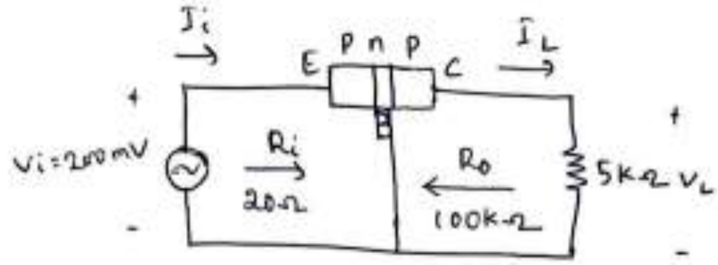
In this mode both the emitter-base & collector-base of a transistor are forward biased. The transistor is operated in this mode when it is used as a closed switch. (ON switch)

③ Cut off Region



In this mode both the emitter-base & collector-base junctions of a transistor are reverse biased. The transistor is operated in this mode, when it is used as an off switch. (open switch)

Transistor as an Amplifier



→ For common base typical value of input resistance varies from 10Ω to 100Ω. (Here we consider 20Ω)

→ Typical values of output resistance varies from 50KΩ to 1 MΩ (Let us consider 100KΩ)

→ The difference in resistance is due to the forward biased junction at the input & the reverse-biased junction at the o/p.

Finding the value of I_i,

$$I_i = \frac{V_i}{R_i} = \frac{200\,mV}{20\Omega} = 10\,mA$$

We know $I_E \approx I_C$, so $\alpha \approx 1$

$$I_i = I_E \quad , \quad I_c = I_L$$

$$I_L = I_i = 10\,mA$$

$$V_L = I_L R = 10\,mA \times 5\,k\Omega = 50\,V$$

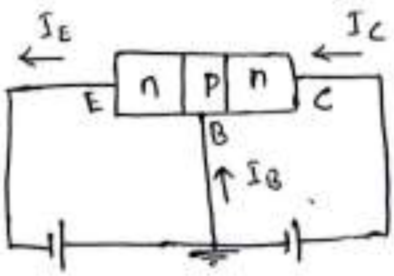
The voltage amplification is

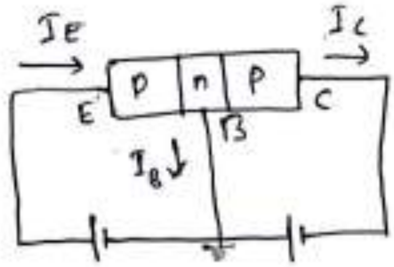
$$A_V = \frac{V_L}{V_i} = \frac{50V}{200\,mV} = 250$$

- Thus transistor works as an Amplifier.

Transistor Configuration

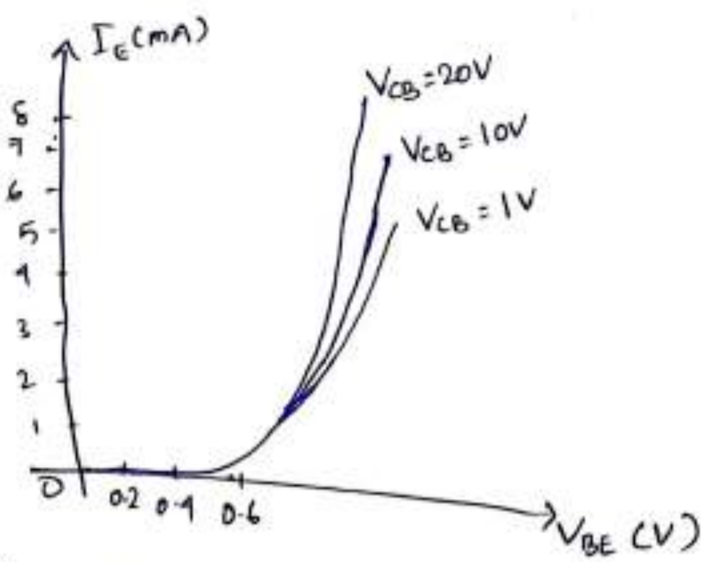
① Common-Base configuration (CB)





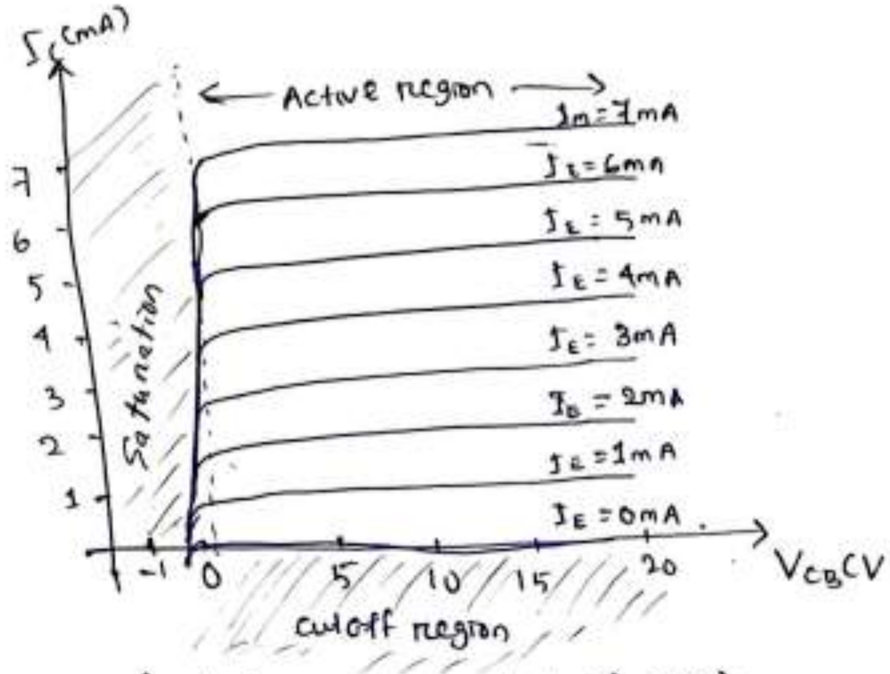
- Here the base is common to both the input and output side of the configuration.
- The input is applied between the emitter and base terminals. The output is taken between the collector and base terminals.

The input characteristics of common base amplifier relates an input current (I_E) to an input voltage (V_{BE}) for various output voltage (V_{CB})



(Input characteristics of CB)

The output characteristics relates an output current (I_C) to an output voltage (V_{CB}) for various levels of input current (I_E). The output or collector characteristics has three basic regions, the active, cutoff & saturation regions.



(output characteristics of CB)

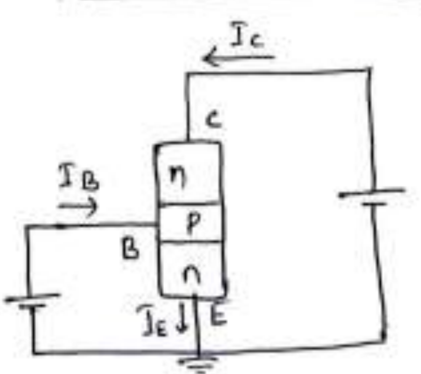
Current Amplification factor (CB) (α)

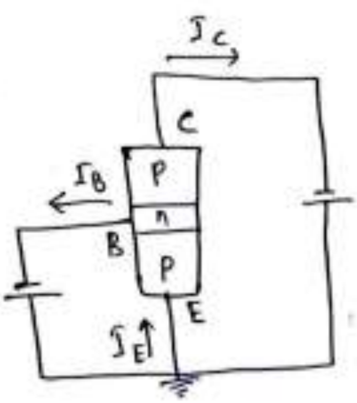
It is defined as the ratio of collector current to the emitter current in common base configuration.

$$\boxed{\alpha = \frac{I_C}{I_E}}$$

- For practical devices α typically ranges from 0.90 to 0.998.

(2) Common Emitter Configuration (CE)

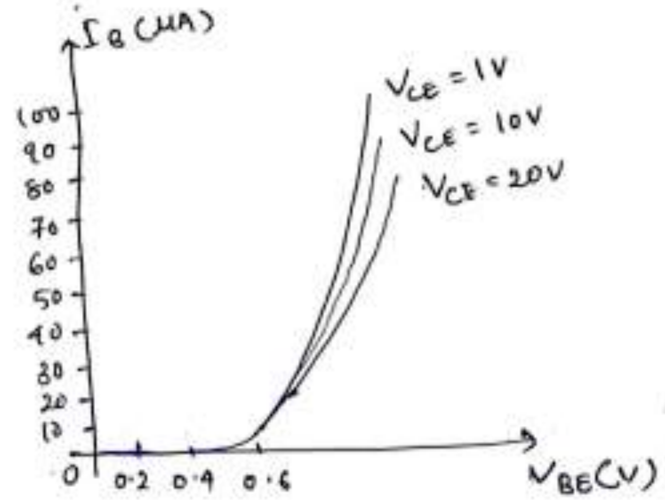




- Here the Emitter is common to both the input and output side of the configuration.

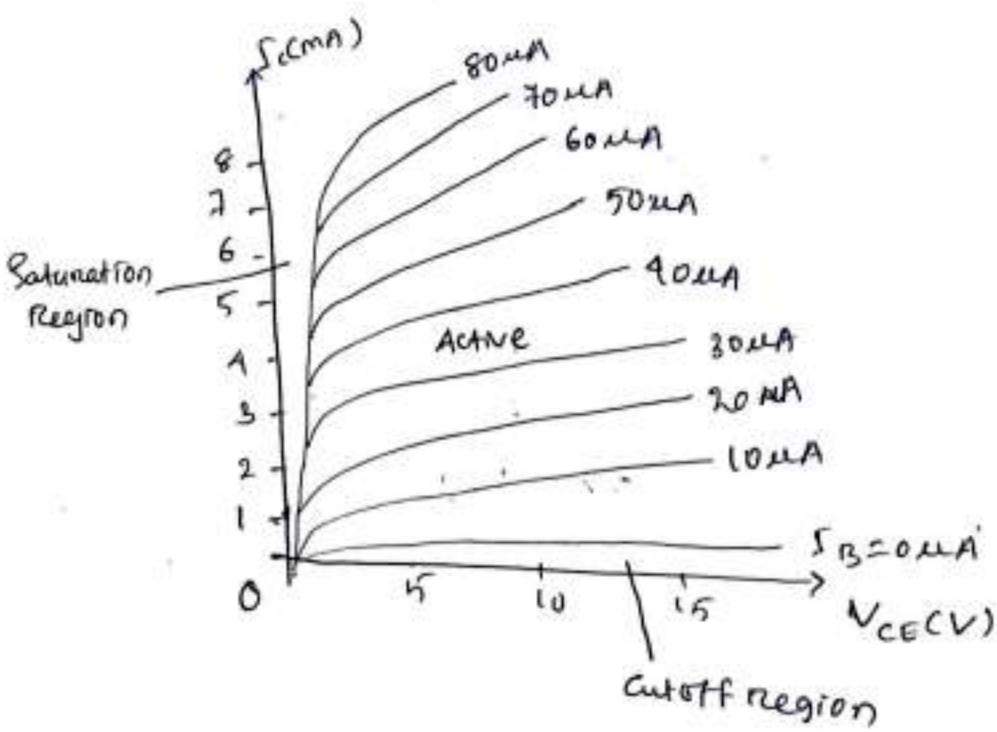
- The input is applied between the emitter and base terminals. The output is taken between the emitter and collector terminals.

- The input characteristics are a plot of the input current (I_B) versus the input voltage (V_{BE}) for a range of values of output voltage (V_{CE}).



(Input characteristics of CE)

- The output characteristics are a plot of the output current (I_C) versus output voltage (V_{CE}) for a range of values of input current (I_B)



(output characteristics of CE)

Current Amplification factor (CE) (β)

It is the ratio of collector current (I_C) to the base current (I_B) in common emitter configuration.

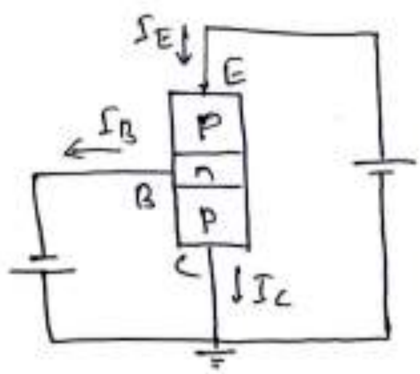
- Here I_C is the o/p current & I_B is the i/p current.
- Denoted as β

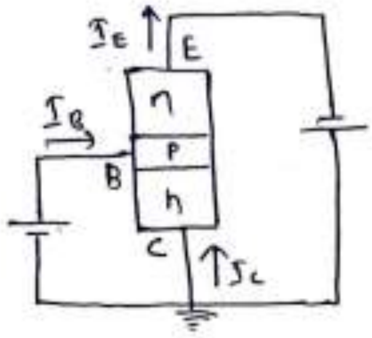
$$\boxed{\beta = \frac{I_C}{I_B}}$$

- For practical devices the level of β ranges from 50 to 400.

(3) Common Collector configuration

- The common collector configuration is used primarily for impedance matching purposes since it has a high input impedance & low output impedance.
- Here the collector is common to both input & output side of the configuration.





- The in-put is applied between the base & collector terminals

The output is applied between the emitter & collector terminals.

- For all practical purposes, the output characteristics of the common collector configuration are the same as for the common emitter configuration.
- Common collector is also known as emitter follower.

Current amplification factor in CC (γ)

It is defined as the ratio of emitter current to the base current in common collector configuration.

$$\boxed{\gamma = \frac{I_E}{I_B}}$$

Relation Between Current gain α & β

we have, $\beta = \frac{I_C}{I_B} \Rightarrow I_B = \frac{I_C}{\beta}$

$$\alpha = \frac{I_C}{I_E} \Rightarrow I_E = \frac{I_C}{\alpha}$$

we know. $I_E = I_C + I_B$

$$\frac{I_C}{\alpha} = I_C + \frac{I_C}{\beta}$$

dividing both side by I_C

$$\frac{1}{\alpha} = 1 + \frac{1}{\beta}$$

$$\Rightarrow \frac{1}{\alpha} = \frac{\beta+1}{\beta} \Rightarrow \beta = \alpha\beta + \alpha \quad = \beta = \alpha(\beta+1)$$

$$\Rightarrow \boxed{\alpha = \frac{\beta}{1+\beta}} \quad \ldots \text{(1)}$$

from eq (1) $\quad \alpha(1+\beta) = \beta \Rightarrow \alpha = \beta - \alpha\beta$

$$\Rightarrow \alpha = \beta(1-\alpha) \Rightarrow \boxed{\beta = \frac{\alpha}{1-\alpha}}$$

Relation between α, β & γ

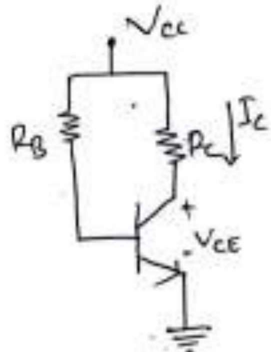
$$\gamma = \frac{I_E}{I_B} = \frac{I_E}{I_B} \cdot \frac{I_C}{I_C} = \frac{I_E}{I_C} \cdot \frac{I_C}{I_B}$$

$$\boxed{\gamma = \alpha^{-1} \cdot \beta} \Rightarrow \boxed{\beta = \alpha\gamma}$$

Transistor Circuits

DC load line & operating point

- DC load line is useful in graphical analysis of BJT circuits.
- It is a straight line plotted on I_C vs V_{CE} graph.
- It can be used to calculate V_{CE} & I_C graphically for a given BJT circuit.
- Equation of DC load line is obtained by applying KVL in collector loop.



KVL in collector loop:

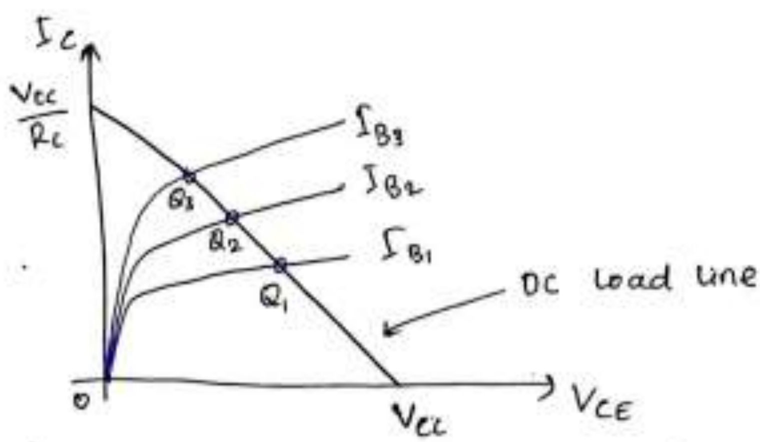
$$-V_{CC} + I_C R_C + V_{CE} = 0$$

$$\Rightarrow I_C R_C = -V_{CE} + V_{CC}$$

$$\Rightarrow I_C = \underbrace{\left(-\frac{1}{R_C}\right)}_{\text{slope}} V_{CE} + \frac{V_{CC}}{R_C} \qquad \text{—— (1)}$$

eq (1) represents straight line having slope $\left(-\frac{1}{R_C}\right)$ & a y-intercept $\frac{V_{CC}}{R_C}$. It is called DC load line.

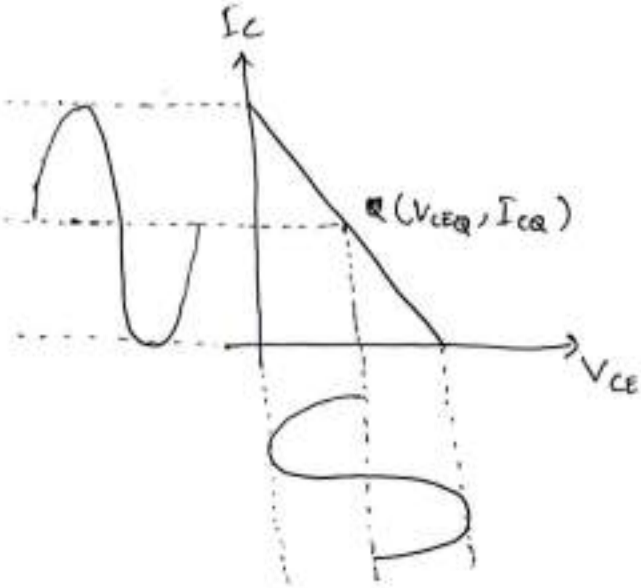
For $I_C = 0$, eq^n (1) becomes $0 = -\frac{1}{R_C} V_{CE} + \frac{V_{CC}}{R_C} \Rightarrow \boxed{V_{CE} = V_{CC}}$

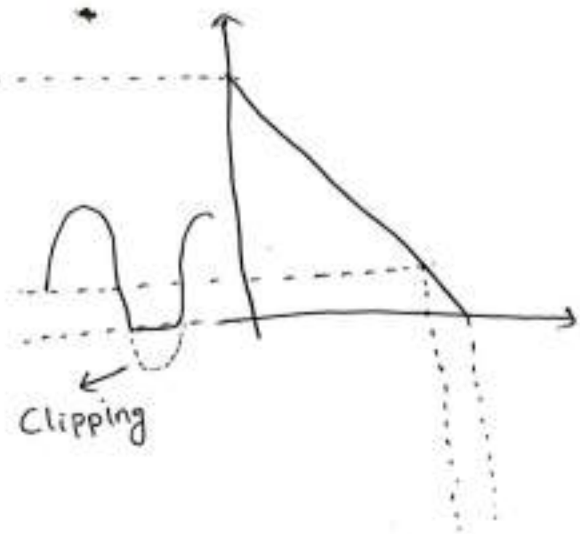


Q-point

- For a given value of I_B, the point of intersection of characteristics curve & DC load line is known as operating point or Quiescent point or Q-point or Bias point.

- operating point is kept at centre of Load line to obtain distortionless output from an Amplifier.





Stability Factor (S)

It is defined as the rate of change of collector current with respect to I_{CO}.

$$\boxed{S = \frac{\partial I_C}{\partial I_{CO}}}$$

$$I_C = \beta I_B + (1+\beta) I_{CO}$$

differentiate w.r.t I_C

$$1 = (1+\beta)\frac{\partial I_{CO}}{\partial I_C} + \beta \frac{\partial I_B}{\partial I_C}$$

$$\boxed{\frac{\partial I_C}{\partial I_{CO}} = \frac{1+\beta}{1-\beta\frac{\partial I_B}{\partial I_C}}}$$

$$\boxed{S = \frac{1+\beta}{1-\beta\frac{\partial I_B}{\partial I_C}}}$$

- Smaller stability factor indicates better stability in collector current. Ideally $\boxed{S=1}$.

Transistor Biasing

- Biasing refers to providing DC current and DC voltage to an electronic device to obtain desired functionality from the device.

