BGD COLLEGE ,KESAIBAHAL

Blended learning modules

2nd Year 3rd SEM

Subject and paper :- **ANALOG SYSTEAM AND APPLICATIOMN (PAPER-vii)**

BIPOLAR JUNCTION TRANSISTOR

INTRODUCTION

A bipolar junction transistor (BJT) is a three terminal device in which operation depends on the interaction of both majority and minority carriers and hence the name bipolar. The BJT is analogues to vacuum triode and is comparatively smaller in size. It is used as amplifier and oscillator circuits, and as a switch in digital circuits. It has wide applications in computers, satellites and other modern communication systems.

CONSTRUCTION OF BJT AND ITS SYMBOLS

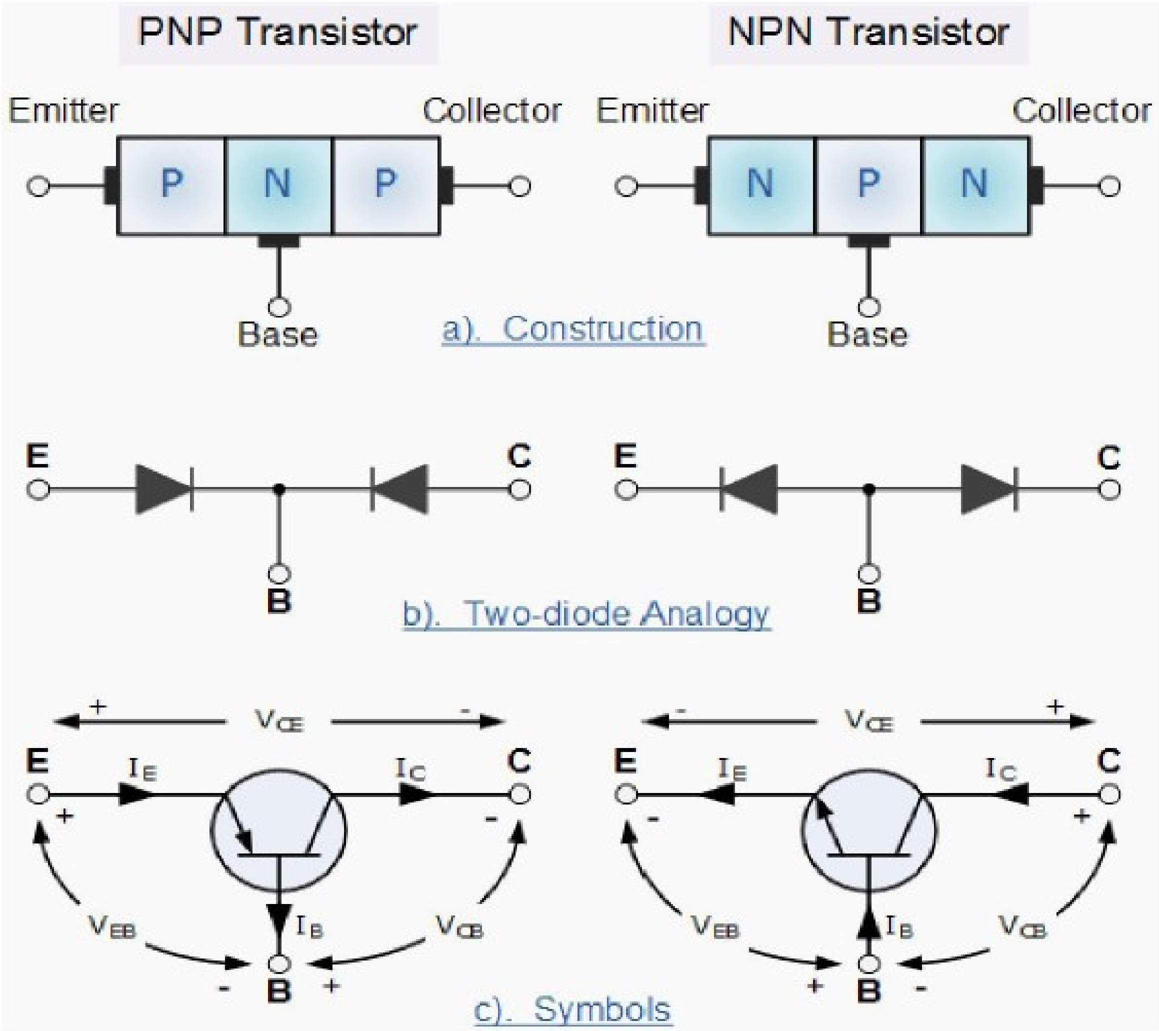
The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively. There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then bipolar transistors have the ability to operate within three different regions:

1. Active Region - the transistor operates as an amplifier and $I_c = \beta . I_b$
2. Saturation - the transistor is "fully-ON" operating as a switch and $I_c = I(saturation)$
3. Cut-off - the transistor is "fully-OFF" operating as a switch and $I_c = 0$

Bipolar Transistors are current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing voltage applied to their base terminal acting like a current-controlled switch. The principle of operation of the two transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Transistor Construction



Bipolar Junction Transistor Symbol

The construction and circuit symbols for both the PNP and NPN bipolar transistor are given above with the arrow in the circuit symbol always showing the direction of "conventional current flow" between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.

