ELEMENTS OF ELECTRONIC ENGG

TRANSISTORS AND APPLICATIONS

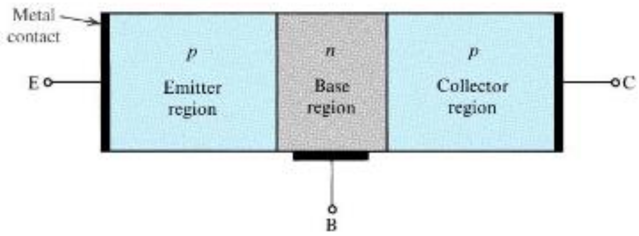
Transistor & Applications: Principle, Operation, Transistor configurations - Common base, common emitter, common collector configuration Input-Output characteristics. DC load line and operating point, Transistor as a switch. Voltage divider bias circuit, Bias stabilization, Small signal CE amplifier, Frequency response, Feedback principle, Advantages of negative feedback.

BIPOLAR JUNTION TRANSISTORS

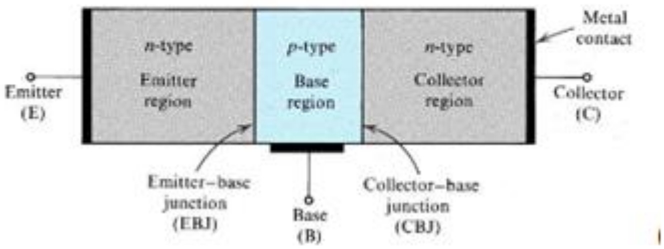
A BJT consists of two coupled pn-junction, connected back-to-back with a common middle layer.
Current is conducted both by electrons and holes-hence the name Bipolar
(It is often referred to as transistor which is a contraction of the word 'transfer resistor')
A transistor is a sandwich of one type of semiconductor (P-type or n-type) between two layers of other types. It is a 3 layer, two junction device.
BJTs are used both in analog and digital circuits.

Bipolar Transistors are classified into two types;

1. **pnp transistor**
   pnp transistor is obtained when a n-type layer of silicon is sandwiched between two p-type silicon material.



2. **npn transistor**
   npn transistor is obtained when a p-type layer of silicon is sandwiched between two n-type silicon materials.



JE=Emitter Junction
JC=collector Junction

Fig 1.1: Symbolic representation

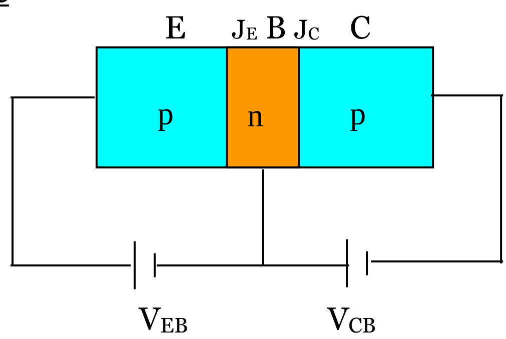
pnp npn

Fig 1.2: Schematic representation

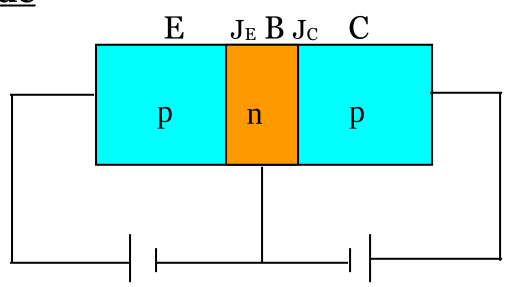
- The three portions of transistors are named as emitter, base and collector. The junction between emitter and base is called emitter-base junction while the junction between the collector and base is called collector-base junction.
- The base is thin and lightly doped, the emitter is heavily doped and it is wider when compared to base, the width of the collector is more when compared to both base and emitter.
- A terminal is connected to each of the three semiconductor regions of a transistor labeled as E, B, C as shown above.
- In order to distinguish the emitter and collector an arrow is included in the emitter. The direction of the arrow depends on the conventional flow of current when emitter base junction is forward biased.
- In a pnp transistor when the emitter junction is forward biased the flow of current is from emitter to base hence, the arrow in the emitter of pnp points towards the base.
- Depending on the bias conditions of the EB and CB junctions different modes of operations of BJT are obtained.
- There are four possible ways of biasing these junctions
  - When emitter base junction is forward biased and CB junction is reverse biased the BJT is said to be in **active mode**. This mode is used if BJT is used to operate as an Amplifier
  - When both junctions are forward biased, BJT is said to be in **saturation mode**.
  - When both junctions are reverse biased, BJT is said to be in **cut-off mode**.
  - Switching applications use cut-off and saturation modes
- When emitter base junction is reverse biased and CB junction is forward biased the BJT is said to be in **Inversion mode or Reverse Active**. Inversion mode is used in TTL gates.

Mode	Emitter-Base Jct.	Collector-Base Jct.
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward
Reverse Active	Reverse	Forward