Need for BJT Biasing :-

① To operate BJT in active region so that BJT can be used as amplifier.

② To maintain collector current stable & there by operating point becomes stable & Thermal runaway can be prevented.

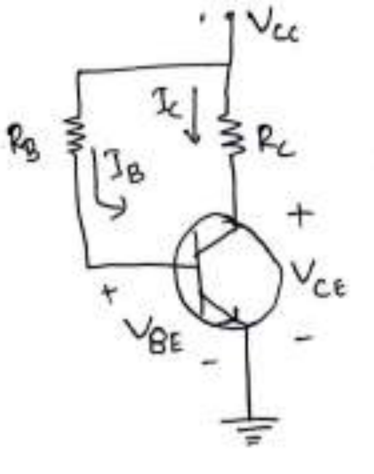
Thermal Runaway

The self destruction of a transistor due to the cummulative rise in the collector junction temperature during reverse bias operation is called Thermal Runaway.

Different method of Transistor Biasing :-

(i) Base resistor method
(ii) Collector to Base bias
(iii) Self bias or voltage divider method

(i) Base resistor method / Fixed bias



- Vcc provides the necessary currents & voltages to BJT.

Applying KVL to input section

$$V_{CC} - I_B R_B - V_{BE} = 0$$

$$\Rightarrow I_B R_B = V_{CC} - V_{BE}$$

$$\Rightarrow I_B = \frac{V_{CC} - V_{BE}}{R_B} \quad \text{— ①}$$

$$\boxed{I_{CQ} = \beta I_B}$$

Applying KVL to output section

$$V_{CC} - I_C R_C - V_{CE} = 0$$

$$\Rightarrow V_{CE} = V_{CC} - I_C R_C$$

$$\boxed{V_{CEQ} = V_{CC} - I_{CQ} R_C}$$

Stability Factor, S

$$S = \frac{1+\beta}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$

from eqⁿ ① $\quad I_B = \frac{V_{CC} - V_{BE}}{R_B} \quad$ — ②

differentiate eqⁿ ② w.r.t I_C

$$\frac{\partial I_B}{\partial I_C} = 0 - 0 = 0$$

$$S = \frac{\partial I_C}{\partial I_{CO}} = 1 + \beta$$

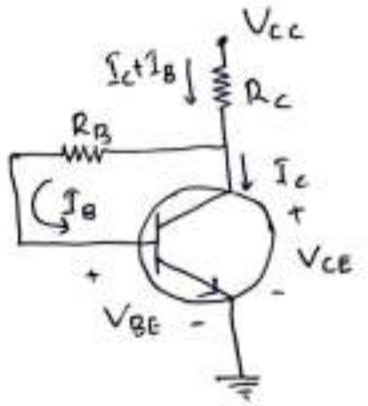
$$\boxed{S = 1 + \beta}$$

Drawbacks

① Highly unstable operating point.

② possibility of thermal runaway.

(ii) Collector to Base Bias



Applying KVL to input Section :-

$$V_{CC} - (I_C + I_B)R_C - I_B R_B - V_{BE} = 0$$

$$\Rightarrow V_{CC} - (\beta I_B + I_B)R_C - I_B R_B - V_{BE} = 0 \qquad (\because I_C = \beta I_B)$$

$$\Rightarrow \beta I_B R_C + I_B R_C + I_B R_B = V_{CC} - V_{BE}$$

$$\Rightarrow I_B [(\beta+1)R_C + R_B] = V_{CC} - V_{BE}$$

$$\Rightarrow I_B = \frac{V_{CC} - V_{BE}}{(1+\beta)R_C + R_B}$$

$$\boxed{I_{CQ} = \beta I_B}$$

Applying KVL to output section :-

$$V_{CC} - (I_C + I_B)R_C - V_{CE} = 0$$

$$\Rightarrow V_{CE} = V_{CC} - \left(I_C + \frac{I_C}{\beta}\right)R_C$$

$$\Rightarrow V_{CEQ} = V_{CC} - I_C R_C \left(1 + \frac{1}{\beta}\right)$$

$$\boxed{V_{CEQ} \simeq V_{CC} - I_C R_C} \qquad (\because \beta \text{ is large})$$

Stability Factor, S

$$S = \frac{1+\beta}{1-\beta\frac{\partial I_B}{\partial I_C}}$$

KVL for i/p Section :-

$$V_{CC}-(I_C+I_B)R_C - I_BR_B - V_{BE} = 0$$

$$\Rightarrow V_{CC} - I_CR_C - I_BR_C - I_BR_B - V_{BE} = 0$$

$$\Rightarrow I_B(R_C+R_B) = V_{CC} - V_{BE} - I_CR_C$$

$$\Rightarrow I_B = \frac{V_{CC}-V_{BE}-I_CR_C}{R_C+R_B} \quad \text{—— (1)}$$

Differentiate eqn (1) w.r.t I_C

$$\frac{\partial I_B}{\partial I_C} = \frac{-R_C}{R_C+R_B}$$

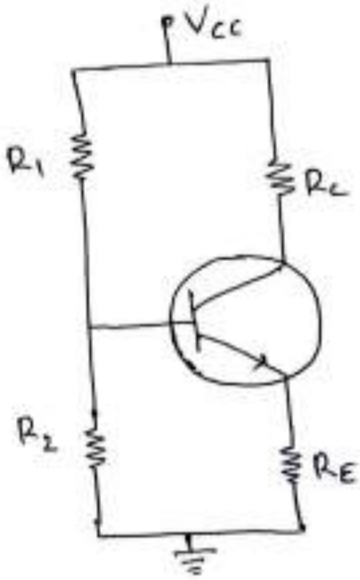
$$S = \frac{1+\beta}{1+\beta\left(\frac{R_C}{R_C+R_B}\right)}$$

- With proper selection of R_C & R_B values the stability factor of a collector to base bias may be maintained around 20.

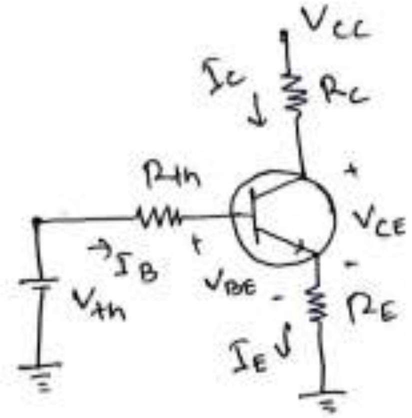
Drawback

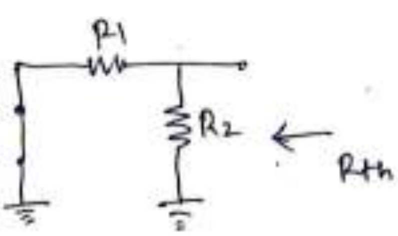
- The resistance R_B connected betn collector & base provides negative feedback, which reduce the overall AC gain of Amplifier.

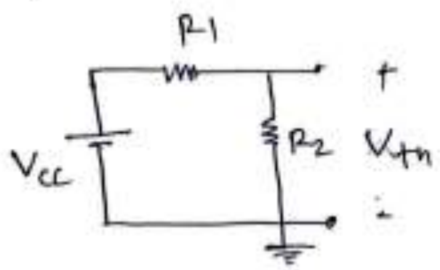
(iii) Self Bias or Voltage divider method



$\Rightarrow$







$R_{th} = R_1 \| R_2$

$$V_{th} = \frac{V_{cc} R_2}{R_1 + R_2}$$

Applying KVL for input

$$V_{th} - I_B R_{th} - V_{BE} - I_E R_E = 0$$

$$\Rightarrow V_{th} - I_B R_{th} - V_{BE} - (I_C + I_B) R_E = 0$$

$$\Rightarrow V_{th} - I_B R_{th} - V_{BE} - \beta I_B R_E - I_B R_E = 0$$

$$\Rightarrow I_B (R_{th} + \beta R_E + R_E) = V_{th} - V_{BE}$$

$$\Rightarrow I_B = \frac{V_{th} - V_{BE}}{R_{th} + (\beta+1) R_E}$$

$$\boxed{I_{CQ} = \beta I_B}$$

Applying KVL to o/p section

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

$$\Rightarrow V_{CE} = V_{CC} - I_C R_C - (I_C + I_B) R_E$$

$$\Rightarrow V_{CE} = V_{CC} - I_C R_C - I_C R_E - \frac{I_C}{\beta} R_E$$

$$\Rightarrow V_{CE} = V_{CC} - I_C \left(R_C + R_E + \frac{R_E}{\beta} \right)$$

$$\Rightarrow V_{CE} = V_{CC} - I_C \left[R_C + R_E \left(1 + \frac{1}{\beta} \right) \right]$$

$$\Rightarrow \boxed{V_{CE_Q} = V_{CC} - I_C (R_C + R_E)} \qquad (\beta \text{ is large})$$

Stability factor, S

$$S = \frac{1+\beta}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$

KVL for i/p section :-

$$V_{th} - I_B R_{th} - V_{BE} - I_E R_E = 0$$

$$\Rightarrow V_{th} - I_B R_{th} - V_{BE} - (I_C + I_B) R_E = 0$$

$$\Rightarrow V_{th} - I_B R_{th} - V_{BE} - I_C R_E - I_B R_E = 0$$

$$\Rightarrow I_B (R_{th} + R_E) = V_{th} - V_{BE} - I_C R_E$$

$$\Rightarrow I_B = \frac{V_{th} - V_{BE} - I_C R_E}{R_{th} + R_E}$$

$$\frac{\partial I_B}{\partial I_C} = \frac{-R_E}{R_{th} + R_E}$$

$$S = \frac{1+\beta}{1 - \beta \frac{\partial I_B}{\partial I_C}} = \frac{1+\beta}{1 + \beta \left(\frac{R_E}{R_{th} + R_E} \right)}$$

$$\boxed{S = \frac{1+\beta}{1 + \beta \left(\frac{R_E}{R_{th} + R_E} \right)}}$$

with proper selection of R_1, R_2 & R_E, the stability factor of a self bias or voltage divider bias circuit may be obtained below 10.

Stabilization

The process of making the operating point independent of temperature changes or variations in transistor parameters is known as stabilization.

- Once the stabilization is achieved, the values of I_C & V_{CE} become independent of temperature variation or replacement of transistor. A good biasing circuit helps in the stabilization of operating point.

Need for Stabilization :-

Stabilization of the operating point has to be achieved due to the following reasons :-

→ Temperature dependance of I_c

→ Individual variations

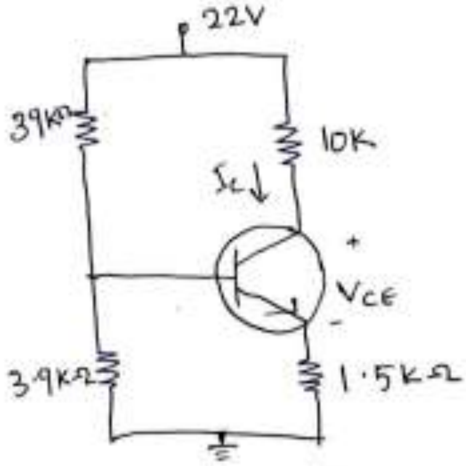
→ Thermal Runaway

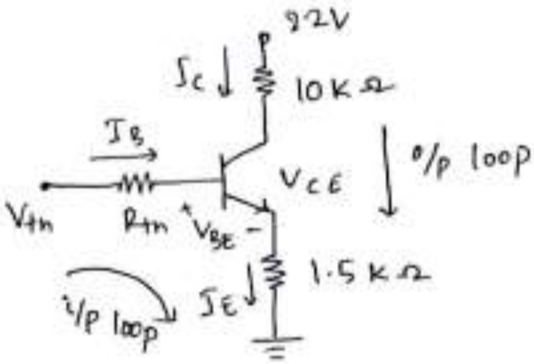
Q What do you mean by early effect ?

Ans - The process where the effective basewidth of transistor is altered by varying collector junction voltage is called base width modulation.

- If the magnitude of collector junction voltage is increased then effective base width of transistor is reduced.
- The property of base narrowing in BJT is known as Early effect.

Q) Determine V_{CE} & I_C for the voltage divider bias. $\beta = 100$





$$V_{th} = \frac{22 \times 3.9}{3.9 + 39} = 2V$$

$$R_{th} = \frac{39 \times 3.9}{3.9 + 39} = 3.55\,k\Omega$$

Apply KVL to input loop:

$$V_{th} - I_B R_{th} - V_{BE} - I_E R_E = 0$$

$$\Rightarrow 2 - I_B(3.55k) - 0.7 - I_B(1+\beta)(1.5k\Omega) = 0$$

$$\Rightarrow I_B[3.55k + 101 \times 1.5k] = 2 - 0.7$$

$$\Rightarrow I_B = 8.38\,\mu A$$

$$I_C = \beta I_B = 100 \times 8.38\,\mu A$$

$$I_C = 0.84\,mA$$

Apply KVL to output loop:

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

$$\Rightarrow V_{CC} - I_C R_C - V_{CE} - (I_C + I_B) R_E = 0$$

$$\Rightarrow V_{CC} - I_C R_C - V_{CE} - \left(I_C + \frac{I_C}{\beta}\right) R_E = 0$$

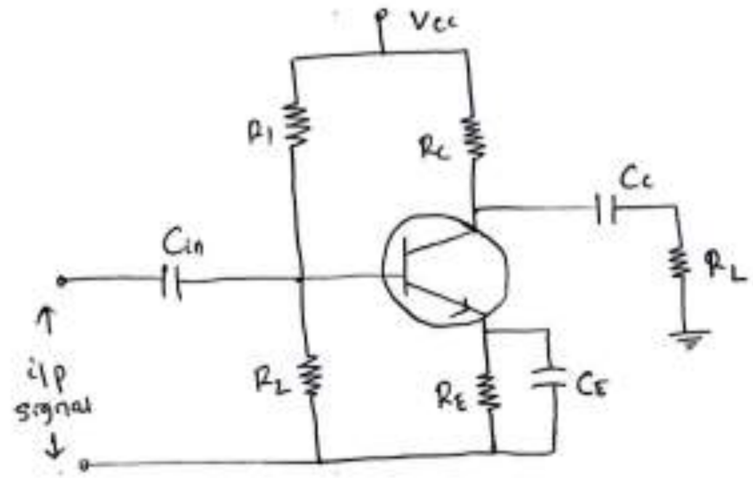
$$\Rightarrow V_{CE} = V_{CC} - I_C\left[R_C + \left(1 + \frac{1}{\beta}\right) R_E\right]$$

$$\Rightarrow V_{CE} = V_{CC} - I_C(R_C + R_E)$$ ($\frac{1}{\beta}$ is neglected)

$$\Rightarrow V_{CE} = 22 - 0.84m\,(10K + 1.5K) = 12.34\,V$$

Transistor Amplifier

Practical circuit of Transistor Amplifier



- The resistor R_1, R_2 & R_E form the biasing and stabilization circuit. The biasing circuit must establish a proper operating point.
- A capacitor Cin is used to couple the signal to the base of the transistor. The capacitor Cin allows only AC signal to flow but isolates the signal source from R_2
- An emitter bypass capacitor C_E is used in parallel with R_E to provide a low reactance path to the amplified ac signal.
- The coupling capacitor C_c couples one stage of amplifier to the next stage. The coupling capacitor C_c isolates the dc of one stage from the next stage but allows the passage of ac signal.

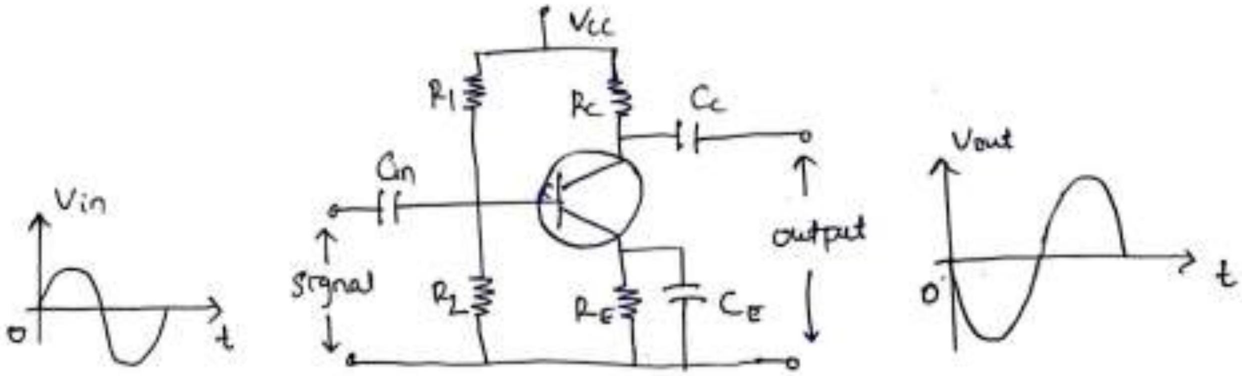
phase Reversal

- The phase difference of 180° between the signal voltage and output voltage in a common emitter amplifier is known as phase reversal.
- In CE configuration, when the input signal voltage increases in the positive sence, the output voltage increases in the negative direction & vice-versa. So there is a phase difference of 180° between input & output in CE configuration.

- The signal is fed at the input terminals & output is taken from collector & emitter end of supply.

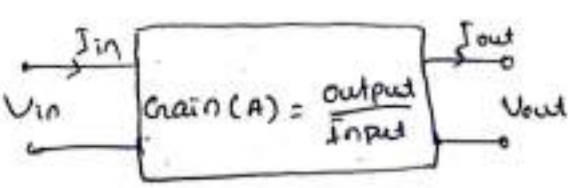
$$\text{output voltage}, \quad V_{CE} = V_{CC} - i_C R_C$$

- When the signal voltage increases in the positive half-cycle, the base current also increases.



- As base current increases, current in collector also increases & hence voltage drop $i_C R_C$ increases.
- As V_{CC} is constant, therefore output voltage V_{CE} decreases. So as the signal voltage is increasing in the positive half-cycle, the output voltage is increasing in the negative sense i.e outputput is 18° out of phase with the input.

Calculation of Gain



$$\text{Voltage Amplifier Gain}(A_v) = \frac{\text{output voltage}}{\text{Input voltage}} = \frac{V_{out}}{V_{in}}$$

$$\text{Current Amplifier Gain}(A_i) = \frac{\text{output current}}{\text{Input current}} = \frac{I_{out}}{I_{in}}$$

$$\text{Power Gain } (A_P) = A_v \cdot A_i$$

Gain in Decibel (dB) :-

Voltage gain in dB : $a_v = 20\log(A_v)$

Current gain in dB : $a_i = 20\log(A_i)$

power gain in dB : $a_p = 10\log(A_p)$

- The positive value of dB represents a Gain and negative value of dB represents a loss.

ex

Determine the voltage, current & power gain of an amplifier that has an input signal of 1mA at 10mV and a corresponding output signal of 10mA at 1V.

$$A_v = \frac{\text{output voltage}}{\text{Input voltage}} = \frac{1V}{10mV} = \frac{1000V}{10V} = 100$$

$$A_v \text{ in dB} = 20\log 100 = 20\log 10^2 = 40dB$$

$$A_i = \frac{\text{output current}}{\text{Input current}} = \frac{10mA}{1mA} = 10$$

$$A_i \text{ in dB} = 20\log 10 = 20 dB$$

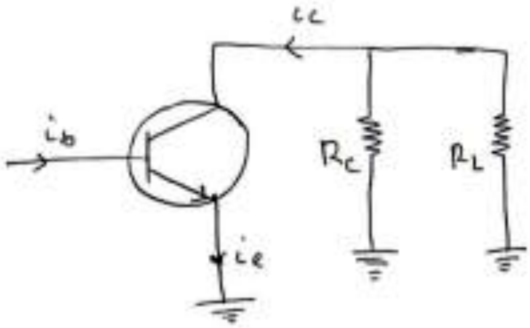
$$A_p = A_v \cdot A_i = 100 \times 10 = 1000$$

$$A_p \text{ in dB} = 10\log 1000 = 10\log 10^3 = 30dB$$

AC Load-line

This is the line on the output characteristics of a transistor circuit which gives the values of i_c & v_{CE} when signal is applied.

we require two end points, one maximum collector-emitter voltage point and the other maximum collector current point.