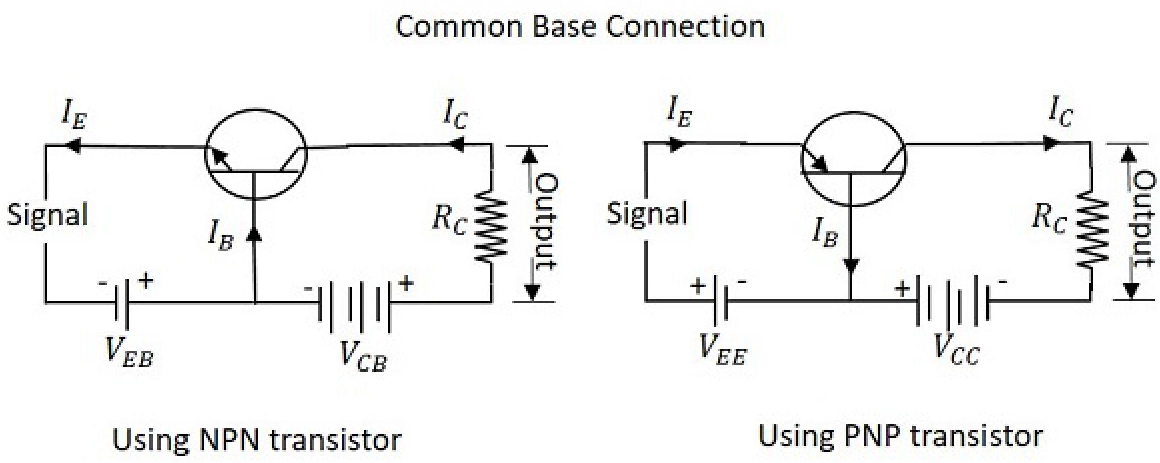
Basic Electronics - Transistor Configurations

A Transistor has 3 terminals, the emitter, the base and the collector. Using these 3 terminals the transistor can be connected in a circuit with one terminal common to both input and output in a 3 different possible configurations.

The three types of configurations are **Common Base, Common Emitter** and **Common Collector** configurations. In every configuration, the emitter junction is forward biased and the collector junction is reverse biased.

Common Base CB Configuration

The name itself implies that the Base terminal is taken as common terminal for both input and output of the transistor. The common base connection for both NPN and PNP transistors is as shown in the following figure.



For the sake of understanding, let us consider NPN transistor in CB configuration. When the emitter voltage is applied, as it is forward biased, the electrons from the negative terminal repel the emitter electrons and current flows through the emitter and base to the collector to contribute collector current. The collector voltage $\mathbf{V_{CB}}$ is kept constant throughout this.

In the CB configuration, the input current is the emitter current $\mathbf{I_E}$ and the output current is the collector current $\mathbf{I_C}$.

Current Amplification Factor α

The ratio of change in collector current ΔI_C to the change in emitter current ΔI_E

when collector voltage $\mathbf{V_{CB}}$ is kept constant, is called as **Current amplification factor**. It is denoted by α.

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \; at\, constant\, V_{CB}$$

Expression for Collector current

With the idea above, let us try to draw some expression for collector current. Along with the emitter current flowing, there is some amount of base current IB which flows through the base terminal due to electron hole recombination. As collector-base junction is reverse biased, there is another current which is flown due to minority charge carriers. This is the leakage current which can be understood as $\mathbf{I_{leakage}}$. This is due to minority charge carriers and hence very small.

The emitter current that reaches the collector terminal is

$$\alpha I_E$$

Total collector current

$$I_C = \alpha I_E + I_{leakage}$$

If the emitter-base voltage V_{EB} = 0, even then, there flows a small leakage current, which can be termed as I_{CBO} $collector - basecurrentwithoutputopen$.