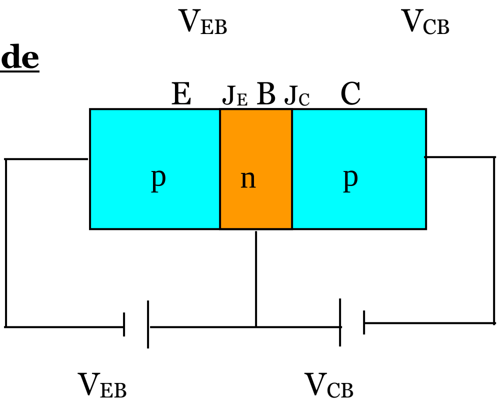
Active mode



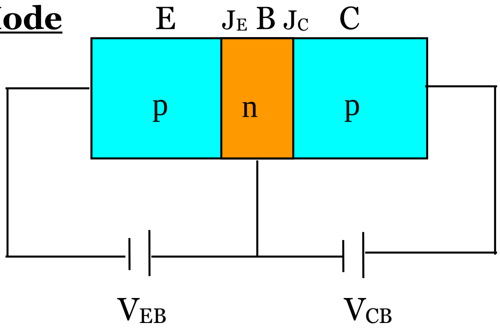
Saturation mode



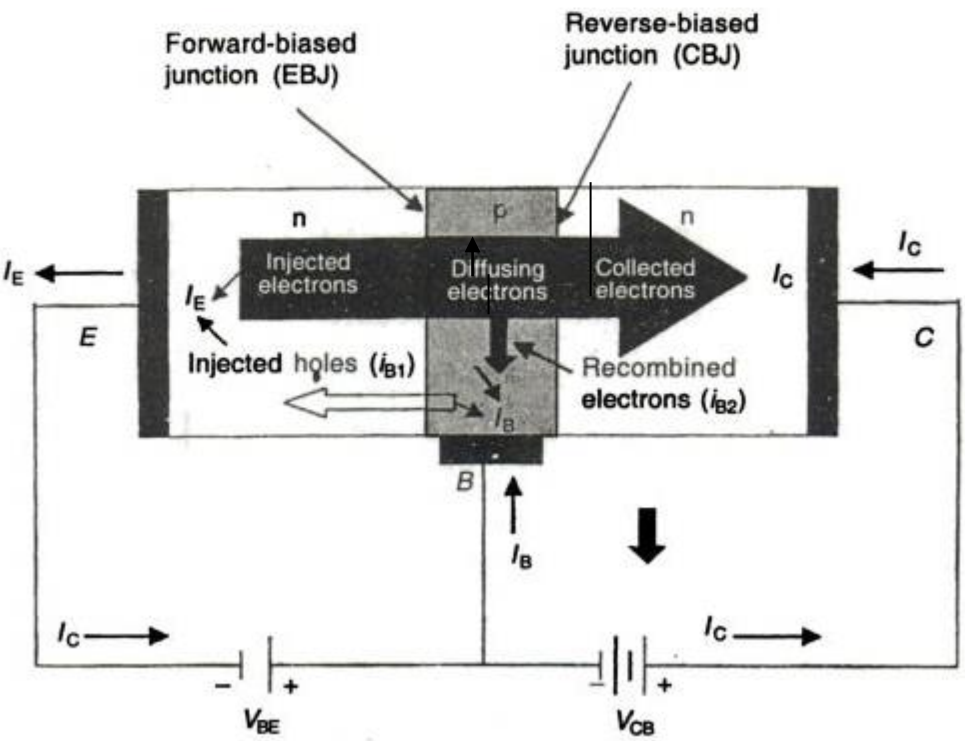
Cut-off mode



Inversion Mode



Principle of operation of NPN transistor



(a) Operation of an n-p-n transistor

Figure (a) shows an idealized NPN bipolar transistor biased in the forward-active mode.

- An NPN bipolar transistor biased in the forward-active mode means base–emitter junction forward biased and base–collector junction reverse biased.
- Since the E-B junction is forward biased, as a result depletion region narrows ,electrons from the emitter are injected across the B–E junction into the base, this constitute emitter current I_e
- Since base is p-type and thin a very few electrons combine with holes in base, this constitute base current I_b.

- The remaining large number of electrons cross the base region and move through the collector region to the +ve terminal of the external dc source vcc, this constitute collector current I_c.
- Thus main current in an NPN transistor is due to electron flow.

Current components of a transistor

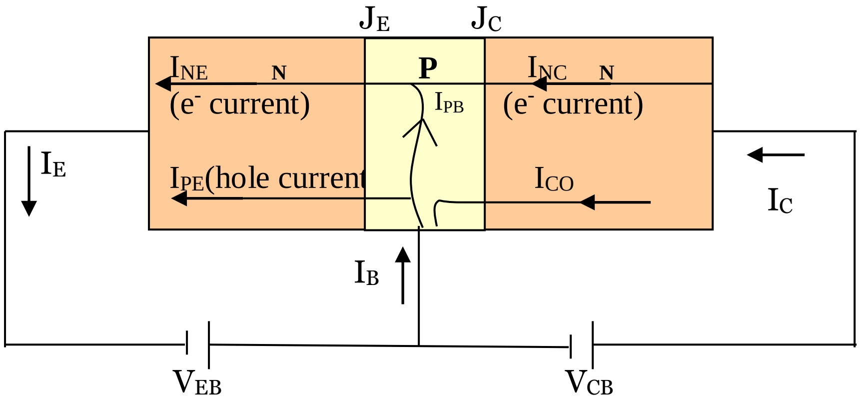


Fig above shows a transistor operated in active region. It can be noted from the diagram the battery V_{EB} forward biases the EB junction while the battery V_{CB} reverse biases the CB junction.

As the EB junction is forward biased the electrons from emitter region flow towards the base causing a electron current I_{NE}. At the same time, the holes from base region flow towards the emitter causing an hole current I_{PE}. Sum of these two currents constitute an emitter current $I_E = I_{PE} + I_{NE}$.

The ratio of hole current I_{PE} to electron current I_{NE} is directly proportional to the ratio of the conductivity of the p-type material to that of n-type material. Since, emitter is highly doped when compared to base; the emitter current consists almost entirely of electrons.

Not all the electrons, crossing EB junction reach the CB junction because some of the them combine with the holes in the p-type base. If I_{NC} is the electron current at (Jc) CB junction. There will be a recombination current $I_{NE} - I_{NC}$ entering the base as shown in figure .

If emitter is open circuited, no charge carriers are injected from emitter into the base and hence emitter current $I_E = 0$. Under this condition CB junction acts a a reverse biased diode and therefore the collector current ($I_C = I_{CO}$) will be equal to the reverse saturation current. Therefore when EB junction is forward biased and collector base junction is reverse biased the total collector current $I_C = I_{NC} + I_{CO}$.

Current relations

- From KCL, the current that enters a transistor should leave it thus from fig the emitter current is equal to sum of the collector current and the base current
  i.e.
  $I_E = I_c + I_b$ ------------------ (1)

- Emitter current cross collector and only a small portion flows in to the base terminal and remaining flows across C-B junction to become collector current
- i.e. $I_c = \alpha I_E$-----------------(2)
- where $\alpha = \frac{I_C}{I_E}$ (typically α is in b/wo .96 to0.995 it is called common base current gain)

- since C-B junction is reverse biased ,a very small reverse saturation current (I_{CBO}) flows across the junction
- I_{CBO} is called as collector to base leakage current
- Then eq(2)can also be written as
  We have
  $I_C = \alpha I_E + I_{CBO}$ -------------------------(3)

- usually I_{CBO} is very small neglect it, then
  $I_c = \alpha I_E$
  $I_c = \alpha(I_c+I_b)$ from eq (1)
  $I_c = \alpha I_B/1-\alpha$
  $I_c = \beta I_B$
- Where
  $\beta= \alpha/1-\alpha$ (where β is called as common emitter current gain and typically it ranges b/w 25 to 300)

Common base Current amplification factor (α)

It is defined as the ratio of D.C. collector current to D.C. emitter current

$\alpha = I_C / I_E$

Common emitter Current amplification factor (β)

It is the ratio of d.c. collector current to d.c. base current.

i.e., $\beta = I_C / I_B$

Relationship between α and β

We know that $\alpha = \frac{I_C}{I_E}$ $\alpha = \frac{I_C}{I_B + I_C}$

Divide both numerator and denominator of RHS by I_C, we get

$$\alpha = \frac{1}{\frac{I_B}{I_C}+1}$$

$$\alpha = \frac{1}{\frac{1}{\beta}+1} \qquad (I_C / I_B = \beta)$$

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

Also we have

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

Biasing of BJT

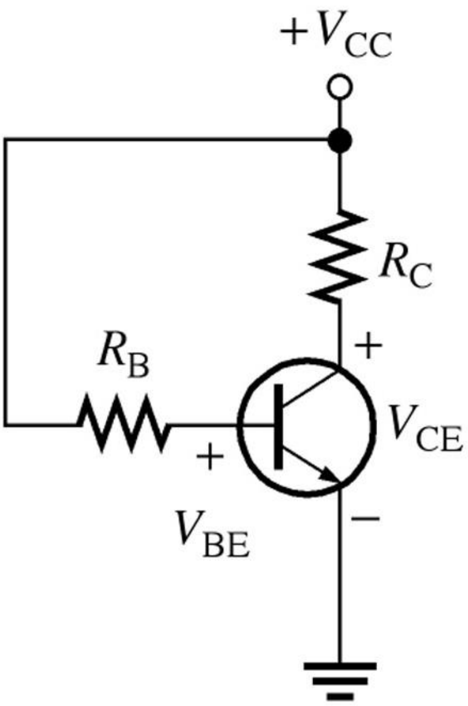
Purpose of biasing a BJT circuit

- Transistors are used in the different kinds of circuits that are designed to serve different purposes.
- In case of transistor amplifier, we need to use the active region of the transistor output characteristics.
- The transistor parameters are not absolute constant, but changes with both temperature and bias conditions.
- For example, transistor β increases with temperature as well as with collector current and an increase of β in turn further increases in collector current.
- The bias point thus shifts with temperature.
- Another parameter that affects the bias point is the collector to base leakage current, which approximately doubles for every 10°c rise in temperature.
- The purpose of dc biasing of a transistor is to obtain the most appropriate values of I_c, I_B, and $V_{CE.}$
- The particular values of Ic, I_B, and V_{CE} represents a particular point in the output characteristics of the transistor, called the quiescent point or Q-point or operating point.
- To obtain a suitable operating point we make use of some circuits and these circuits are called biasing circuit.

