10

Transistors

Introduction

When a third doped element is added to a crystal diode in such a way that two *pn* junctions are formed, the resulting device is known as a *transistor*. The transistor—an entirely new type of electronic device—is capable of achieving amplification of weak signals in a fashion comparable and often superior to that realised by vacuum tubes. Transistors are far smaller than vacuum tubes, have no filament and hence need no heating power and may be operated in any position. They are mechanically strong, have practically unlimited life and can do some jobs better than vacuum tubes.

Invented in 1948 by J. Bardeen and W.H. Brattain of Bell Telephone Laboratories, U.S.A.; transistor has now become the heart of most electronic applications. Though transistor is only slightly more than 54 years old, yet it is fast replacing vacuum tubes in almost all applications. In this chapter, we shall focus our attention on the various aspects of transistors and their increasing applications in the fast developing electronics industry.

10.1 Transistor

A **transistor** *consists of two pn junctions formed by *sandwiching either p-type or n-type semiconductor between a pair of opposite types.* Accordingly ; there are two types of transistors, namely;

(*i*) *n-p-n* transistor (*ii*) *p-n-p* transistor

An *n-p-n* transistor is composed of two *n*-type semiconductors separated by a thin section of *p*-type as shown in Fig. 10.1 (*i*). However, a *p-n-p* transistor is formed by two *p*-sections separated by a thin section of *n*-type as shown in Fig. 10.1 (*ii*).

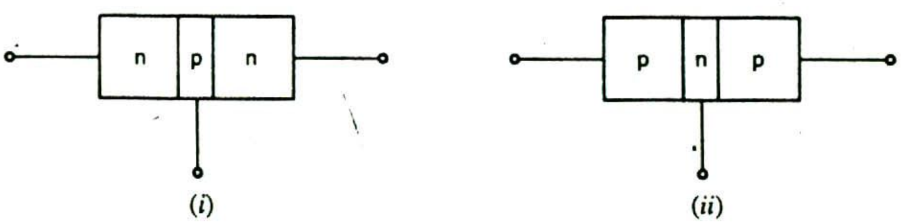

Fig. 10.1

In each type of transistor, the following points may be noted :

* In practice, these three blocks *p, n, p* are grown out of the same crystal by adding corresponding impurities in turn.

(i) These are two *pn* junctions. Therefore, a transistor may be regarded as a combination of two diodes connected back to back.

(ii) There are three terminals, taken from each type of semiconductor.

(iii) The middle section is a very thin layer. This is the most important factor in the function of a transistor.

Origin of the name "Transistor". When new devices are invented, scientists often try to devise a name that will appropriately describe the device. A transistor has two *pn* junctions. As discussed later, one junction is forward biased and the other is reverse biased. The forward biased junction has a low resistance path whereas a reverse biased junction has a high resistance path. The weak signal is introduced in the low resistance circuit and output is taken from the high resistance circuit. Therefore, a transistor *transfers* a signal from a low resistance to high resistance. The prefix 'trans' means the signal transfer property of the device while 'istor' classifies it as a solid element in the same general family with resistors.

10.2 Naming the Transistor Terminals

A transistor (*pnp* or *npn*) has three sections of doped semiconductors. The section on one side is the *emitter* and the section on the opposite side is the *collector*. The middle section is called the *base* and forms two junctions between the emitter and collector.

(i) **Emitter.** The section on one side that supplies charge carriers (electrons or holes) is called the *emitter*. *The emitter is always forward biased w.r.t. base* so that it can supply a large number of *majority carriers. In Fig. 10.2 (*i*), the emitter (*p*-type) of *pnp* transistor is forward biased and supplies hole charges to its junction with the base. Similarly, in Fig. 10.2 (*ii*), the emitter (*n*-type) of *npn* transistor has a forward bias and supplies free electrons to its junction with the base.

(ii) **Collector.** The section on the other side that collects the charges is called the *collector*. *The collector is always reverse biased.* Its function is to remove charges from its junction with the base. In Fig. 10.2 (*i*), the collector (*p*-type) of *pnp* transistor has a reverse bias and receives hole charges that flow in the output circuit. Similarly, in Fig. 10.2 (*ii*), the collector (*n*-type) of *npn* transistor has reverse bias and receives electrons.

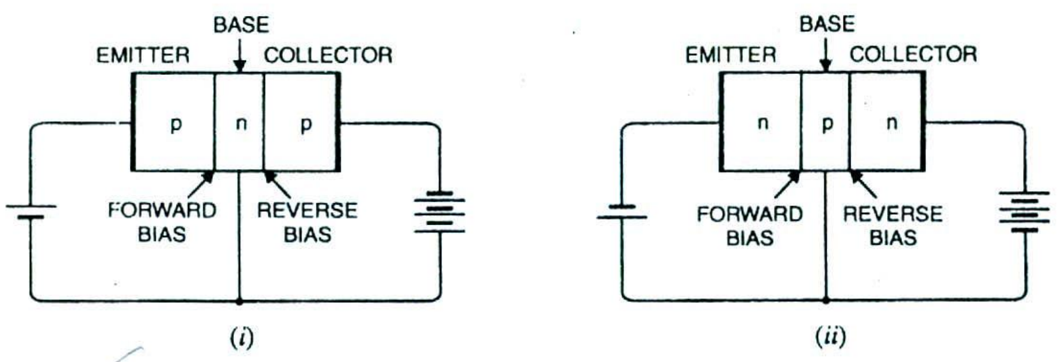

Fig. 10.2

(iii) **Base.** The middle section which forms two *pn*-junctions between the emitter and collector is called the *base*. The base-emitter junction is forward biased, allowing low resistance for the emitter circuit. The base-collector junction is reverse biased and provides high resistance in the collector circuit.

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* Holes if emitter is *p*-type and electrons if the emitter is *n*-type.

10.3 Some Facts about the Transistor

Before discussing transistor action, it is important that the reader may keep in mind the following facts about the transistor :

(*i*) The transistor has three regions, namely ; *emitter*, *base* and *collector*. The base is much thinner than the emitter while *collector is wider than both as shown in Fig. 10.3. However, for the sake of convenience, it is customary to show emitter and collector to be of equal size.

(*ii*) The emitter is heavily doped so that it can inject a large number of charge carriers (electrons or holes) into the base. The base is lightly doped and very thin ; it passes most of the emitter injected charge carriers to the collector. The collector is moderately doped.

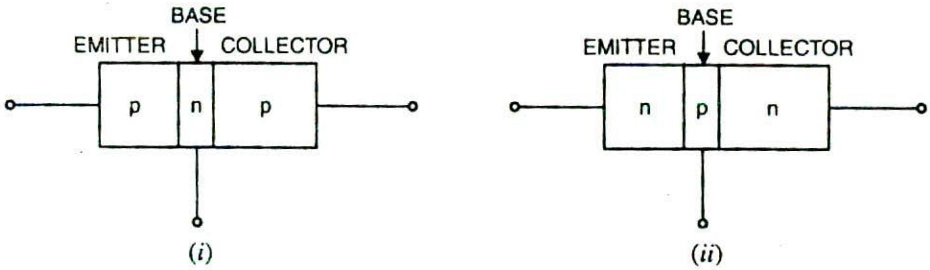

Fig. 10.3

(*iii*) The transistor has two *pn* junctions *i.e.* it is like two diodes. The junction between emitter and base may be called *emitter-base diode* or simply the *emitter diode*. The junction between the base and collector may be called *collector-base diode* or simply *collector diode*.

(*iv*) The emitter diode is always forward biased whereas collector diode is always reverse biased.

(*v*) The resistance of emitter diode (forward biased) is very small as compared to collector diode (reverse biased). Therefore, forward bias applied to the emitter diode is generally very small whereas reverse bias on the collector diode is much higher.

10.4 Transistor Action

The emitter-base junction of a transistor is forward biased whereas collector-base junction is reverse biased. If for a moment, we ignore the presence of emitter-base junction, then *practically*** no current would flow in the collector circuit because of the reverse bias. However, if the emitter-base junction is also present, then forward bias on it causes the emitter current to flow. It is seen that this emitter current almost entirely flows in the collector circuit. Therefore, the current in the collector circuit depends upon the emitter current. If the emitter current is zero, then collector current is nearly zero. However, if the emitter current is 1mA, then collector current is also about 1mA. This is precisely what happens in a transistor. We shall now discuss this transistor action for *npn* and *pnp* transistors.

(*i*) **Working of npn transistor.** Fig. 10.4 shows the *npn* transistor with forward bias to emitter-base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the *n*-type emitter to flow towards the base. This constitutes the emitter current I_E. As these electrons

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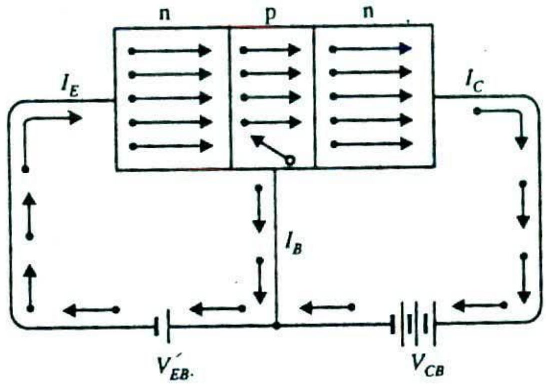
* During transistor operation, much heat is produced at the collector junction. The collector is made larger to dissipate the heat.

** In actual practice, a very little current (a few μA) would flow in the collector circuit. This is called collector cut off current and is due to minority carriers.

flow through the p-type base, they tend to combine with holes. As the base is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base* current I_B. The remainder (**more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It is clear that emitter current is the sum of collector and base currents *i.e.*

$$I_E = I_B + I_C$$



Basic connection of *npn* transistor

Fig. 10.4

(*ii*) **Working of pnp transistor.** Fig. 10.5 shows the basic connection of a *pnp* transistor. The forward bias causes the holes in the p-type emitter to flow towards the base. This constitutes the emitter current I_E. As these holes cross into n-type base, they tend to combine with the electrons. As

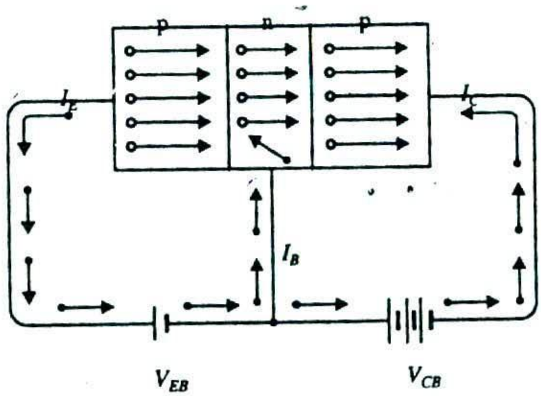


Fig. 10.5

the base is lightly doped and very thin, therefore, only a few holes (less than 5%) combine with the electrons. The remainder (more than 95%) cross into the collector region to constitute collector

* The electrons which combine with holes become valence electrons. Then as valence electrons, they flow down through holes and into the external base lead. This constitutes base current I_B.

** The reasons that most of the electrons from emitter continue their journey through the base to collector to form collector current are : (*i*) The base is lightly doped and very thin. Therefore, there are a few holes which find enough time to combine with electrons. (*ii*) The reverse bias on collector is quite high and exerts attractive forces on these electrons.

current I_C. In this way, almost the entire emitter current flows in the collector circuit. It may be noted that current conduction within *pnp* transistor is by holes. However, in the external connecting wires, the current is still by electrons.

Importance of transistor action. The input circuit (*i.e.* emitter-base junction) has low resistance because of forward bias whereas output circuit (*i.e.* collector-base junction) has high resistance due to reverse bias. As we have seen, the input emitter current almost entirely flows in the collector circuit. Therefore, a transistor transfers the input signal current from a low-resistance circuit to a high-resistance circuit. This is the key factor responsible for the amplifying capability of the transistor. We shall discuss the amplifying property of transistor later in this chapter.

10.5 Transistor Symbols

In the earlier diagrams, the transistors have been shown in diagrammatic form. However, for the sake of convenience, the transistors are represented by schematic diagrams. The symbols used for *npn* and *pnp* transistors are shown in Fig. 10.6.

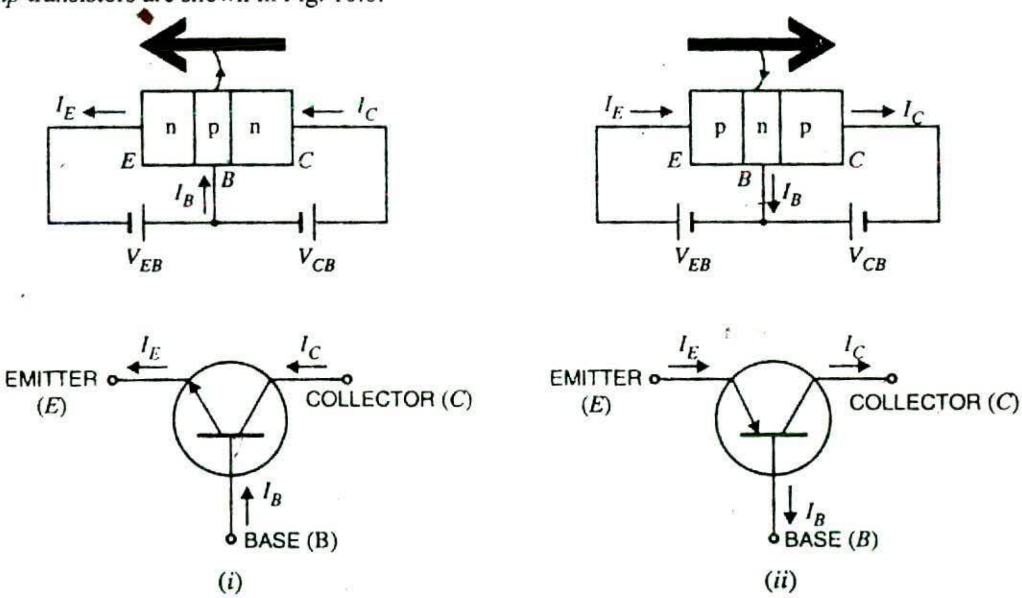


Fig. 10.6

Note that emitter is shown by an arrow which indicates the direction of conventional current flow with forward bias. For *npn* connection, it is clear that conventional current flows out of the emitter as indicated by the outgoing arrow in Fig. 10.6 (*i*). Similarly, for *pnp* connection, the conventional current flows into the emitter as indicated by inward arrow in Fig. 10.6 (*ii*).

10.6 Transistor as an Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier. Fig. 10.7 shows the basic circuit of a transistor amplifier. The weak signal is applied between emitter-base junction and output is taken across the load R_C connected in the collector circuit. In order to achieve faithful amplification, the input circuit should always remain forward biased. To do so, a d.c. voltage V_{EE} is applied in the input circuit in addition to the signal as shown. This d.c. voltage is known as bias*

* It may be recalled that biasing is also necessary in vacuum tube amplifiers for faithful amplification (see Chapter 5). The reader may find the detailed discussion on transistor biasing in Chapter 11.

voltage and its magnitude is such that it always keeps the input circuit forward biased regardless of the polarity of the signal.

As the input circuit has low resistance, therefore, a small change in signal voltage causes an appreciable change in emitter current. This causes almost the *same change in collector current due to transistor action. The collector current flowing through a high load resistance R_C produces a large voltage across it. Thus, a weak signal applied in the input circuit appears in the amplified form in the collector circuit. It is in this way that a transistor acts as an amplifier.

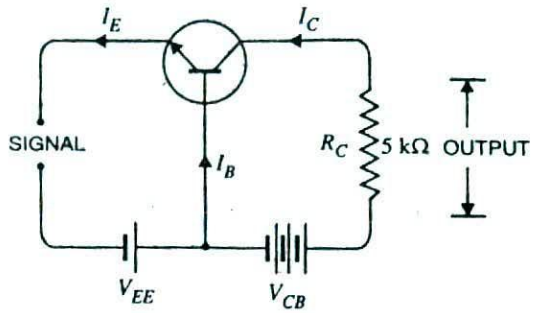


Fig. 10.7

Illustration. The action of a transistor as an amplifier can be made more illustrative if we consider typical circuit values. Suppose collector load resistance $R_C = 5$ kΩ. Let us further assume that a change of 0.1V in signal voltage produces a change of 1 mA in emitter current. Obviously, the change in collector current would also be approximately 1 mA. This collector current flowing through collector load R_C would produce a voltage = 5 kΩ × 1 mA = 5 V. Thus, a change of 0.1 V in the signal has caused a change of 5 V in the output circuit. In other words, the transistor has been able to raise the voltage level of the signal from 0.1 V to 5 V *i.e.* voltage amplification is 50.

Example 10.1. *A common base transistor amplifier has an input resistance of 20 Ω and output resistance of 100 kΩ. The collector load is 1 kΩ. If a signal of 500 mV is applied between emitter and base, find the voltage amplification. Assume α_{ac} to be nearly one.*

Solution. **Fig. 10.8 shows the conditions of the problem. Note that output resistance is very high as compared to input resistance. This is not surprising because input junction (base to emitter) of the transistor is forward biased while the output junction (base to collector) is reverse biased.