The collector current therefore can be expressed as

$$I_C = \alpha I_E + I_{CBO}$$

$$I_E = I_C + I_B$$

$$I_C = \alpha(I_C + I_B) + I_{CBO}$$

$$I_C(1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = (\frac{\alpha}{1 - \alpha})\, I_B + (\frac{I_{CBO}}{1 - \alpha})$$

$$I_C = (\frac{\alpha}{1 - \alpha})\, I_B + (\frac{1}{1 - \alpha})I_{CBO}$$

Hence the above derived is the expression for collector current. The value of collector current depends on base current and leakage current along with the current amplification factor of that transistor in use.

Characteristics of CB configuration

- This configuration provides voltage gain but no current gain.
- Being $\mathbf{V_{CB}}$ constant, with a small increase in the Emitter-base voltage V_{EB}, Emitter current $\mathbf{I_E}$ gets increased.
- Emitter Current $\mathbf{I_E}$ is independent of Collector voltage $\mathbf{V_{CB}}$.
- Collector Voltage $\mathbf{V_{CB}}$ can affect the collector current $\mathbf{I_C}$ only at low voltages, when V_{EB} is kept constant.
- The input resistance ri is the ratio of change in emitter-base voltage ΔV_{EB} to the change in emitter current ΔI_E at constant collector base voltage $\mathbf{V_{CB}}$.

$$\eta = \frac{\Delta V_{EB}}{\Delta I_E} \; at\ constant\ V_{CB}$$

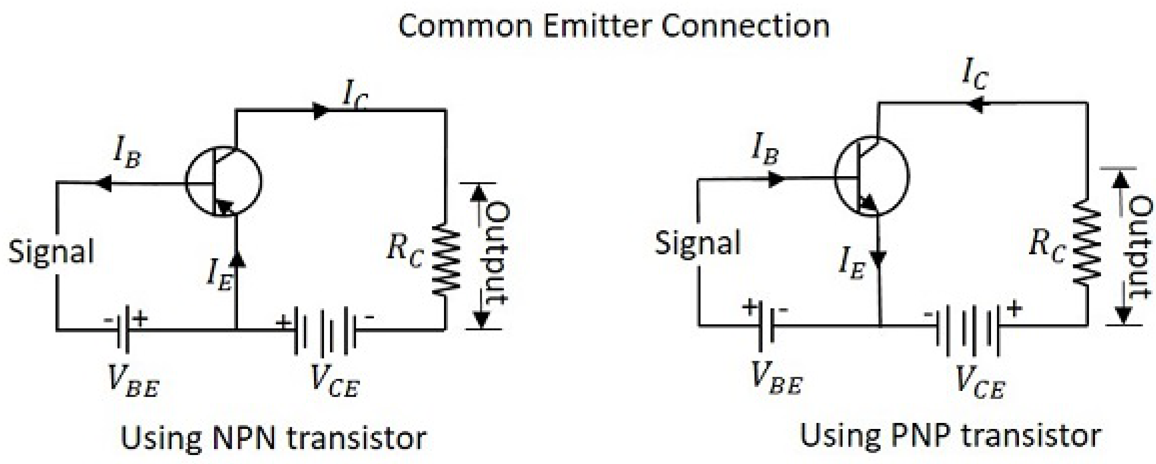
- As the input resistance is of very low value, a small value of V_{EB} is enough to produce a large current flow of emitter current $\mathbf{I_E}$.
- The output resistance r_o is the ratio of change in the collector base voltage ΔV_{CB} to the change in collector current ΔI_C at constant emitter current $\mathbf{I_E}$.

$$r_o = \frac{\Delta V_{CB}}{\Delta I_C} \; at\ constant\ l_E$$

- As the output resistance is of very high value, a large change in $\mathbf{V_{CB}}$ produces a very little change in collector current $\mathbf{I_C}$.
- This Configuration provides good stability against increase in temperature.
- The CB configuration is used for high frequency applications.

Common Emitter CE Configuration

The name itself implies that the **Emitter** terminal is taken as common terminal for both input and output of the transistor. The common emitter connection for both NPN and PNP transistors is as shown in the following figure.



Just as in CB configuration, the emitter junction is forward biased and the collector junction is reverse biased. The flow of electrons is controlled in the same manner. The input current is the base current $\mathbf{I_B}$ and the output current is the collector current $\mathbf{I_C}$ here.

Base Current Amplification factor β

The ratio of change in collector current ΔI_C to the change in base current ΔI_B is known as **Base Current Amplification Factor**. It is denoted by β

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

Relation between β and α

Let us try to derive the relation between base current amplification factor and emitter current amplification factor.

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

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

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

We can write

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$$

Dividing by $$

$$\beta = \frac{\frac{\Delta I_C}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

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

We have

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

Therefore,

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

From the above equation, it is evident that, as α approaches 1, β reaches infinity.

Hence, **the current gain in Common Emitter connection is very high**. This is the reason this circuit connection is mostly used in all transistor applications.