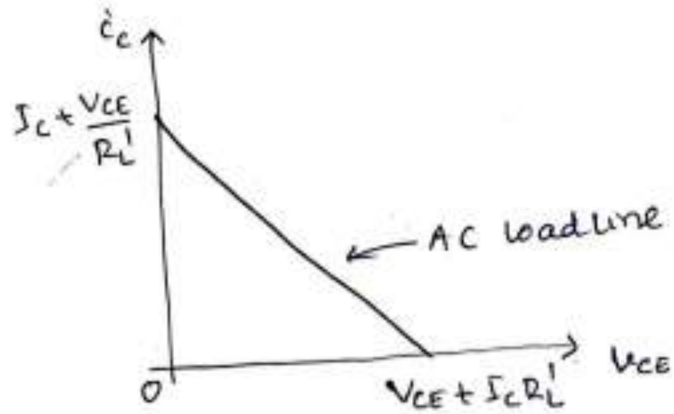


$$R_L' = R_c \parallel R_L = \frac{R_c R_L}{R_c + R_L}$$

maximum collector emitter voltage $= V_{CE} + I_c R_L'$

maximum collector current $= I_c + \frac{V_{CE}}{R_L'}$

AC load line is obtained by joining that two points.

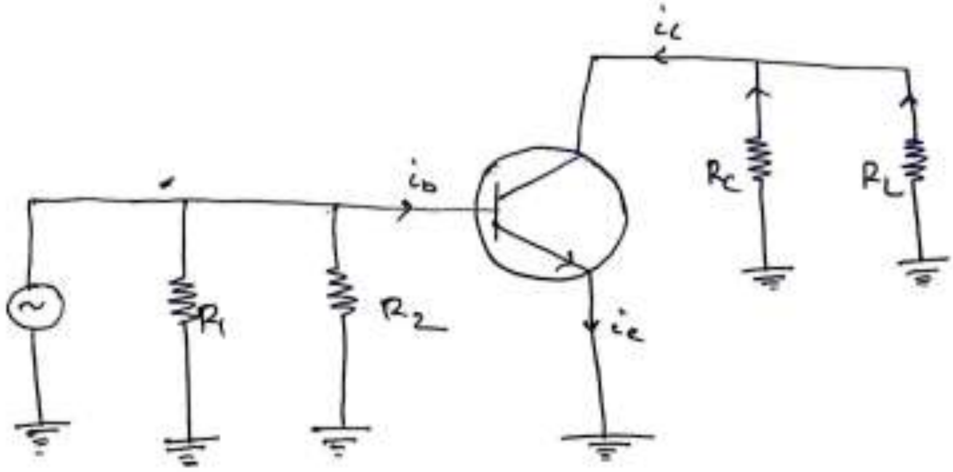


AC equivalent circuit

To draw the a.c. equivalent circuit :-

(1) Reduce all d.c sources to zero i.e $V_{cc} = 0$

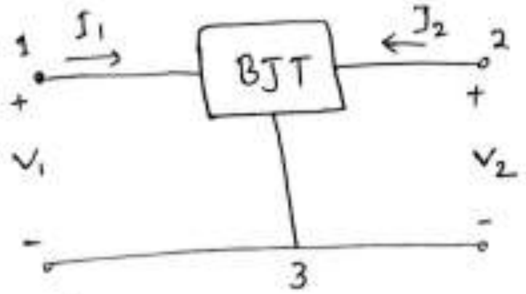
(2) All the capacitors are shorted.

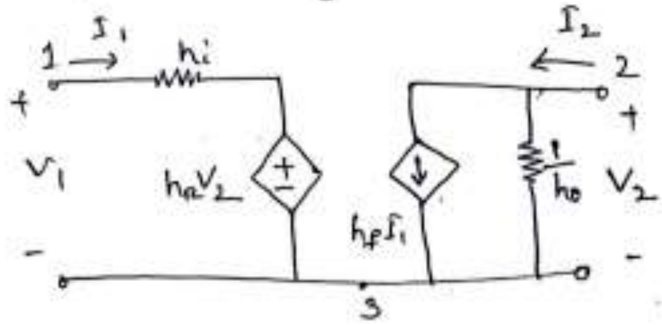


Hybrid or h-parameter model

$$V_1 = h_i I_1 + h_r V_2 \quad \text{--- (1)}$$

$$I_2 = h_f I_1 + h_o V_2 \quad \text{--- (2)}$$





(h-parameter model)

(1) $h_i = \left.\frac{V_1}{I_1}\right|_{V_2=0}$; h_i is i/p resistance, when o/p node is shorted.

(2) $h_r = \left.\frac{V_1}{V_2}\right|_{I_1=0}$; h_r is reverse voltage gain when input is open.

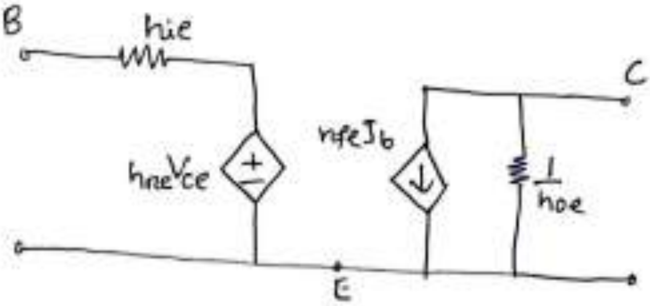
(3) $h_f = \left.\frac{I_2}{I_1}\right|_{V_2=0}$; h_f is forward current gain when o/p node shorted

(4) $h_o = \left.\frac{I_2}{V_2}\right|_{I_1=0}$; h_o is o/p conductance when i/p is open circuit.

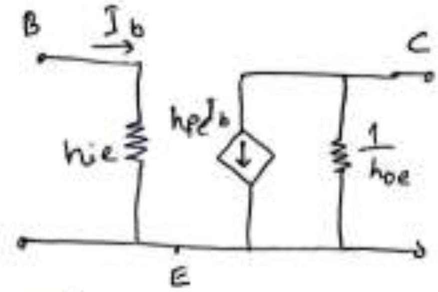
$\frac{1}{h_o}$: output resistance

Approximate h-parameter model

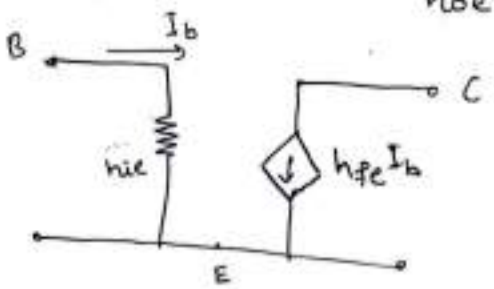
In approximate analysis, BJT is replaced with approximate common emitter h-parameter model which is obtained by neglecting h_{re}.



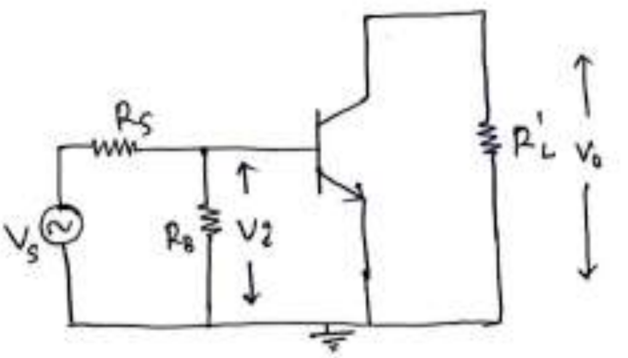
$\xrightarrow{h_{re} \cong 0}$



- Approximate analysis becomes valid if $h_{oe}R_L' < 0.1$.
- If hoe is negligible then $\frac{1}{h_{oe}}$ is replaced with open circuit



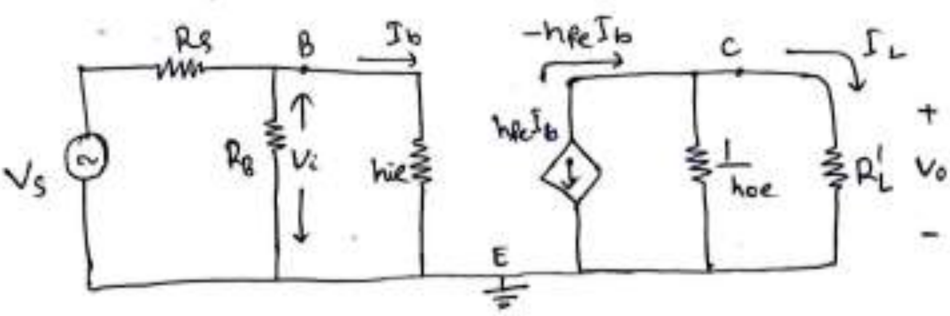
(I) Common Emitter Amplifier



$R_B = R_1 \parallel R_2$

$R_L' = R_C \parallel R_L$

Replacing BJT with approximate h-parameter model.



$R_L'' = R' \parallel \frac{1}{h_{oe}}$

(i) Current Gain

$$A_I = \frac{I_L}{I_b}$$

Current division for I_L

$$I_L = \frac{-h_{fe} I_b \times \frac{1}{h_{oe}}}{\frac{1}{h_{oe}} + R_L'}$$

$$\frac{I_L}{I_b} = \frac{-h_{fe}}{1 + h_{oe}R_L'} \Rightarrow \boxed{A_I = \frac{-h_{fe}}{1 + h_{oe}R_L'}}$$

If $h_{oe}R_L' < 0.1 \Rightarrow \boxed{A_I \cong -h_{fe}}$

(ii) Input Resistance

$$R_i = \frac{V_i}{I_b}$$

from input circuit :

$$V_i = I_b h_{ie} \Rightarrow \frac{V_i}{I_b} = h_{ie} \Rightarrow \boxed{R_i = h_{ie}}$$

(iii) Voltage Gain

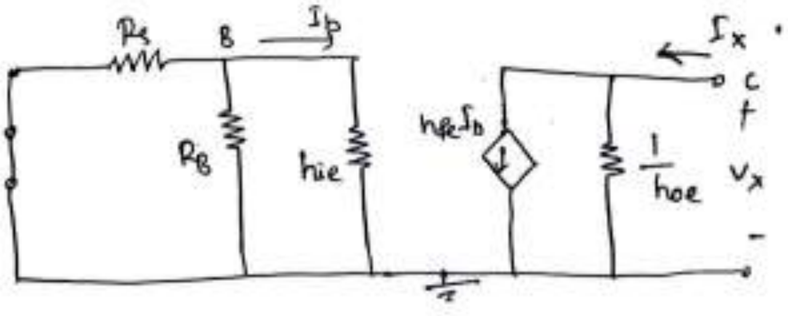
$$A_V = \frac{V_o}{V_i} = \frac{-h_{fe} I_b R_L''}{I_b h_{ie}} = \frac{-h_{fe} R_L''}{h_{ie}} \qquad \left[R_L'' = R_L' \parallel \frac{1}{h_{oe}}\right]$$

If $h_{oe} \cong 0$ the $R_L'' = R_L'$ $\qquad \left[R_L' = R_C \parallel R_L\right]$

$$\boxed{A_V = \frac{-h_{fe} R_L'}{h_{ie}}}$$

- Negative sign indicates phase shift of 180° between V_o & V_i.

(iv) Output Resistance



$$R_s' = R_s \parallel R_B$$

- To calculate R_o

(i) Replace V_s with a short circuit
(ii) Disconnect load R_L'
(iii) Assume that a voltage V_x is applied across o/p port.

$$I_b R_s' + I_b h_{ie} = 0$$

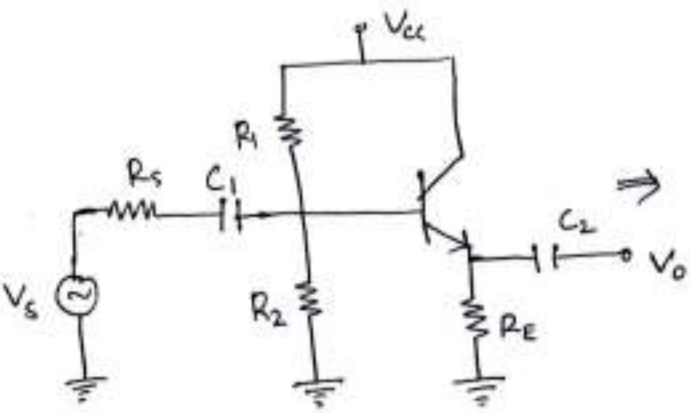
$$I_b = 0$$

$$I_x = h_{oe} V_x + h_{fe} I_b$$

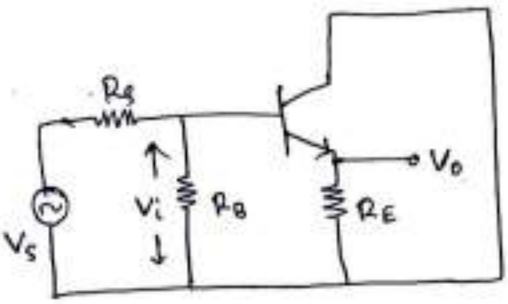
$$I_x = h_{oe} V_x \implies \frac{V_x}{I_x} = \frac{1}{h_{oe}}$$

$$\boxed{R_o = \frac{1}{h_{oe}}}$$

② Common collector Amplifier

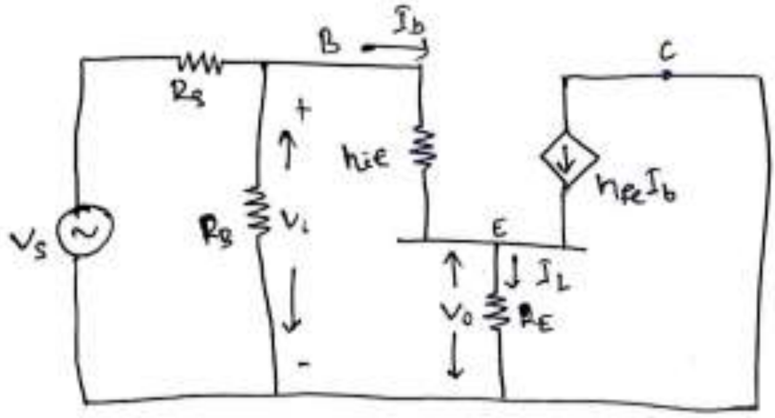


⇒



$[R_B = R_1 \parallel R_2]$

- Resistor R_E will act as Load in common collector amplifier.
- Replace BJT with approximate CE parameter model & neglect h_{oe}



(i) Current Gain

$$A_I = \frac{I_L}{I_b}$$

KCL: $I_L = I_b + h_{fe} I_b$

$I_L = I_b(1 + h_{fe})$

$$\boxed{A_I = 1 + h_{fe}}$$

(ii) Input Resistance

$$R_i = \frac{V_i}{I_b}$$

$$V_i = I_b h_{ie} + I_L R_E$$

$$V_i = I_b h_{ie} + I_b(1+h_{fe}) R_E$$

$$V_i = I_b [h_{ie} + (1+h_{fe}) R_E]$$

$$\boxed{R_i = h_{ie} + (1+h_{fe}) R_E}$$

(iii) Voltage Gain

$$A_V = \frac{V_o}{V_i} = \frac{I_L R_E}{V_i} = \frac{I_b (1+h_{fe}) R_E}{I_b (h_{ie} + (1+h_{fe}) R_E)}$$

$$\boxed{A_V = \frac{(1+h_{fe}) R_E}{h_{ie} + (1+h_{fe}) R_E}}$$

But $(1+h_{fe}) R_E \gg h_{ie}$

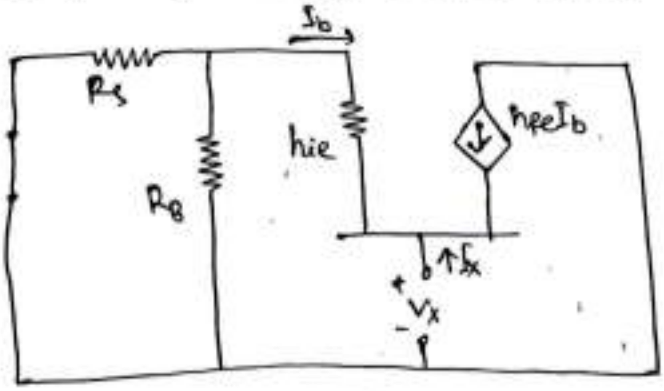
$$\boxed{A_V = 1}$$

- Common collector amplifier has unity voltage gain.
- AC output voltage is equal to AC input voltage.
- Common collector amplifier is also called emitter follower, because emitter voltage follows input voltage.

(iv) Output Resistance

To calculate R_o

(i) Replace V_s with a short circuit
(ii) Disconnect load R_E
(iii) Apply voltage V_x across output port.



$$R_s' = R_s \parallel R_B$$

KVL :-

$$I_b R_s' + I_b h_{ie} + V_x = 0$$

$$\Rightarrow V_x = -I_b (R_s' + h_{ie})$$

KCL :-

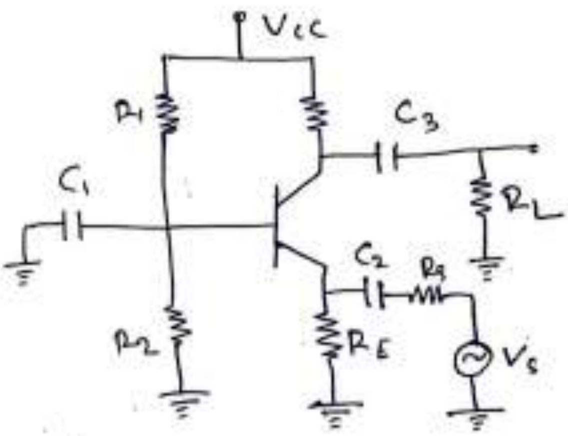
$$I_x + I_b + h_{fe} I_b = 0$$

$$I_x = -I_b (1 + h_{fe})$$

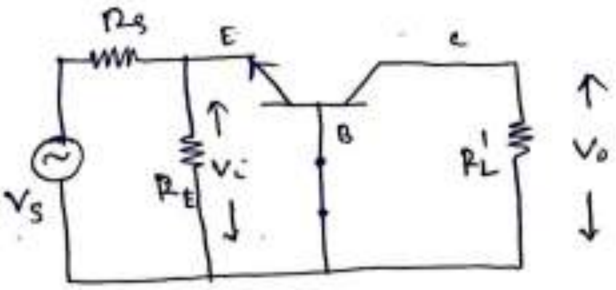
$$\therefore \frac{V_x}{I_x} = \frac{R_s' + h_{ie}}{1 + h_{fe}}$$

$$\boxed{R_o = \frac{R_s' + h_{ie}}{1 + h_{fe}}}$$

③ Common Base Amplifier



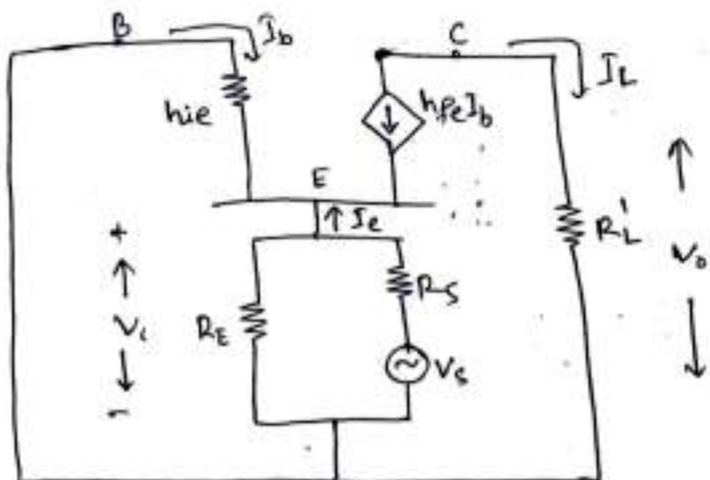
$\Rightarrow$



[$R_1 \parallel R_2 \parallel$ Short circuit = Short circuit]

[$R_L' = R_C \parallel R_L$]

- R_1 & R_2 do not appear in the AC equivalent circuit because they are in parallel to capacitor C_1 which is acting as short circuit.
- Replacing BJT with approximate CE parameter & neglect hoe :-



(i) Current Gain

$$A_I = \frac{I_L}{I_e}$$

$$I_L = -h_{fe} I_b$$

KCL

$$I_e + I_b + h_{fe} I_b = 0$$

$$\Rightarrow I_e = -I_b(1+h_{fe})$$

$$\frac{I_L}{I_e} = \frac{-h_{fe} I_b}{-I_b(1+h_{fe})}$$

$$\boxed{A_I = \frac{h_{fe}}{1+h_{fe}}} \cong 1$$

- Unity current Gain

(ii) Input Resistance

$$R_i = \frac{V_i}{I_e}$$

KVL:

$$I_b h_{ie} + V_i = 0$$

$$\Rightarrow V_i = -I_b h_{ie}$$

$$\frac{V_i}{I_e} = \frac{-I_b h_{ie}}{-I_b(1+h_{fe})}$$

$$\boxed{R_i = \frac{h_{ie}}{1+h_{fe}}}$$

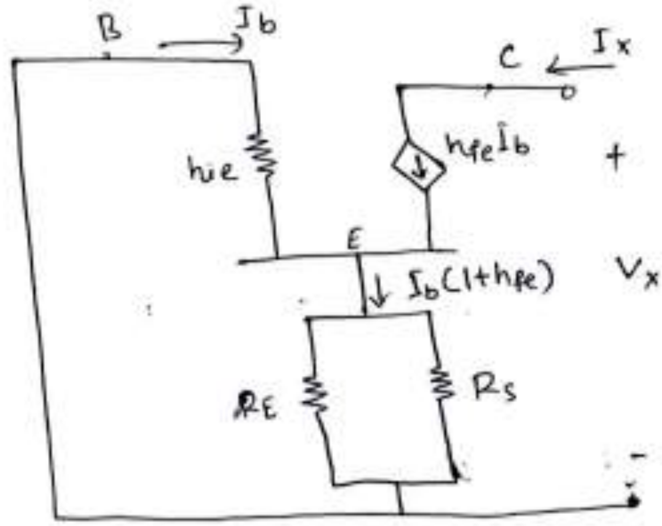
(iii) Voltage Gain

$$A_V = \frac{V_o}{V_i} = \frac{I_L R_L'}{V_i}$$

$$A_V = \frac{-h_{fe} I_b R_L'}{-I_b h_{ie}}$$

$$\boxed{A_V = \frac{h_{fe} R_L'}{h_{ie}}}$$

(iv) Output Resistance



$$R_E \parallel R_S = R_S'$$

KVL : $$I_b h_{ie} + I_b(1+h_{fe})R_s' = 0$$

$$\Rightarrow I_b[h_{ie} + (1+h_{fe})R_s'] = 0$$

$$\Rightarrow I_b = 0$$

$$I_x = h_{fe} I_b = 0$$

$$R_0 = \frac{V_x}{I_x} = \frac{V_x}{0} = \infty$$

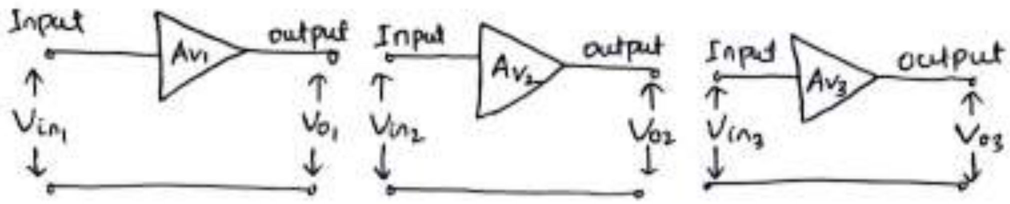
$$\boxed{R_0 = \infty}$$

Common Emitter	Common Base	Common Collector
- Large current Gain	- Unity current Gain	- Large current gain
- Large voltage Gain	- Large voltage gain	- Unity voltage gain
- Medium input resistance	- Small input resistance	- Large input resistance
- Medium output resistance	- Large output resistance	- Small output resistance

Multistage Transistor Amplifier

To achieve greater voltage & power gain, we have to use more than one stage of amplification. Such an amplifier is called a multistage amplifier.