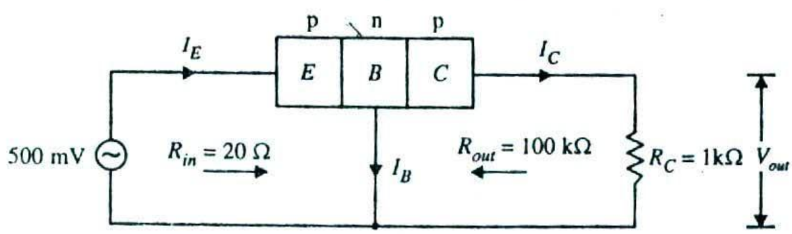


Fig. 10.8

Input current, $I_E = \dfrac{\text{Signal}}{R_{in}} = \dfrac{500 \text{ mV}}{20\ \Omega} = 25$ mA. Since α_{ac} is nearly 1, output current, $I_C = I_E = 25$ mA.

$$\text{Output voltage, } V_{out} = I_C R_C = 25 \text{ mA} \times 1 \text{ k}\Omega = 25 \text{ V}$$

* The reason is as follows. The collector-base junction is reverse biased and has a very high resistance of the order of mega ohms. Thus collector-base voltage has little effect on the collector current. This means that a large resistance R_C can be inserted in series with collector without disturbing the collector current relation to the emitter current *viz.* $I_C = \alpha I_E + I_{CBO}$. Therefore, collector current variations caused by a small base-emitter voltage fluctuations result in voltage changes in R_C that are quite high—often hundreds of times larger than the emitter-base voltage.

** The d.c. biasing is omitted in the figure because our interest is limited to amplification.

$\therefore$ Voltage amplification, $A_v = \frac{V_{out}}{\text{signal}} = \frac{25\ V}{500\ mV} = 50$

Comments. The reader may note that basic amplifying action is produced by transferring a current from a *low-resistance* to a *high-resistance* circuit. Consequently, the name transistor is given to the device by combining the two terms given in bold letters below :

Transfer + Resistor ⟶ Transistor

10.7 Transistor Connections

There are three leads in a transistor *viz.*, emitter, base and collector terminals. However, when a transistor is to be connected in a circuit, we require four terminals; two for the input and two for the output. This difficulty is overcome by making one terminal of the transistor common to both input and output terminals. The input is fed between this common terminal and one of the other two terminals. The output is obtained between the common terminal and the remaining terminal. Accordingly; a transistor can be connected in a circuit in the following three ways :

(*i*) common base connection (*ii*) common emitter connection

(*iii*) common collector connection

Each circuit connection has specific advantages and disadvantages. It may be noted here that regardless of circuit connection, the emitter is always biased in the forward direction, while the collector always has a reverse bias.

10.8 Common Base Connection

In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base. Here, base of the transistor is common to both input and output circuits and hence the name common base connection. In Fig. 10.9 (*i*), a common base *npn* transistor circuit is shown whereas Fig. 10.9 (*ii*) shows the common base *pnp* transistor circuit.

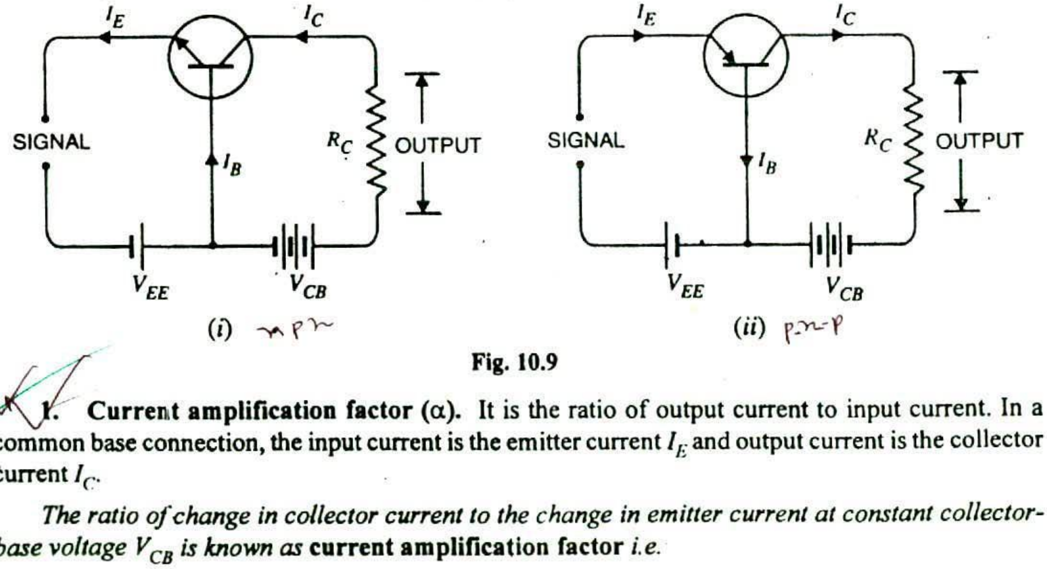


Fig. 10.9

1. Current amplification factor (α). It is the ratio of output current to input current. In a common base connection, the input current is the emitter current I_E and output current is the collector current I_C.

The ratio of change in collector current to the change in emitter current at constant collector-base voltage V_{CB} is known as **current amplification factor** *i.e.*

$$^*\alpha = \frac{\Delta I_C}{\Delta I_E} \text{ at constant } V_{CB}$$

* If only d.c. values are considered, then $\alpha = I_C/I_E$.

It is clear that current amplification factor is less than *unity. This value can be increased (but not more than unity) by decreasing the base current. This is achieved by making the base thin and doping it lightly. Practical values of α in commercial transistors range from 0.9 to 0.99.

2. Expression for collector current. The whole of emitter current does not reach the collector. It is because a small percentage of it, as a result of electron-hole combinations occurring in base area, gives rise to base current. Moreover, as the collector-base junction is reverse biased, therefore, some leakage current flows due to minority carriers. It follows, therefore, that total collector current consists of :

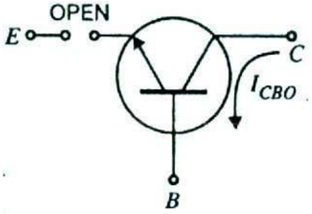


Fig. 10.10

(*i*) That part of emitter current which reaches the collector terminal *i.e.* **αI_E.

(*ii*) The leakage current $I_{leakage}$. This current is due to the movement of minority carriers across base-collector junction on account of it being reverse biased. This is generally much smaller than αI_E.

∴ Total collector current, $I_C = \alpha I_E + I_{leakage}$

It is clear that if $I_E = 0$ (*i.e.*, emitter circuit is open), a small leakage current still flows in the collector circuit. This $I_{leakage}$ is abbreviated as I_{CBO}, meaning collector-base current with emitter open. The I_{CBO} is indicated in Fig. 10.10.

$$\therefore \quad I_C = \alpha I_E + I_{CBO} \qquad \text{...(i)}$$

Now $\quad I_E = I_C + I_B$

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

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

or $$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha} \qquad \text{...(ii)}$$

Relation (*i*) or (*ii*) can be used to find I_C. It is further clear from these relations that the collector current of a transistor can be controlled by either the emitter or base current.

Fig. 10.11 shows the concept of I_{CBO}. In *CB* configuration, a small collector current flows even when the emitter current is zero. This is the leakage collector current (*i.e.* the collector current when emitter is open) and is denoted by I_{CBO}. When the emitter voltage V_{EE} is also applied, the various currents are as shown in Fig. 10.11 (*ii*).

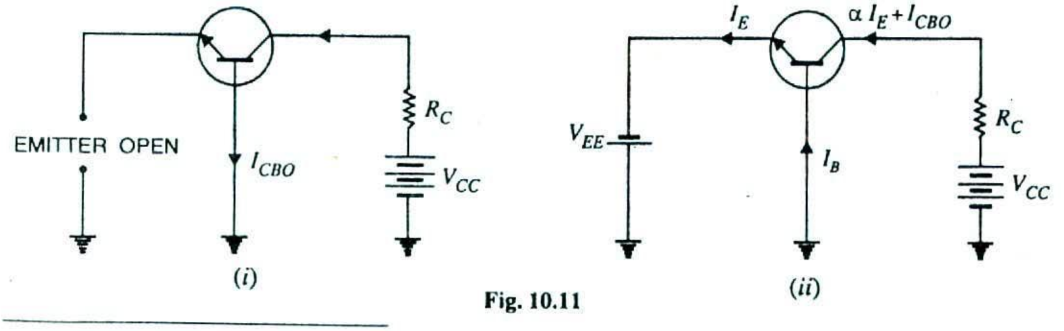


Fig. 10.11

* At first sight, it might seem that since there is no current gain, no voltage or power amplification could be possible with this arrangement. However, it may be recalled that output circuit resistance is much higher than the input circuit resistance. Therefore, it does give rise to voltage and power gain.

** $$\alpha = \frac{I_C}{I_E} \quad \therefore \quad I_C = \alpha I_E$$

In other words, αI_E part of emitter current reaches the collector terminal.

Note. Owing to improved construction techniques, the magnitude of I_{CBO} for general-purpose and low-powered transistors (especially silicon transistors) is usually very small and may be neglected in calculations. However, for high power applications, it will appear in microampere range. Further, I_{CBO} is very much temperature dependent; it increases rapidly with the increase in temperature. Therefore, at higher temperatures, I_{CBO} plays an important role and must be taken care of in calculations.

Example 10.2. *In a common base connection, I_E = 1mA, I_C = 0.95mA. Calculate the value of I_B.*

Solution. Using the relation, $I_E = I_B + I_C$

or $1 = I_B + 0.95$

$\therefore$ $I_B = 1 - 0.95 = \mathbf{0.05\ mA}$

Example 10.3. *In a common base connection, current amplification factor is 0.9. If the emitter current is 1mA, determine the value of base current.*

Solution. Here $\alpha = 0.9$, $I_E = 1$ mA

Now $\alpha = \dfrac{I_C}{I_E}$

or $I_C = \alpha I_E = 0.9 \times 1 = 0.9$ mA

Also $I_E = I_B + I_C$

$\therefore$ Base current, $I_B = I_E - I_C = 1 - 0.9 = \mathbf{0.1\ mA}$

Example 10.4. *In a common base connection, I_C = 0.95 mA and I_B = 0.05 mA. Find the value of α.*

Solution. We know $I_E = I_B + I_C = 0.05 + 0.95 = 1$ mA

$\therefore$ Current amplification factor, $\alpha = \dfrac{I_C}{I_E} = \dfrac{0.95}{1} = \mathbf{0.95}$

Example 10.5. *In a common base connection, the emitter current is 1mA. If the emitter circuit is open, the collector current is 50 μA. Find the total collector current. Given that α = 0.92.*

Solution. Here, I_E = **1 mA**, α = **0.92**, I_{CBO} = **50 μA**

$\therefore$ Total collector current, $I_C = \alpha I_E + I_{CBO} = 0.92 \times 1 + 50 \times 10^{-3}$

$= 0.92 + 0.05 = \mathbf{0.97\ mA}$

Example 10.6. *In a common base connection, α = 0.95. The voltage drop across 2 kΩ resistance which is connected in the collector is 2V. Find the base current.*

Solution. Fig. 10.12 shows the required common base connection. The voltage drop across R_C (= 2 kΩ) is 2V.

$\therefore$ $I_C = 2\ \text{V}/2\ \text{k}\Omega = 1$ mA

Now $\alpha = I_C/I_E$

$\therefore$ $I_E = \dfrac{I_C}{\alpha} = \dfrac{1}{0.95} = 1.05$ mA

Using the relation, $I_E = I_B + I_C$

$\therefore$ $I_B = I_E - I_C = 1.05 - 1$

$= \mathbf{0.05\ mA}$

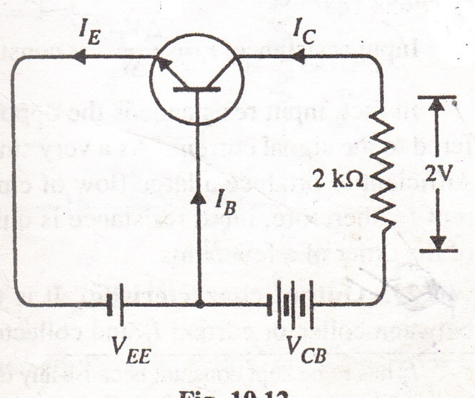


Fig. 10.12

Example 10.7. *For the common base circuit shown in Fig. 10.13, determine I_C and V_{CB}. Assume the transistor to be of silicon.*

Solution. Since the transistor is of silicon, $V_{BE} = 0.7$V. Applying Kirchhoff's voltage law to the emitter-side loop, we get,

$$V_{EE} = I_E R_E + V_{BE}$$

or
$$I_E = \frac{V_{EE} - V_{BE}}{R_E}$$

$$= \frac{8V - 0.7V}{1.5 \text{ k}\Omega} = 4.87 \text{ mA}$$

$$\therefore \quad I_C \simeq I_E = \textbf{4.87 mA}$$

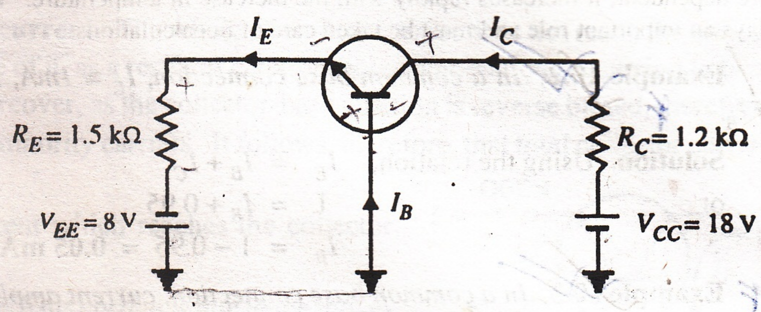


Fig. 10.13

Applying Kirchhoff's voltage law to the collector-side loop, we have,

$$V_{CC} = I_C R_C + V_{CB}$$

$$\therefore \quad V_{CB} = V_{CC} - I_C R_C = 18 \text{ V} - 4.87 \text{ mA} \times 1.2 \text{ k}\Omega = \textbf{12.16 V}$$

10.9 Characteristics of Common Base Connection

The complete electrical behaviour of a transistor can be described by stating the interrelation of the various currents and voltages. These relationships can be conveniently displayed graphically and the curves thus obtained are known as the characteristics of transistor. The most important characteristics of common base connection are *input characteristics* and *output characteristics.*

(1) Input characteristic. It is the curve between emitter current I_E and emitter-base voltage V_{EB} at constant collector-base voltage V_{CB}. The emitter current is generally taken along *y*-axis and emitter-base voltage along *x*-axis. Fig. 10.14 shows the input characteristics of a typical transistor in *CB* arrangement. The following points may be noted from these characteristics :

(*i*) The emitter current I_E increases rapidly with small increase in emitter-base voltage V_{EB}. It means that input resistance is very small.

(*ii*) The emitter current is almost independent of collector-base voltage V_{CB}. This leads to the conclusion that emitter current (and hence collector current) is almost independent of collector voltage.

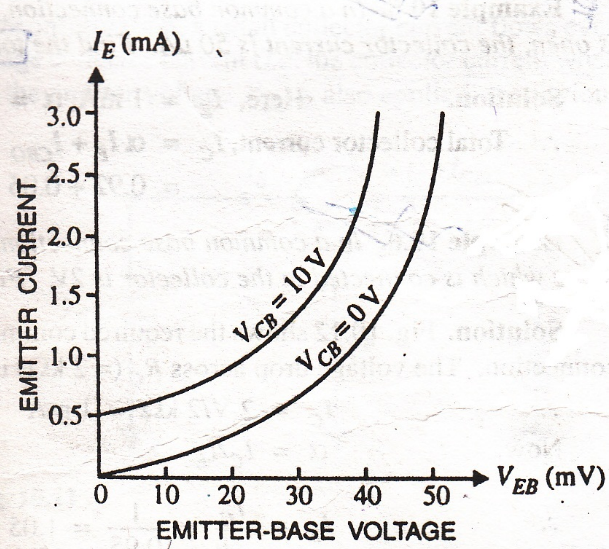


Fig. 10.14

Input resistance. It is the ratio of change in emitter-base voltage (ΔV_{EB}) to the resulting change in emitter current (ΔI_E) at constant collector-base voltage (V_{CB}) *i.e.*

$$\text{Input resistance, } r_i = \frac{\Delta V_{BE}}{\Delta I_E} \text{ at constant } V_{CB}$$

In fact, input resistance is the opposition offered to the signal current. As a very small V_{EB} is sufficient to produce a large flow of emitter current I_E, therefore, input resistance is quite small, of the order of a few ohms.

(2) Output characteristic. It is the curve between collector current I_C and collector-base voltage V_{CB} at *constant emitter current I_E. Gener-

* I_E has to be kept constant because any change in I_E will produce corresponding change in I_C. Here, we are interested to see how V_{CB} influences I_C.

ally, collector current is taken along *y*-axis and collector-base voltage along *x*-axis. Fig. 10.15 shows the output characteristics of a typical transistor in *CB* arrangement.

The following points may be noted from the characteristics :

(*i*) The collector current I_C varies with V_{CB} only at very low voltages (< 1V). The transistor is *never* operated in this region.