DC load line and Bias point

DC load line

- Dc load line for a transistor is o straight line drawn on output characteristics.
- For common emitter, the load line is line drawn on graph of Ic Vs $V_{CE.}$
- The load line shows all corresponding levels of Ic and V_{CE} that can exist in a particular circuit.



Consider the common emitter circuit as shown in the fig note that the polarities of the terminal voltages are such that base-emitter junction is forward biased and collector-base junction is reverse biased.

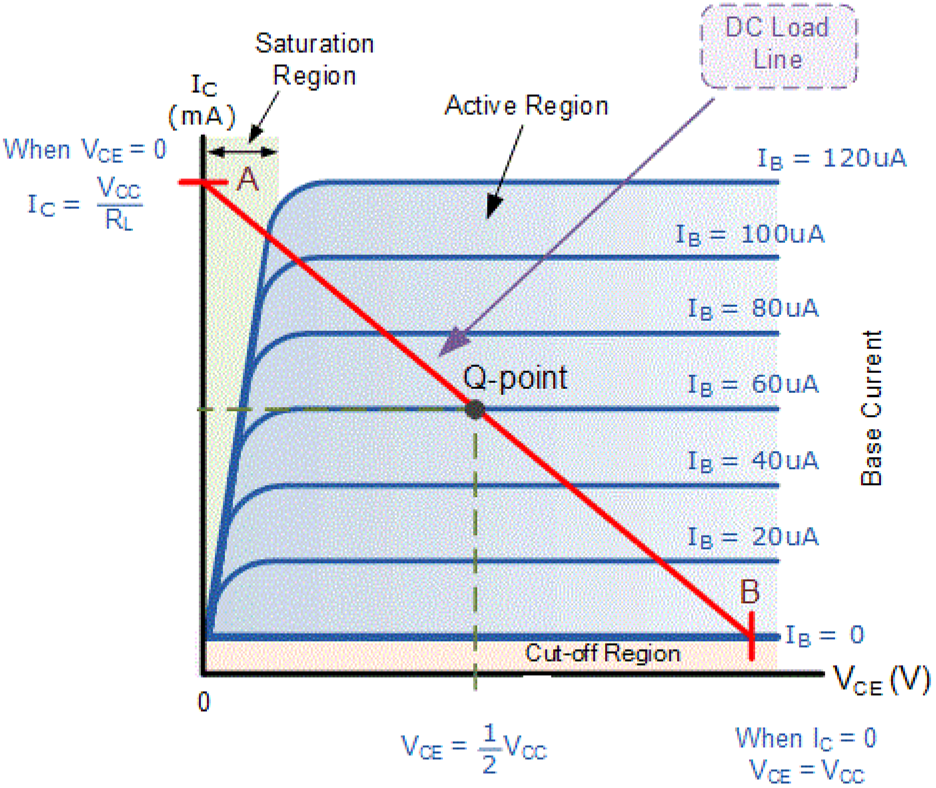
Applying KVL to output loop, we get

$V_{CE=}$ Vcc –Ic Rc---------------------(1)

Substitute Ic=0 in eq 1,

V_{CE}= 20v –0* Rc = 20v (point A)

Plot point A on the C-E characteristics as shown at Ic=0 and Vcc=20v, one point of dc load line



If Vce=0v in eq 1, then

0= 20v –Ic* 10

Ic=Vcc/Rc=20/10=2mA (point B)

Plot point B on the C-E characteristics as shown at Ic=2mA and Vcc=0v, another point of dc load line.

The Straight line drawn through A and B is dc load line for Rc=10KΩ and Vcc=20v.

If either of these 2 quantities changed, anew load line must be drawn.

Operating point (Q)

A point on the d.c. load line which represent the signal values of V_{CE} and I_C in a transistor is called as operating point or silent point or quiescent point or Q-point.

The Q-point is selected where the DC load line intersects the curve of output characteristics for particular value of signal current.

i.e. $\boxed{\textbf{Q-point} = (V_{CE}, I_C)}$

Bias stabilization

The process of making operating point independent of temperature changes or variation in transistor parameters is called the Bias stabilization.

We know that for transistor to operate it should be properly biased so that we can have a fixed operating point. To avoid any distortions, the Q-point should be at the center of the load line.

But in practice this Q-point may shift to any operating region (saturation or cur-off region) making the transistor unstable. Therefore in order to avoid this, biasing stability should be maintained.

Causes for shift of operating point or Bias instability

Bias instability occurs mainly due to two reasons.

1. Temperature
2. Current gain

1. Temperature (T)

The temperature at the junctions of a transistor depends on the amount of current flowing through it. Due to increase in temperature following parameters of a transistor will change.

(a) Base-emitter voltage (V_{BE})

V_{BE} decreases at a rate of 1.8mV/^{o}C with one degree rise in temperature for Si diode and V_{BE} decreases at a rate of 2.02mV/^{o}C with one degree rise in temperature for Ge diode.
The base current I_B will increase if V_{BE} decreases and since $I_C= \beta I_B$, I_C will also increases resulting in changing the Q-point.

(b) Reverse saturation current (I_{CBO})

We know that $I_C = \beta I_B + (1+\beta) I_{CBO}$ where I_{CBO} is the reverse saturation current. I_{CBO} doubles for every 10^{o}C rise in temperature there by increase in I_C and hence changing the Q-point.

2. Current gain (β)

In the process of manufacturing the transistors different transistors of same type may have different parameters (i.e. if we take two transistor units of same type and use them in the circuit there is a change in the β value in actual practice). The biasing circuit will be designed according to the required β value but due to the change in β from unit to unit the operating point may shift.

In summary increase in temperature always increases collector current Ic Because β and I_{CBO} increase with temperature and V_{BE} decreases with increase in temperature.

Thermal runaway

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

As temperature increases, I_{CBO} will increase, Increase in I_{CBO} causes Ic to increase, increase in Ic increases the C-B junction temperature, In turn results in a further increase in I_{CBO}. The effect is cumulative it leads to substantial increase in Ic. This could produce significant shift in Q-point or in the worst case Ic might keep on increasing and the C-B junction over heats and burns out resulting in the process called **Thermal Runway.**

Self-Bias (voltage divider or potential divider bias) circuit

Our objective is now to develop a common-emitter bias circuit with the following requirements:

1) Establish the Q point in the center of the active region of the output characteristics curve, so that on applying the input signal this instantaneous operating point does not move either to the saturation region or to the cut-off region, even at the extreme values of the input signal.
2) Stabilize the collector current against the temperature variations.
3) Make the operating point independent of the transistor used ,i.e. replacement by the same type is possible.

Furthermore, bias circuits that are relatively unaffected by the changes in β also tend to be independent of changes in other temperature-sensitive parameters such as I_{CBO} and V_{BE}. The process of designing a bias circuit to make it insensitive to parameter changes is called bias stabilization.