Expression for Collector Current

In the Common Emitter configuration, $\mathbf{I_B}$ is the input current and $\mathbf{I_C}$ is the output current.

We know

$$I_E = I_B + I_C$$

And

$$I_C = \alpha I_E + I_{CBO}$$

$$= \alpha(I_B + I_C) + I_{CBO}$$

$$I_C(1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$$

If base circuit is open, i.e. if $\mathbf{I_B}$ = 0,

The collector emitter current with base open is I_{CEO}

$$I_{CEO} = \frac{1}{1-\alpha} I_{CBO}$$

Substituting the value of this in the previous equation, we get

$$I_C = \frac{\alpha}{1-\alpha} I_B + I_{CEO}$$

$$I_C = \beta I_B + I_{CEO}$$

Hence the equation for collector current is obtained.

Knee Voltage

In CE configuration, by keeping the base current $\mathbf{I_B}$ constant, if $\mathbf{V_{CE}}$ is varied, $\mathbf{I_C}$ increases nearly to 1v of $\mathbf{V_{CE}}$ and stays constant thereafter. This value of $\mathbf{V_{CE}}$ up to which collector current $\mathbf{I_C}$ changes with $\mathbf{V_{CE}}$ is called the **Knee Voltage**. The transistors while operating in CE configuration, they are operated above this knee voltage.

Characteristics of CE Configuration

- This configuration provides good current gain and voltage gain.
- Keeping $\mathbf{V_{CE}}$ constant, with a small increase in $\mathbf{V_{BE}}$ the base current $\mathbf{I_B}$ increases rapidly than in CB configurations.
- For any value of $\mathbf{V_{CE}}$ above knee voltage, $\mathbf{I_C}$ is approximately equal to $\beta \mathbf{I_B}$.
- The input resistance $\mathbf{r_i}$ is the ratio of change in base emitter voltage ΔV_{BE} to the change in base current ΔI_B at constant collector emitter voltage $\mathbf{V_{CE}}$.

$$r_i = \frac{\Delta V_{BE}}{\Delta I_B} \; at\; constant\; V_{CE}$$

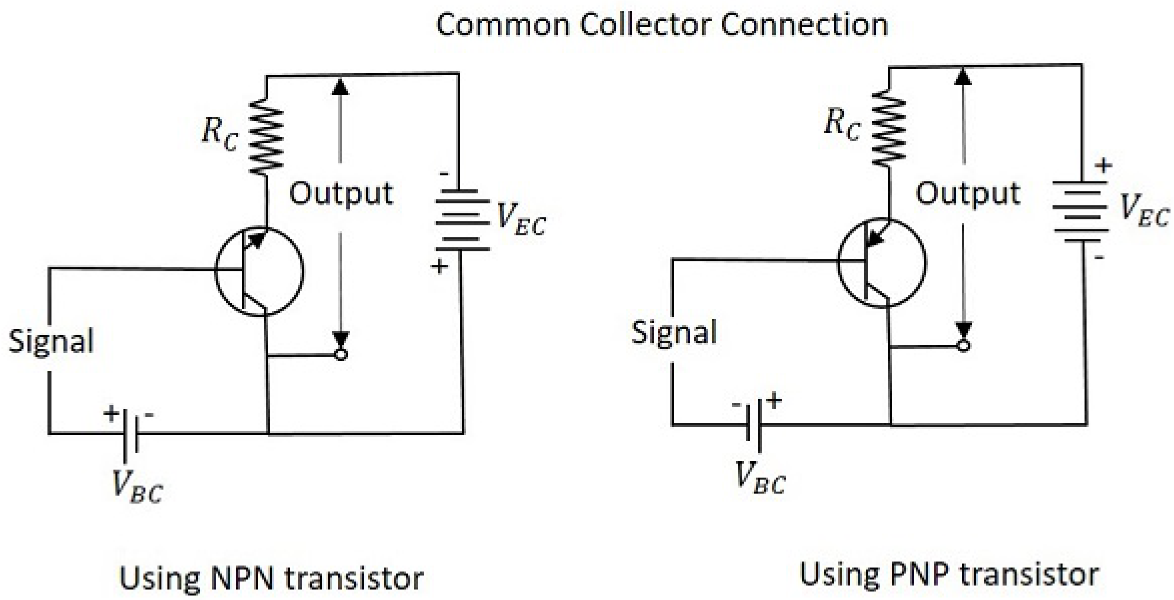
- As the input resistance is of very low value, a small value of $\mathbf{V_{BE}}$ is enough to produce a large current flow of base current $\mathbf{I_B}$.
- The output resistance $\mathbf{r_o}$ is the ratio of change in collector emitter voltage ΔV_{CE} to the change in collector current ΔI_C at constant $\mathbf{I_B}$.