(*ii*) When the value of V_{CB} is raised above 1 – 2 V, the collector current becomes constant as indicated by straight horizontal curves. It means that now I_C is independent of V_{CB} and depends upon I_E only. This is consistent with the theory that the emitter current flows *almost* entirely to the collector terminal. The transistor is *always* operated in this region.

(*iii*) A very large change in collector-base voltage produces only a tiny change in collector current. This means that output resistance is very high.

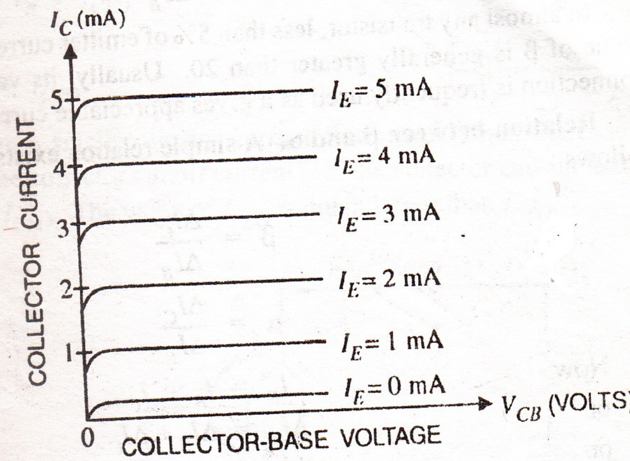


Fig. 10.15

Output resistance. It is the ratio of change in collector-base voltage (ΔV_{CB}) to the resulting change in collector current (ΔI_C) at constant emitter current *i.e.*

$$\text{Output resistance, } r_o = \frac{\Delta V_{CB}}{\Delta I_C} \text{ at constant } I_E$$

The output resistance of *CB* circuit is very high, of the order of several tens of kilo-ohms. This is not surprising because the collector current changes very slightly with the change in V_{CB}.

10.10 Common Emitter Connection

In this circuit arrangement, input is applied between base and emitter and output is taken from the collector and emitter. Here, emitter of the transistor is common to both input and output circuits and hence the name common emitter connection. Fig. 10.16 (*i*) shows common emitter *npn* transistor circuit whereas Fig. 10.16 (*ii*) shows common emitter *pnp* transistor circuit.

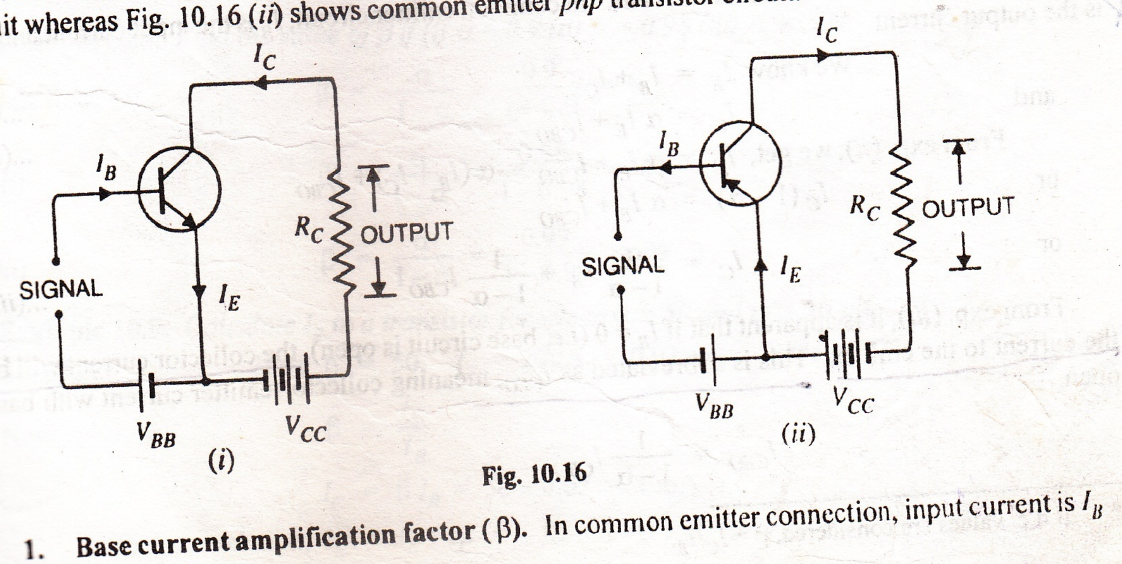


Fig. 10.16

1. Base current amplification factor (β). In common emitter connection, input current is I_B and output current is I_C.

The ratio of change in collector current (ΔI_C) to the change in base current (ΔI_B) is known as **base current amplification factor** *i.e.*

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

In almost any transistor, less than 5% of emitter current flows as the base current. Therefore, the value of β is generally greater than 20. Usually, its value ranges from 20 to 500. This type of connection is frequently used as it gives appreciable current gain as well as voltage gain.

Relation between β and α. A simple relation exists between β and α. This can be derived as follows :

$$\beta = \frac{\Delta I_C}{\Delta I_B} \quad \text{...(i)}$$

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad \text{...(ii)}$$

Now $I_E = I_B + I_C$

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

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

Substituting the value of ΔI_B in exp. (*i*), we get,

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C} \quad \text{...(iii)}$$

Dividing the numerator and denominator of R.H.S. of exp. (*iii*) by ΔI_E, we get,

$$\beta = \frac{\Delta I_C / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{\alpha}{1-\alpha} \qquad \left[\alpha = \frac{\Delta I_C}{\Delta I_E}\right]$$

∴ $$\beta = \frac{\alpha}{1-\alpha}$$

It is clear that as α approaches unity, β approaches infinity. In other words, the current gain in common emitter connection is very high. It is due to this reason that this circuit arrangement is used in about 90 to 95 percent of all transistor applications.

2. Expression for collector current. In common emitter circuit, I_B is the input current and I_C is the output current.

We know $I_E = I_B + I_C$

and $$I_C = \alpha I_E + I_{CBO} \quad \text{...(i)}$$

From exp. (*ii*), we get, $$I_C = \alpha I_E + I_{CBO} = \alpha (I_B + I_C) + I_{CBO} \quad \text{...(ii)}$$

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

or $$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} \quad \text{...(iii)}$$

From exp. (*iii*), it is apparent that if $I_B = 0$ (*i.e.* base circuit is open), the collector current will be the current to the emitter. This is abbreviated as I_{CEO}, meaning collector-emitter current with base open.

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

* If d.c. values are considered, $\beta = I_C / I_B$.

Substituting the value of $\frac{1}{1-\alpha} I_{CBO} = I_{CEO}$ in exp. (*iii*), we get,

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

or

$$I_C = \beta I_B + I_{CEO} \qquad \left(\because \beta = \frac{\alpha}{1-\alpha}\right)$$

Concept of I_{CEO}. In *CE* configuration, a small collector current flows even when the base current is zero [See Fig. 10.17 (*i*)]. This is the collector cut off current (*i.e.* the collector current that flows when base is open) and is denoted by I_{CEO}. The value of I_{CEO} is much larger than I_{CBO}.

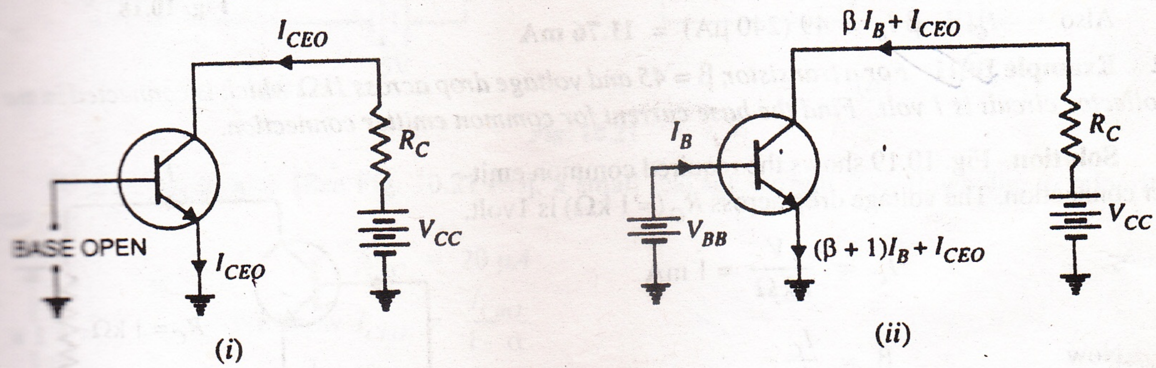


Fig. 10.17

When the base voltage is applied as shown in Fig. 10.17 (*ii*), then the various currents are :

Base current $= I_B$

Collector current $= \beta I_B + I_{CEO}$

Emitter current = Collector current + Base current

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

It may be noted here that :

$$I_{CEO} = \frac{1}{1-\alpha} I_{CBO} = (\beta + 1) I_{CBO} \qquad \left[\because \frac{1}{1-\alpha} = \beta + 1\right]$$

Example 10.8. *Find the value of β if (i) α = 0.9 (ii) α = 0.98 (iii) α = 0.99.*

Solution. (*i*)

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.9}{1-0.9} = 9$$

(*ii*)

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = 49$$

(*iii*)

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99$$

Example 10.9. *Calculate I_E in a transistor for which β = 50 and I_B = 20 μA.*

Solution. Here $\beta = 50, \quad I_B = 20\mu A = 0.02 \text{ mA}$

Now

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

$\therefore$

$$I_C = \beta I_B = 50 \times 0.02 = 1 \text{ mA}$$

Using the relation, $I_E = I_B + I_C = 0.02 + 1 = $ **1.02 mA**

Example 10.10. *Find the α rating of the transistor shown in Fig. 10.18. Hence determine the value of I_C using both α and β rating of the transistor.*

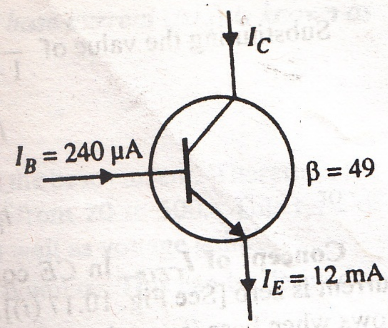


Fig. 10.18

Solution. Fig. 10.18 shows the conditions of the problem.

$$\alpha = \frac{\beta}{1+\beta} = \frac{49}{1+49} = \mathbf{0.98}$$

The value of I_C can be found by using either α or β rating as under :

$$I_C = \alpha I_E = 0.98 \text{ (12 mA)} = \mathbf{11.76 \text{ mA}}$$

Also $$I_C = \beta I_B = 49 \text{ (240 μA)} = \mathbf{11.76 \text{ mA}}$$

Example 10.11. *For a transistor, β = 45 and voltage drop across 1kΩ which is connected in the collector circuit is 1 volt. Find the base current for common emitter connection.*

Solution. Fig. 10.19 shows the required common emitter connection. The voltage drop across R_C (= 1 kΩ) is 1volt.

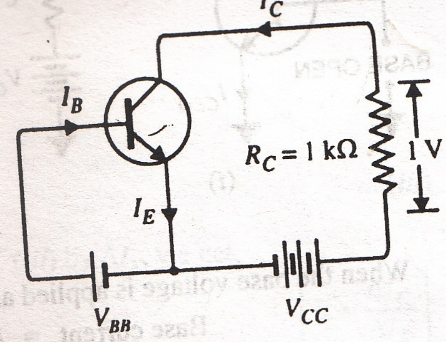


Fig. 10.19

$$\therefore \quad I_C = \frac{1 \text{ V}}{1 \text{ k}\Omega} = 1 \text{ mA}$$

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

$$\therefore \quad I_B = \frac{I_C}{\beta} = \frac{1}{45} = \mathbf{0.022 \text{ mA}}$$

Example 10.12. *A transistor is connected in common emitter (CE) configuration in which collector supply is 8V and the voltage drop across resistance R_C connected in the collector circuit is 0.5V. The value of R_C = 800 Ω. If α = 0.96, determine :*

(i) collector-emitter voltage *(ii) base current*

Solution. Fig. 10.20 shows the required common emitter connection with various values.

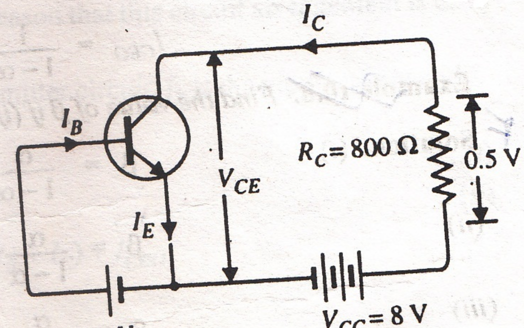


Fig. 10.20

(*i*) Collector-emitter voltage,

$$V_{CE} = V_{CC} - 0.5 = 8 - 0.5 = \mathbf{7.5 \text{ V}}$$

(*ii*) The voltage drop across R_C (= 800 Ω) is 0.5 V.

$$\therefore \quad I_C = \frac{0.5 \text{ V}}{800 \ \Omega} = \frac{5}{8} \text{ mA} = 0.625 \text{ mA}$$

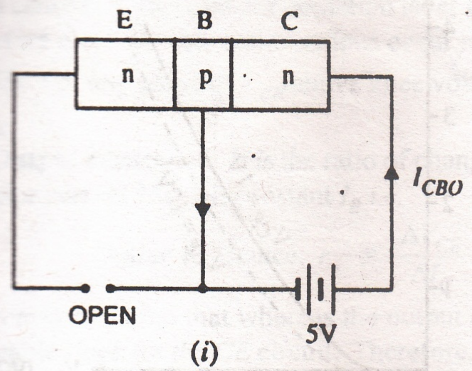
Now $$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$

$$\therefore \quad \text{Base current, } I_B = \frac{I_C}{\beta} = \frac{0.625}{24} = \mathbf{0.026 \text{ mA}}$$

Example 10.13. *An n-p-n transistor at room temperature has its emitter disconnected. A voltage of 5V is applied between collector and base. With collector positive, a current of 0.2 μA flows. When the base is disconnected and the same voltage is applied between collector and emitter, the current is found to be 20 μA. Find α, I_E and I_B when collector current is 1mA.*

Solution. When the emitter circuit is open [See Fig. 10.21 (*i*)], the collector-base junction is reverse biased. A small leakage current I_{CBO} flows due to minority carriers.

$\therefore \quad I_{CBO} = 0.2\ \mu A$ ...given



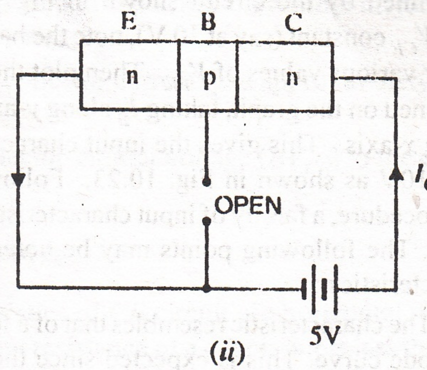


Fig. 10.21

When base is open [See Fig. 10.21 (*ii*)], a small leakage current I_{CEO} flows due to minority carriers.

$\therefore \quad I_{CEO} = 20\ \mu A$ ... *given*

We know $I_{CEO} = \dfrac{I_{CBO}}{1-\alpha}$

or $\quad 20 = \dfrac{0.2}{1-\alpha}$

$\therefore \quad \alpha = 0.99$

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

Here $I_C = 1\text{mA} = 1000\ \mu A$; $\alpha = 0.99$; $I_{CBO} = 0.2\ \mu A$

$\therefore \quad 1000 = 0.99 \times I_E + 0.2$

or $\quad I_E = \dfrac{1000 - 0.2}{0.99} = 1010\ \mu A$

and $\quad I_B = I_E - I_C = 1010 - 1000 = 10\ \mu A$

10.11 Characteristics of Common Emitter Connection

The important characteristics of this circuit arrangement are the *input characteristics* and *output characteristics.*

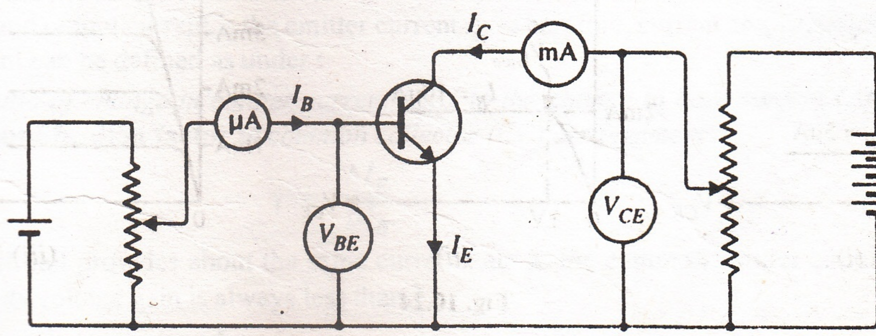


Fig. 10.22

1. Input characteristic. *It is the curve between base current I_B and base-emitter voltage V_{BE} at constant collector-emitter voltage V_{CE}.*

The input characteristics of a *CE* connection can be determined by the circuit shown in Fig. 10.22. Keeping V_{CE} constant (say at 10 V), note the base current I_B for various values of V_{BE}. Then plot the readings obtained on the graph, taking I_B along *y*-axis and V_{BE} along *x*-axis. This gives the input characteristic at V_{CE} = 10V as shown in Fig. 10.23. Following a similar procedure, a family of input characteristics can be drawn. The following points may be noted from the characteristics :

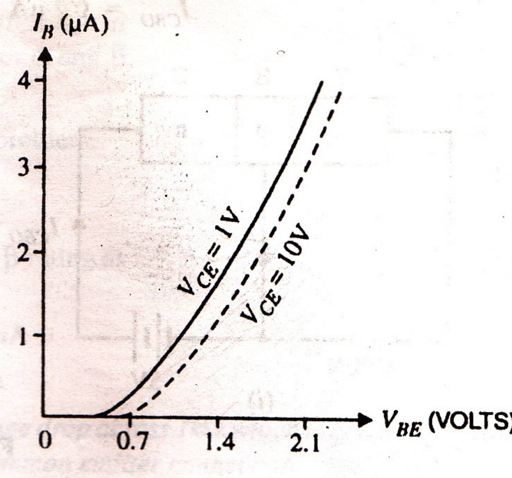


Fig. 10.23

(*i*) The characteristic resembles that of a forward biased diode curve. This is expected since the base-emitter section of transistor is a diode and it is forward biased.