A bias-stabilized circuit that is most widely used in discrete BJT designs is shown as in fig 3 A voltage-divider network composed of resistors R1 and R2 has been used to determine the base-to–ground voltage (V_B) . For this reason, this bias circuit also called the voltage-divider-bias circuit. The most important stabilization component in the bias circuit as in Fig 3 is the emitter resistor R_E, which tends to make the operating point independent of parameter changes.

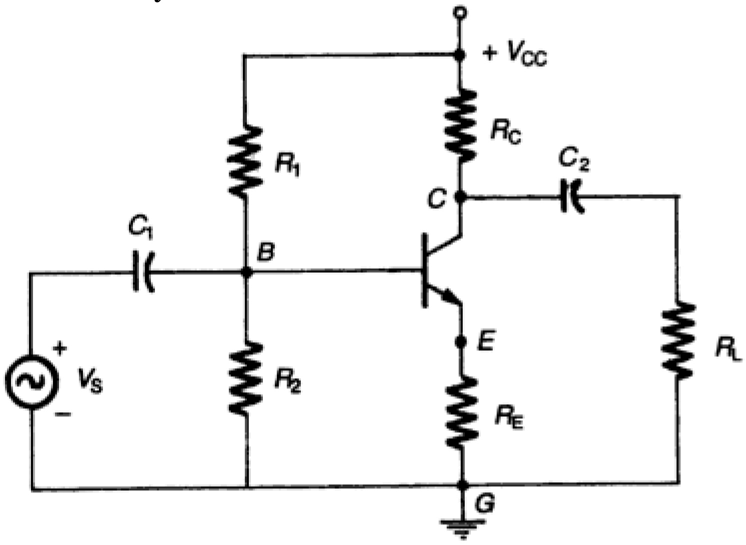
In this circuit V_E is the emitter–to-ground voltage, and

$$V_E = I_E R_E \text{----------------} 1$$

Now base-to-emitter voltage is given by

$$V_{BE} = V_B - V_E \text{----------} 2$$

Any change of transistor parameter that causes I_C to increase will cause I_E to increase by almost same amount.an increase in V_E; refer to eq 1. But V_B is essentially constant and so Eq2 shows that V_{BE} reduces with an increase in V_E. The reduction in V_{BE} reduces I_B, which then reduces I_C, thus compensating for the parameter change that tried to increase I_C. Similarly, any parameter change that tends to reduce Ic is compensated for by an increase in I_B.



Self-bias (voltage-divider-bias) circuit of an n-p-n transistor in CE configuration.

In summary, changes in the bias value of I_C automatically change the input voltage in a way that has opposite effect on I_C, thus tending to restore IC to its original value. So the bias circuit as in fig 3 is called self –bias circuit. The use of an emitter resistor to stabilize the bias point is called emitter stabilization.

AMPLIFER

Introduction

Amplifier is a circuit that is used for amplifying a signal. The input signal to an amplifier will be a current or voltage and the output will be an amplified version of the input signal. An amplifier circuit which is purely based on a transistor or transistors is called a transistor amplifier.

Transistors amplifiers are commonly used in applications like RF (radio frequency), audio, OFC (optic fibre communication) etc. Anyway the most common application we see in our day to day life is the usage of transistor as an audio amplifier.

As you know there are three transistor configurations that are used commonly i.e. common base (CB), common collector (CC) and common emitter (CE). In common base configuration has a gain less than unity and common collector configuration (emitter follower) has a gain almost equal to unity). Common emitter follower has a gain that is positive and greater than unity. So, common emitter configuration is most commonly used in audio amplifier applications.

A good transistor amplifier must have the following parameters; high input impedance, high band width, high gain, high slew rate, high linearity, high efficiency, and high stability

CE AMPLIFER

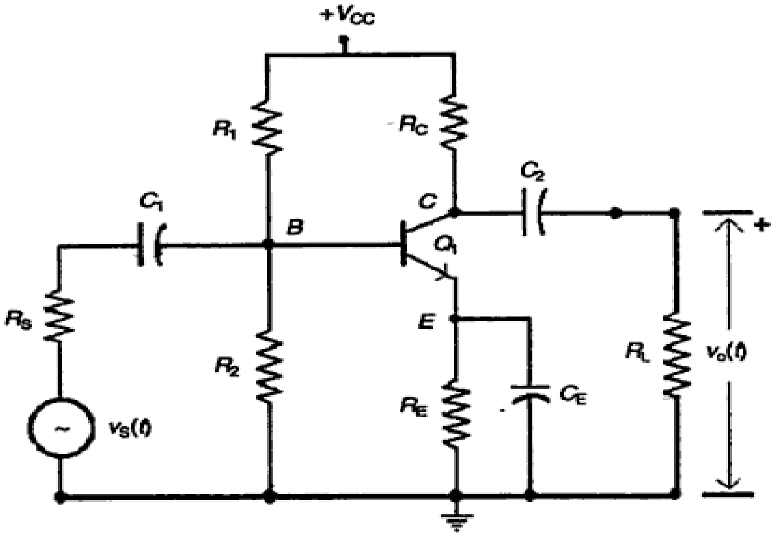
Basic features of an amplifier

The functional block that accomplishes the task of signal amplification is called amplifier.one of the basic features of amplifier is that the output waveform must be identical in nature to those in the input waveform. The amplifier preserves the details of the signal waveform and any deviation of the input waveform is considered as distortion.

Biasing of an amplifier

The purpose of biasing in a transistor amplifier is to set a dc operating, i.e. to fix base current, collector current and collector-emitter voltage such that the transistor operates in the linear region of the output characteristics even after superposition of ac signal voltage at the base.

Both the forward-bias voltage at the base-emitter junction and the reverse-bias voltage at the collector-base junction are derived from the single dc supply voltage Vcc. The circuit diagram of a transistor CE amplifier is shown as in fig.



The bias voltage at the base-emitter junction is given by

$$V_B = \frac{V_{CC} R_2}{R_1 + R_2}$$

The ac input voltage causes the output voltage to vary above and below the bias voltage. Output is given by

$$v_o(t) = V_o + A_o \sin \omega t$$

Where Vo is bias voltage or dc component of the output and Ao is the peak value of the sinusoidal ac component.

Amplifier Gain

An amplifier is characterized by the linear relationship between input (v_i) and output (v_o) signals. A relation between v_i and v_o signals is shown as:

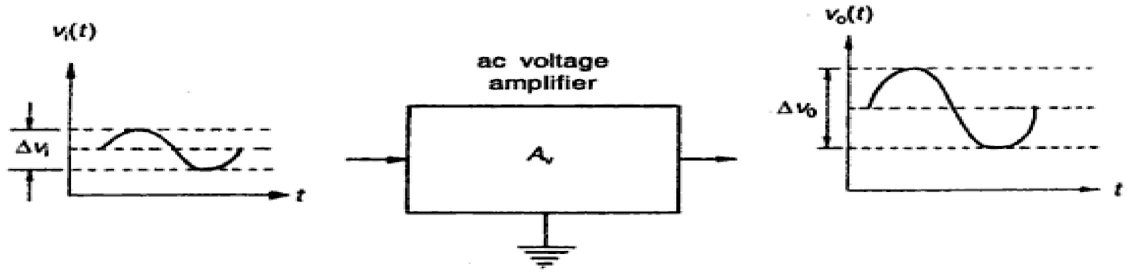
$$v_o(t) = A v_i(t)$$

where A is a constant, known as *amplifier gain*.

If the relationship between v_o and v_i contains higher powers of v_i, the output waveform will no longer be identical to that of input and the amplifier is then said to exhibit *nonlinear distortion*.