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} \; at\; constant\; I_B$$

- As the output resistance of CE circuit is less than that of CB circuit.
- This configuration is usually used for bias stabilization methods and audio frequency applications.

Common Collector CC Configuration

The name itself implies that the **Collector** terminal is taken as common terminal for both input and output of the transistor. The common collector connection for both NPN and PNP transistors is as shown in the following figure.



Just as in CB and CE configurations, the emitter junction is forward biased and the collector junction is reverse biased. The flow of electrons is controlled in the same manner. The input current is the base current $\mathbf{I_B}$ and the output current is the emitter current $\mathbf{I_E}$ here.

Current Amplification Factor γ

The ratio of change in emitter current ΔI_E to the change in base current ΔI_B is known as **Current Amplification factor** in common collector CC configuration. It is denoted by **γ**.

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

- The current gain in CC configuration is same as in CE configuration.
- The voltage gain in CC configuration is always less than 1.

Relation between γ and α

Let us try to draw some relation between γ and α

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

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

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

Substituting the value of I_B, we get

$$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$$

Dividing by ΔI_E

$$\gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

$$\frac{1}{1 - \alpha}$$

$$\gamma = \frac{1}{1 - \alpha}$$

Expression for collector current

We know

$$I_C = \alpha I_E + I_{CBO}$$

$$I_E = I_B + I_C = I_B + (\alpha I_E + I_{CBO})$$

$$I_E(1 - \alpha) = I_B + I_{CBO}$$

$$I_E = \frac{I_B}{1 - \alpha} + \frac{I_{CBO}}{1 - \alpha}$$

$$I_C \cong I_E = (\beta + 1)I_B + (\beta + 1)I_{CBO}$$

The above is the expression for collector current.

Characteristics of CC Configuration

- This configuration provides current gain but no voltage gain.
- In CC configuration, the input resistance is high and the output resistance is low.
- The voltage gain provided by this circuit is less than 1.
- The sum of collector current and base current equals emitter current.
- The input and output signals are in phase.
- This configuration works as non-inverting amplifier output.
- This circuit is mostly used for impedance matching. That means, to drive a low impedance load from a high impedance source.

Transistor Regions of Operation

The DC supply is provided for the operation of a transistor. This DC supply is given to the two PN junctions of a transistor which influences the actions of majority carriers in these emitter and collector junctions.

The junctions are forward biased and reverse biased based on our requirement. **Forward biased** is the condition where a positive voltage is applied to the p-type and negative voltage is applied to the n-type material. **Reverse biased** is the condition where a positive voltage is applied to the n-type and negative voltage is applied to the p-type material.

Transistor biasing

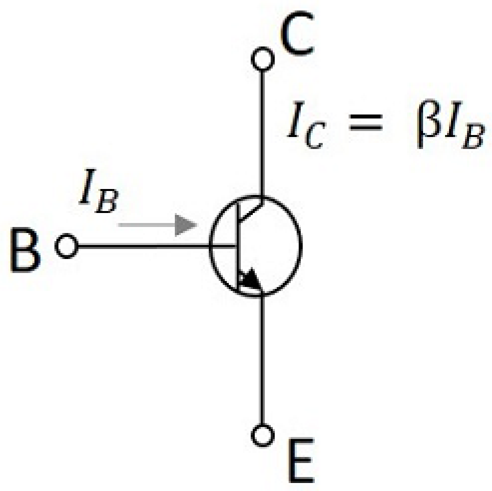
The supply of suitable external dc voltage is called as **biasing**. Either forward or reverse biasing is done to the emitter and collector junctions of the transistor. These biasing methods make the transistor circuit to work in four kinds of regions such as **Active region, Saturation region, Cutoff region** and **Inverse active region** $seldomused$. This is understood by having a look at the following table.

EMITTER JUNCTION	COLLECTOR JUNCTION	REGION OF OPERATION
Forward biased	Forward biased	Saturation region
Forward biased	Reverse biased	Active region
Reverse biased	Forward biased	Inverse active region
Reverse biased	Reverse biased	Cutoff region

Among these regions, Inverse active region, which is just the inverse of active region, is not suitable for any applications and hence not used.

Active region

This is the region in which transistors have many applications. This is also called as **linear region**. A transistor while in this region, acts better as an **Amplifier**.