(*ii*) As compared to *CB* arrangement, I_B increases less rapidly with V_{BE}. Therefore, input resistance of a *CE* circuit is higher than that of *CB* circuit.

Input resistance. It is the ratio of change in base-emitter voltage (ΔV_{BE}) to the change in base current (ΔI_B) at constant V_{CE} *i.e.*

$$\text{Input resistance, } r_i = \frac{\Delta V_{BE}}{\Delta I_B} \text{ at constant } V_{CE}$$

The value of input resistance for a *CE* circuit is of the order of a few hundred ohms.

2. Output characteristic. *It is the curve between collector current* I_C *and collector-emitter voltage* V_{CE} *at constant base current* I_B.

The output characteristics of a *CE* circuit can be drawn with the help of the circuit shown in Fig. 10.22. Keeping the base current I_B fixed at some value say, 5 μA, note the collector current I_C for various values of V_{CE}. Then plot the readings on a graph, taking I_C along *y*-axis and V_{CE} along *x*-axis. This gives the output characteristic at I_B = 5 μA as shown in Fig. 10.24 (*i*). The test can be repeated for I_B = 10 μA to obtain the new output characteristic as shown in Fig. 10.24 (*ii*). Following similar procedure, a family of output characteristics can be drawn as shown in Fig. 10.24 (*iii*).

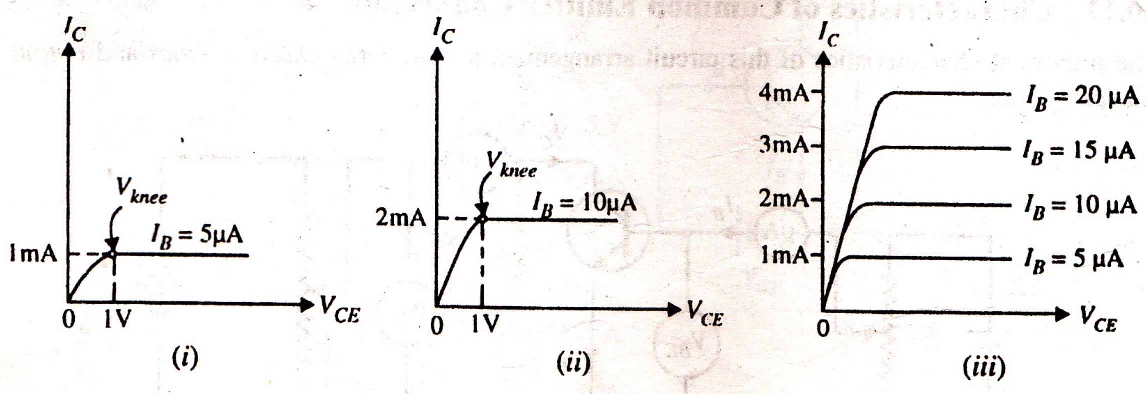


Fig. 10.24

The following points may be noted from the characteristics :

(*i*) The collector current I_C varies with V_{CE} for V_{CE} between 0 and 1V only. After this, collector current becomes *almost* constant and independent of V_{CE}. This value of V_{CE} upto which collector current I_C changes with V_{CE} is called the *knee voltage* (V_{knee}). *The transistors are always operated in the region above knee voltage.*

(*ii*) Above knee voltage, I_C is almost constant. However, a small increase in I_C with increasing V_{CE} is caused by the collector depletion layer getting wider and capturing a few more majority carriers before electron-hole combinations occur in the base area.

(*iii*) For any value of V_{CE} above knee voltage, the collector current I_C is approximately equal to $\beta \times I_B$.

Output resistance. It is the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant I_B *i.e.*

$$\text{Output resistance, } r_o = \frac{\Delta V_{CE}}{\Delta I_C} \text{ at constant } I_B$$

It may be noted that whereas the output characteristics of *CB* circuit are horizontal, they have noticeable slope for the *CE* circuit. Therefore, the output resistance of a *CE* circuit is less than that of *CB* circuit. Its value is of the order of 50 kΩ.

10.12 Common Collector Connection

In this circuit arrangement, input is applied between base and collector while output is taken between the emitter and collector. Here, collector of the transistor is common to both input and output circuits and hence the name common collector connection. Fig. 10.25 (*i*) shows common collector *npn* transistor circuit whereas Fig. 10.25 (*ii*) shows common collector *pnp* circuit.

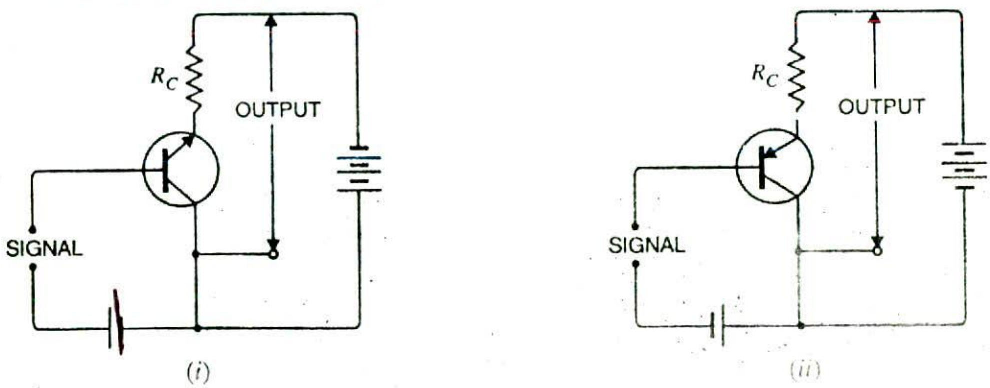


Fig. 10.25

(*i*) **Current amplification factor** γ. In common collector circuit, input current is the base current I_B and output current is the emitter current I_E. Therefore, current amplification in this circuit arrangement can be defined as under :

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) arrangement i.e.*

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

This circuit provides about the same current gain as the common emitter circuit as $\Delta I_E \simeq \Delta I_C$. However, its voltage gain is always less than 1.

Relation between γ and α

$$\gamma = \frac{\Delta I_E}{\Delta I_B} \quad ...(i)$$

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad ...(ii)$$

Now $I_E = I_B + I_C$

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

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

Substituting the value of ΔI_B in exp. (*i*), we get,

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

Dividing the numerator and denominator of R.H.S. by ΔI_E, we get,

$$\gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{1}{1-\alpha} \qquad \left(\because \alpha = \frac{\Delta I_C}{\Delta I_E}\right)$$

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

(*ii*) **Expression for collector current**

We know $I_C = \alpha I_E + I_{CBO}$ (See Art. 10.8)

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

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

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

or $I_E = *(\beta + 1) I_B + (\beta + 1) I_{CBO}$

(*iii*) **Applications.** The common collector circuit has very high input resistance (about 750 kΩ) and very low output resistance (about 25 Ω). Due to this reason, the voltage gain provided by this circuit is always less than 1. Therefore, this circuit arrangement is seldom used for amplification. However, due to relatively high input resistance and low output resistance, this circuit is primarily used for impedance matching *i.e.* for driving a low impedance load from a high impedance source.

10.13 Comparison of Transistor Connections

The comparison of various characteristics of the three connections is given below in the tabular form.

S. No.	Characteristic	Common base	Common emitter	Common collector
1.	Input resistance	Low (about 100 Ω)	Low (about 750 Ω)	Very high (about 750 kΩ)
2.	Output resistance	Very high (about 450 kΩ)	High (about 45 kΩ)	Low (about 50 Ω)
3.	Voltage gain	about 150	about 500	less than 1
4.	Applications	For high frequency applications	For audio frequency applications	For impedance matching

10.14 Commonly Used Transistor Connection

Out of the three transistor connections, the common emitter circuit is the most efficient. It is used in

* $\beta = \frac{\alpha}{1-\alpha} \quad \therefore \quad \beta + 1 = \frac{\alpha}{1-\alpha} + 1 = \frac{1}{1-\alpha}$

about 90 to 95 per cent of all transistor applications. The main reasons for the widespread use of this circuit arrangement are :

(*i*) **High current gain.** In a common emitter connection, I_C is the output current and I_B is the input current. In this circuit arrangement, collector current is given by ;

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

As the value of β is very large, therefore, the output current I_C is much more than the input current I_B. Hence, the current gain in CE arrangement is very high. It may range from 20 to 500.

(*ii*) **High voltage and power gain.** Due to high current gain, the common emitter circuit has the highest voltage and power gain of three transistor connections. This is the major reason for using the transistor in this circuit arrangement.

(*iii*) **Moderate output to input impedance ratio.** In a common emitter circuit, the ratio of output impedance to input impedance is small (about 50). This makes this circuit arrangement an ideal one for coupling between various transistor stages. However, in other connections, the ratio of output impedance to input impedance is very large and hence coupling becomes highly inefficient due to gross mismatching.

10.15 Transistor as an Amplifier in *CE* Arrangement

Fig. 10.26 shows the common emitter *npn* amplifier circuit. Note that a battery V_{BB} is connected in the input circuit in addition to the signal voltage. This d.c. voltage is known as *bias voltage* and its magnitude is such that it always keeps the emitter-base junction forward *biased regardless of the polarity of the signal source.

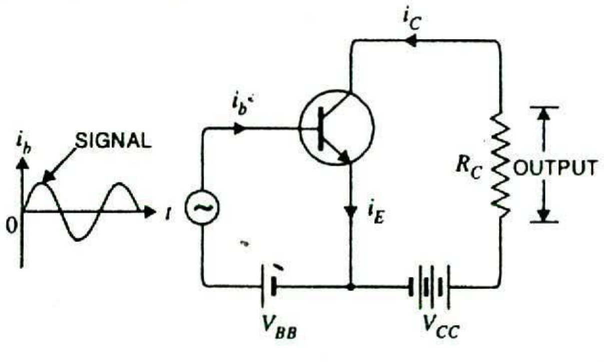


Fig. 10.26

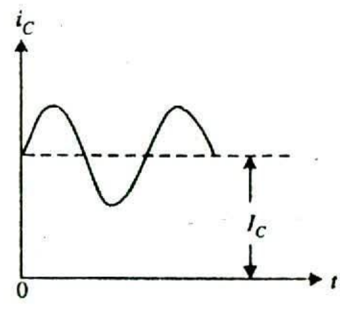


Fig. 10.27

Operation. During the positive half-cycle of the **signal, the forward bias across the emitter-base junction is increased. Therefore, more electrons flow from the emitter to the collector *via* the base. This causes an increase in collector current. The increased collector current produces a greater voltage drop across the collector load resistance R_C. However, during the negative half-cycle of the signal, the forward bias across emitter-base junction is decreased. Therefore, collector current de-

* If d.c. bias voltage is not provided, then during negative half-cycle of the signal, the emitter-base junction will be reverse biased. This will upset the transistor action.

** Throughout the book, we shall use sine wave signals because these are convenient for testing amplifiers. But it must be realised that signals (*e.g.* speech, music etc.) with which we work are generally complex having little resemblance to a sine wave. However, fourier series analysis tells us that such complex signals may be expressed as a sum of sine waves of various frequencies.

creases. This results in the decreased output voltage (in the opposite direction). Hence, an amplified output is obtained across the load.

Analysis of collector currents. When no signal is applied, the input circuit is forward biased by the battery V_{BB}. Therefore, a d.c. collector current I_C flows in the collector circuit. This is called *zero signal collector current*. When the signal voltage is applied, the forward bias on the emitter-base junction increases or decreases depending upon whether the signal is positive or negative. During the positive half-cycle of the signal, the forward bias on emitter-base junction is increased, causing total collector current i_C to increase. Reverse will happen for the negative half-cycle of the signal.

Fig. 10.27 shows the graph of total collector current i_C versus time. From the graph, it is clear that total collector current consists of two components, namely ;

(*i*) The d.c. collector current I_C (zero signal collector current) due to bias battery V_{BB}. This is the current that flows in the collector in the absence of signal.

(*ii*) The a.c. collector current i_c due to signal.

$\therefore$ Total collector current, $i_C = i_c + I_C$

The useful output is the voltage drop across collector load R_C due to the a.c. component i_c. The purpose of zero signal collector current is to ensure that the emitter-base junction is forward biased at all times. The table below gives the symbols usually employed for currents and voltages in transistor applications.

S. No.	Particular	Instantaneous a.c.	d.c.	Total
1.	Emitter current	i_e	I_E	i_E
2.	Collector current	i_c	I_C	i_C
3.	Base current	i_b	I_B	i_B
4.	Collector-emitter voltage	v_{ce}	V_{CE}	v_{CE}
5.	Emitter-base voltage	v_{eb}	V_{EB}	v_{EB}

10.16 Transistor Load Line Analysis

In the transistor circuit analysis, it is generally required to determine the collector current for various collector-emitter voltages. One of the methods can be to plot the output characteristics and determine the collector current at any desired collector-emitter voltage. However, a more convenient method, known as *load line method* can be used to solve such problems. As explained later in this section, this method is quite easy and is frequently used in the analysis of transistor applications.

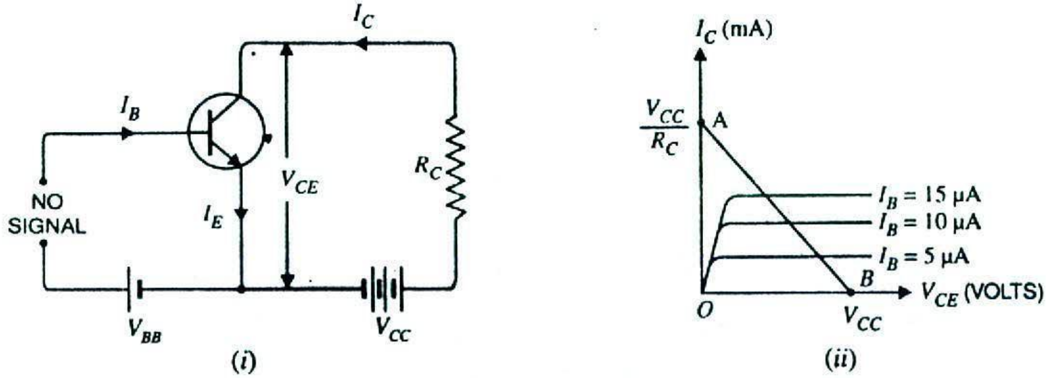


Fig. 10.28

d.c. load line. Consider a common emitter *npn* transistor circuit shown in Fig. 10.28 (*i*) where no signal is applied. Therefore, d.c. conditions prevail in the circuit. The output characteristics of this circuit are shown in Fig 10.28 (*ii*).

The value of collector-emitter voltage V_{CE} at any time is given by ;

$$V_{CE} = V_{CC} - I_C R_C \quad ...(i)$$

As V_{CC} and R_C are fixed values, therefore, it is a first degree equation and can be represented by a straight line on the output characteristics. This is known as *d.c. load line* and determines the locus of $V_{CE} - I_C$ points for any given value of R_C. To add load line, we need two end points of the straight line. These two points can be located as under :

(*i*) When the collector current $I_C = 0$, then collector-emitter voltage is maximum and is equal to V_{CC} *i.e.*

$$\text{Max. } V_{CE} = V_{CC} - I_C R_C$$
$$= V_{CC} \quad (\because I_C = 0)$$

This gives the first point B ($OB = V_{CC}$) on the collector-emitter voltage axis as shown in Fig. 10.28 (*ii*).

(*ii*) When collector-emitter voltage $V_{CE} = 0$, the collector current is maximum and is equal to V_{CC}/R_C *i.e.*

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

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

$\therefore$
$$\text{Max. } I_C = V_{CC}/R_C$$

This gives the second point A ($OA = V_{CC}/R_C$) on the collector current axis as shown in Fig. 10.28 (*ii*). By joining these two points, d.c. *load line AB is constructed.