In an ac voltage amplifier, total change in the output voltage (Δv_o) from a device is greater than that of total change in input voltage (Δv_i). The concept of ac voltage amplification is illustrated in Fig. The ac voltage gain (A_v) is defined as the ratio of the change in output voltage to the change in input voltage:

$$A_v = \frac{\Delta v_o}{\Delta v_i} = \frac{v_o\,(\text{r.m.s.})}{v_i\,(\text{r.m.s.})}$$



Block schematic of a voltage amplifier

Similarly ac current gain (A_i) is defined as the ratio of the total output current variation (Δi_o) to the total input current variation (Δi_i) and $A_i > 1$ in an ac current amplifier.

$$A_i = \frac{\Delta i_o}{\Delta i_i} = \frac{i_o(\text{r.m.s.})}{i_i(\text{r.m.s.})}$$

amplifier gains defined above are ratios of quantities of similar dimensions and are expressed as dimensionless numbers. Alternatively, the amplifier gain is expressed with a logarithmic measure. Specifically, the voltage gain A_v and the current gain A_i are expressed as

$$\text{Voltage gain} = 20 \log A_v \text{ dB}, \qquad \text{Current gain} = 20 \log A_i \text{ dB}$$

In some cases, voltage and current gains may be negative numbers and so the absolute values are used in calculating gain in decibels. A negative A_v simply means that there is a 180° phase difference between input and output signals and it does not imply that the amplifier is attenuating the signal. On the other hand, if the gain in decibel is negative, the amplifier will attenuate the input signal.

Input and Output Resistance

The total equivalent resistance at the input terminals of the amplifier is known as *input resistance.* The dc input resistance, R_i, is the resistance that a dc source would see when connected to the input terminals, and the ac resistance r_i, is the resistance that an ac input source would see at the terminals. In either case, the input resistance can be computed as the ratio of input voltage to input current.

$$R_i = \frac{V_i}{I_i} \text{ (for dc)}, \qquad r_i = \frac{v_i}{i_i} \text{ (for ac)}$$

The output resistance of an amplifier is the total equivalent resistance at its output terminals. It is same as the Thevenin equivalent resistance that would appear in series with the output if the amplifier were replaced by its Thevenin equivalent circuit. Output resistance can be defined as a dc resistance R_o, or as an ac resistance, r_o and can be determined as the ratio of output voltage to output current.

$$R_o = \frac{V_o}{I_o} \text{ (for dc)}, \qquad r_o = \frac{v_o}{i_o} \text{ (for ac)}$$

Frequency Response and Bandwidth

An important characterization of an amplifier is in terms of its response to input sinusoids of different frequencies. Such a characterization of amplifier performance is known as *frequency response* of the amplifier.

we assume the input signal voltage as $v_s = V_i \sin \omega t$ with signal amplitude V_i and radian frequency ω. The signal measured at the output is also a sinusoid with the same frequency ω but with different amplitude V_o and shifting in phase φ relative to the input. Thus, $v_o = V_o \sin(\omega t + \varphi)$. The ratio of the amplitude of the output sinusoid (V_o) to the amplitude of the input sinusoid (V_i) is the magnitude of the amplifier gain (A_v) at the test frequency ω.

$$|A_v(\omega)| = \frac{V_o}{V_i} \quad \text{and} \quad \angle A_v(\omega) = \phi$$

Equation describes the response of the amplifier to a sinusoid of frequency ω. Now, the values of $|A_v|$ and $\angle A_v$ are measured at different frequencies of the input sinusoid and the gain magnitude $|A_v(\omega)|$, phase angle $\angle A_v(\omega)$ are plotted with frequency. These two plots together constitute the frequency response of the amplifier; the first is known as *amplitude response* and the second is the *phase response*. A typical amplitude response of an amplifier is shown in Fig. It indicates that the gain is almost constant (A_m) over a wide frequency range, roughly between ω_1 and ω_2. The gain decreases below ω_1 and above ω_2. The voltage gain in decibel (dB) may be expressed as

$$\text{Voltage gain} = 20 \log_{10} \frac{V_2}{V_1} \text{ dB}$$

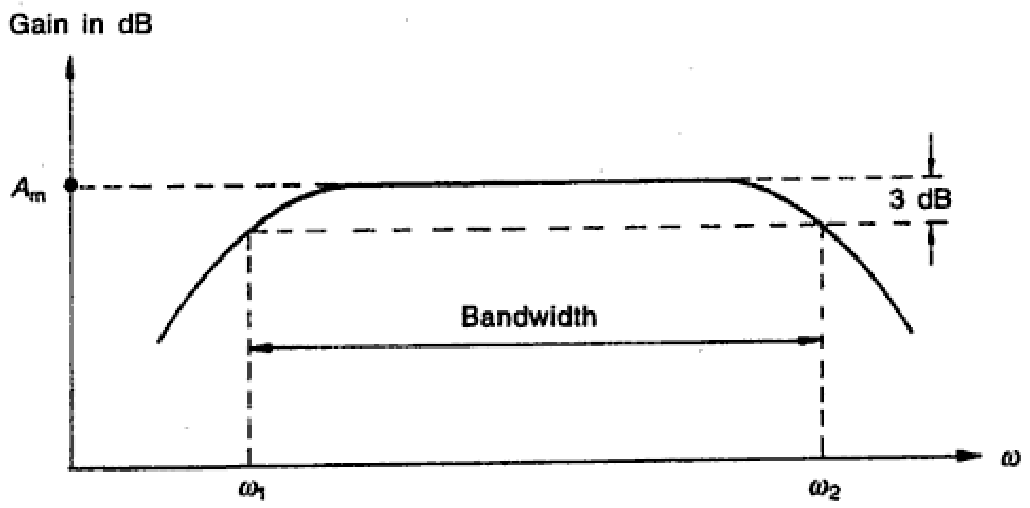


Fig. A typical amplitude response of an amplifier showing bandwidth and cut-off frequencies.

The band of frequencies over which the gain of the amplifier is almost constant, up to a certain number of decibels (usually 3 dB), is called the *amplifier bandwidth*. The frequency range over which the gain is more or less constant is called the *mid-band range*.

As seen in Fig. , one would expect a lower frequency cut-off as the capacitor C_1 offers a large reactance $1/(j\omega C_1)$ at low frequencies causing a significant signal loss. As the frequency is increased above the lower frequency cut-off (ω_1) the gain attains its maximum value. However, as the frequency is increased further the effect of small junction capacitances of the transistor appearing effectively in shunt path for the signal, becomes predominant. This brings down, the amplifier gain at higher frequencies resulting an upper cut-off (ω_2) in the frequency response. Thus the amplifier offers the desired gain over the bandwidth $(\omega_2 - \omega_1)$.

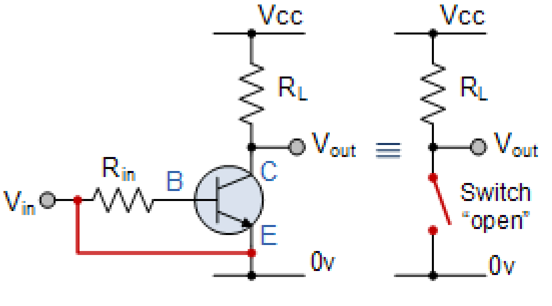
Transistor as a switch

A transistor acts as a switch as explained below

1. When the base emitter junction is open or reverse biased (i.e., IB=0) no collector current(IC) flows, the transistor is said to be OFF.