- In multistage amplifier, the output of one stage is fed to the input of the next. It is called cascading.



- A multistage amplifier using two or more single stage common emitter amplifiers, is called a cascade amplifier.
- A multistage amplifier with common emitter amplifier as the first stage and common base or common collector amplifier as the second stage, is called a cascode amplifier.

Gain of a Multistage Amplifier :-

The voltage gain of a multistage amplifier is equal to the product of the gains of the individual stages.

- If $A_{v_1}, A_{v_2}, A_{v_3}$ are the individual stage gains, then overall voltage gain :-

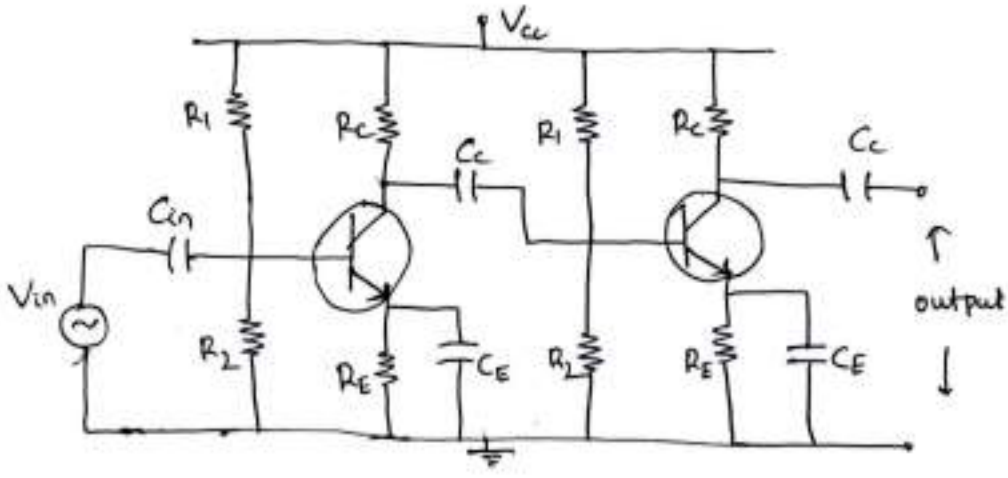
$$\boxed{A_v = A_{v_1} \times A_{v_2} \times A_{v_3}}$$

- If gains are in decibel (dB) then overall gain is the sum of individual gain.
- If G_{v_1}, G_{v_2} & G_{v_3} are gain in decibel, the overall gain is

$$G_v = G_{v_1} + G_{v_2} + G_{v_3}$$
$$= 20\log(A_{v_1}) + 20\log(A_{v_2}) + 20\log(A_{v_3}) = 20\log A_v \text{ dB}$$

* Power gain in dB, $G_p = 10\log A_p$

RC coupled Amplifier



- A coupling capacitor C_c is used to connect the output of first stage to the base i.e input of the second stage. As the coupling from one stage to next is achieved by a coupling capacitor followed by a connection to a shunt resistor, therefore such amplifier is called Resistance-capacitance or RC coupled amplifier.

- The coupling capacitor C_c transmit ac signal but blocks d.c. This prevents dc interference between various stages & the shifting of operating point.

- When ac signal is applied to the base of the first transistor, it appears in the amplified form across its collector load R_c. The amplified signal developed across R_C is given to the base of next stage through coupling capacitor C_c.

- The second stage does further amplification of the signal. So the cascaded stages amplify the signal & the overall gain is considerably increased.

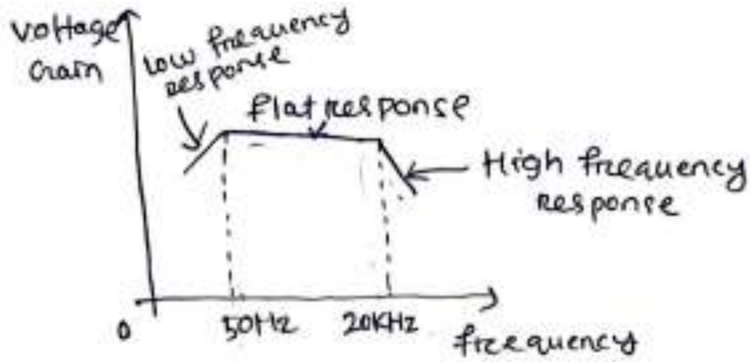
Frequency Response

(i) Low frequency :- The reactance of coupling capacitor C_c is high & hence very small part of signal will pass from one stage to the next stage. C_E can not shunt the emitter resistance R_E because of its large reactance at low frequency.

Therefore voltage gain falling at low frequencies.

(ii) High frequency : The reactance of C_c is very small & it behaves as a short circuit. This increases the loading effect of next stage & serves to reduce the voltage gain. At high frequency capacitive reactance of base emitter junction is low which increases the base current. This reduces the β. So the voltage drops off at high frequency.

(iii) Mid Frequency : The effect of coupling capacitor C_c decreases which tends to increase the gain, at the frequency increases. lower the reactance means higher loading of first stage & hence lower gain. These two factors almost cancel each other, resulting in a uniform gain at mid-frequency.



Advantages

(i) It has excellent frequency response.

(ii) It has lower cost since it employs resistors & capacitors which are cheap.

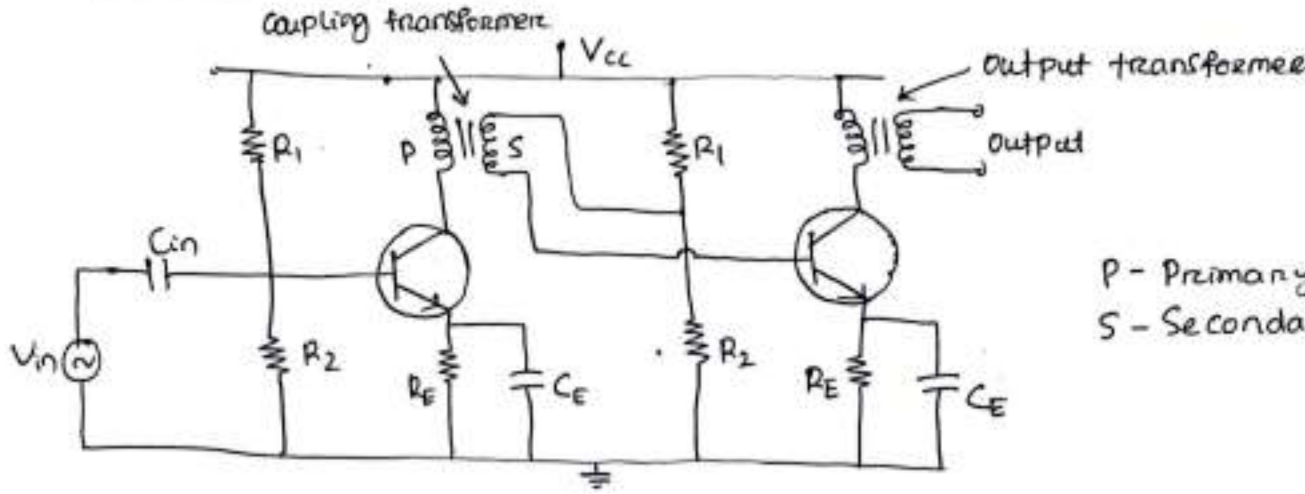
(iii) The circuit is very compact as the modern resistors & capacitors are small & extremely light.

Disadvantage

(i) The RC coupled amplifiers have low voltage & power gain.

(ii) Impedance matching is poor.

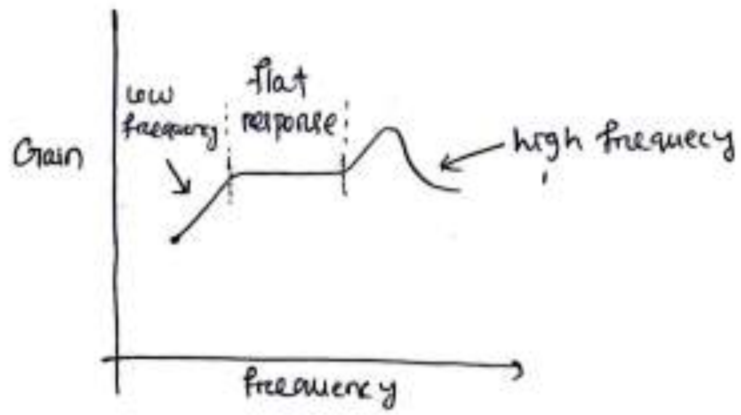
Transformer coupled Amplifier



P - Primary
S - Secondary

- Transformer coupling is generally employed when the load is small. It is mostly used for power amplification.
- A coupling transformer is used to feed the output of one stage to the input of the next stage. The primary P of this transformer is made the collector load and its secondary S gives input to the next stage.
- when a c signal is applied to the base of first transistor, it appears in the amplified form across primary P of the coupling transformer. The voltage developed across primary is transferred to the input of the next stage by the transformer secondary.

Frequency Response



- Gain is constant only over a small range of frequency.
- At low frequencies, the reactance of primary begins to fall, resulting in decreased gain.

- At high frequency the capacitance between turns of windings acts as a bypass condenser to reduce the output voltage & hence gain.

- There will be disproportionate amplification of frequencies in a complete signal. Hence transformer coupled amplifier introduces frequency distortion.

Advantage

(i) No signal power is lost in the collector or base resistors.

(ii) An excellent impedance matching can be achived in a transformer coupled amplifier.

(iii) Due to impedance matching, transformer coupling provides higher gain.

Disadvantage

(i) It has a poor frequency response.

(ii) The coupling transformers are bulky & fairly expensive.

(iii) Frequency distortion is higher.

Feedback in Amplifier

Feedback: It refers to mixing a part of the amplifier output with applied input.

Feedback signal is proportional to output signal

$$x_f \propto x_o$$

$$x_f = \beta x_o \qquad (\beta : \text{Feedback factor})$$

$$\beta = \frac{x_f}{x_o}$$

(i) If feedback signal gets added to applied input, it is called positive feedback.

$$\boxed{x_i = x_s + x_f}$$

x_s : Applied input

x_f : Feedback Signal ($x_f = \beta x_o$)

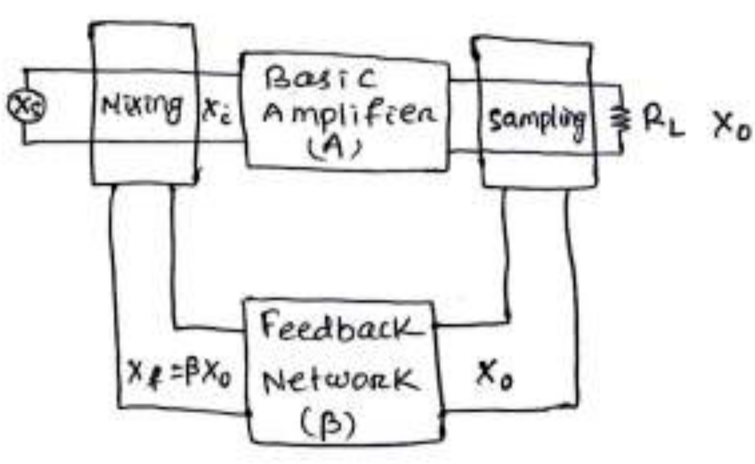
x_i : Net input

- positive feedback is used in oscillators to generate an ac waveform.

(ii) If feedback signal is subtracted from the applied input it is called negative feedback.

$$\boxed{x_i = x_s - x_f}$$

- In negative feedback applied input & feedback signal are out of phase.



Feedback Network

In a feedback system the feedback network must be design :-

① To provide the type of feedback require. (positive or Negative)
② To provide the amount of feedback require (10%, 20% ... etc)
③ To provide type of feedback require. (voltage or current)

Sampling Technique

(i) If the output is voltage, the sampling must be done in parallel or in shunt with the output terminals. Such a sampling technique is called as voltage (or) shunt (or) node sampling.

(ii) If the output signal is current, the sampling must be done in series with the output terminals. Such a sampling technique is called as current (or) series (or) loop sampling.

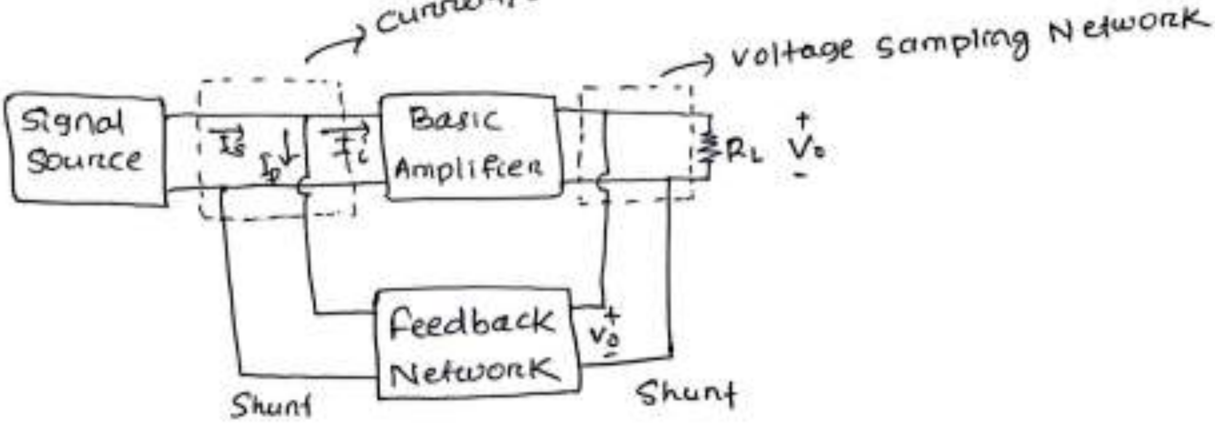
Mixing Technique

(i) If the source signal is voltage, the feedback signal should be voltage & it must be mixed in series with the existing voltage signal. Such a mixing technique is called as series (or) voltage (or) loop mixing.

(ii) If the source signal is current, the feedback signal should be current & it must be mixed in shunt with the existing source signal of the amplifier. Such a mixing technique is called as shunt (or) current (or) node mixing.

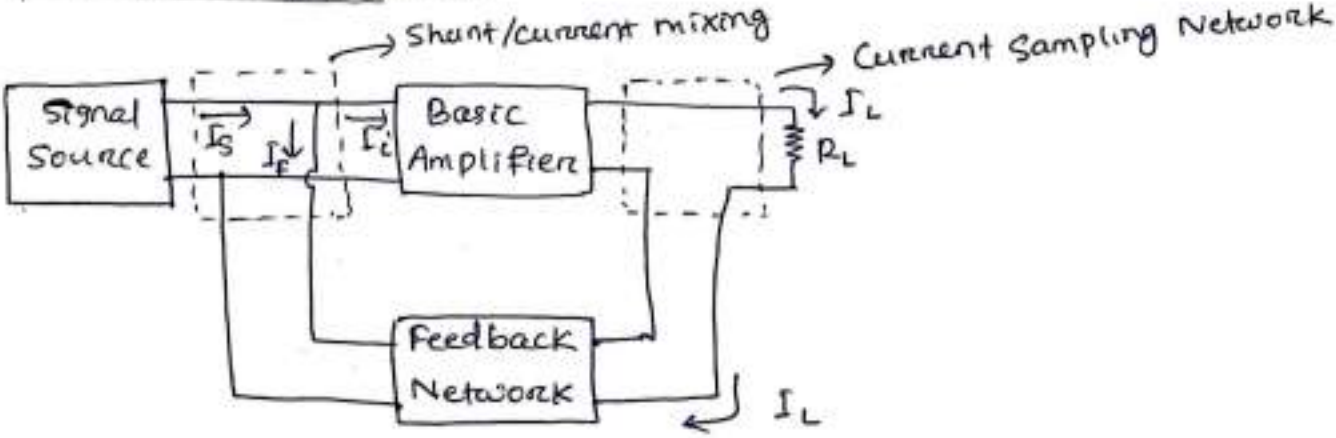
Types of feedback

① Shunt-Shunt Feedback



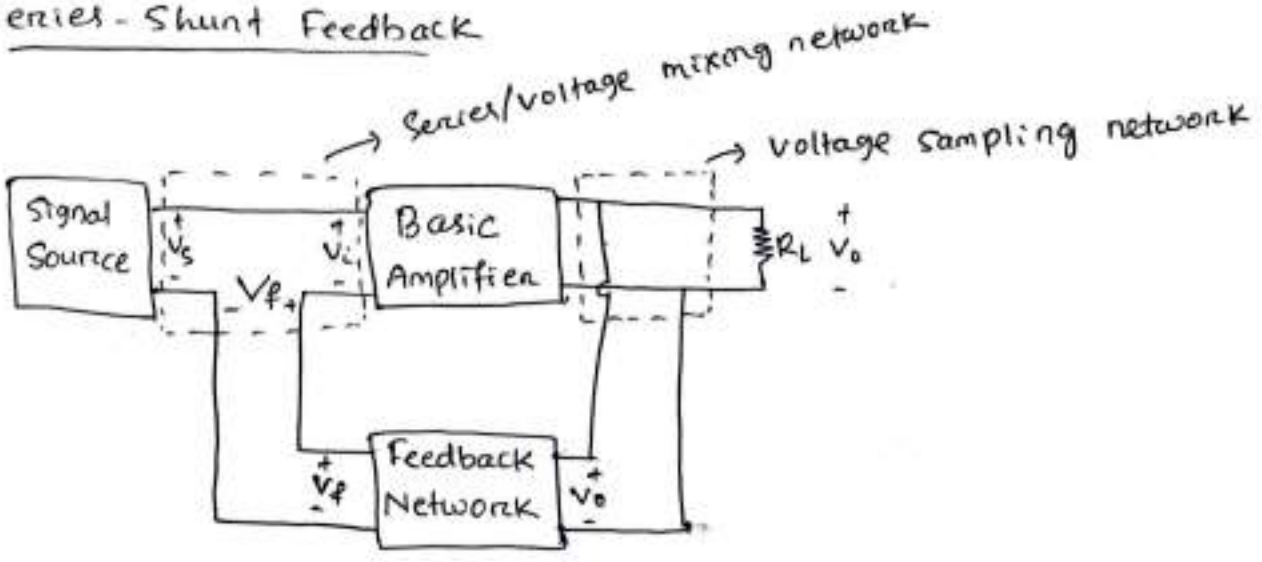
- If feedback network is connected in shunt with load resistor then output voltage Vo will appear as input to feedback network.
- Shunt-shunt feedback is also called voltage-shunt feedback or voltage-current feedback.
- Voltage shunt feedback is also called transresistance amplifier because input is current & output is voltage.