Importance. The current (I_C) and voltage (V_{CE}) conditions in the transistor circuit are represented by some point on the output characteristics. The same information can be obtained from the load line. Thus when I_C is maximum ($= V_{CC}/R_C$), then $V_{CE} = 0$ as shown in Fig. 10.29. If $I_C = 0$, then V_{CE} is maximum and is equal to V_{CC}. For any other value of collector current say OC, the collector-emitter voltage $V_{CE} = OD$. It follows, therefore, that load line gives a far more convenient and direct solution to the problem.

Note. If we plot the load line on the output characteristic of the transistor, we can investigate the behaviour of the transistor amplifier. It is because we have the transistor output current and voltage specified in the form of load line equation and the transistor behaviour itself specified implicitly by the output characteristics.

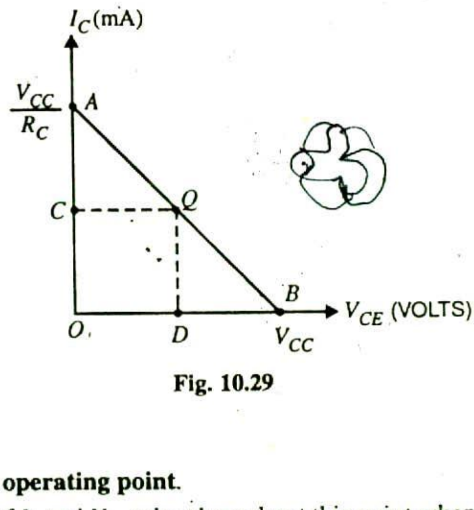


Fig. 10.29

10.17 Operating Point

The zero signal values of I_C and V_{CE} are known as the **operating point.**

It is called operating point because the variations of I_C and V_{CE} take place about this point when signal is applied. It is also called quiescent (silent) point or *Q-point* because it is the point on $I_C - V_{CE}$ characteristic when the transistor is silent *i.e.* in the absence of the signal.

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* **Why load line ?** The resistance R_C connected to the device is called load or load resistance for the circuit and, therefore, the line we have just constructed is called the load line.

Suppose in the absence of signal, the base current is 5 μA. Then I_C and V_{CE} conditions in the circuit must be represented by some point on I_B = 5 μA characteristic. But I_C and V_{CE} conditions in the circuit should also be represented by some point on the d.c. load line AB. The point Q where the load line and the characteristic intersect is the only point which satisfies both these conditions. Therefore, the point Q describes the actual state of affairs in the circuit in the zero signal conditions and is called the operating point. Referring to Fig. 10.30, for I_B = 5 μA, the zero signal values are :

$$V_{CE} = OC \text{ Volts}$$
$$I_C = OD \text{ mA}$$

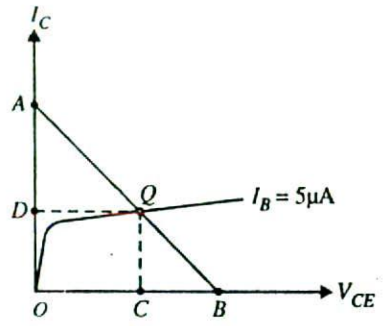


Fig. 10.30

It follows, therefore, that the zero signal values of I_C and V_{CE} (*i.e.* operating point) are determined by the point where d.c. load line intersects the proper base current curve.

Example 10.14. *For the circuit shown in Fig. 10.31 (i), draw the d.c. load line.*

Solution. The collector-emitter voltage V_{CE} is given by ;

$$V_{CE} = V_{CC} - I_C R_C \quad \text{...(i)}$$

When $I_C = 0$

$$V_{CE} = V_{CC} = 12.5 \text{ V}$$

This locates the point B of the load line on the collector-emitter voltage axis.

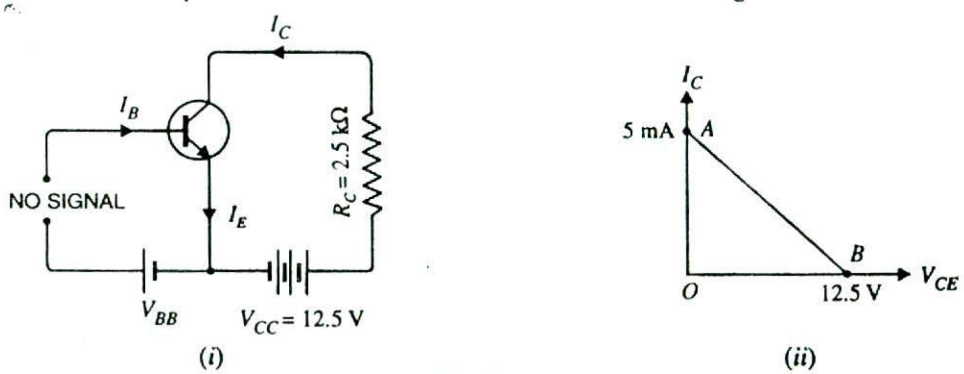


Fig. 10.31

When $V_{CE} = 0$

$$I_C = V_{CC}/R_C = 12.5 \text{ V}/2.5 \text{ k}\Omega = 5 \text{ mA}$$

This locates the point A of the load line on the collector current axis. By joining these two points, we get the d.c. load line AB as shown in Fig. 10.31 (*ii*).

Example 10.15. *In the circuit diagram shown in Fig. 10.32 (i), if V_{CC} = 12V and R_C = 6 kΩ draw the d.c. load line. What will be the Q point if zero signal base current is 20μA and β = 50 ?*

Solution. The collector-emitter voltage V_{CE} is given by ;

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

When $I_C = 0$, $V_{CE} = V_{CC}$ = 12 V. This locates the point B of the load line. When $V_{CE} = 0$, $I_C = V_{CC}/R_C$ = 12 V/6 kΩ = 2 mA. This locates the point A of the load line. By joining these two points, load line AB is constructed as shown in Fig. 10.32 (*ii*).

Zero signal base current, I_B = 20 μA = 0.02 mA

Current amplification factor, $\beta = 50$

$\therefore$ Zero signal collector current, $I_C = \beta I_B = 50 \times 0.02 = 1$ mA

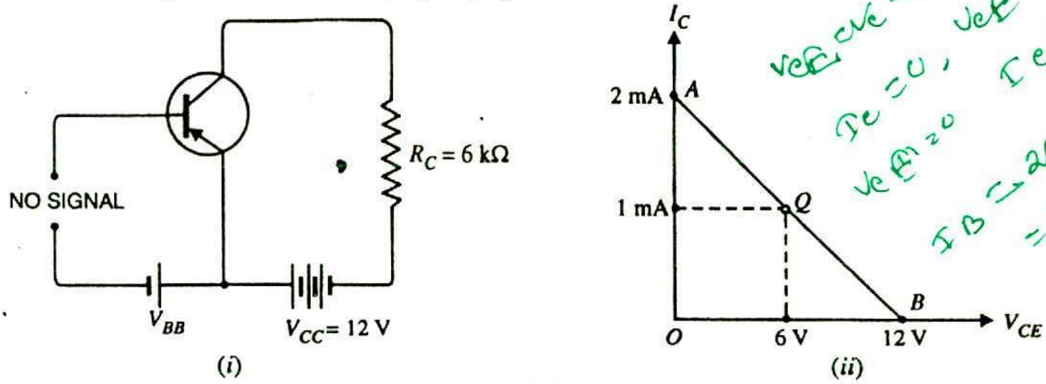


Fig. 10.32

Zero signal collector-emitter voltage is

$$V_{CE} = V_{CC} - I_C R_C = 12 - 1 \text{ mA} \times 6 \text{ k}\Omega = 6 \text{ V}$$

$\therefore$ Operating point is **6 V, 1 mA.**

Fig. 10.32 (*ii*) shows the Q point. Its co-ordinates are $I_C = 1$ mA and $V_{CE} = 6$ V.

Example 10.16. *In a transistor circuit, collector load is 4 kΩ whereas quiescent current (zero signal collector current) is 1mA.*

(*i*) *What is the operating point if $V_{CC} = 10$ V ?*

(*ii*) *What will be the operating point if $R_C = 5$ kΩ ?*

Solution. $V_{CC} = 10$ V, $I_C = 1$ mA

(*i*) When collector load $R_C = 4$ kΩ

$$V_{CE} = V_{CC} - I_C R_C = 10 - 1 \text{ mA} \times 4 \text{ k}\Omega = 10 - 4 = 6 \; V$$

$\therefore$ Operating point is **6 V, 1 mA.**

(*ii*) When collector load $R_C = 5$ kΩ

$$V_{CE} = V_{CC} - I_C R_C = 10 - 1 \text{ mA} \times 5 \text{ k}\Omega = 10 - 5 = 5 \; V$$

$\therefore$ Operating point is **5 V, 1 mA.**

10.18 Practical Way of Drawing CE Circuit

The common emitter circuits drawn so far can be shown in another convenient way. Fig. 10.33 shows

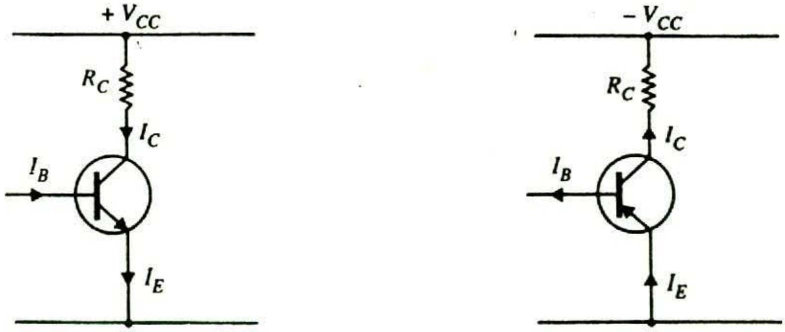


Fig. 10.33

the practical way of drawing *CE* circuit. In Fig. 10.33 (*i*), the practical way of drawing common emitter *npn* circuit is shown. Similarly, Fig. 10.33 (*ii*) shows the practical way of drawing common emitter *pnp* circuit. In our further discussion, we shall often use this scheme of presentation.

10.19 Output from Transistor Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier. Fig. 10.34 shows the common emitter amplifier. There are two ways of taking output from this transistor connection. The output can be taken either across R_C or across terminals 1 and 2. In either case, the magnitude of output is the same. This is clear from the following discussion :

(*i*) **First method.** We can take the output directly by putting a load resistance R_C in the collector circuit *i.e.*

$$\text{Output} = \text{voltage across } R_C = i_c R_C \quad ...(i)$$

This method of taking output from collector load is used only in single stage of amplification.

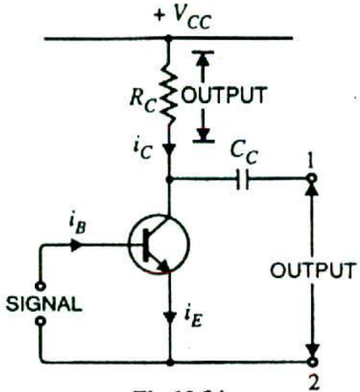


Fig.10.34

(*ii*) **Second method.** The output can also be taken across terminals 1 and 2 *i.e.* from collector and emitter end of supply.

$$\text{Output} = \text{Voltage across terminals 1 and 2}$$
$$= V_{CC} - i_C R_C$$

As V_{CC} is a direct voltage and cannot pass through capacitor C_C, therefore, only varying voltage $i_c R_C$ will appear across terminals 1 and 2.

$$\therefore \quad \text{Output} = -\, i_c R_C \quad ...(ii)$$

From exps. (*i*) and (*ii*), it is clear that magnitude of output is the same whether we take output across collector load or terminals 1 and 2. The minus sign in exp. (*ii*) simply indicates the phase reversal. The second method of taking output is used in multistages of amplification.

10.20 Performance of Transistor Amplifier

The performance of a transistor amplifier depends upon input resistance, output resistance, effective collector load, current gain, voltage gain and power gain. As *common emitter connection* is universally adopted, therefore, we shall explain these terms with reference to this mode of connection.

(*i*) **Input resistance.** *It is the ratio of small change in base-emitter voltage (ΔV_{BE}) to the resulting change in base current (ΔI_B) at constant collector-emitter voltage i.e.*

$$\text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B}$$

The value of input resistance is quite small because the input circuit is always forward biased. It ranges from 500 Ω for small low powered transistors to as low as 5 Ω for high powered transistors. In fact, input resistance is the opposition offered by the base-emitter junction to the signal flow. Fig. 10.35 shows the general form of an amplifier. The input voltage V_{BE} causes an input current I_B.

$$\therefore \quad \text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{V_{BE}}{I_B}$$

Thus if the input resistance of an amplifier is 500 Ω and the signal voltage at any instant is 1 V, then,

$$\text{Base current, } i_b = \frac{1\text{ V}}{500\ \Omega} = 2\text{ mA}$$

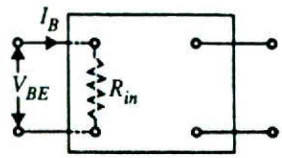


Fig. 10.35

18. The output impedance of a transistor is ....

(*i*) high (*ii*) zero

(*iii*) low (*iv*) very low

19. In a transistor, I_C = 100 mA and I_E = 100.5 mA. The value of β is ....

(*i*) 100 (*ii*) 50

(*iii*) about 1 (*iv*) 200

20. In a transistor if β = 100 and collector current is 10 mA, then I_E is ....

(*i*) 100 mA (*ii*) 100.1 mA

(*iii*) 110 mA (*iv*) none of the above

21. The relation between β and α is ....

(*i*) $\beta = \frac{1}{1-\alpha}$ (*ii*) $\beta = \frac{1-\alpha}{\alpha}$

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

22. The value of β for a transistor is generally ....

(*i*) 1 (*ii*) less than 1

(*iii*) between 20 and 500

(*iv*) above 500

23. The most commonly used transistor arrangement is .... arrangement.

(*i*) common emitter

(*ii*) common base

(*iii*) common collector

(*iv*) none of the above

24. The input impedance of a transistor connected in .... arrangement is the highest.

(*i*) common emitter

(*ii*) common collector

(*iii*) common base

(*iv*) none of the above

25. The output impedance of a transistor connected in .... arrangement is the highest.

(*i*) common emitter

(*ii*) common collector

(*iii*) common base

(*iv*) none of the above

26. The phase difference between the input and output voltages in a common base arrangement is ....

(*i*) 180° (*ii*) 90°

(*iii*) 270° (*iv*) 0°

27. The power gain of a transistor connected in .... arrangement is the highest.

(*i*) common emitter

(*ii*) common base

(*iii*) common collector

(*iv*) none of the above

28. The phase difference between the input and output voltages of a transistor connected in common emitter arrangement is ....

(*i*) 0° (*ii*) 180°

(*iii*) 90° (*iv*) 270°

29. The voltage gain of a transistor connected in .... arrangement is the highest.

(*i*) common base (*ii*) common collector

(*iii*) common emitter

(*iv*) none of the above

30. As the temperature of a transistor goes up, the base-emitter resistance ....

(*i*) decreases (*ii*) increases

(*iii*) remains the same

(*iv*) none of the above

31. The voltage gain of a transistor connected in common collector arrangement is ....

(*i*) equal to 1 (*ii*) more than 10

(*iii*) more than 100 (*iv*) less than 1

32. The phase difference between the input and output voltages of a transistor connected in common collector arrangement is ....

(*i*) 180° (*ii*) 0°

(*iii*) 90° (*iv*) 270°

33. $I_C = \beta I_B +$ ....

(*i*) I_{CBO} (*ii*) I_C

(*iii*) I_{CEO} (*iv*) αI_E

34. $I_C = \frac{\alpha}{1-\alpha} I_B +$ ....

(*i*) I_{CEO} (*ii*) I_{CBO}

(*iii*) I_C (*iv*) $(1-\alpha) I_B$

35. $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{\cdots\cdots}{1-\alpha}$

(*i*) I_{CBO} (*ii*) I_{CEO}

(*iii*) I_C (*iv*) I_E

36. BC 147 transistor indicates that it is made of ....

(i) germanium (ii) silicon
(iii) carbon (iv) none of the above

37. I_{CEO} = (........) I_{CBO}

(i) β (ii) 1 + α
(iii) 1 + β (iv) none of the above

38. A transistor is connected in *CB* mode. If it is now connected in *CE* mode with same bias voltages, the values of I_E, I_B and I_C will ....