In Active region

This region lies between saturation and cutoff. The transistor operates in active region when the emitter junction is forward biased and collector junction is reverse biased. In the active state, collector current is β times the base current, i.e.,

$$I_C = \beta I_B$$

Where,

I_C = collector current

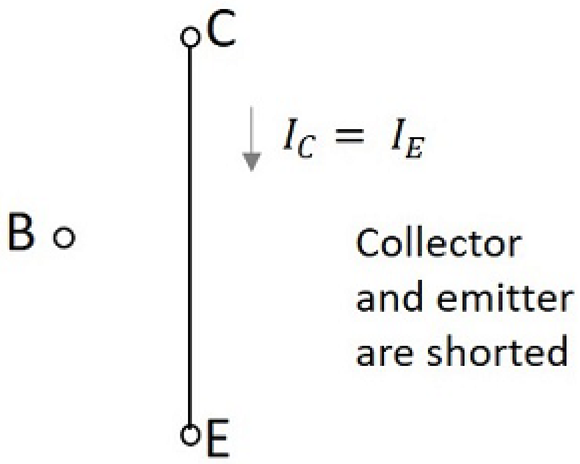
β = current amplification factor

I_B = base current

Saturation region

This is the region in which transistor tends to behave as a closed switch. The transistor has the effect of its collector and Emitter being shorted. The collector and Emitter currents are maximum in this mode of operation.

The figure below shows a transistor working in saturation region.



In Saturated region

The transistor operates in saturation region when both the emitter and collector junctions are forward biased. As it is understood that, in the saturation region the transistor tends to behave as a closed switch, we can say that,

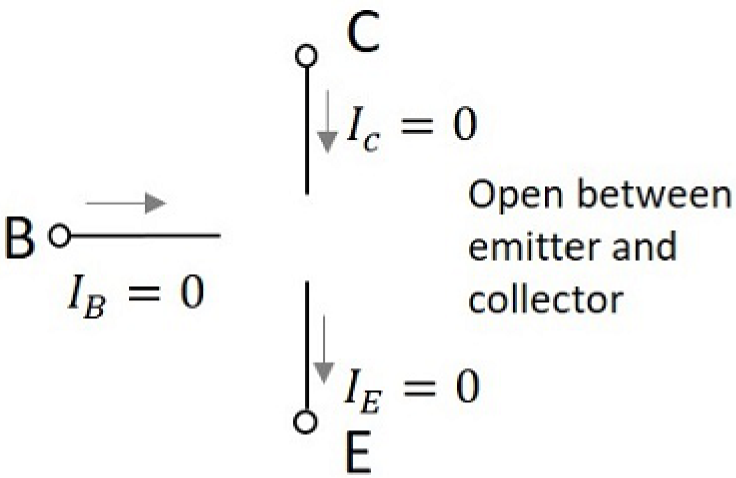
$$I_C = I_E$$

Where I_C = collector current and I_E = emitter current.

Cutoff region

This is the region in which transistor tends to behave as an open switch. The transistor has the effect of its collector and base being opened. The collector, emitter and base currents are all zero in this mode of operation.

The following figure shows a transistor working in cutoff region.



In Cutoff region

The transistor operates in cutoff region when both the emitter and collector junctions are reverse biased. As in cutoff region, the collector current, emitter current and base currents are nil, we can write as

$$I_C = I_E = I_B = 0$$

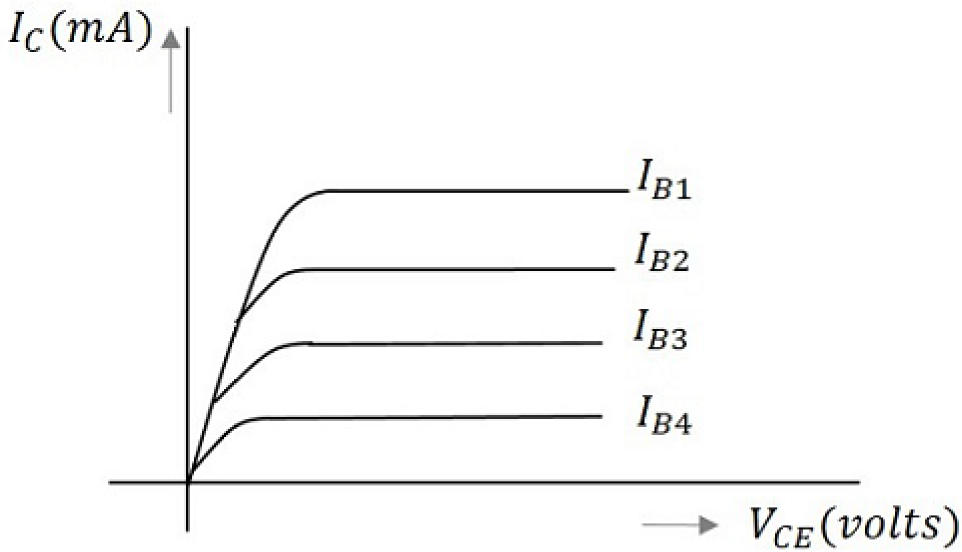
Where I_C = collector current, I_E = emitter current, and I_B = base current.