② Shunt-Series Feedback



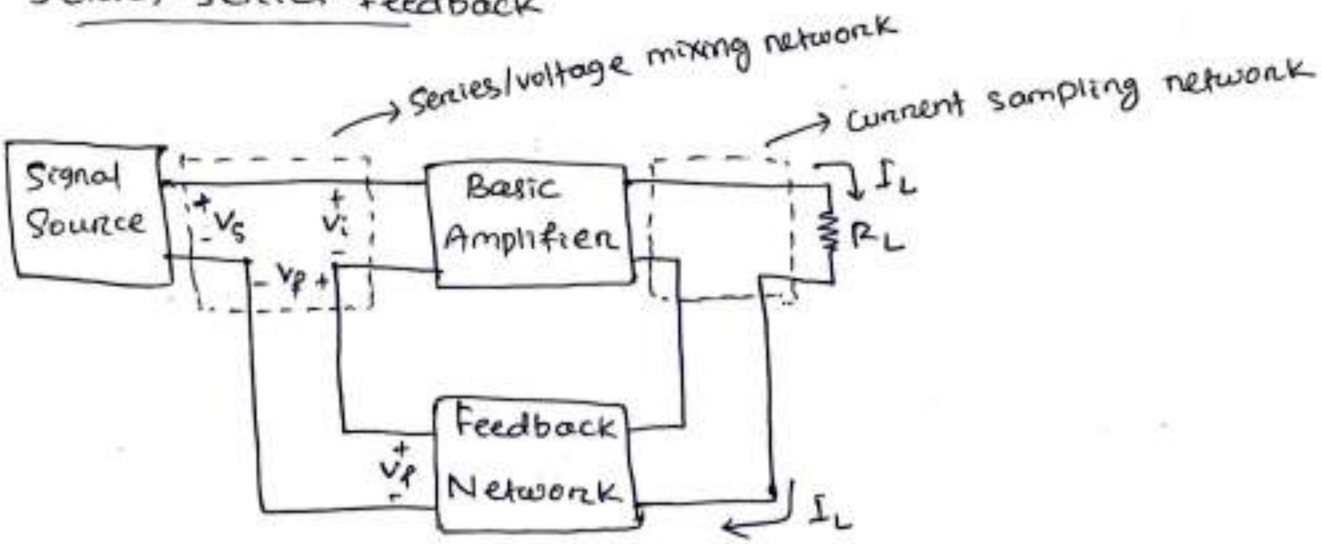
- If feedback network is in series with R_L then load current will appear as input to feedback network. It is called current sampling
- Shunt series feedback is also called current-shunt feedback (or) current-current feedback or current feedback.
- Current shunt feedback is a current feedback.

③ Series-Shunt Feedback



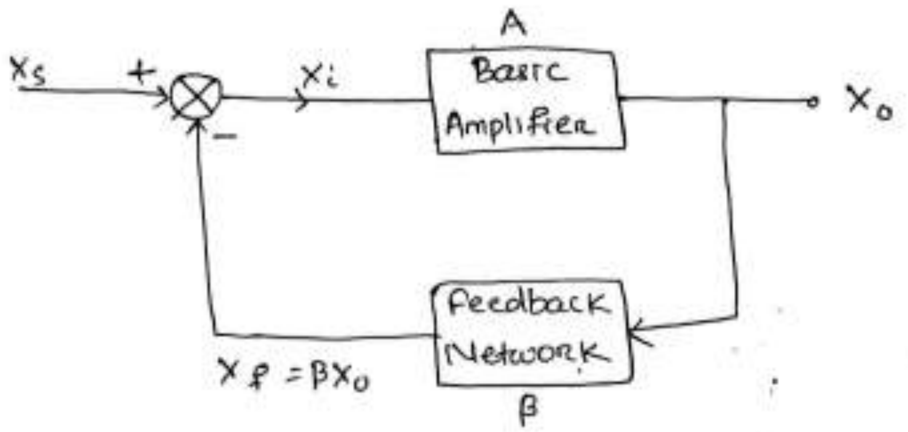
- Series-shunt feedback is voltage series feedback or voltage-voltage feedback or voltage feedback
- It is a voltage amplifier

④ Series-Series Feedback



- Series-series feedback is current-series or current-voltage amplifier.
- It is a transconductance amplifier.

Negative Feedback



- when the feedback voltage or current is out of phase with the input signal and thus opposes it, it is called negative feedback.

- Feedback network is a passive network. It consists of resistors in negative feedback.

Gain

A : Gain of Basic amplifier , $A = \frac{x_o}{x_i}$

A_f : Gain of feedback Amplifier , $A_f = \frac{x_o}{x_s}$

$$x_i = x_s - x_f$$

$$x_s = x_i + x_f = x_i + \beta x_o$$

$$x_s = x_i + A\beta x_i = x_i(1 + A\beta)$$

$$A_f = \frac{x_o}{x_s} = \frac{x_o}{x_i(1+A\beta)}$$

$$\boxed{A_f = \frac{A}{1+A\beta}}$$

Negative feedback is used in amplifier :-

(i) To make the gain stable.

(ii) To reduce distortion.

(iii) To obtain desired values of input & output impedances.

(iv) To increase Bandwidth.

Advantage of Negative Feedback

(i) Amplifier gain can be made independent of transistor parameters or supply voltage variations. Hence the gain of Amplifier is extremely Stable.

(ii) The negative feedback reduces the non-linear distortion in large signal amplifiers.

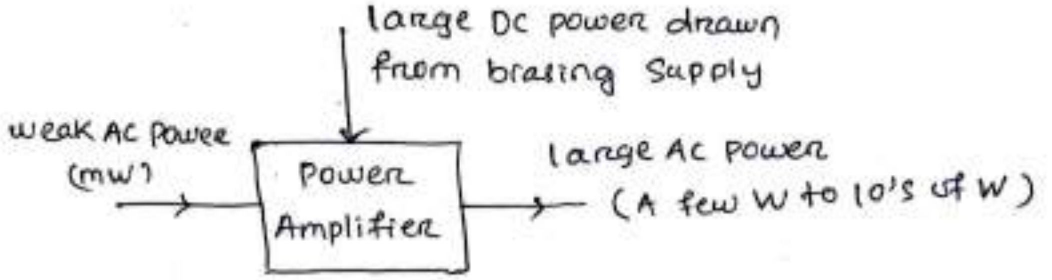
(iii) The negative feedback improves the frequency response of the amplifier.

(iv) The negative feedback increases the input impedance and decreases the output impedance of amplifier.

(v) Negative feedback improves or increases Bandwidth.

Power Amplifier

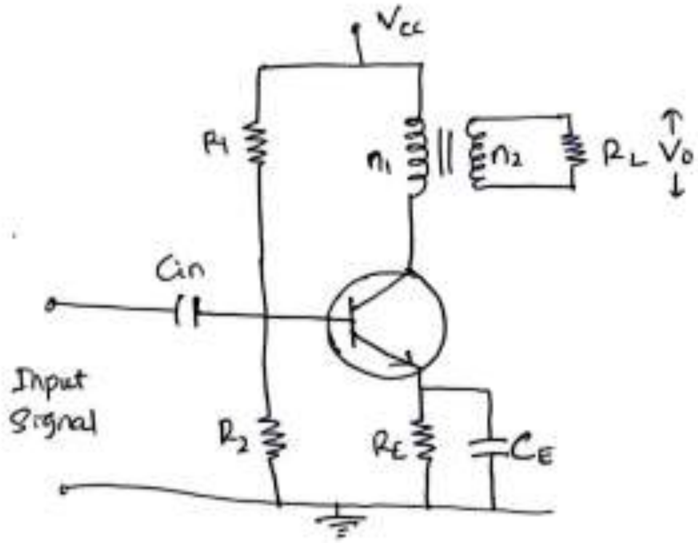
- It is a large signal amplifier.
- Due to large signal variation it has large AC output current & voltage. Hence it can supply large AC signal power to load.
- In power amplifier, a power transistor is used which is operated at a greater I_c & V_{CE}.
- A power amplifier supplies large AC power to load because it internally convert a part of DC power drawn from biasing supply into AC power.



Difference Between Voltage & Power Amplifiers

Voltage Amplifier	Power Amplifier
- It is designed to achieve maximum voltage amplification	- It is designed to obtain maximum output power.
- β value is high.	- β value is low.
- Collector resistance, R_C is high.	- R_C is low.
- R-C coupling is used.	- Transformer coupling is used.
- Input voltage is low.	- Input voltage is high.
- Collector current is low.	- Collector current is high.
- Power output is low.	- Power output is high.
- Output impedance is high.	- Output impedance is low.

Transformer coupled class A power Amplifier



- Transformer coupling is prefered in power amplifiers because -

(i) It results in better efficiency.

(ii) Maximum power can be transfered to load due to impedance matching property of transformer.

(iii) It provides DC isolation between amplifier & load.

DC load line

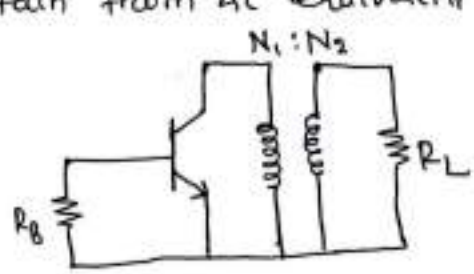
$$-V_{cc} + \underbrace{I_c \cdot 0}_{} + V_{CE} = 0$$

Internal resistance of primary winding

$$\boxed{V_{CE} = V_{cc}} \rightarrow \text{DC load line} \quad \text{(vertical line)}$$

AC load line

obtain from AC equivalent



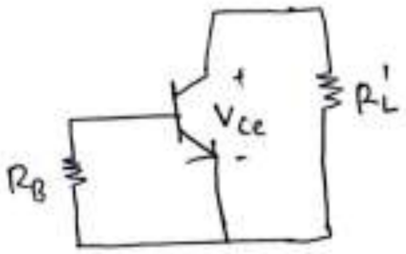
$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow V_1 = \frac{N_1}{N_2} V_2$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \Rightarrow I_1 = \frac{N_2}{N_1} I_2$$

$$R_L' = \left(\frac{N_1}{N_2}\right)^2 R_L \qquad \left(\frac{V_1}{I_1} = R_L' \; , \; \frac{V_2}{I_2} = R_L \right)$$

$$R_L' = n^2 R_L \qquad \left(n = \frac{N_1}{N_2} \right)$$

At medium frequencies primary & secondary windings offer high reactance, Hence they are replaced with open circuit.

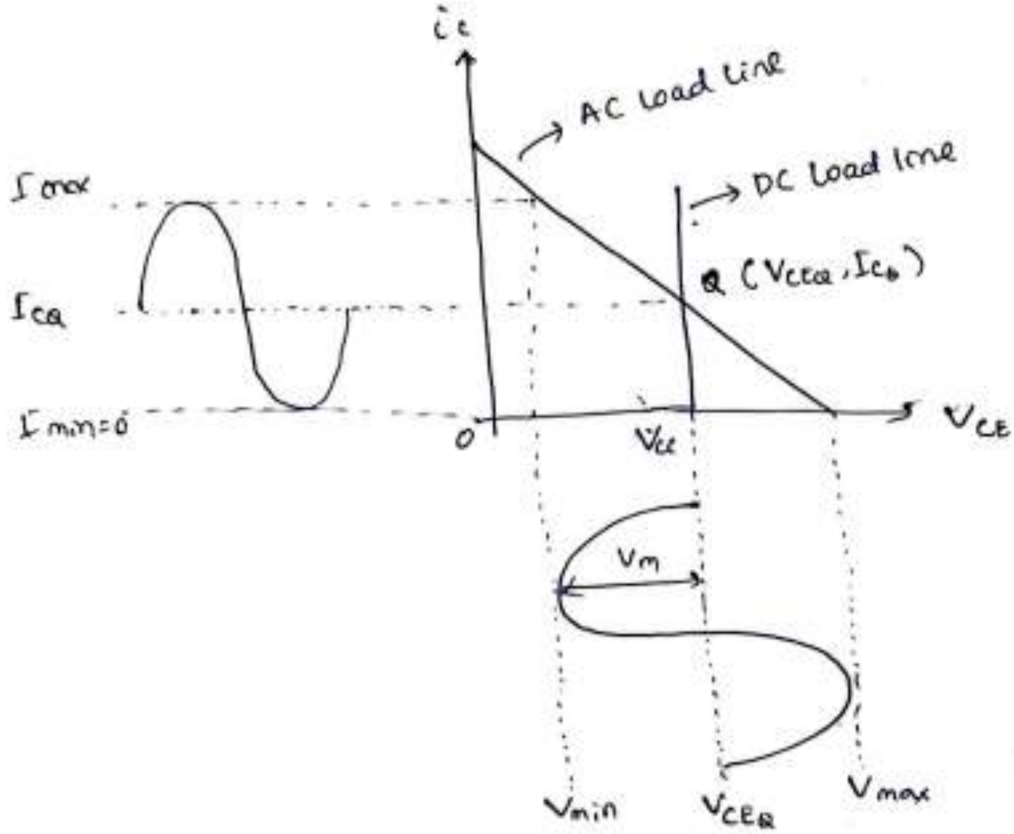


$$i_c R_L' + v_{ce} = 0$$

$$i_c = -\frac{1}{R_L'} \times v_{ce}$$

$$(i_c - i_{cQ}) = -\frac{1}{R_L'}(v_{CE} - V_{CEQ})$$

- AC load line has slope $-\frac{1}{R_L'}$ & it passes through the Q-point.



conversion efficiency

$$\%\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$

AC signal power supplied to load is multiplication of RMS o/p voltage & current.

$$P_{AC} = V_{RMS} \times I_{RMS}$$

$$= \frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} = \frac{V_m I_m}{2}$$

$$P_{AC} = \frac{(V_{cc} - V_{min})}{2} I_{CQ}$$

$$P_{DC} = V_{CC}(I_{CQ} + I_B)$$

$$P_{DC} \simeq V_{CC} I_{CQ}$$

$$\eta\% = \frac{\frac{(V_{CC} - V_{min})}{2} I_{CQ}}{V_{CC} I_{CQ}} \times 100$$

$$\boxed{\eta\% = \frac{V_{CC} - V_{min}}{V_{CC}} \times 50\%}$$

- If Q point is exactly at centre & signal variation is maximum possible then $V_{min} = 0$ & efficiency of 50% can be achieved.

Transformer coupling results in greater efficiency because -

(i) Power dissipation in primary winding is zero

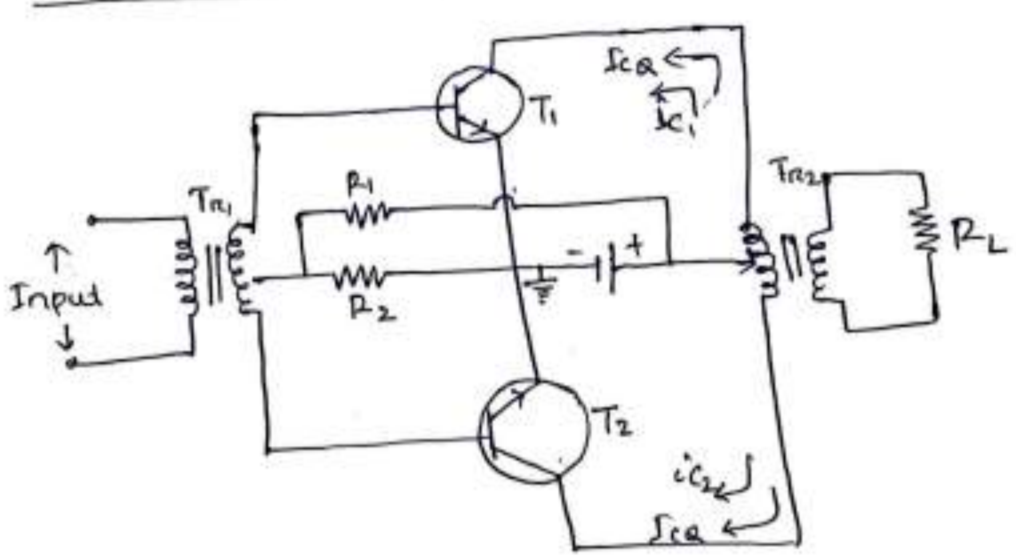
(ii) DC power dissipation in load is zero.

Application

- class A transformer coupled amplifier is used as audio frequency power amplifier.

-

Class A push pull Amplifier



- In push-pull arrangement, the two identical transistors T_1 & T_2 have their emitter terminals shorted.

- The input signal is applied to the transistors through the transformer T_{R_1} which provides opposite polarity signals to both the transistor bases.

- The output is collected from the output transformer T_{R_2}. The primary of this transformer T_{R_2} has practically no dc component through it. The transistors T_1 & T_2 have their collectors connected to the primary of transformer T_{R_2} so that their currents are equal in magnitude & flow in opposite directions through the primary of transformer T_{R_2}.

- When the ac input signal is applied, the base of transistor T_1 is more positive while the base of transistor T_2 is less positive. Hence the collector current i_{c_1} of transistor T_1 increases while the collector current i_{c_2} of transistor T_2 decreases. These currents flow in opposite directions in two halves of the primary of output transformer. The flux produced by these currents will also be in opposite directions.

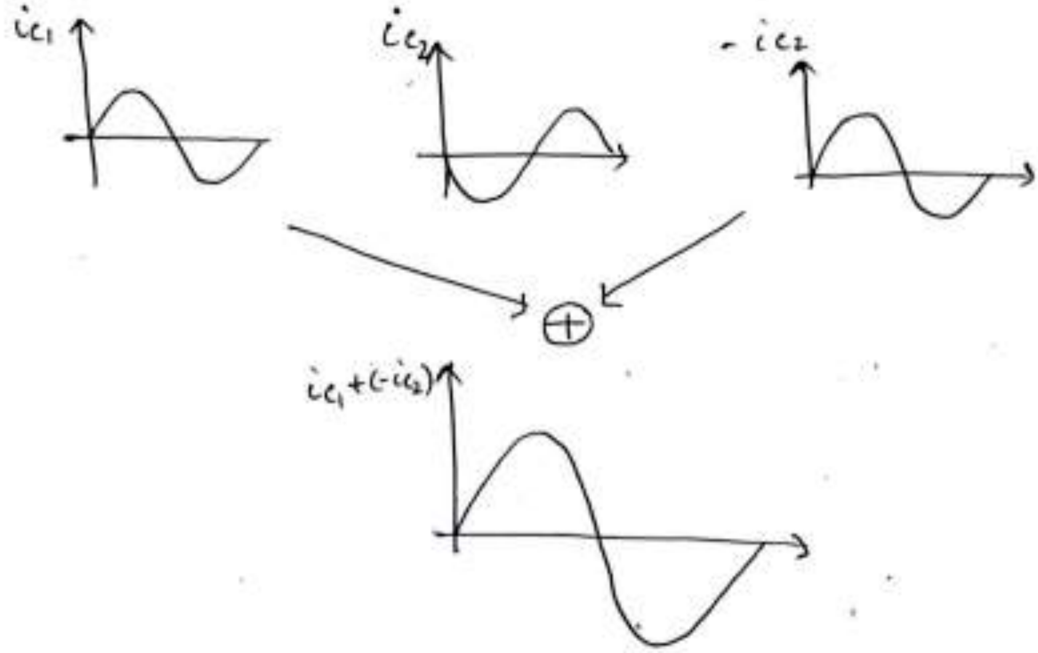
- Hence the voltage across the load will be induced voltage whose magnitude will be proportional to the difference of collector currents i.e $(i_{c_1} - i_{c_2})$

- Similarly for the negative input signal, the collector current i_2 will be more than i_{c_1}. In this case the voltage developed across the load will again be due to the difference $(i_{c_1} - i_{c_2})$

As $i_{c_2} > i_{c_1}$, the polarity of voltage induced across load will be reversed.

$$i_{c_1} - i_{c_2} = i_{c_1} + (-i_{c_2})$$

- The overall operation results in an ac voltage induced in the secondary of output transformer & hence ac power is delivered to that load.



- During any given half cycle of input signal, one transistor is being driven deep into conduction while the other being non-conducting. The harmonic distortion in push pull amplifier is minimized such that all the even harmonics are eliminated.

Advantages

- High ac output is obtained.
- The output is free from even harmonics.