(i) remain the same
(ii) increase
(iii) decrease (iv) none of the above

39. If the value of α is 0.9, then value of β is ....

(i) 9 (ii) 0.9
(iii) 900 (iv) 90

40. In a transistor, signal is transferred from a .... circuit.

(i) high resistance to low resistance
(ii) low resistance to high resistance
(iii) high resistance to high resistance
(iv) low resistance to low resistance

41. The arrow in the symbol of a transistor indicates the direction of ....

(i) electron current in the emitter
(ii) electron current in the collector
(iii) hole current in the emitter
(iv) donor ion current

42. The leakage current in *CE* arrangement is .... that in *CB* arrangement.

(i) more than (ii) less than
(iii) the same as (iv) none of the above

43. A heat sink is generally used with a transistor to ....

(i) increase the forward current
(ii) decrease the forward current
(iii) compensate for excessive doping
(iv) prevent excessive temperature rise

44. The most commonly used semiconductor in the manufacture of a transistor is ....

(i) germanium (ii) silicon
(iii) carbon (iv) none of the above

45. The collector-base junction in a transistor has ....

(i) forward bias at all times
(ii) reverse bias at all times
(iii) low resistance
(iv) none of the above

Answers to Multiple-Choice Questions

1. (ii)	**2.** (iv)	**3.** (iii)	**4.** (i)	**5.** (iv)
6. (ii)	**7.** (i)	**8.** (ii)	**9.** (ii)	**10.** (iv)
11. (iii)	**12.** (ii)	**13.** (iii)	**14.** (i)	**15.** (iv)
16. (ii)	**17.** (iii)	**18.** (i)	**19.** (iv)	**20.** (ii)
21. (iii)	**22.** (iii)	**23.** (i)	**24.** (ii)	**25.** (iii)
26. (iv)	**27.** (i)	**28.** (ii)	**29.** (iii)	**30.** (i)
31. (iv)	**32.** (ii)	**33.** (iii)	**34.** (i)	**35.** (i)
36. (ii)	**37.** (iii)	**38.** (i)	**39.** (iv)	**40.** (ii)
41. (iii)	**42.** (i)	**43.** (iv)	**44.** (ii)	**45.** (ii)

Chapter Review Topics

1. What is a transistor ? Why is it so called ?
2. Draw the symbol of *npn* and *pnp* transistor and specify the leads.
3. Show by means of a diagram how you normally connect external batteries in (i) *pnp* transistor (ii) *npn* transistor.
4. Describe the transistor action in detail.
5. Explain the operation of transistor as an amplifier.

(*ii*) **Output resistance.** *It is the ratio of change in collector-emitter voltage (ΔV_{CE}) to the resulting change in collector current (ΔI_C) at constant base current i.e.*

$$\text{Output resistance, } R_O = \frac{\Delta V_{CE}}{\Delta I_C}$$

The output characteristics reveal that collector current changes very slightly with the change in collector-emitter voltage. Therefore, output resistance of a transistor amplifier is very high– of the order of several hundred kilo-ohms. The physical explanation of high output resistance is that collector-base junction is reverse biased.

(*iii*) **Effective collector load.** *It is the total load as seen by the a.c. collector current.*

In case of single stage amplifiers, the effective collector load is a parallel combination of R_C and R_O as shown in Fig. 10.36 (*i*).

$$\text{Effective collector load, } R_{AC} = R_C \parallel R_O = \frac{R_C \times R_O}{R_C + R_O} = {}^{*}R_C$$

It follows, therefore, that for a single stage amplifier, effective load is equal to collector load R_C.

However, in a multistage amplifier (*i.e.* having more than one amplification stage), the input resistance R_i of the next stage also comes into picture as shown in Fig. 10.36 (*ii*). Therefore, effective collector load becomes parallel combination of R_C, R_O and R_i *i.e.*

$$\text{Effective collector load, } R_{AC} = R_C \parallel R_O \parallel R_i$$

$$= {}^{**}R_C \parallel R_i = \frac{R_C\, R_i}{R_C + R_i}$$

As input resistance R_i is quite small (25 Ω to 500 Ω), therefore, effective load is reduced.

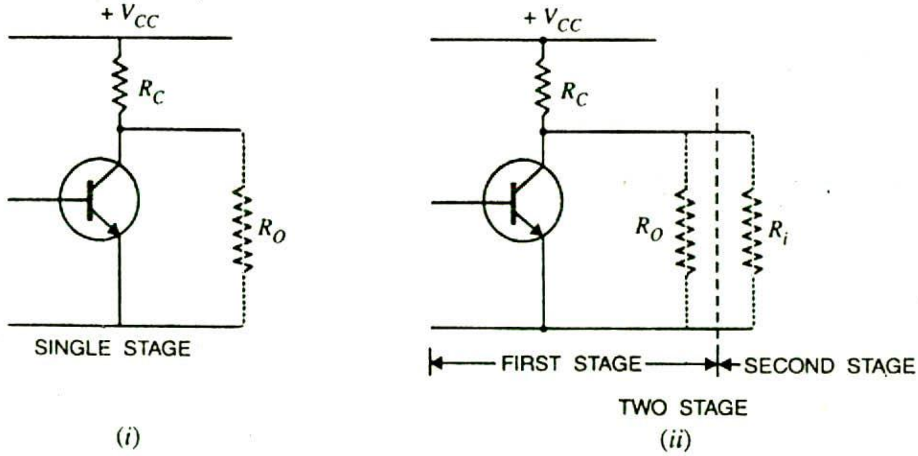


Fig. 10.36

(*iv*) **Current gain.** *It is the ratio of change in collector current (ΔI_C) to the change in base current (ΔI_B) i.e.*

* As output resistance R_O is several times R_C, therefore, R_C can be neglected as compared to R_O.

$$R_{AC} = \frac{R_C \times R_O}{R_O} = R_C$$

** $R_C \parallel R_O = R_C$ as already explained.

$$\text{Current gain, } \beta = \frac{\Delta I_C}{\Delta I_B}$$

The value of β ranges from 20 to 500. The current gain indicates that input current becomes β times in the collector circuit.

(*v*) **Voltage gain.** *It is the ratio of change in output voltage* (ΔV_{CE}) *to the change in input voltage* (ΔV_{BE}) *i.e*

$$\text{Voltage gain, } A_v = \frac{\Delta V_{CE}}{\Delta V_{BE}}$$

$$= \frac{\text{Change in output current} \times \text{effective load}}{\text{Change in input current} \times \text{input resistance}}$$

$$= \frac{\Delta I_C \times R_{AC}}{\Delta I_B \times R_i} = \frac{\Delta I_C}{\Delta I_B} \times \frac{R_{AC}}{R_i} = \beta \times \frac{R_{AC}}{R_i}$$

For single stage, $R_{AC} = R_C$. However, for multistage, $R_{AC} = \frac{R_C \times R_i}{R_C + R_i}$ where R_i is the input resistance of the next stage.

(*vi*) **Power gain.** *It is the ratio of output signal power to the input signal power i.e.*

$$\text{Power gain, } A_p = \frac{(\Delta I_C)^2 \times R_{AC}}{(\Delta I_B)^2 \times R_i} = \left(\frac{\Delta I_C}{\Delta I_B}\right) \times \frac{\Delta I_C \times R_{AC}}{\Delta I_B \times R_i}$$

$$= \text{current gain} \times \text{voltage gain}$$

Example 10.17. *A change of 200 mV in base-emitter voltage causes a change of 100 μA in the base current. Find the input resistance of the transistor.*

Solution. Change in base-e mitter voltage is

$$\Delta V_{BE} = 200 \text{ mV}$$

$$\text{Change in base current, } \Delta I_B = 100 \ \mu\text{A}$$

$$\therefore \quad \text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{200 \text{ mV}}{100 \ \mu \text{ A}} = \mathbf{2 \ k\Omega}$$

Example 10.18. *If the collector current changes from 2 mA to 3mA in a transistor when collector-emitter voltage is increased from 2V to 10V, what is the output resistance ?*

Solution. Change in collector-emitter voltage is

$$\Delta V_{CE} = 10 - 2 = 8 \text{ V}$$

Change in collector current is

$$\Delta I_C = 3 - 2 = 1 \text{ mA}$$

$$\therefore \quad \text{Output resistance, } R_O = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{8 \text{ V}}{1 \text{ mA}} = \mathbf{8 \ k\Omega}$$

Example 10.19. *For a single stage transistor amplifier, the collector load is $R_C = 2k\Omega$ and the input resistance $R_i = 1k\Omega$ If the current gain is 50, calculate the voltage gain of the amplifier.*

Solution. Collector load, $R_C = 2 \text{ k}\Omega$

Input resistance, $R_i = 1 \text{ k}\Omega$

Current gain, $\beta = 50$

$$\therefore \quad \text{Voltage gain, } A_v = \beta \times \frac{R_{AC}}{R_i} = \beta \times \frac{R_C}{R_i} \qquad [\because \text{ For single stage, } R_{AC} = R_C]$$

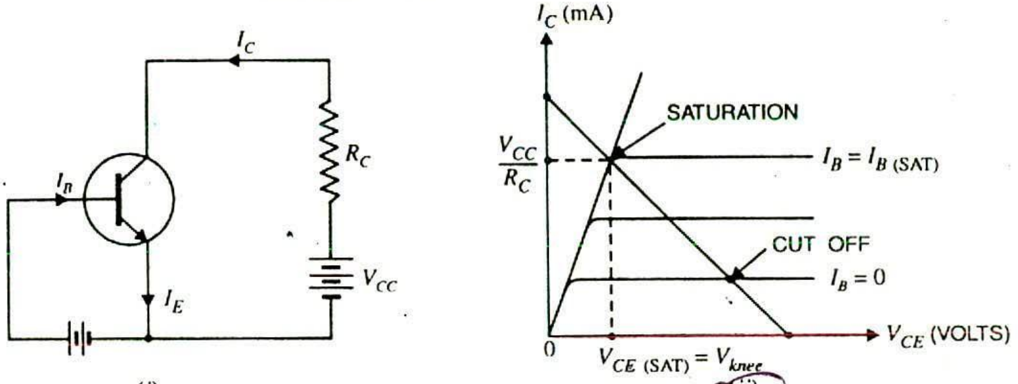
$$= 50 \times (2/1) = \mathbf{100}$$

10.21 Cut off and Saturation Points

Fig. 10.37 (*i*) shows *CE* transistor circuit while Fig. 10.37 (*ii*) shows the output characteristcs along with the d.c. load line.

(*i*) **Cut off.** The point where the load line intersects the $I_B = 0$ curve is known as *cut off*. At this point, $I_B = 0$ and only small collector current (*i.e.* collector leakage current I_{CEO}) exists. At cut off, the base-emitter junction no longer remains forward biased and normal transistor action is lost. The collector-emitter voltage is nearly equal to V_{CC} *i.e.*

$$V_{CE\,(cut\,off)} = V_{CC}$$



(*i*) (*ii*)

Fig. 10.37

(*ii*) **Saturation.** The point where the load line intersects the $I_B = I_{B(Sat)}$ curve is called *saturation*. At this point, the base current is maximum and so is the collector current. At saturation, collector-base junction no longer remains reverse biased and normal transistor action is lost.

$$I_{C\,(sat)} \simeq \frac{V_{CC}}{R_C}\,;\; V_{CE} = V_{CE(sat)} = V_{knee}$$

If base current is greater than $I_{B(sat)}$, then collector current cannot increase because collector-base junction is no longer reverse-biased.

(*iii*) **Active region.** The region between cut off and saturation is known as *active region*. In the active region, collector-base junction remains reverse biased while base-emitter junction remains forward biased. Consequently, the transistor will function normally in this region.

Note. We provide biasing to the transistor to ensure that it operates in the active region. The reader may find the detailed discussion on transistor biasing in the next chapter.

Example 10.20. *Find $I_{C(sat)}$ and $V_{CE(cut\,off)}$ for the circuit shown in Fig. 10.38 (i).*

Solution As we decrease R_B, base current and hence collector current increases. The increased collector current causes a greater voltage drop across R_C; this decreases the collector-emitter voltage. Eventually at some value of R_B, V_{CE} decreases to V_{knee}. At this point, collector-base junction is no longer reverse biased and transistor action is lost. Consequently, further increase in collector current is not possible. The transistor conducts maximum collector current ; we say the transistor is saturated.

$$I_{C(sat)} = \frac{V_{CC} - {}^{*}V_{knee}}{R_C} = \frac{V_{CC}}{R_C} = \frac{20\ V}{1\ k\Omega} = \mathbf{20\ mA}$$

* V_{knee} is 0.5 V for Ge transistor and 1 V for Si transistor. Consequently, V_{knee} can be neglected as compared to V_{CC} (= 20 V in this case).

As we increase R_B, base current and hence collector current decreases. This decreases the voltage drop across R_C. This increases the collector-emitter voltage. Eventually, when $I_B = 0$, the emitter-base junction is no longer forward biased and transistor action is lost. Consequently, further increase in V_{CE} is not possible. In fact, V_{CE} now equals to V_{CC}.

$$V_{CE(cut\text{-}off)} = V_{CC} = 20 \text{ V}$$

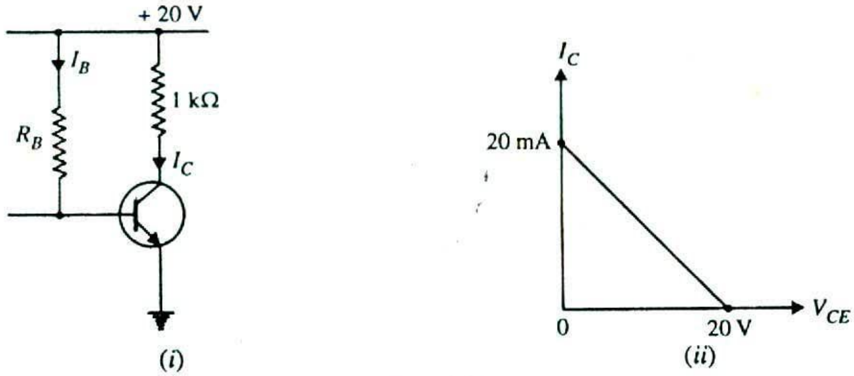


Fig. 10.38

Figure 10.38 (*ii*) shows the saturation and cut off points. Incidentally, they are end points of the d.c. load line.

Note. The exact value of $V_{CE(cut\text{-}off)} = V_{CC} - I_{CEO} R_C$. Since the collector leakage current I_{CEO} **is very small,** we can neglect $I_{CEO} R_C$ as compared to V_{CC}.

10.22 Power Rating of Transistor

The maximum power that a transistor can handle without destruction is known as **power rating** *of the transistor.*

When a transistor is in operation, almost all the power is dissipated at the reverse biased *collector-base junction. The power rating (or maximum power dissipation) is given by ;

$$P_D = \text{Collector current} \times \text{Collector-base voltage}$$

$$= I_C \times V_{CB}$$

$$\therefore \quad P_D = I_C \times V_{CE}$$

$[\because V_{CE} = V_{CB} + V_{BE}$. Since V_{BE} is very small, $V_{CB} \simeq V_{CE}]$

While connecting transistor in a circuit, it should be ensured that its power rating is not exceeded otherwise the transistor may be destroyed due to excessive heat. For example, suppose the power rating of a transistor is 300 mW. In order to avoid the destruction of the transistor, the product $V_{CE} \times I_C$ should not exceed 300 mW.

Example 10.21. *The maximum power dissipation of a transistor is 100mW. If $V_{CE} = 20V$, what is the maximum collector current that can be allowed without destruction of the transistor?*

Solution.

$$P_D = V_{CE} \times I_C$$

$$100 \text{ mW} = 20 \text{ V} \times I_C$$

---

* The base-emitter junction conducts about the same current as the collector-base junction (*i.e.* $I_E \simeq I_C$). However, V_{BE} is very small (0.3 V for Ge transistor and 0.7 V for Si transistor). For this reason, power dissipated at the base-emitter junction is negligible.

$$\therefore \quad I_C = \frac{100 \text{ mW}}{20 \text{ V}} = \mathbf{5 \text{ mA}}$$

Thus for V_{CE} = 20V, the maximum collector current allowed is 5 mA. If collector current exceeds this value, the transistor may be burnt due to excessive heat.

Note. Suppose the collector current becomes 7mA. The power produced will be 20 V × 7 mA = 140 mW. The transistor can only dissipate 100 mW. The remaining 40 mW will raise the temperature of the transistor and eventually it will be burnt due to excessive heat.

10.23 Semiconductor Devices Numbering System

From the time semiconductor engineering came to existence, several numbering systems were adopted by different countries. However, the accepted numbering system is that announced by Proelectron Standardisation Authority in Belgium. According to this system of numbering semiconductor devices :

(*i*) Every semiconductor device is numbered by five alpha-numeric symbol, comprising either two letters and three numbers (*e.g.* BF194) or three letters and two numbers (*e.g.* BFX63). When two numbers are included in the symbol (*e.g.* BFX63), the device is intended for industrial and professional equipment. When the symbol contains three numbers (*e.g.* BF194) , the device is intended for entertainment or consumer equipment.

(*ii*) The first letter indicates the nature of semiconductor material. For example :

A = germanium, B = silicon, C = gallium arsenide, R = compound material (e.g. cadmium sulphide)

Thus AC125 is a germanium transistor whereas BC149 is a silicon transistor.

(*iii*) The second letter indicates the device and circuit function.

A =	diode	*B* =	Variable capacitance diode
C =	A.F. low powered transistor	*D* =	A.F. power transistor
E =	Tunnel diode	*F* =	H.F. low power transistor
G =	Multiple device	*H* =	Magnetic sensitive diode
K =	Hall-effect device	*L* =	H.F. power transistor
M =	Hall-effect modulator	*P* =	Radiation sensitive diode
Q =	Radiation generating diode	*R* =	Thyristor (SCR or triac)
S =	Low power switching transistor	*T* =	Thyristor (power)
U =	Power switching transistor	*X* =	diode, multiplier
Y =	Power device	*Z* =	Zener diode

10.24 Transistor Lead Identification

There are three leads in a transistor *viz.* collector, emitter and base. When a transistor is to be connected in a circuit, it is necessary to know which terminal is which. The identification of the leads of transistor varies with manufacturer. However, there are three systems in general use as shown in Fig. 10.39.