Even if IB=0, IC= ICEO, which is very small and thus for practical purposes, the transistor is said to be non-conducting and is in OFF region.

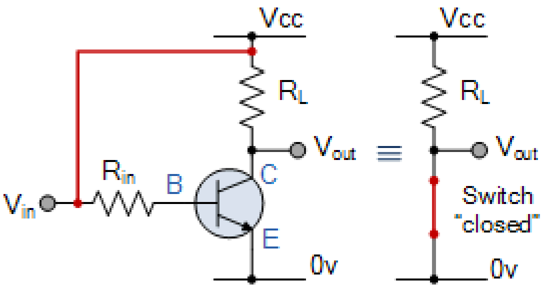
Cut-off Characteristics



- The input and Base are grounded (0v)
- Base-Emitter voltage VBE < 0.7v
- Base-Emitter junction is reverse biased
- Base-Collector junction is reverse biased
- Transistor is "fully-OFF" (Cut-off region)
- No Collector current flows (IC = 0)
- VOUT = VCE = VCC = "1"
- Transistor operates as an "open switch"

2.When the base emitter junction is forward biased and IB flows, as a result of which IC flows and at some value of IB , IC becomes saturated, i.e., it does not increase further and becomes independent of IB.at this point, the may be treated as fully ON as it is conducting in saturation region.

Saturation Characteristics

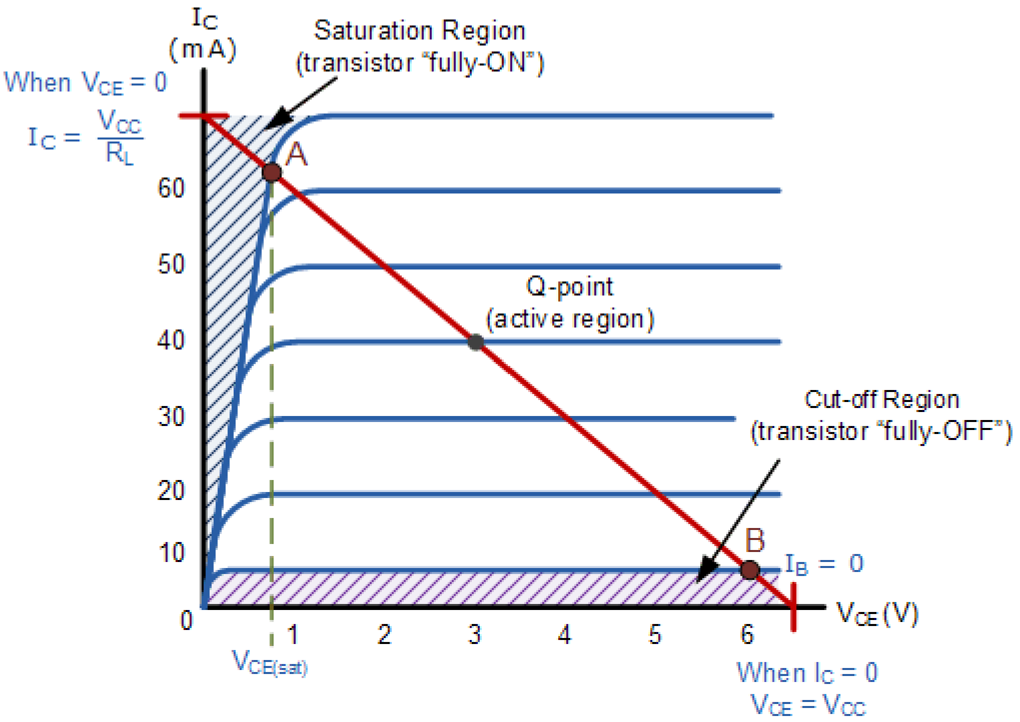


- The input and Base are connected to VCC
- Base-Emitter voltage VBE > 0.7v
- Base-Emitter junction is forward biased
- Base-Collector junction is forward biased
- Transistor is "fully-ON" (saturation region)
- Max Collector current flows (IC = Vcc/RL)
- VCE = 0 (ideal saturation)
- VOUT = VCE = "0"
- Transistor operates as a "closed switch"

The transistor can be made OFF, if IB is reduced to zero.

The areas of operation for a Transistor Switch are known as the **Saturation Region** and the **Cut-off Region**. The transistor as a switch by driving it back and forth between its "fully-OFF" (cut-off) and "fully-ON" (saturation) regions as shown below.

Operating Regions



The shaded area at the bottom of the curves represents the "Cut-off" region while the shaded area to the left represents the "Saturation" region of the transistor.

FEEDBACK

Feedback is a process in which a fraction of the output energy of a system is fed back to its input. Most of the physical systems incorporate some or the other form of feedback. The concept of feedback is used in areas like engineering applications and modelling of biological systems. Feedback plays an important role in electronic circuits and systems for a variety of reasons. Sometimes feedback through parasitic component is unavoidable in electronic circuits but in most cases it is introduced deliberately to obtain some desirable features. In this chapter, we concentrate on the use of feedback and its consequences in electronic circuits.

Depending upon whether the feedback signal aids or opposes the input signal, there are two basic types of feedbacks in amplifiers: *positive (or regenerative)* feedback and *negative (or degenerative)* feedback. When application of feedback signal increases the input signal i.e. the signal fed back is in phase with the input signal, it is called positive feedback. Positive feedback increases the gain of the amplifier, but it also increases distortion and instability of amplifier. So, positive feedback is normally not used in amplifier. If the positive feedback in an amplifier is sufficiently large, it leads to oscillation and hence it is used in oscillators. On the other hand if the feedback signal reduces the input signal, i.e. it is out of phase with the input, it is called negative feedback. When used in amplifiers, negative feedback stabilizes the gain, increases the bandwidth, reduces distortion and changes input and output resistance. So, negative feedback is frequently used in amplifier circuits. All these desirable properties of amplifier are obtained at the expense of a reduction in gain.

FEEDBACK PRINCIPLES

The basic structure of a feedback amplifier is shown as in Fig. , which is basically a signal flow diagram. A feedback amplifier is sometimes known as a *closed-loop* amplifier because the feedback forms a closed loop between the input and the output. It essentially consists of two blocks: an amplifier and a feedback circuit. Depending on the desired application, the feedback circuit can be made using passive components or active components or a combination of both. The assumptions made to derive the basic feedback equation are:

(i) reverse transmission from the amplifier output to the input is zero and
(ii) forward transmission through the feedback network is zero. Therefore, ideally the signal flows only in certain direction as shown by the arrows.

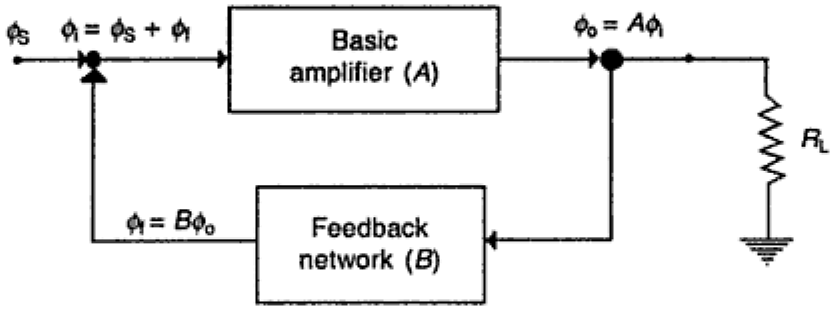


Fig. Block diagram of a feedback amplifier.