Disadvantage

- The transformer used is centre-tapped. So it is bulky and costly.

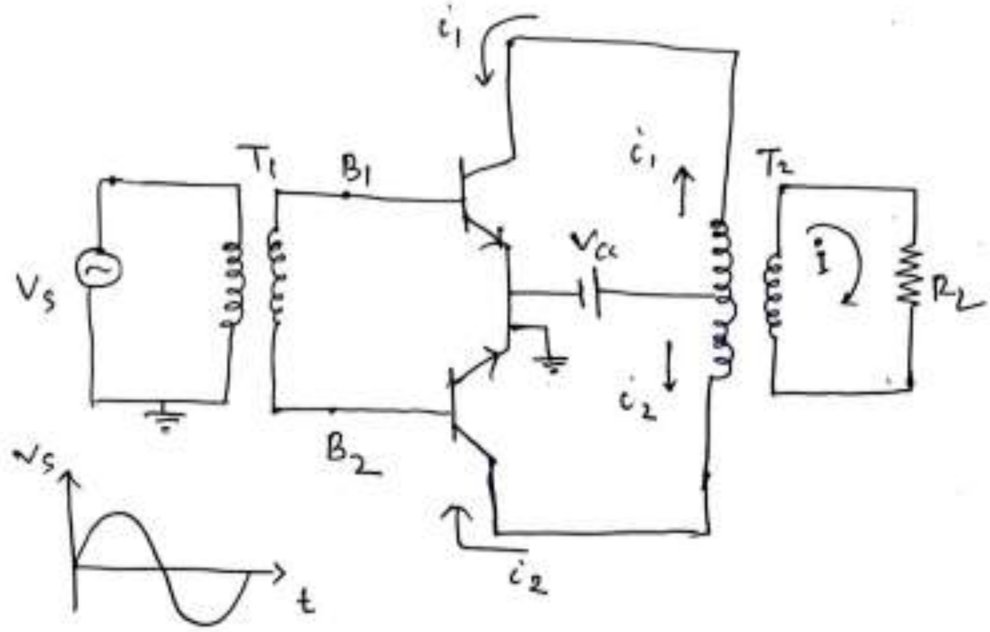
* Conversion efficiency :- Conversion efficiency describes the ability of power amplifier to convert DC power to AC power.

mathematically, $\eta = \dfrac{\text{AC signal power supplied to load}}{\text{DC power drawn from biasing supply}}$

* Figure of merit : It is the ratio of maximum power dissipation in the transistor & maximum AC signal power which can be supplied to load.

$$\boxed{F = \frac{P_{Omax}}{P_{ACmax}}}$$

Class - B push-pull amplifier



- If AC input V_s is not applied then both transistors remains off or they operate in cutoff because DC voltage between base & emitter is zero. Hence power dissipation of transformer will be zero in absence of AC input.

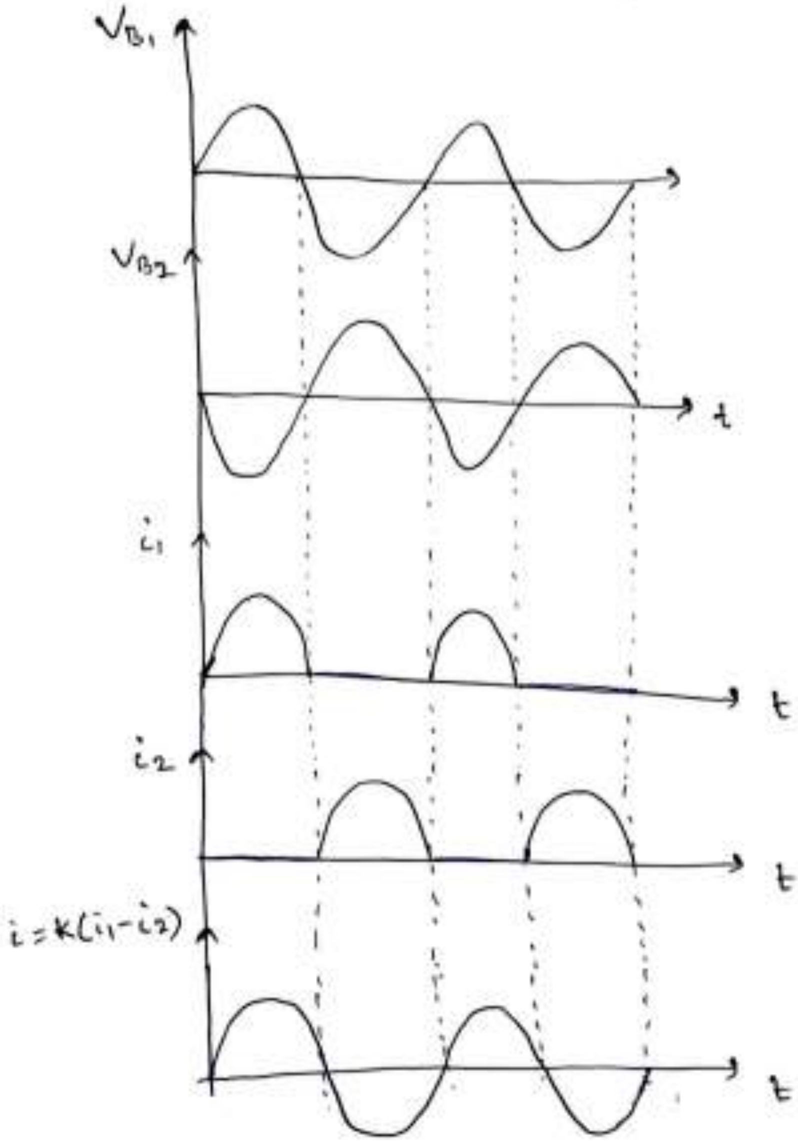
- When AC input is applied, AC voltages appear at the base of Q_1 & Q_2.

- Since secondary winding of input transformer T_1 is centre tapped, AC voltages which appear at B_1 & B_2 are equal in magnitude but opposite in sign.

- During 1st half cycle of V_s voltage is +ve at B_1 & -ve at B_2. Then Q_1 starts conducting & collector current I_1 is drawn from V_{cc} where Q_2 remains off.

- During 2nd half cycle of V_s voltage becomes -ve at B_1 & +ve at B_2. Then Q_1 becomes off & Q_2 starts conduction. Therefore collector current i_2 is drawn from V_{cc}.

- As i_1 & i_2 are in opposite direction in the primary winding of output transformer T_2, the resulting current through R_L will be bidirectional or sinusoidal.



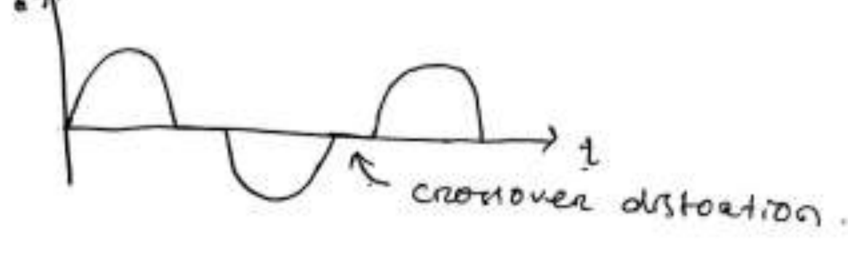
- Maximum efficiency of class-B push-pull amplifier is 78.5%

<u>Advantage</u>

- Greater efficiency
- Smaller Figure of merit
- Quiescent power dissipation is zero

<u>Disadvantage</u>

- class B push pull amplifier causes crossover distortion in the output signal.



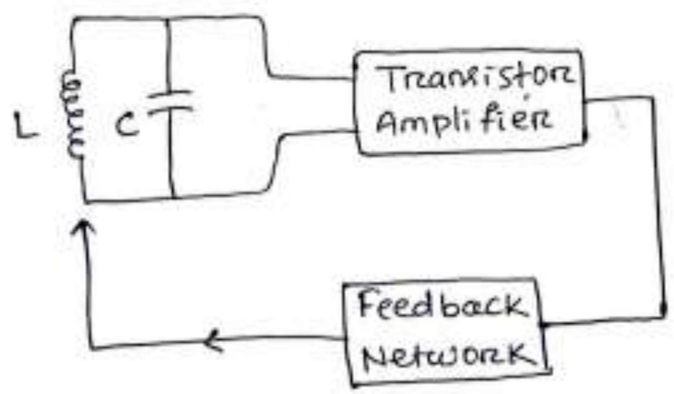
Oscillator

An electronic circuit which generates AC output waveform without any external AC input.

Types of transistor oscillator

(i) Tuned collector oscillator
(ii) Hartley oscillator
(iii) Colpitt's oscillator
(iv) phase shift oscillator
(v) wien Bridge oscillator

Essentials of transistor oscillator



① Tank circuit :- It consists of inductance coil L connected in parallel with capacitor C. The frequency of oscillations in the circuit depends upon the values of inductance of the coil and capacitance of the capacitor.

② Transistor Amplifier :- The transistor amplifier receives dc power from the battery and changes it into AC power for supplying to the tank circuit. The oscillations occuring in the tank circuit are applied to the input of the transistor amplifier. Because of the amplifying properties of the transistor, we get increased output of these oscillations.

③ Feedback circuit : The feedback circuit supplies a part of collector energy to the tank circuit in correct phase to aid the oscillation i.e it provides positive feedback.

Barkhausen criterion

Barkhausen criterion is that in order to produce continuous undamped oscillations at the output of an amplifier, the positive feedback should be such that:

$$\boxed{A\beta = 1}$$

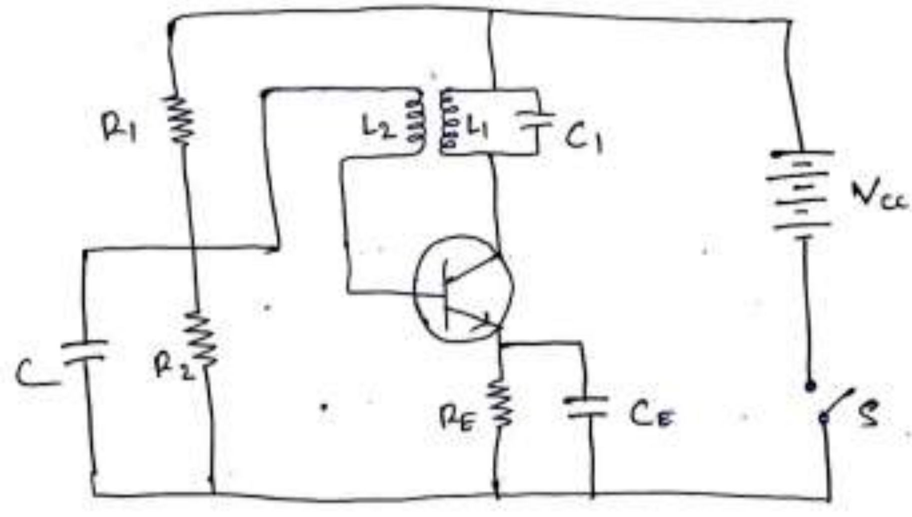
- A is the loop gain & β is the feedback factor.

Types of Transistor Oscillator

(i) Tuned collector oscillator

- It contains tuned circuit $L_1 - C_1$ in the collector. The frequency of oscillations depends upon the values of L_1 and C_1 & the frequency of oscillations is given by

$$\boxed{f = \frac{1}{2\pi\sqrt{L_1 C_1}}}$$



- When switch S is closed, collector current starts increasing and charges the capacitor C_1. When this capacitor is fully charged, it discharges through coil L_1, setting up oscillation.

- These oscillation induced some voltage in coil L_2 by mutual induction. The frequency of voltage in coil L_2 is the same as that of tank circuit but its magnitude depends upon the number of turns of L_2 and coupling between L_1 & L_2.

- The voltage across L_2 is applied between base and emitter and appears in the amplified form in the collector circuit. thus overcoming the losses occuring in the tank circuit.

- The number of turns of L_2 and coupling between L_1 & L_2 are so adjusted that oscillations across L_2 are amplified to a level just sufficient to supply losses, to the tank circuit.

- A phase shift of 180° is created between the voltages of L_1 and L_2 due to transformer action. A further phase shift of 180° takes place between base-emitter & collector circuit due to transistor property. As a result, the energy fedback to the tank circuit is in phase with the generated oscillations.

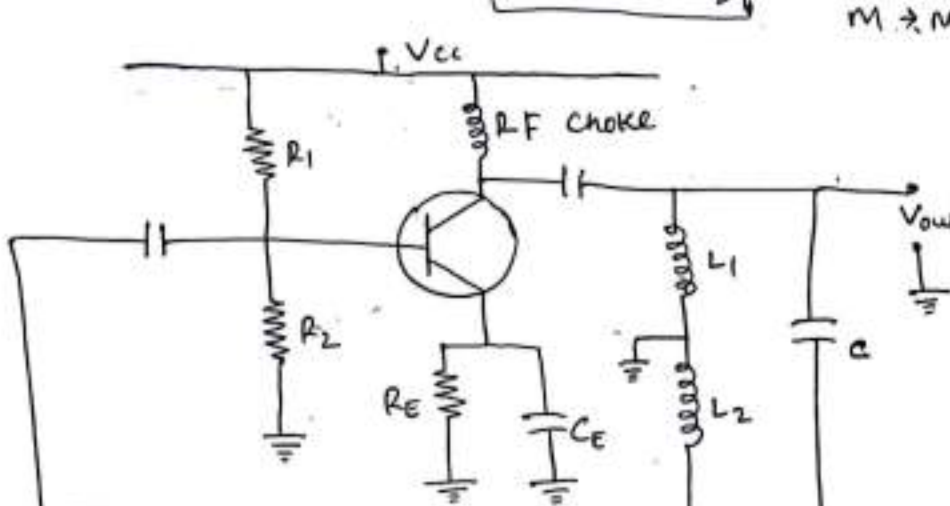
(ii) Hartley oscillator

The tank circuit is made up of L_1, L_2 and C. The frequency of oscillations is given by

$$\boxed{f = \frac{1}{2\pi\sqrt{C L_{eq}}}}$$

$L_{eq} = L_1 + L_2 + 2M$

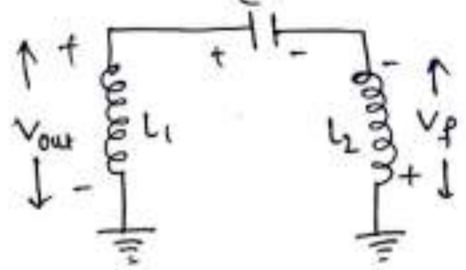
M → Mutual Inductance



- When circuit is turned on, the capacitor is charged. When this capacitor is fully charged, it discharges through coils L_1 & L_2 setting up oscillations.

- The output voltage of the amplifier appears across L_1 & feedback voltage across L_2.

- The voltage across L_2 is 180° out of phase with the voltage developed across L_1 (V_{out}). It is easy to see that voltage feedback (i.e voltage across L_2) to the transistor provides positive feedback.

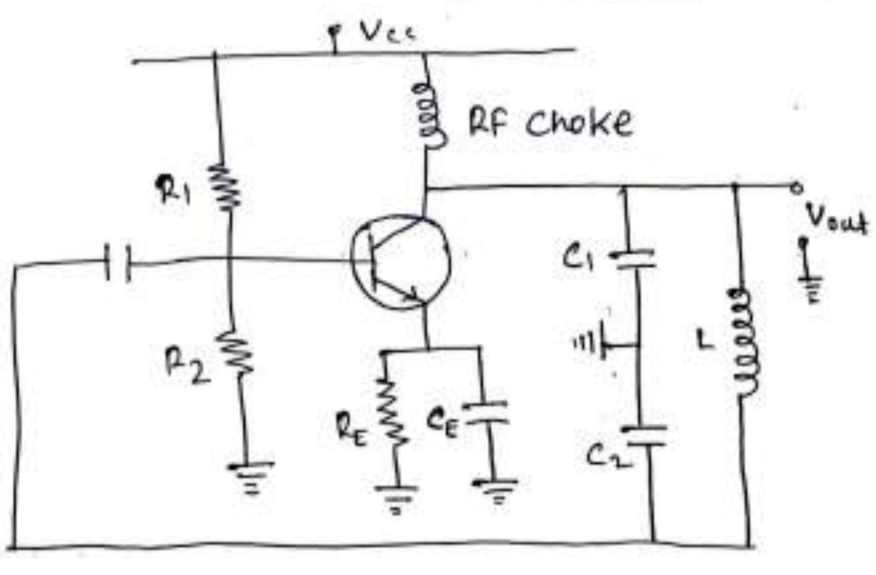


- A phase shift of 180° is produced by the transistor and a further phase shift of 180° is produced by L_2-L_1 voltage divider.

(iii) <u>Colpitt's oscillator</u>

The tank circuit is made up of C_1, C_2 & L. The frequency of oscillations is given by :-

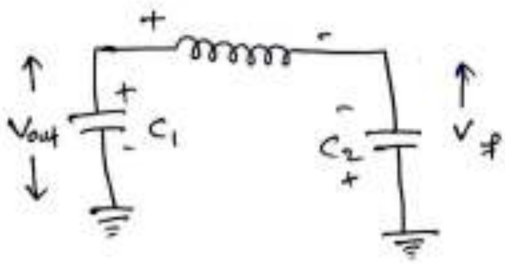
$$\boxed{f = \frac{1}{2\pi\sqrt{LC_{eq}}}} \qquad C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$



- When the circuit is turned on, the capacitors C_1 & C_2 are charged. The capacitors discharge through L, setting up oscillations.

- The output voltage of the amplifier appears across C_1 & feedback voltage is developed across C_2. The voltage across it is 180° out of phase with the voltage developed across C_1 (V_{out}).

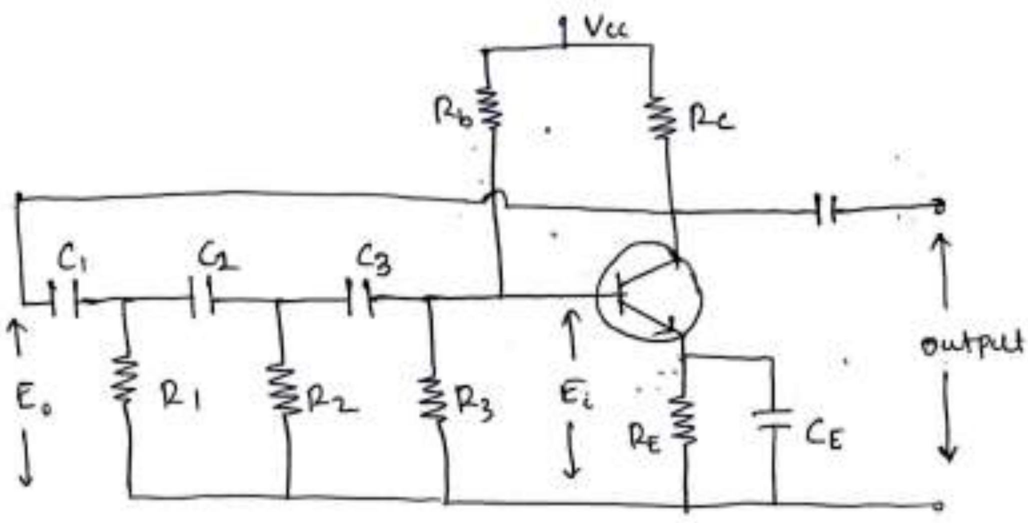
- A phase shift of 180° is produced by the transistor & a further phase shift of 180° is produced by C_1-C_2 voltage divider. Hence feedback is properly phased to produced continuous undamped oscillation.



(iv) Phase shift oscillator

- The phase shift network consists of three sections R_1C_1, R_2C_2 & R_3C_3.
- At some particular frequency f_0, the phase shift in each RC section is 60° so that the total phase-shift produced by the RC network is 180°. The frequency of oscillations is given by :-

$$\boxed{f_0 = \frac{1}{2\pi RC\sqrt{6}}} \qquad \begin{aligned} R_1 = R_2 = R_3 &= R \\ C_1 = C_2 = C_2 &= C \end{aligned}$$



- when the circuit is switched on, it produces oscillations.
- The output E_0 of the amplifier is fed back to RC feedback network. This network produces a phase shift of 180° and a voltage E_i appears at its output which is applied to the transistor amplifier.
- A phase shift of 180° is produced by the transistor amplifier. A further phase shift of 180° is produced by the RC network. As a result, the phase shift around the entire loop is 360°.