(*i*) When the leads of a transistor are in the same plane and unevenly spaced [See Fig. 10.39 (*i*)], they are identified by the position and spacings of leads. The central lead is the base lead. The collector lead is identified by the larger spacing existing between it and the base lead. The remaining lead is the emitter.

(*ii*) When the leads of a transistor are in the same plane but evenly spaced [See Fig. 10.39 (*ii*)], the central lead is the base, the lead identified by dot is the collector and the remaining lead is the emitter.

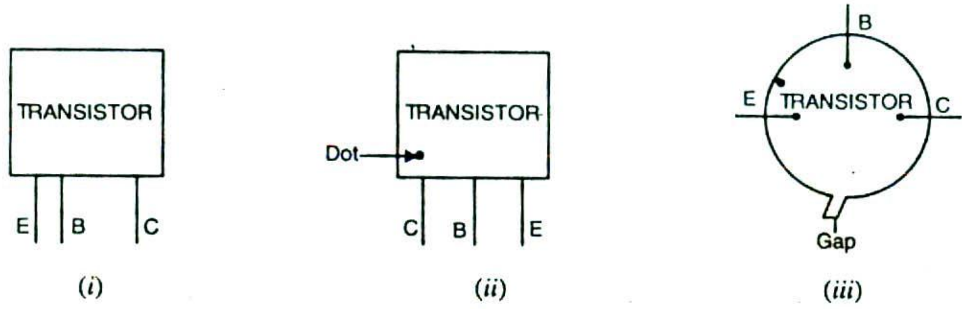


Fig. 10.39

(*iii*) When the leads of a transistor are spaced around the circumference of a circle [See Fig. 10.39 (*iii*)], the three leads are generally in E-B-C order clockwise from a gap.

10.25 Transistor Testing

An ohmmeter can be used to check the state of a transistor *i.e.*, whether the transistor is good or not. We know that base-emitter junction of a transistor is forward biased while collector-base junction is reverse biased. Therefore, forward biased base-emitter junction should have low resistance and reverse biased collector-base junction should register a much higher resistance. Fig. 10.40 shows the process of testing an *npn* transistor with an ohmmeter.

(*i*) The forward biased base-emitter junction (biased by internal supply) should read a low resistance, typically 100 Ω to 1 kΩ as shown in Fig. 10.40 (*i*). If that is so, the transistor is good. However, if it fails this check, the transistor is faulty and it must be replaced.

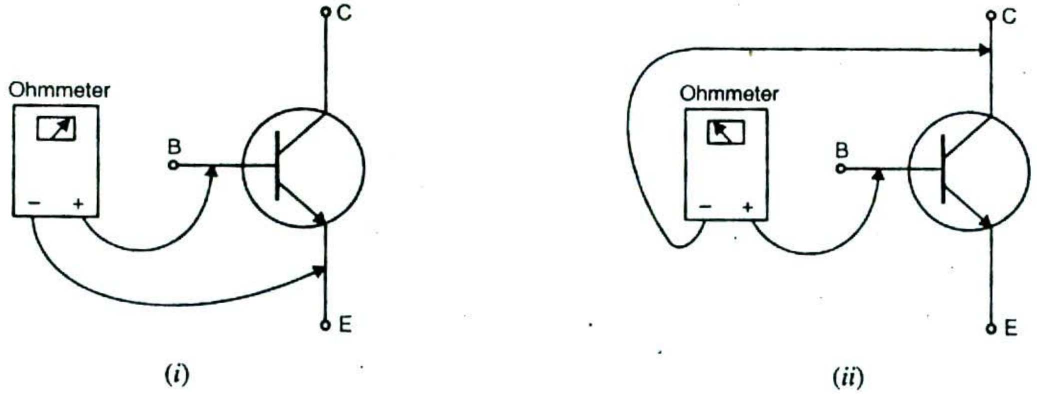


Fig. 10.40

(*ii*) The reverse biased collector-base junction (again reverse biased by internal supply) should be checked as shown in Fig. 10.40 (*ii*). If the reading of the ohmmeter is 100 kΩ or higher, the transistor is good. If the ohmmeter registers a small resistance, the transistor is faulty and requires replacement.

Note. When testing a *pnp* transistor, the ohmmeter leads must be reversed. The results of the tests, however, will be the same.

10.26 Applications of Common Base Amplifiers

Common base amplifiers are not used as frequently as the *CE* amplifiers. The two important applications of *CB* amplifiers are : (*i*) to provide voltage gain without current gain and (*ii*) for impedance matching in high frequency applications. Out of the two, the high frequency applications are far more common.

(*i*) **To provide voltage gain without current gain.** We know that a *CB* amplifier has a high voltage gain while the current gain is nearly 1 (*i.e.* $A_i \simeq 1$). Therefore, this circuit can be used to provide high voltage gain without increasing the value of circuit current. For instance, consider the case where the output current from an amplifier has sufficient value for the required application but the voltage gain needs to be increased. In that case, *CB* amplifier will serve the purpose because it would increase the voltage without increasing the current. This is illustrated in Fig. 10.41. The *CB* amplifier will provide voltage gain without any current gain.

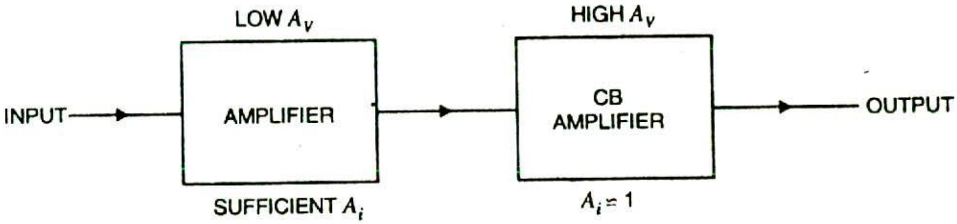


Fig. 10.41

(*ii*) **For impedance matching in high frequency applications.** Most high-frequency voltage sources have a very *low output impedance.* When such a low-impedance source is to be connected to a high-impedance load, you need a circuit to match the source impedance to the load impedance. Since a common-base amplifier has *low input impedance* and *high output impedance*, the common-base circuit will serve well in this situation. Let us illustrate this point with a numerical example. Suppose a high-frequency source with internal resistance 25 Ω is to be connected to a load of 8 kΩ as shown in Fig. 10.42. If the source is directly connected to the load, small source power will be transferred to the load due to mismatching. However, it is possible to design a *CB* amplifier that has an input impedance of nearly 25 Ω and output impedance of nearly 8 kΩ. If such a *CB* circuit is placed between the source and the load, the source will be matched to the load as shown in Fig. 10.43.

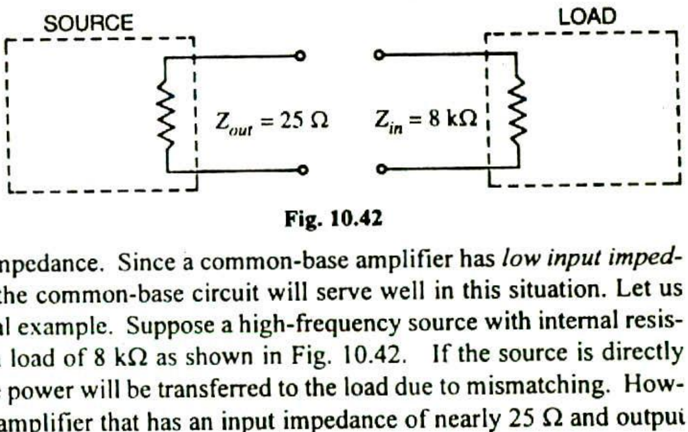


Fig. 10.42

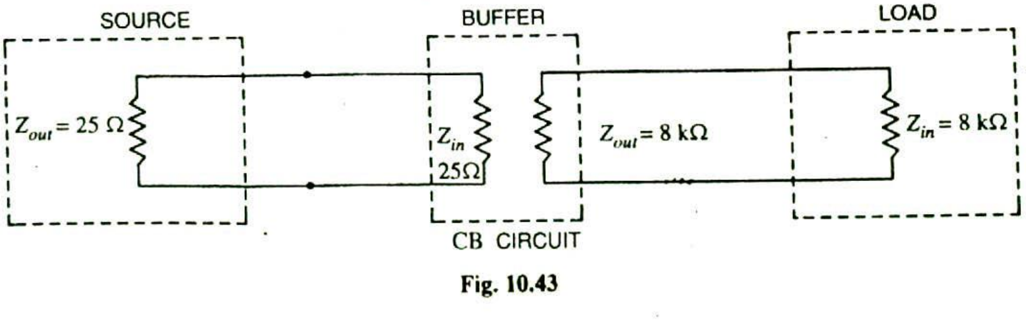


Fig. 10.43

Note that source impedance very closely matches the input impedance of *CB* amplifier. Therefore, there is a maximum power transfer from the source to input of *CB* amplifier. The high output impedance of the amplifier very nearly matches the load resistance. As a result, there is a maximum power transfer from the amplifier to the load. The net result is that maximum power has been transferred from the original source to the original load. A common-base amplifier that is used for this purpose is called a *buffer amplifier*.

Multiple-Choice Questions

1. A transistor has ....
   (*i*) one *pn* junction
   (*ii*) two *pn* junctions
   (*iii*) three *pn* junctions
   (*iv*) four *pn* junctions
2. The number of depletion layers in a transistor is ....
   (*i*) four (*ii*) three
   (*iii*) one (*iv*) two
3. The base of a transistor is .... doped.
   (*i*) heavily (*ii*) moderately
   (*iii*) lightly (*iv*) none of the above
4. The element that has the biggest size in a transistor is ....
   (*i*) collector (*ii*) base
   (*iii*) emitter
   (*iv*) collector-base junction
5. In a *pnp* transistor, the current carriers are ....
   (*i*) acceptor ions (*ii*) donor ions
   (*iii*) free electrons (*iv*) holes
6. The collector of a transistor is .... doped.
   (*i*) heavily (*ii*) moderately
   (*iii*) lightly (*iv*) none of the above
7. A transistor is a .... operated device.
   (*i*) current (*ii*) voltage
   (*iii*) both voltage and current
   (*iv*) none of the above
8. In an *npn* transistor, ... are the minority carriers.
   (*i*) free electrons (*ii*) holes
   (*iii*) donor ions (*iv*) acceptor ions
9. The emitter of a transistor is .... doped.
   (*i*) lightly (*ii*) heavily
   (*iii*) moderately (*iv*) none of the above
10. In a transistor, the base current is about .... of emitter current.
    (*i*) 25% (*ii*) 20%
    (*iii*) 35% (*iv*) 5%
11. At the base-emitter junction of a transistor, one finds ....
    (*i*) reverse bias
    (*ii*) a wide depletion layer
    (*iii*) low resistance
    (*iv*) none of the above
12. The input impedance of a transistor is ......
    (*i*) high (*ii*) low
    (*iii*) very high (*iv*) almost zero
13. Most of the majority carriers from the emitter ....
    (*i*) recombine in the base
    (*ii*) recombine in the emitter
    (*iii*) pass through the base region to the collector
    (*iv*) none of the above
14. The current I_B is ....
    (*i*) electron current
    (*ii*) hole current
    (*iii*) donor ion current
    (*iv*) acceptor ion current
15. In a transistor, ...
    (*i*) $I_C = I_E + I_B$ (*ii*) $I_B = I_C + I_E$
    (*iii*) $I_E = I_C - I_B$ (*iv*) $I_E = I_C + I_B$
16. The value of α of a transistor is ....
    (*i*) more than 1 (*ii*) less than 1
    (*iii*) 1 (*iv*) none of the above
17. $I_C = \alpha I_E +$ ....
    (*i*) I_B (*ii*) I_{CEO}
    (*iii*) I_{CBO} (*iv*) βI_B

6. Name the three possible transistor connections.
7. Define α. Show that it is always less than unity.
8. Draw the input and output characteristics of *CB* connection. What do you infer from these characteristics ?
9. Define β. Show that : $\beta = \frac{\alpha}{1-\alpha}$.
10. How will you determine the input and output characteristics of *CE* connection experimentally ?
11. Establish the following relations :

(*i*) $I_C = \alpha I_E + I_{CBO}$ (*ii*) $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$

(*iii*) $I_C = \beta I_B + I_{CEO}$ (*iv*) $\gamma = \frac{1}{1-\alpha}$

(*v*) $I_E = (\beta + 1) I_B + (\beta + 1) I_{CBO}$

12. How will you draw d.c. load line on the output characteristics of a transistor ? What is its importance?
13. Explain the following terms : (*i*) voltage gain (*ii*) power gain (*iii*) effective collector load.
14. Write short notes on the following : (*i*) advantages of transistors (*ii*) operating point (*iii*) d.c. load line.

Problems

1. In a transistor if $I_C = 4.9$mA and $I_E = 5$mA, what is the value of α ? **[0.98]**
2. In a transistor circuit, $I_E = 1$mA and $I_C = 0.9$mA. What is the value of I_B ? **[0.1 mA]**
3. Find the value of β if $\alpha = 0.99$. **[100]**
4. In a transistor, $\beta = 45$, the voltage across 5kΩ resistance which is connected in the collector circuit is 5 volts. Find the base current. **[0.022 mA]**
5. In a transistor, $I_B = 68$ μA, $I_E = 30$ mA and $\beta = 440$. Find the value of α. Hence determine the value of I_C **[0.99 ; 29.92 mA]**
6. The maximum collector current that a transistor can carry is 500 mA. If $\beta = 300$, what is the maximum allowable base current for the device ? **[1.67 mA]**
7. For the circuit shown in Fig. 10.44, draw the d.c. load line.

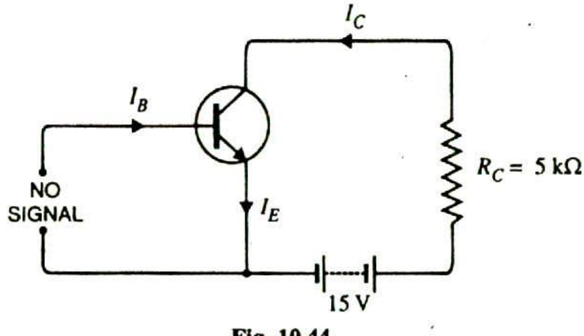


Fig. 10.44

Discussion Questions

1. Why is a transistor low powered device ?
2. What is the significance of arrow in the transistor symbol ?
3. Why is collector wider than emitter and base ?
4. Why is collector current slightly less than emitter current ?
5. Why is base made thin ?

11

Transistor Biasing

Introduction

The basic function of transistor is to do amplification. The weak signal is given to the base of the transistor and amplified output is obtained in the collector circuit. One important requirement during amplification is that only the magnitude of the signal should increase and there should be no change in signal shape. This increase in magnitude of the signal without any change in shape is known as *faithful amplification*. In order to achieve this, means are provided to ensure that input circuit (*i.e.* base-emitter junction) of the transistor remains forward biased and output circuit (*i.e.* collector-base junction) always remains reverse biased during all parts of the signal. This is known as transistor biasing. In this chapter, we shall discuss how transistor biasing helps in achieving faithful amplification.

11.1 Faithful Amplification

The process of raising the strength of a weak signal without any change in its general shape is known as **faithful amplification.**

The theory of transistor reveals that it will function properly if its input circuit (*i.e.* base-emitter junction) remains forward biased and output circuit (*i.e.* collector-base junction) remains reverse biased at all times. This is then the key factor for achieving faithful amplification. To ensure this, the following basic conditions must be satisfied :

(*i*) Proper zero signal collector current

(*ii*) Minimum proper base-emitter voltage (V_{BE}) at any instant

(*iii*) Minimum proper collector-emitter voltage (V_{CE}) at any instant

The conditions (*i*) and (*ii*) ensure that base-emitter junction shall remain properly forward biased during all parts of the signal. On the other hand, condition (*iii*) ensures that base-collector junction shall remain properly reverse biased at all times. In other words, the fulfilment of these conditions will ensure that transistor works over the active region of the output characteristics *i.e.* between saturation to cut off.

(*i*) **Proper zero signal collector current.** Consider an *npn* transistor circuit shown in Fig. 11.1 (*i*). During the positive half-cycle of the signal, base is positive w.r.t. emitter and hence base-emitter junction is forward biased. This will cause a base current and much larger collector current to flow in the circuit. The result is that positive half-cycle of the signal is amplified in the collector as shown. However, during the negative half-cycle of the signal, base-emitter junction is reverse biased and hence no current flows in the circuit. The result is that there is no output due to the negative half-cycle of the signal. Thus we shall get an amplified output of the signal with its negative half-cycles completely cut off which is unfaithful amplification.