In Fig. , the quantity ϕ represents either a voltage or a current signal. The open-loop amplifier voltage gain, i.e. gain without feedback is A. Thus its output ϕ_o is related to the input ϕ_i by

$$\phi_o = A\phi_i$$

The output signal ϕ_o is fed to the load as well as to a feedback network. A fraction of ϕ_o is fed back to the input and added with externally applied input signal ϕ_S. The sampled signal (ϕ_f) is related to ϕ_o by the feedback function B,

$$\phi_f = B\phi_o$$

The feedback signal is ϕ_f added with the external input signal ϕ_S either in phase or in opposite phase to produce the input signal ϕ_i, which is input to the basic amplifier. Therefore,

$$\phi_i = \phi_S + \phi_f = \phi_S + B\phi_o$$

(ii) forward transmission through the feedback network is zero. Therefore, ideally the signal flows only in certain direction as shown by the arrows.

In Fig. , the quantity ϕ represents either a voltage or a current signal. The open-loop amplifier voltage gain, i.e. gain without feedback is A. Thus its output ϕ_o is related to the input ϕ_i by

$$\phi_o = A\phi_i$$

The output signal ϕ_o is fed to the load as well as to a feedback network. A fraction of ϕ_o is fed back to the input and added with externally applied input signal ϕ_S. The sampled signal (ϕ_f) is related to ϕ_o by the feedback function B,

$$\phi_f = B\phi_o$$

The feedback signal is ϕ_f added with the external input signal ϕ_S either in phase or in opposite phase to produce the input signal ϕ_i, which is input to the basic amplifier. Therefore,

$$\phi_i = \phi_S + \phi_f = \phi_S + B\phi_o$$

It has been assumed that the source, the load and the feedback network do not load the basic amplifier, i.e. gain A does not depend on any of these three networks. The gain of the feedback amplifier A_f can be obtained , as follows:

$$A_f = \frac{\phi_o}{\phi_S} = \frac{A\phi_i}{\phi_i - B\phi_o} = \frac{A\phi_i}{\phi_i - AB\phi_i}$$

or

$$A_f = \frac{A}{1-(AB)}$$

Equation gives the gain of a feedback amplifier and is known as *general feedback equation*. The quantity AB is known as *loop-gain* or *loop transmission function*. The term $(1 - AB)$ is called *feedback factor* or *return difference*.

Positive feedback. If the feedback signal ϕ_f is added in phase with the input signal ϕ_S, feedback is called positive. Therefore

$$\phi_i = \phi_S + \phi_f \qquad \text{implies } A_f = \frac{A}{1-(AB)}$$

If AB is positive and less than one, i.e.

$$1-(AB) < 1 \qquad \text{then} \quad A_f > A$$

Thus, positive feedback in a controlled amount increases the overall gain of the amplifier. When $AB = 1$, A_f is infinity, which means output signal is available even if ϕ_S is zero. This phenomenon is utilized in making electronic oscillators and is discussed in Section 6.5.

Negative feedback. Here the feedback signal ϕ_f is out of phase with the input signal ϕ_S and so ϕ_f is subtracted from the input source ϕ_S. Therefore,

$$\phi_i = \phi_S - \phi_f \qquad \text{implies } A_f = \frac{A}{1+AB}$$

and

$$A_f < A$$

Thus the gain of feedback amplifier with negative feedback is always less than that of the basic amplifier without feedback. For negative feedback loop gain, AB is negative and as the basic amplifier changes phase by 180°, the feedback network will not introduce any additional phase change.

If the loop gain AB is large, $AB >> 1$, and from Eq. it follows that $A_f \approx 1/B$ which means that the gain of the feedback amplifier is entirely determined by the feedback network.

ADVANTAGES OF NEGATIVE FEEDBACK AMPLIFIERS

Although the overall gain of the negative feedback amplifier gets reduced, there is considerable improvement of some performance measures of the amplifier. Negative feedback in amplifiers makes them less sensitive to parameter variations of the active devices, reduces non-linear distortion as well as amplitude distortion, improves frequency response (bandwidth increases), improves circuit stability. Some of these properties of negative feedback amplifier are considered in detail in this section.

Gain Stability

Active devices in an amplifier are more affected by the environmental conditions, manufacturing tolerance, quiescent point variation, etc. The gain of the amplifier changes slowly with ageing, temperature, humidity, etc. Negative feedback makes the amplifier less sensitive to these parameters. Gain desensitivity is defined as

$$S_A = \frac{\partial A_f / A_f}{\partial A / A}$$

We consider a situation in which there is a change in the gain of the basic amplifier due to some reason. Assuming B is constant and taking differentials on both sides of Eq.

$$A_f = \frac{A}{1 + AB}$$

$$dA_f = \frac{dA}{(1 + AB)^2}$$

Dividing Eq. by Eq. yields

$$\frac{dA_f}{A_f} = \frac{1}{1 + (AB)} \frac{dA}{A}$$

Comparing Eqs. and , we get

$$S_A = \frac{1}{1 + (AB)}$$

Equation indicates that the percentage change in A_f is smaller than the percentage change in A by an amount of feedback factor $(1 + AB)$. Thus an improvement of stability in gain is obtained with use of negative feedback. This will be clear by considering an example. Let an amplifier has open loop gain as 200 and feedback is 0.1 (10%). If the open loop gain changes by 10% due to temperature, the per cent change in closed loop gain is

$$\frac{dA_f}{A_f} = 10\% \frac{1}{1 + (0.1 \times 200)} \approx 0.5\%$$

Thus, the feedback gain changes only by 0.5% when the amplifier gain changes by 10%, i.e. 20 times improvement.

Noise Reduction

The sources of noise in an amplifier may be from power supply ripple voltage, non-linearity of active devices and other disturbances in the amplifier. Output power amplifier stage of an audio amplifier suffers from a problem known as *power-supply hum* due to drawing of large currents from the power supply and the difficulty in providing adequate power supply filtering. Negative feedback may be employed to reduce noise or interference in an amplifier. Any noise introduced at the input of the amplifier is treated like a signal by it and the amplifier amplifies both the signal and the noise equally.

To illustrate the effect of negative feedback on noise or distortion, we consider the two-stage amplifier as shown in Fig. 6.2. Distortion introduced at the output of the first as well as the second stage of the amplifier is designated by ϕ_{d1} and ϕ_{d2} respectively. The output signal ϕ_o in terms of ϕ_i is given by

$$\phi_o = \phi_S \frac{A_1 A_2}{1 - A_1 A_2 B} + \phi_{d1} \frac{A_2}{1 - A_1 A_2 B} + \phi_{d2} \frac{1}{1 - A_1 A_2 B} \tag{6.13}$$

Assuming $|A_1 A_2 B| >> 1$, Eq. (6.13) reduces to

$$\phi_o = -\frac{\phi_i}{B} - \frac{\phi_{d1}}{A_1 B} - \frac{\phi_{d2}}{A_1 A_2 B} \tag{6.14}$$

Equation (6.14) indicates that ϕ_{d2} is reduced by a factor of $A_1 A_2 B$ while ϕ_{d1} is reduced by $A_1 B$. The amount of reduction in noise/distortion depends very much on the origin of the noise signal. Since in most of the amplifier non-linear distortion is introduced when the signal level is high, the

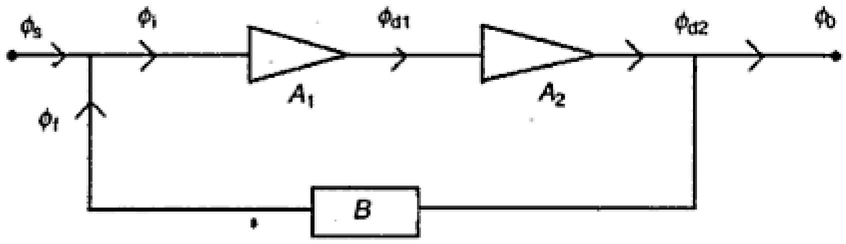


Fig. 6.2 Illustrating the application of negative feedback to improve noise and distortion in an amplifier.

distortion is mainly be contributed by the last stage at the output of the amplifier and the distortion introduced at the last of the amplifier is reduced drastically. Thus noise/distortion is reduced approximately by the feedback factor in the negative feedback amplifier.