Advantages

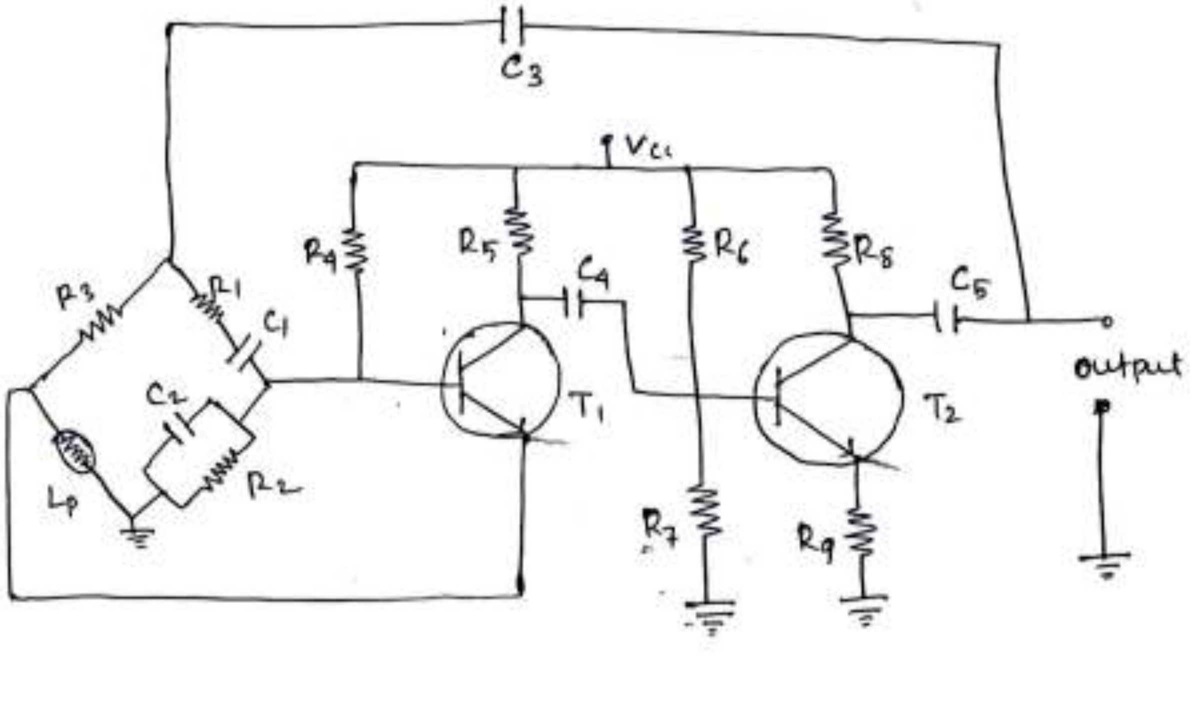
- It does not required transformers or inductors
- It can be used to produce very low frequencies.
- The circuit provides good frequency stability.

Disadvantages

- It is difficult for the circuit to start oscillations as the feedback is generally small.
- The circuit gives small output.

(v) wein Bridge oscillator

- It is a two-stage amplifier with RC bridge circuit.



Frequency of oscillation :-

$$\boxed{f = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}}$$

If $R_1 = R_2 = R$

$C_1 = C_2 = C$, then,

$$\boxed{f = \frac{1}{2\pi RC}}$$

- When the circuit is started, bridge circuit produces oscillation.
- The two transistors produce a total phase shift of 360° so that proper positive feedback is maintained.

Advantages

- It gives constant output.
- The circuit works quite easily.
- The overall gain is high because of two transistor
- The frequency of oscillations can be easily changed by using a potentiometer.

Disadvantage

- The circuit requires two transistors and a large number of components.
- It cannot generate very high frequency.

Field Effect Transistor (FET)

Classification of FET

- FET
  - JFET (Junction Field Effect Transistor)
    - N-channel
    - P-channel
  - MOSFET (metal oxide semiconductor FET)
    - Depletion type
      - N-Channel
      - P-channel
    - Enhancement type
      - N-Channel
      - P-Channel

Advantage of FET over BJT

- FET is simpler to fabricate & occupies less space in integrated form.
- It exhibits a high input resistance, typically many megaohms.
- FET is less noisy than a BJT.
- It exhibits no offset voltage at zero drain current and hence makes an excellent signal chopper.
- It has higher switching speed.
- It has longer life & high efficiency.

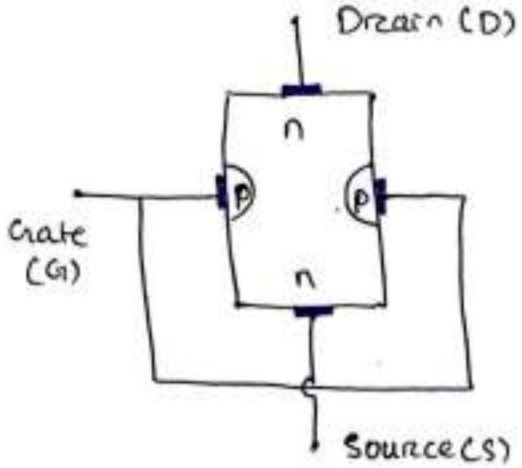
Junction Field Effect Transistor (JFET)

A JFET is a three terminal semiconductor device in which current conduction is by one type of charge carrier i.e electrons or holes.

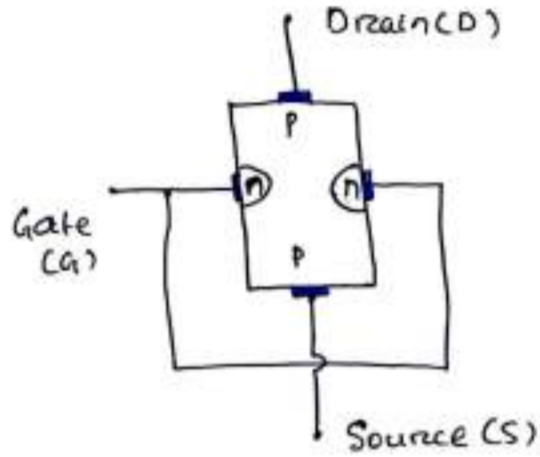
- A JFET consists of a p-type or n-type similar bar containing two pn junctions at the sides. The bar forms the conducting channel for the charge carriers.
- If the bar is of n-type, it is called n-channel JFET & if the bar is of p-type, it is called a p-channel JFET.

- A JFET has essentially three terminals :-

(i) gate (G)
(ii) Source (S
(iii) Drain (D)

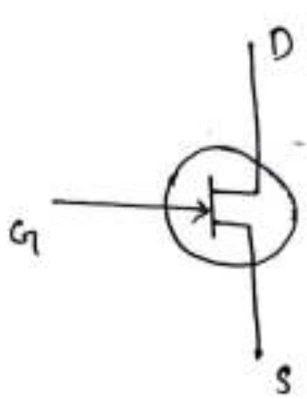


(n-channel JFET)

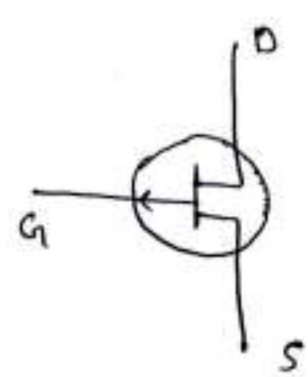


(P-channel JFET)

- The input circuit of a JFET is reverse biased. This means that the device has high input impedance.
- The drain to source is so biased that drain current I_D flows from the source to drain.
- In all JFETs, Source current I_S is equal to the drain current i.e $I_S = I_D$.



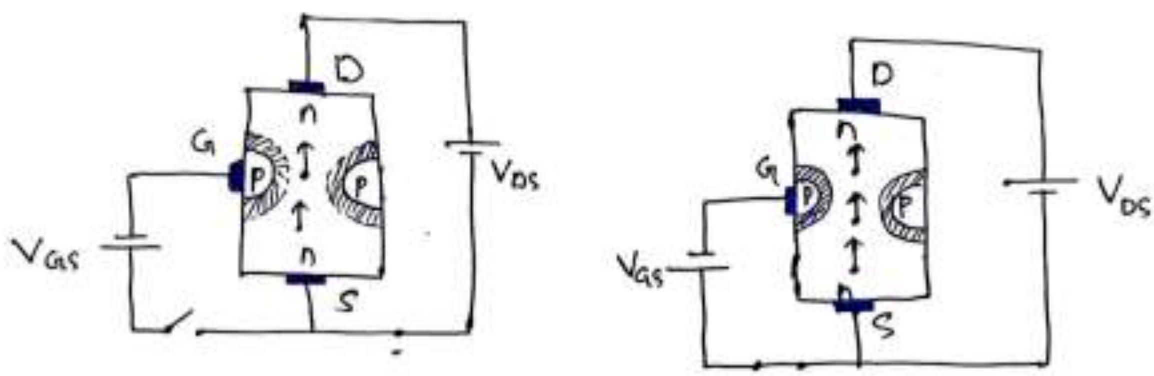
(n-channel JFET)



(P-Channel JFET)

Principle of operation of JFET

Consider an n-channel JFET



- The two pn junctions at the sides form two depletion layers. The current conduction by charge carriers is through the channel between the two depletion layers & out of the drain.
- The width & hence resistance of this channel can be controlled by changing the input voltage V_{GS}. The greater the reverse voltage V_{GS}, the wider will be the depletion layers & narrower will be the conducting channel. The narrower channel means greater resistance & hence source to drain current decreases. If V_{GS} decreases wide channel results smaller resistance & hence source to drain current increases.
- Therefore FET operates on the principle that width and hence resistance of the conducting channel can be varied by changing the reverse voltage V_{GS}. The magnitude of drain current I_D can be changed by altering V_{GS}.

Working

- When a voltage V_{DS} is applied between drain & source terminals & voltage on the gate is zero, the two pn junctions at the sides of the bar establish depletion layers.
- The electrons will flow from source to drain through a channel between the depletion layers. The size of these layers determines the width of the channel & hence the current conduction through the bar.

- when a reverse voltage V_{GS} is applied between the gate & source, the width of the depletion layers is increased. This reduces the width of conducting channel, thereby increasing the resistance of n-type bar.

- So the current from source to drain is decreased. If the reverse voltage on the gate is decreased, the width of the depletion layers also decreases. This increases the width of the conducting channel & hence source to drain current.

- Current from source to drain can be controlled by the application of potential i.e electric field on the gate. Therefore the device is called field effect transistor.

- For a p-channel JFET current carriers will be the holes instead of electrons & the polarities of V_{GS} & V_{DS} are reversed.

Pinch off voltage (V_P)

It is the minimum drain-source voltage at which the drain current essentially becomes constant.

Shockley Equation

$$\boxed{I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2}$$

Parameters of JFET

(i) AC drain resistance

(ii) Transconductance

(iii) Amplification factor

(iv) DC drain resistance

(i) Ac drain resistance (r_d)

It is the ratio of change in drain-to source voltage (ΔV_{DS}) to the change in drain current (ΔI_D) at constant gate to source voltage i.e.

$$\text{ac drain resistance, } r_d = \frac{\Delta V_{DS}}{\Delta I_D} \quad \text{at constant } V_{GS}$$

- It is also called dynamic drain resistance.

(ii) Transconductance (g_m)

It is the ratio of change in drain current (ΔI_D) to the change in gate-source voltage (ΔV_{GS}) at constant drain to source voltage i.e

$$\text{Transconductance, } g_m = \frac{\Delta I_D}{\Delta V_{GS}} \quad \text{at constant } V_{DS}$$

(iii) Amplification factor (μ)

It is the ratio of change in drain to source voltage (ΔV_{DS}) to the change in gate to source voltage (ΔV_{GS}) at constant drain current i.e

$$\text{Amplification factor, } \mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} \quad \text{at constant } I_D$$

(iv) DC drain resistance (R_{DS})

It is given by the ratio of voltage (V_{DS}) to the drain current (I_D). Mathematically dc drain resistance,

$$R_{DS} = \frac{V_{DS}}{I_{DS}}$$

- It is also called the static or ohmic resistance of the channel.

Relation among the parameters of FET

we know,

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}}\bigg|_{I_D = \text{constant}} \quad \text{--- (1)}$$

multiply & divide by ΔI_D in eqn (1)

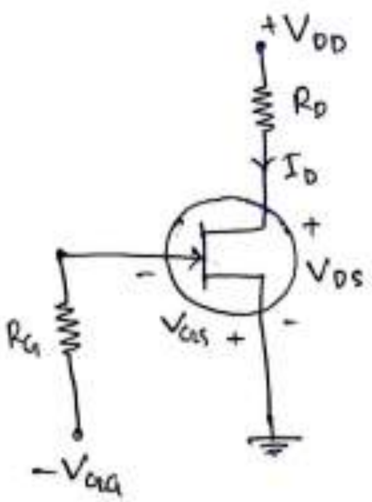
$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} \times \frac{\Delta I_D}{\Delta I_D}$$

$$\mu = \frac{\Delta V_{DS}}{\Delta I_D} \times \frac{\Delta I_D}{\Delta V_{GS}}$$

$$\boxed{\mu = r_d \times g_m}$$

Biasing of JFET.

(1) Gate bias circuit



V_{DD} : Drain supply

V_{GG} : Gate supply

Since $I_G = 0$, There will be no voltage drop across R_G.

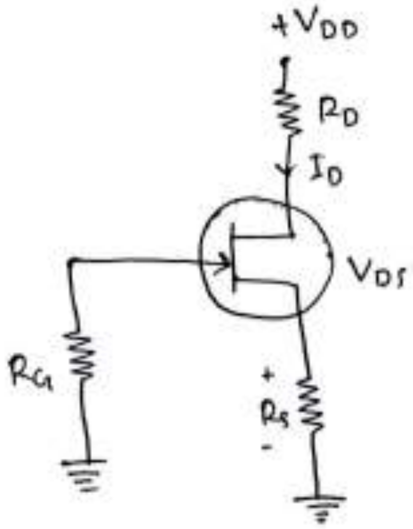
KVL at i/p : $\boxed{V_{GG} = V_{GS}}$

we can find the value of I_D from $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$

KVL at o/p : $-V_{DD} + I_D R_D + V_{DS} = 0$

$$\Rightarrow \boxed{V_{DS} = V_{DD} - I_D R_D}$$

② Self Bias



R_S : self bias resistor

$(I_G = 0)$

KVL at I/p :-

$$I_G R_G + V_{GS} + I_D R_S = 0$$

$$\boxed{V_{GS} = -I_D R_S}$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

KVL at O/p :

$$-V_{DD} + I_D R_D + V_{DS} + I_D R_S = 0$$

$$\Rightarrow \boxed{V_{DS} = V_{DD} - I_D(R_D + R_S)}$$

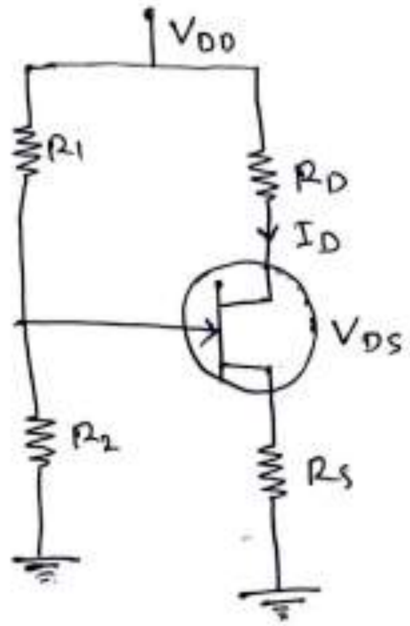
Advantage

- Single biasing supply is needed.
- Resistor R_S causes -ve feedback which helps in keeping the drain current stable.

Disadvantage

- Negative feedback reduces voltage gain.

③ Voltage Divider Bias



$$V_G = \frac{V_{DD} \times R_2}{R_1 + R_2}$$

(voltage division rule)

$$V_{GS} = V_G - V_S$$

$$V_{GS} = V_G - I_D R_S \qquad \left(V_G = \frac{V_{DD} \times R_2}{R_1 + R_2} \right)$$

KVL at o/p :

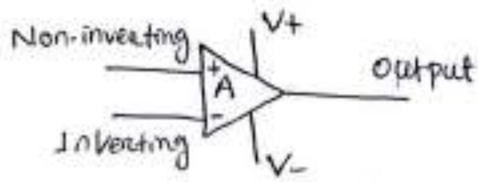
$$-V_{DD} + I_D R_D + V_{DS} + I_D R_S = 0$$

$$\Rightarrow V_{DS} = V_{DD} - I_D R_D - I_D R_S$$

$$\Rightarrow \boxed{V_{DS} = V_{DD} - I_D (R_D + R_S)}$$

Operational Amplifier (OP-AMP)

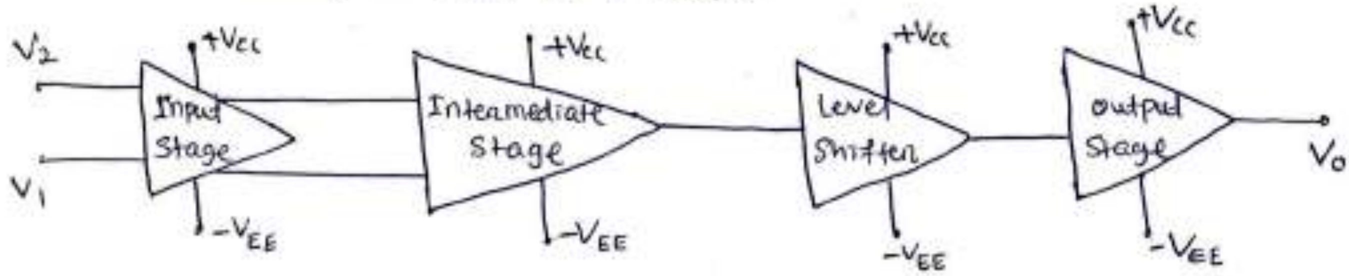
- It is a direct coupled amplifier having high voltage gain.
- It can be used to perform mathematical operations on analog signals. Hence it is called operational amplifier.
- Opamp is available as IC 741 : General purpose OPAMP IC



A : open loop gain

Operational Amplifier Stages

- IC 741 internally consists of 4 stages.



- Input stage is dual input, balance output differential amplifier.
- Intermediate stage is dual input, unbalanced output differential amplifier.
- Two differential amplifier are used in the internal circuit of IC 741 to achieve high voltage gain & high CMRR.

CMRR (Common Mode Rejection Ratio)

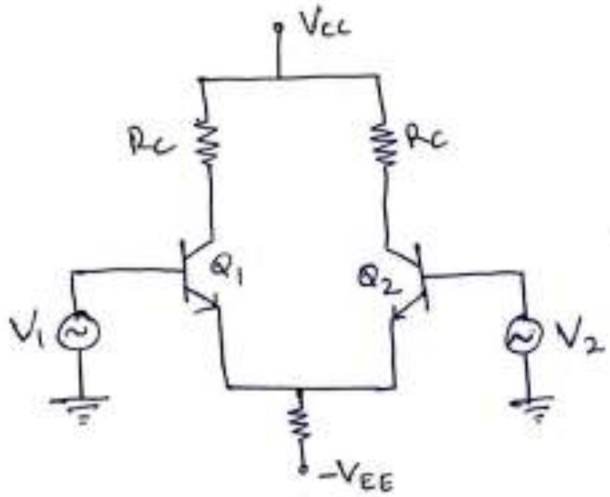
It is the ratio of differential mode gain to common mode gain.

$$\boxed{CMRR = \frac{A_{DM}}{A_{CM}}}$$

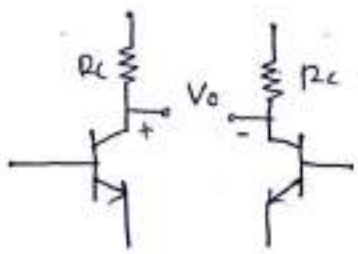
- A level shifter is used as 3rd stage to eliminate the DC bias voltage present in output of intermediate stage.
- Output stage is a complementary symmetry push pull power amplifier.

Differential Amplifier

- It is a circuit which amplify the difference of two input voltages.
- It should have 2 identical transistors.
- Two biasing supply $+V_{cc}$ & $-V_{EE}$ are used to operate two transistor in active region.

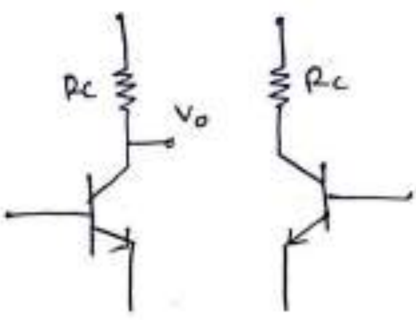


Balanced output



- It is measured between two collectors.