Transistor Load Line Analysis

Till now we have discussed different regions of operation for a transistor. But among all these regions, we have found that the transistor operates well in active region and hence it is also called as **linear region**. The outputs of the transistor are the collector current and collector voltages.

Output Characteristics

When the output characteristics of a transistor are considered, the curve looks as below for different input values.



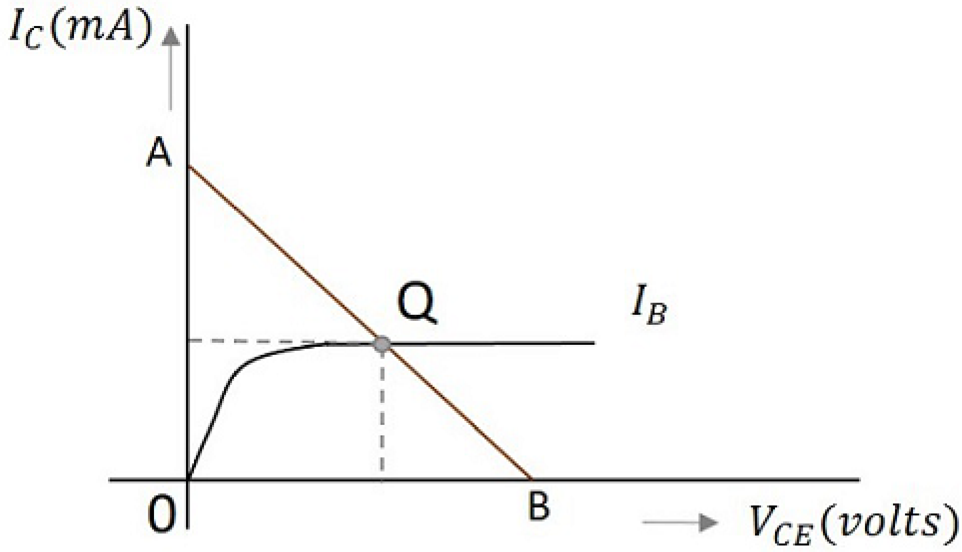
In the above figure, the output characteristics are drawn between collector current $\mathbf{I_C}$ and collector voltage $\mathbf{V_{CE}}$ for different values of base current $\mathbf{I_B}$. These are considered here for different input values to obtain different output curves.

Operating point

When a value for the maximum possible collector current is considered, that point will be present on the Y-axis, which is nothing but the **saturation point**. As well, when a value for the maximum possible collector emitter voltage is considered, that point will be present on the X-axis, which is the **cutoff point**.

When a line is drawn joining these two points, such a line can be called as **Load line**. This is called so as it symbolizes the output at the load. This line, when drawn over the output characteristic curve, makes contact at a point called as **Operating point**.

This operating point is also called as **quiescent point** or simply **Q-point**. There can be many such intersecting points, but the Q-point is selected in such a way that irrespective of AC signal swing, the transistor remains in active region. This can be better understood through the figure below.