Bandwidth Enhancement

The use of negative feedback increases the overall bandwidth of an amplifier. Bandwidth is defined by the difference between the higher (ω_H) and lower (ω_L) 3-dB cut-off frequencies. We shall investigate the effect of negative feedback on the higher and lower 3-dB frequencies. The gain of an amplifier as a function of frequency is given by

$$A(\omega) = -\frac{A_M}{1 + (j\omega/\omega_H)} \tag{6.15}$$

where A_M and ω_H are respectively the mid-band gain and upper 3-dB cut-off frequency respectively. Assuming the feedback function B to be frequency independent, the close-loop gain given in Eq. (6.5) may be written as

$$A_f(\omega) = \frac{A(\omega)}{1 - A(\omega)B} \tag{6.16}$$

Substituting the value of $A(\omega)$ from Eq. (6.15) in Eq. (6.16), we get

$$A_f(\omega) = \frac{-A_M/[1+(j\omega/\omega_H)]}{1+\{A_M B/[1+(j\omega/\omega_H)]\}} = \frac{-A_M\omega_H}{j\omega + \omega_H(1+A_M B)} \tag{6.17}$$

Comparing Eqs. (6.15) and (6.17) we find that the new upper 3-dB frequency increases by a factor of $(1 + A_M B)$. Upper 3-dB frequency ω_{Hf} is given by

$$\omega_{Hf} = \omega_H(1 + A_M B) \tag{6.18}$$

The upper 3-dB frequency increases by an amount equal to feedback factor.

Similarly, it can be shown that the feedback amplifier will have a lower 3-dB frequency (ω_{Lf}) given by

$$\omega_{Lf} = \frac{\omega_L}{1 + A_M B} \tag{6.19}$$

Lower 3-dB frequency is also reduced by an amount equal to feedback factor. The bandwidth of the amplifier with feedback is given by

$$BW_f = \omega_H(1 + A_M B) - \frac{\omega_L}{1 + A_M B} \tag{6.20}$$

Thus overall bandwidth increases by using negative feedback. The effect of negative feedback on the frequency response is as shown in Fig. 6.3. It may be noted that the amplifier bandwidth is increased by the same factor by which its mid-band gain is decreased, maintaining the gain-bandwidth product constant.

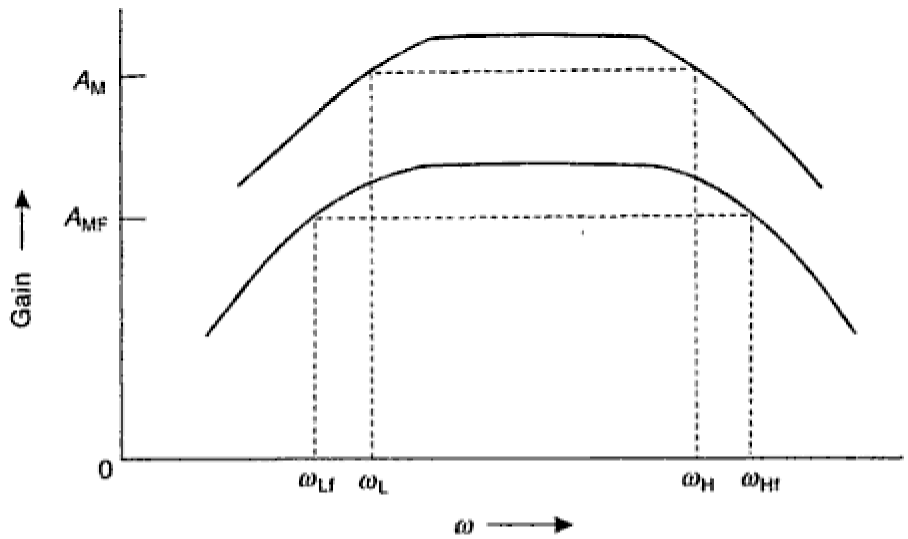


Fig. 6.3 Effect of negative feedback on bandwidth.

Improvement in Linearity and Signal Handling Capacity

Input–output characteristics of an amplifier are called *linearity* characteristics. Figure 6.4 shows the input–output characteristics of an amplifier with and without negative feedback. Slope of this characteristics ($\Delta v_o/\Delta v_i$) is called the *gain* of the amplifier. Input–output characteristic is linear up to a maximum input signal level of v_c, known as *signal handling capacity* of the amplifier. As the input signal level increases further beyond v_c, the output signal becomes saturated and amplifier enters into non-linear region. With the use of negative feedback, gain of the amplifier decreases and consequently slope of the linearity characteristics also decreases. So the output signal of the amplifier will change linearly with input signal till higher values of input signal than v_c. Thus, signal handling capacity increases and also non-linear distortion decreases with application of negative feedback in an amplifier.

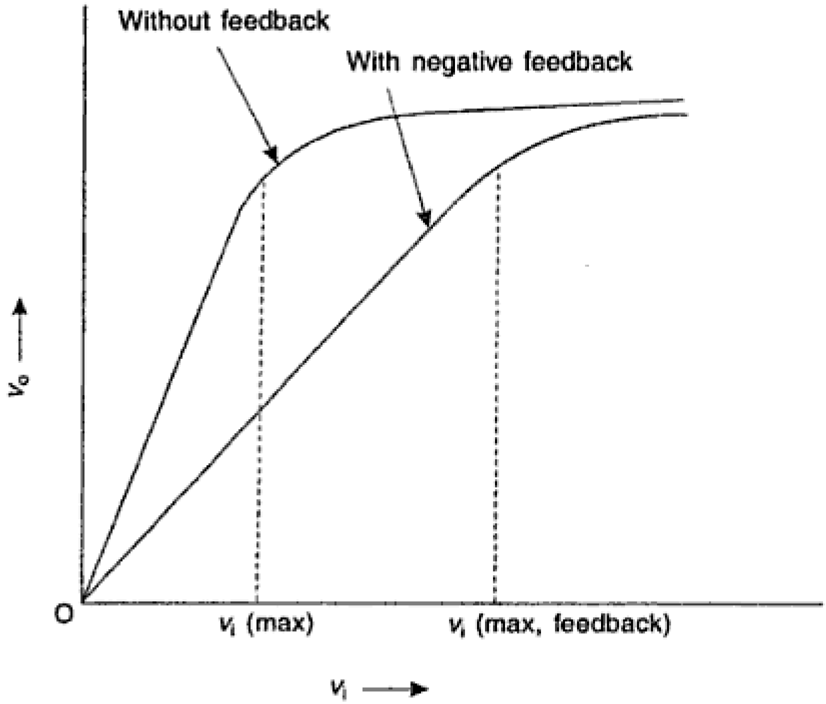


Fig. 6.4 Input–output characteristics of an amplifier with and without feedback.