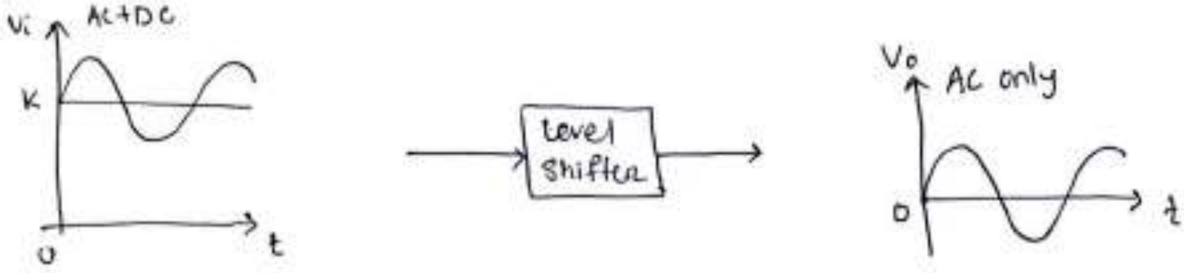
Unbalanced output



- It is measured between one collector & ground.

Level Shifter

- A circuit which shifts the DC voltage level to zero volt i.e it eliminates DC voltage from a signal



Properties of Ideal OPAMP

1. Open loop voltage gain is ∞. ($A_{OL} = \infty$)
2. Input resistance is ∞ i.e currents are zero.
3. Output resistance is zero.
4. Bandwidth is ∞ i.e it can amplify signal of any frequency.
5. Common mode rejection ratio (CMRR) is ∞.
6. Slew rate is ∞.

Slew Rate

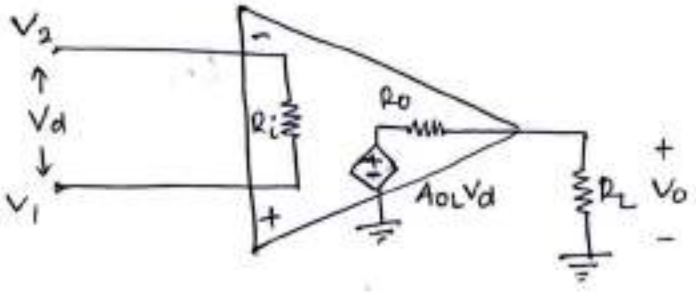
The maximum rate of change in the output of OPAMP is called as slew rate.

$$\boxed{\text{Slew rate} = \left(\frac{dv_o}{dt}\right)_{max}}$$

- unit of Slew rate : volt / μsec

Equivalent circuit of OPAMP

According to the values of R_i & R_o, ideal OPAMP is ideal voltage amplifier or voltage dependent voltage source.



Virtual Short circuit

when OPAMP is in linear region, differential input will be very small (μV) hence mathematical analysis of such small value of Vd can be approximated to zero.

$$V_d \cong 0 \Rightarrow \boxed{V_1 = V_2}$$

- The two input terminals of OPAMP will be approximately at equal voltage without any physical short circuit between them. Hence the two input terminals are said to be virtually shorted.

Virtual Ground

If virtual short circuit is present between two node A & B and if node B is physically grounded then voltage at node A also becomes zero or node A gets virtually grounded.

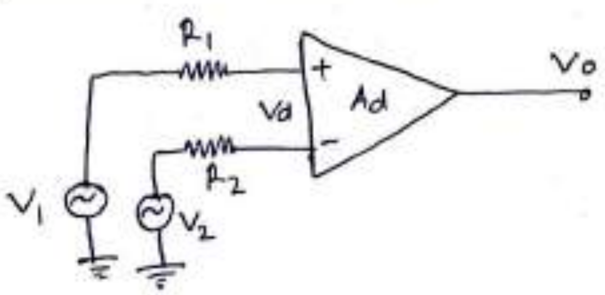
- If a node voltage become zero without physically grounded, then it is called virtual ground.

Open loop OPAMP configuration

- Here the output signal is not fedback in any form as part of the input signal.
- There are three openloop OPAMP configuration.

Differential Amplifier

Since the OPAMP amplifies the difference between the two input signal this configuration is called the differential amplifier.



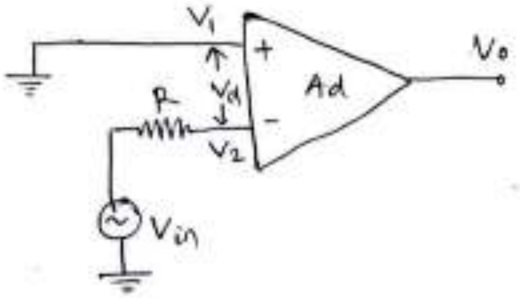
$$V_d = V_1 - V_2$$

$$V_o = A_d V_d = A_d (V_1 - V_2)$$

A_d : open loop gain

Inverting Amplifier

If the input is applied to only inverting terminal & non-inverting terminal is grounded then it is called inverting amplifier.



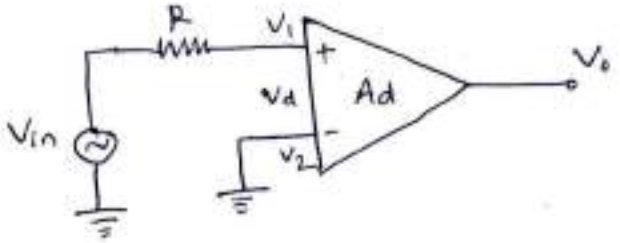
$V_1 = 0 \quad , V_2 = V_{in}$

$V_d = V_1 - V_2 = -V_{in}$

$V_o = A_d V_d = -A_d V_{in}$

Non inverting Amplifier

In this configuration, the input voltage is applied to non-inverting terminal and inverting terminal is grounded.



$V_1 = V_{in} \quad , V_2 = 0$

$V_d = V_1 - V_2 = V_{in}$

$V_o = A_d V_d = A_d V_{in}$

- In open loop configuration any input signal slightly greater than zero, it drives the output to saturation level. This is because of very high gain.
- Thus when operated in open-loop, the output of the OPAMP is either negative or positive saturation or switches between positive & negative saturation levels.

Application of OPAMP

Open loop

- OPAMP when in open loop acts as voltage comparator.
- Here OPAMP is used without feedback.

Closed loop

Negative feedback : Amplifier, mathematical operation etc.

Positive feedback : Schmitt trigger, waveform generator & oscillator

Negative feedback Application of OPAMP

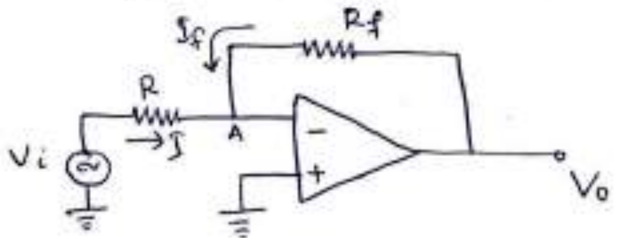
Assumptions used in the analysis of OPAMP in negative feedback :-

① OPAMP is in linear region & hence two input terminal virtually shorted.

② The input current of OPAMP are negligible.

Inverting Amplifier

In inverting OPAMP input is applied at negative terminal.



Apply KCL at node A

$$I + I_f = 0$$

$$\Rightarrow \frac{V_i - V_A}{R} + \frac{V_0 - V_A}{R_f} = 0$$

- According to virtual ground connection $V_A = 0$ (As other terminal is grounded)

$$\Rightarrow \frac{V_i}{R} + \frac{V_0}{R_f} = 0$$

$$\Rightarrow \frac{V_0}{R_f} = -\frac{V_i}{R}$$

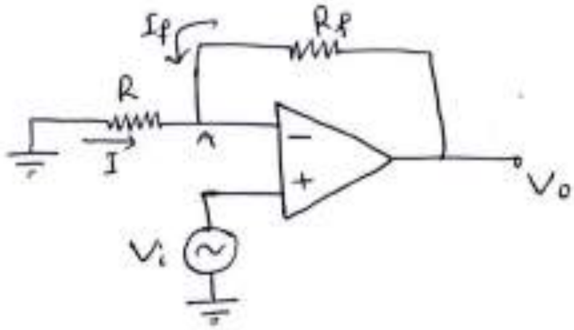
$$\boxed{V_0 = -\frac{R_f}{R} V_i}$$

$$\boxed{A_f = -\frac{R_f}{R}}$$

A_f : Gain

Non Inverting OPAMP

In non inverting OPAMP input is applied at positive terminal.



According to virtual ground connection, $V_A = V_i$.

Apply KCL at node A :

$$I + I_f = 0$$

$$\Rightarrow \frac{0 - V_A}{R} + \frac{V_o - V_A}{R_f} = 0$$

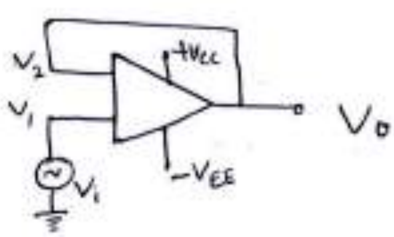
$$\Rightarrow -\frac{V_A}{R} + \frac{V_o}{R_f} - \frac{V_A}{R_f} = 0$$

$$\Rightarrow \frac{V_o}{R_f} = \frac{V_A}{R} + \frac{V_A}{R_f} = V_A\left(\frac{1}{R} + \frac{1}{R_f}\right)$$

$$\Rightarrow V_o = V_A R_f \left(\frac{R + R_f}{R \cdot R_f}\right)$$

$$\Rightarrow \boxed{V_o = V_i\left(1 + \frac{R_f}{R}\right)} \qquad \boxed{A_f = 1 + \frac{R_f}{R}}$$

Voltage follower



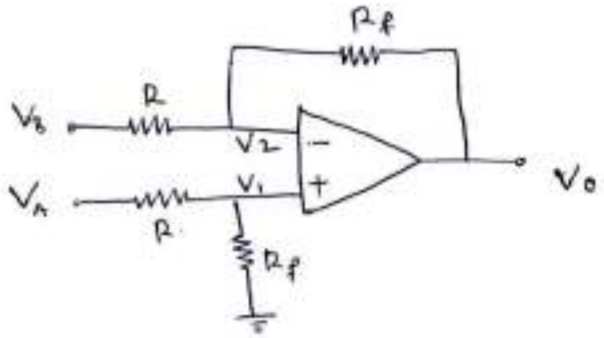
According to virtual ground connection, $V_1 = V_i$ - - - ①

As output is shorted, $V_2 = V_o$ - - - ②

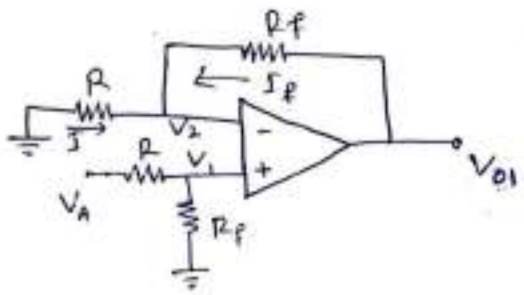
From ① & ② : $\boxed{V_o = V_i}$

- It is known as voltage follower because output follows input i.e equal.
- It is used as a voltage buffer in the practical electronic circuit.

Differential Amplifier



Case-I : Let $V_B = 0$



According to virtual ground connection, $V_1 = V_2$

Applying voltage division rule at V_1, $V_1 = \frac{V_A R_f}{R_f + R}$

KCL at node V_2 : $I + I_f = 0$

$$\Rightarrow \frac{0 - V_2}{R} + \frac{V_{01} - V_2}{R_f} = 0$$

$$\Rightarrow -\frac{V_2}{R} - \frac{V_2}{R_f} + \frac{V_{01}}{R_f} = 0$$

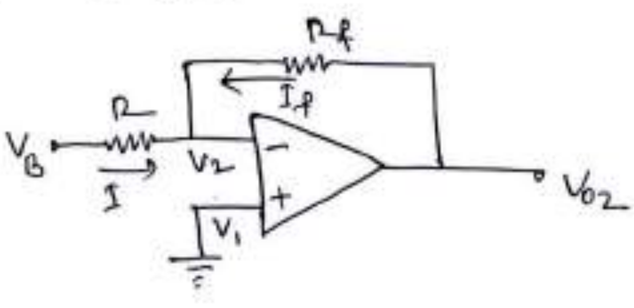
$$\Rightarrow V_{01} = R_f V_2 \left(\frac{1}{R} + \frac{1}{R_f}\right) = V_2 R_f \left(\frac{R + R_f}{R \cdot R_f}\right)$$

$$\Rightarrow V_{01} = V_2 \left(1 + \frac{R_f}{R}\right) = V_1 \left(1 + \frac{R_f}{R}\right)$$

$$\Rightarrow V_{01} = V_A \left(\frac{R_f}{R_f + R}\right)\left(\frac{R + R_f}{R}\right)$$

$$\Rightarrow V_{01} = V_A \frac{R_f}{R} \quad \text{—— (1)}$$

Case-II : Let $V_A = 0$



According to virtual ground connection ; $V_1 = V_2$

$$V_1 = 0 \ , \therefore V_2 = 0$$

KCL at node V_2 : $\quad I + I_f = 0$

$$\Rightarrow \frac{V_B - V_2}{R} + \frac{V_{o2} - V_2}{R_f} = 0$$

$$\Rightarrow \frac{V_B}{R} + \frac{V_{o2}}{R_f} = 0$$

$$\Rightarrow V_{o2} = -\frac{R_f}{R} V_B \quad \text{—— (2)}$$

From equation (1) & (2)

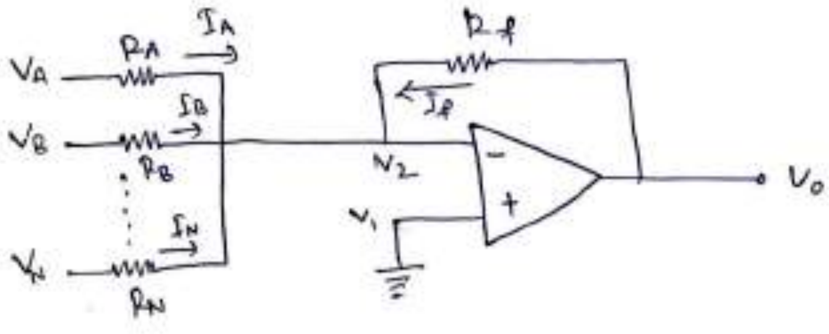
$$V_o = V_{o1} + V_{o2}$$

$$V_o = V_A \frac{R_f}{R} - \frac{R_f}{R} V_B$$

$$\boxed{V_o = \frac{R_f}{R}(V_A - V_B)}$$

- If R_f & R are equal then $\boxed{V_o = V_A - V_B}$, which is a <u>subtractor</u>.

<u>Adder using OPAMP</u>



According to virtual ground connection, $V_2 = V_1 = 0$

KCL at node V_2 : $I_A + I_B + \cdots + I_N + I_f = 0$

$$\Rightarrow \frac{V_A}{R_A} + \frac{V_B}{R_B} + \cdots \frac{V_N}{R_N} + \frac{V_o}{R_f} = 0$$

$$\Rightarrow \frac{V_o}{R_f} = -\left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \cdots \frac{V_N}{R_N}\right)$$

$$\Rightarrow V_o = -R_f\left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \cdots \frac{V_N}{R_N}\right)$$

(i) If $R_A = R_B = \cdots = R_N = R_f = R$

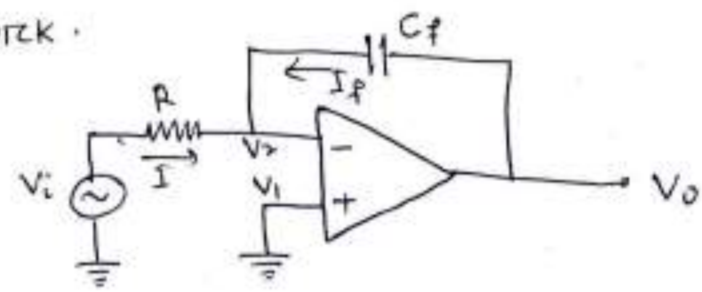
$$\boxed{V_0 = -[V_A + V_B + \cdots + V_N]}$$ → It is an Adder.

(ii) If $R_A = R_B = \cdots = R_N = R_f = KR$

$$\boxed{V_0 = -K[V_A + V_B + \cdots + V_N]}$$ → It is a summing Amplifier.

Integrator using OPAmp

It consists of a resistor at input side & a capacitor at feedback network.



According to virtual ground connection, $V_2 = V_1 = 0$

Apply KCL at node V_2 : $I + I_f = 0$

$$\Rightarrow \frac{V_i - V_2}{R_1} + C_f \frac{d(V_0 - V_2)}{dt} = 0$$

(current across Capacitor $i_c = c\frac{dv}{dt}$)

$$\Rightarrow \frac{V_i}{R} + C_f \frac{dV_0}{dt} = 0$$

$$\Rightarrow C_f \frac{dV_0}{dt} = -\frac{V_i}{R}$$

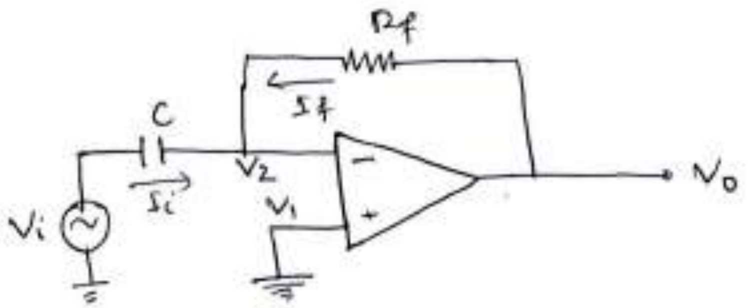
$$\Rightarrow \frac{dV_0}{dt} = \frac{-1}{RC_f} V_i$$

$$\Rightarrow V_0 = \frac{-1}{RC_f} \int V_i \, dt$$

- Output is integration of input signal. Hence it is known as Integrator.

Differentiator using OPAMP

It consists of a resistor at feedback network & a capacitor at the input side.



According to virtual ground connection, $V_2 = V_1 = 0$

KCL at node V_2 : $I_i + I_f = 0$

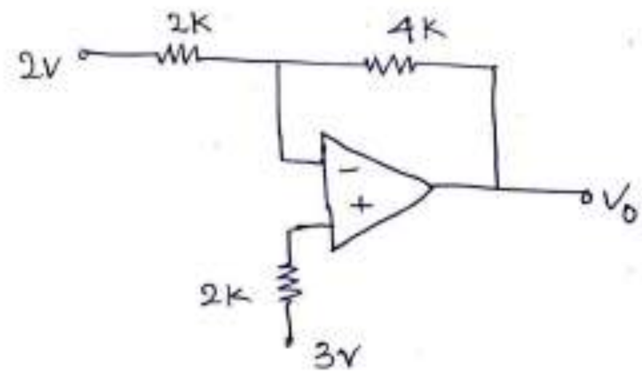
$$\Rightarrow C\frac{dv_i}{dt} + \frac{V_o}{R_f} = 0$$

$$\Rightarrow \frac{V_o}{R_f} = -C\frac{dv_i}{dt}$$

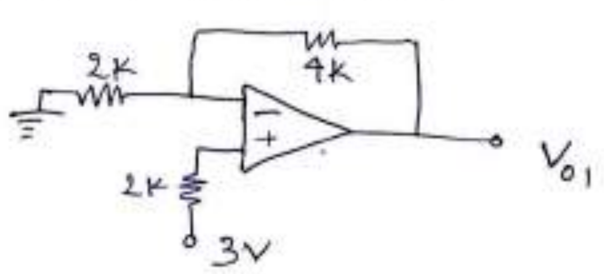
$$\Rightarrow \boxed{V_o = -R_f C\frac{dv_i}{dt}}$$

- output is derivative of input signal. Hence it is called Differentiator.

(Q) In the OPAMP circuit shown in figure find the output voltage.



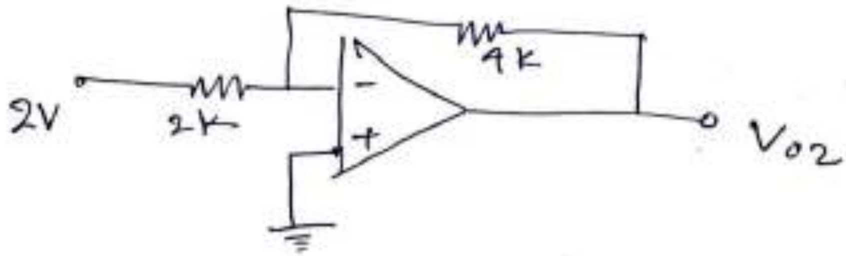
Case-I (only 3V is considered)



$$V_{o1} = \left(1 + \frac{4k}{2k}\right) 3V = 3 \times 3 = 9V$$

$$\boxed{V_{o1} = 9V}$$

Case II (only 2V is considered)



$$V_{o2} = -\frac{4k}{2k} \times 2V = -4V$$

$$\boxed{V_{o2} = -4V}$$

$$V_o = V_{o1} + V_{o2} = 9 - 4 = 5V$$

$$\boxed{V_o = 5V}$$

Ans