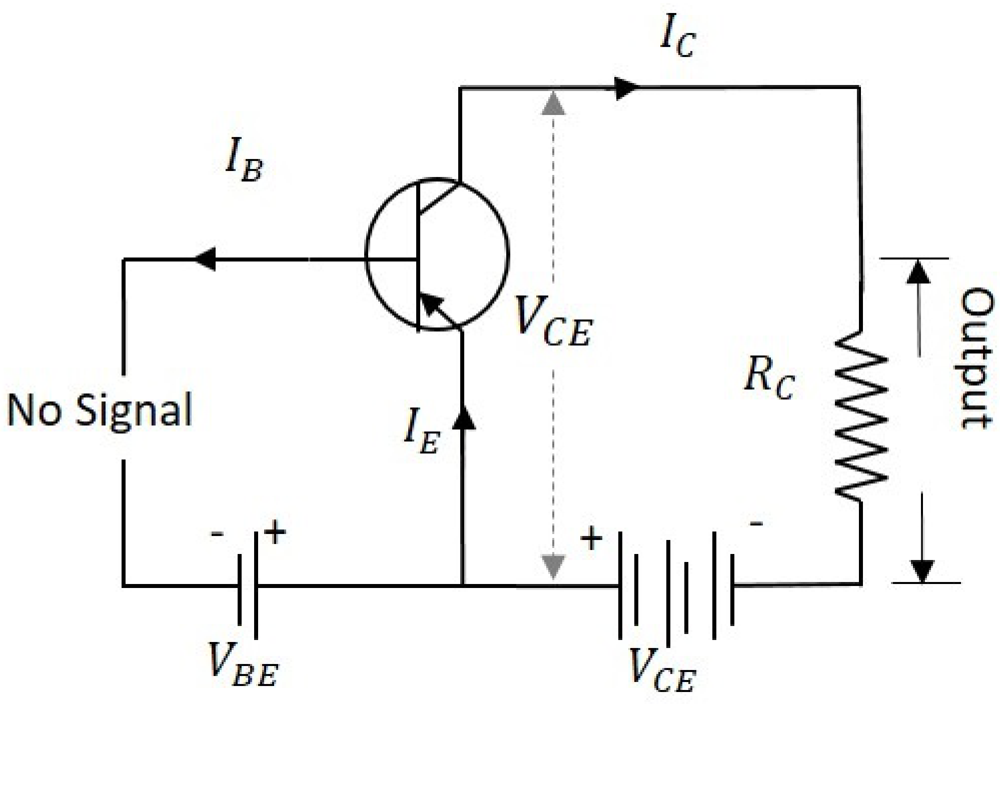


The load line has to be drawn in order to obtain the Q-point. A transistor acts as a good amplifier when it is in active region and when it is made to operate at Q-point, faithful amplification is achieved.

Faithful amplification is the process of obtaining complete portions of input signal by increasing the signal strength. This is done when AC signal is applied at its input. This is discussed in AMPLIFIERS tutorial.

DC Load line

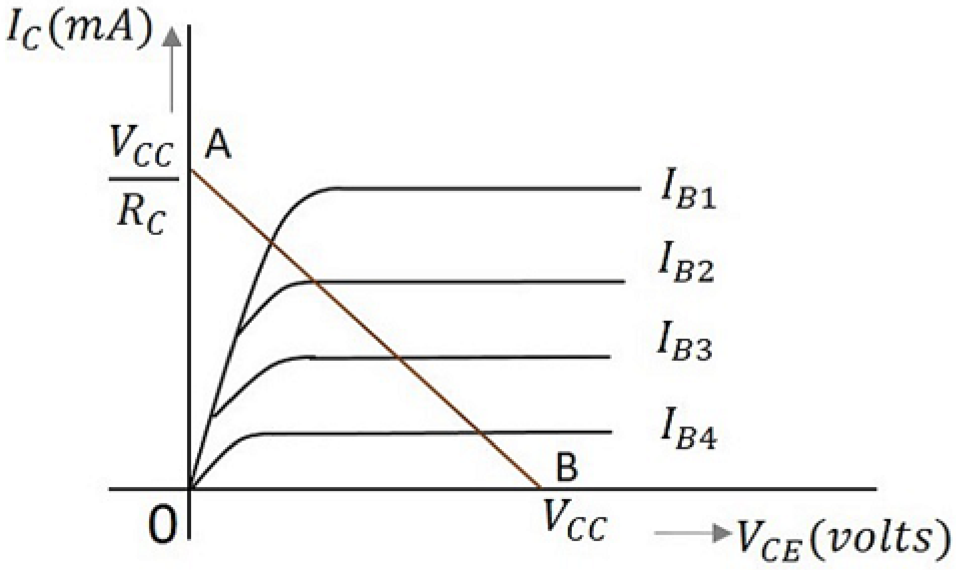
When the transistor is given the bias and no signal is applied at its input, the load line drawn at such condition, can be understood as **DC** condition. Here there will be no amplification as the signal is absent. The circuit will be as shown below.



The value of collector emitter voltage at any given time will be

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

As V_{CC} and R_C are fixed values, the above one is a first degree equation and hence will be a straight line on the output characteristics. This line is called as **D.C. Load line**. The figure below shows the DC load line.



To obtain the load line, the two end points of the straight line are to be determined. Let those two points be A and B.

To obtain A

When collector emitter voltage V_{CE} = 0, the collector current is maximum and is equal to V_{CC}/R_C. This gives the maximum value of V_{CE}. This is shown as

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

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

$$I_C = \frac{V_{CC}}{R_C}$$

This gives the point A (OA = V_{CC}/R_C) on collector current axis, shown in the above figure.

To obtain B

When the collector current IC = 0, then collector emitter voltage is maximum and will be equal to the VCC. This gives the maximum value of IC. This is shown as

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

$$= V_{CC}$$

(As $I_C = 0$)

This gives the point B, which means (OB = V_{CC}) on the collector emitter voltage axis shown in the above figure.

Hence we got both the saturation and cutoff point determined and learnt that the load line is a straight line. So, a DC load line can be drawn.

The importance of this operating point is further understood when an AC signal is given at the input. This will be discussed in AMPLIFIERS tutorial.