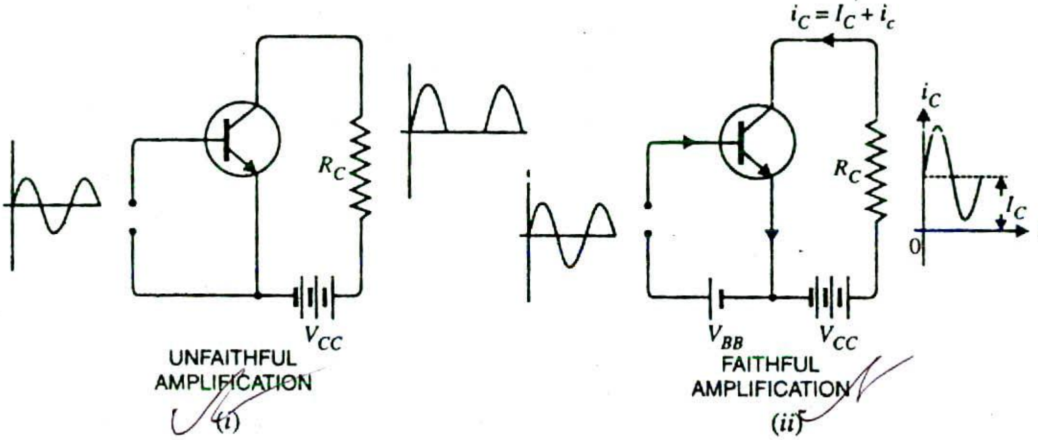


Fig. 11.1

Now, introduce a battery source V_{BB} in the base circuit as shown in Fig. 11.1 (*ii*). The magnitude of this voltage should be such that it keeps the input circuit forward biased even during the peak of negative half-cycle of the signal. When no signal is applied, a d.c. current I_C will flow in the collector circuit due to V_{BB} as shown. This is known as *zero signal collector current* I_C. During the positive half-cycle of the signal, input circuit is more forward biased and hence collector current increases. However, during the negative half-cycle of the signal, the input circuit is less forward biased and collector current decreases. In this way, negative half-cycle of the signal also appears in the output and hence faithful amplification results. It follows, therefore, that for faithful amplification, proper zero signal collector current must flow. *The value of zero signal collector current should be atleast equal to the maximum collector current due to signal alone i.e.*

Zero signal collector current $\geq$ max. collector current due to signal alone

Illustration. Suppose a signal applied to the base of a transistor gives a peak collector current of 1mA. Then zero signal collector current must be atleast equal to 1mA so that even during the peak of negative half-cycle of the signal, there is no cut off as shown in Fig. 11.2 (*i*).

If zero signal collector current is less, say 0.5 mA as shown in Fig. 11.2 (*ii*), then some part (shaded portion) of the negative half-cycle of signal will be cut off in the output.

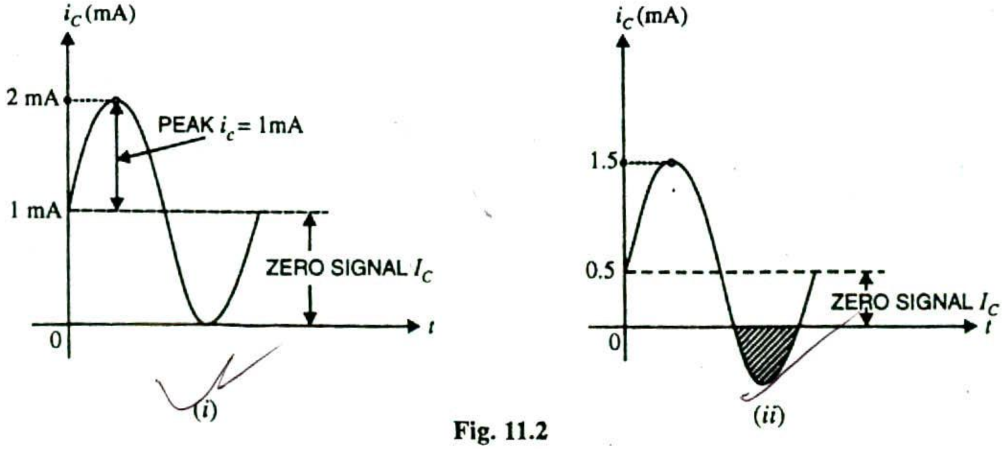


Fig. 11.2

(*ii*) **Proper minimum base-emitter voltage.** In order to achieve faithful amplification, the base-emitter voltage (V_{BE}) should not fall below 0.5V for germanium transistors and 0.7V for *Si* transistors at any instant.

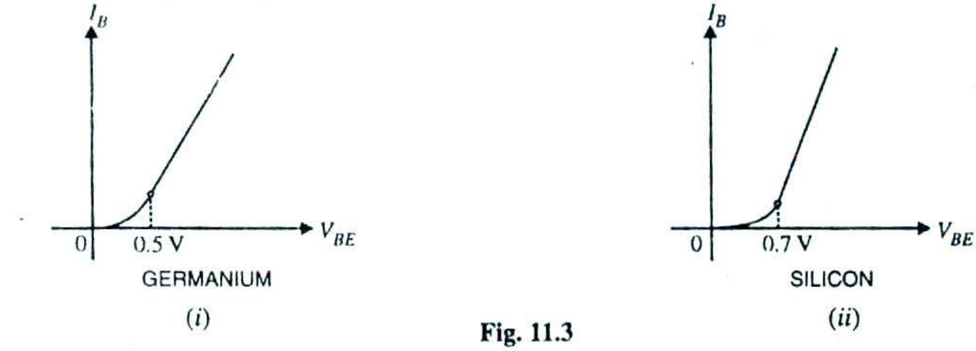


Fig. 11.3

The base current is very small until the *input voltage overcomes the potential barrier at the base-emitter junction. The value of this potential barrier is 0.5V for Ge transistors and 0.7V for *Si* transistors as shown in Fig. 11.3. Once the potential barrier is overcome, the base current and hence collector current increases sharply. Therefore, if base-emitter voltage V_{BE} falls below these values during any part of the signal, that part will be amplified to lesser extent due to small collector current. This will result in unfaithful amplification.

(*iii*) **Proper minimum V_{CE} at any instant.** For faithful amplification, the collector-emitter voltage V_{CE} should not fall below, 0.5V for Ge transistors and 1V for silicon transistors. This is called *knee voltage* (See Fig. 11.4).

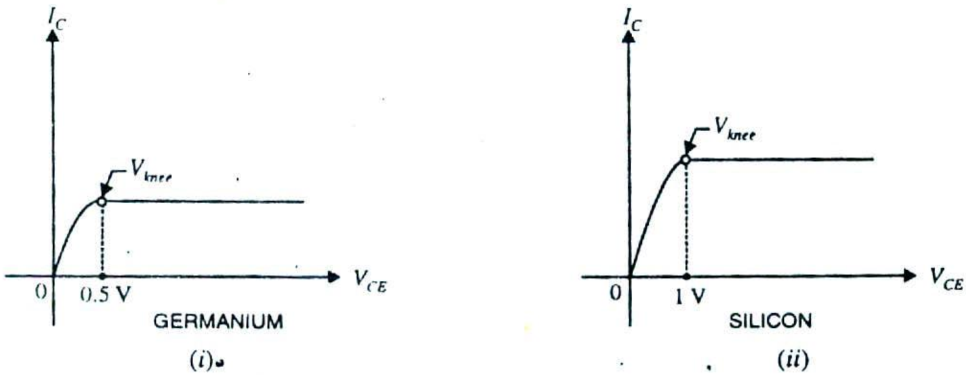


Fig. 11.4

When V_{CE} is too low (less than 0.5V for *Ge* transistors and 1V for *Si* transistors), the collector-base junction is not properly reverse biased. Therefore, the collector cannot attract the charge carriers emitted by the emitter and hence a greater portion of them goes to the base. This decreases the collector current while base current increases. Hence, value of β falls. Therefore, if V_{CE} is allowed to fall below V_{knee} during any part of the signal, that part will be less amplified due to reduced β. This will result in unfaithful amplification. However, when V_{CE} is greater than V_{knee}, the collector-base junction is properly reverse biased and the value of β remains constant, resulting in faithful amplification.

* In practice, a.c. signals have small voltage level (< 0.1V) and if applied directly will not give any collector current.

11.2 Transistor Biasing

It has already been discussed that for faithful amplification, a transistor amplifier must satisfy three basic conditions, namely : (*i*) proper zero signal collector current, (*ii*) proper base-emitter voltage at any instant and (*iii*) proper collector-emitter voltage at any instant. It is the fulfilment of these conditions which is known as transistor biasing.

The proper flow of zero signal collector current and the maintenance of proper collector-emitter voltage during the passage of signal is known as **transistor biasing.**

The basic purpose of transistor biasing is to keep the base-emitter junction properly forward biased and collector-base junction properly reverse biased during the application of signal. This can be achieved with a bias battery or associating a circuit with a transistor. The latter method is more efficient and is frequently employed. The circuit which provides transistor biasing is known as *biasing circuit*. It may be noted that transistor biasing is very essential for the proper operation of transistor in any circuit.

Example 11.1. *An npn silicon transistor has* V_{CC} = *6 V and the collector load* R_C = *2.5 kΩ. Find :*

(i) The maximum collector current that can be allowed during the application of signal for faithful amplification.

(ii) The minimum zero signal collector current required.

Solution. Collector supply voltage, $V_{CC} = 6$ V

Collector load, $R_C = 2.5$ kΩ

(*i*) We know that for faithful amplification, V_{CE} should not be less than 1V for silicon transistor.

∴ Max. voltage allowed across $R_C = 6 - 1 = 5$ V

∴ Max. allowed collector current $= 5\text{ V}/R_C = 5\text{ V}/2.5\text{ k}\Omega =$ **2 mA**

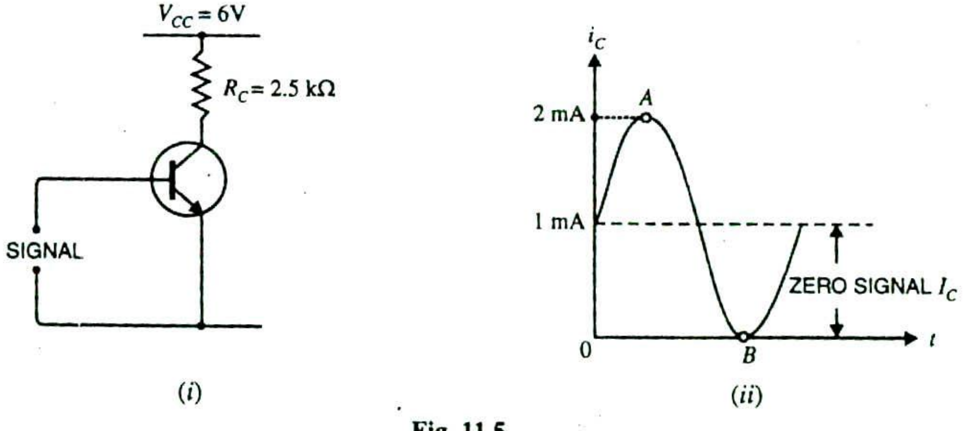


Fig. 11.5

Thus, the maximum collector current allowed during any part of the signal is 2 mA. If the collector current is allowed to rise above this value, V_{CE} will fall below 1 V. Consequently, value of β will fall, resulting in unfaithful amplification.

(*ii*) During the negative peak of the signal, collector current can at the most be allowed to become zero. As the negative and positive half cycles of the signal are equal, therefore, the change in collector current due to these will also be equal but in opposite direction.

∴ Minimum zero signal collector current required = 2 mA/2 = **1 mA**

During the positive peak of the signal [point *A* in Fig. 11.5 (*ii*)], $i_C = 1 + 1 = 2\text{mA}$ and during the negative peak (point *B*),

$$i_C = 1 - 1 = 0 \text{ mA}$$

Example 11.2. *A transistor employs a 4 kΩ load and V_{CC} = 13V. What is the maximum input signal if β = 100 ? Given V_{knee} = 1V and a change of 1V in V_{BE} causes a change of 5mA in collector current.*

Solution.

$$\text{Collector supply voltage, } V_{CC} = 13 \text{ V}$$

$$\text{Knee voltage, } V_{knee} = 1 \text{ V}$$

$$\text{Collector load, } R_C = 4 \text{ k}\Omega$$

$$\therefore \quad \text{Max. allowed voltage across } R_C = 13 - 1 = 12 \text{ V}$$

$$\therefore \quad \text{Max. allowed collector current, } i_C = \frac{12 \text{ V}}{R_C} = \frac{12 \text{ V}}{4 \text{ k}\Omega} = 3 \text{ mA}$$

$$\text{Maximum base current, } i_B = \frac{i_C}{\beta} = \frac{3 \text{ mA}}{100} = 30 \ \mu\text{A}$$

$$\text{Now} \quad \frac{\text{Collector current}}{\text{Base voltage (signal voltage)}} = 5 \text{ mA/V}$$

$$\therefore \quad \text{Base voltage (signal voltage)} = \frac{\text{Collector current}}{5 \text{ mA/V}} = \frac{3 \text{ mA}}{5 \text{ mA/V}} = \mathbf{600 \text{ mV}}$$

11.3 Inherent Variations of Transistor Parameters

In practice, the transistor parameters such as β, V_{BE} are not the same for every transistor even of the same type. To give an example, BC147 is a silicon *npn* transistor with β varying from 100 to 600 *i.e.* β for one transistor may be 100 and for the other it may be 600, although both of them are *BC*147. This large variation in parameters is a characteristic of transistors. The major reason for these variations is that transistor is a new device and manufacturing techniques have not too much advanced. For instance, it has not been possible to control the base width and it may vary, although slightly, from one transistor to the other even of the same type. Such small variations result in large change in transistor parameters such as β, V_{BE} etc.

The inherent variations of transistor parameters may change the operating point, resulting in unfaithful amplification. It is, therefore, very important that biasing network be so designed that it should be able to work with all transistors of one type whatever may be the spread in β or V_{BE}. In other words, the operating point should be independent of transistor parameters variations.

11.4 Stabilisation

The collector current in a transistor changes rapidly when

(*i*) the temperature changes,

(*ii*) the transistor is replaced by another of the same type. This is due to the inherent variations of transistor parameters.

When the temperature changes or the transistor is replaced, the operating point (*i.e.* zero signal I_C and V_{CE}) also changes. However, for faithful amplification, it is essential that operating point remains fixed. This necessitates to make the operating point independent of these variations. This is known as stabilisation.

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

Once stabilisation is done, the zero signal I_C and V_{CE} become independent of temperature variations or replacement of transistor *i.e.* the operating point is fixed. A good biasing circuit always ensures the stabilisation of operating point.

Need for stabilisation. Stabilisation of the operating point is necessary due to the following reasons :

(*i*) Temperature dependence of I_C

(*ii*) Individual variations

(*iii*) Thermal runaway.

(*i*) **Temperature dependence of I_C.** The collector current I_C for CE circuit is given by ;

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

The collector leakage current I_{CBO} is greatly influenced (especially in germanium transistor) by temperature changes. A rise of 10°C doubles the collector leakage current which may be as high as 0.2 mA for low powered germanium transistors. As biasing conditions in such transistors are generally so set that zero signal I_C = 1mA, therefore, the change in I_C due to temperature variations cannot be tolerated. This necessitates to stabilise the operating point *i.e.* to hold I_C constant inspite of temperature variations.

(*ii*) **Individual variations.** The value of β and V_{BE} are not exactly the same for any two transistors even of the same type. Further, V_{BE} itself decreases when temperature increases. When a transistor is replaced by another of the same type, these variations change the operating point. This necessitates to stabilise the operating point *i.e.* to hold I_C constant irrespective of individual variations in transistor parameters.

(*iii*) **Thermal runaway.** The collector current for a *CE* configuration is given by ;

$$I_C = \beta I_B + (\beta + 1) I_{CBO} \quad ...(i)$$

The collector leakage current I_{CBO} is strongly dependent on temperature. The flow of collector current produces heat within the transistor. This raises the transistor temperature and if no stabilisation is done, the collector leakage current I_{CBO} also increases. It is clear from exp. (*i*) that if I_{CBO} increases, the collector current I_C increases by $(\beta + 1) I_{CBO}$. The increased I_C will raise the temperature of the transistor, which in turn will cause I_{CBO} to increase. This effect is cumulative and in a matter of seconds, the collector current may become very large, causing the transistor to burn out.

The self-destruction of an unstabilised transistor is known as **thermal runaway.**

In order to avoid thermal runaway and consequent destruction of transistor, it is very essential that operating point is stabilised *i.e.* I_C is kept constant. In practice, this is done by causing I_B to decrease automatically with temperature increase by circuit modification. Then decrease in βI_B will compensate for the increase in $(\beta + 1) I_{CBO}$, keeping I_C nearly constant. In fact, this is what is always aimed at while building and designing a biasing circuit.

11.5 Essentials of a Transistor Biasing Circuit

It has already been discussed that transistor biasing is required for faithful amplification. The biasing network associated with the transistor should meet the following requirements :

(*i*) It should ensure proper zero signal collector current.

(*ii*) It should ensure that V_{CE} does not fall below 0.5 V for *Ge* transistors and 1 V for silicon transistors at any instant.

(*iii*) It should ensure the stabilisation of operating point.

11.6 Stability Factor

It is desirable and necessary to keep I_C constant in the face of variations of I_{CBO} (sometimes represented as I_{CO}). The extent to which a biasing circuit is successful in achieving this goal is measured by stability factor S. It is defined as under :

*The rate of change of collector current I_C w.r.t. the collector leakage current *I_{CO} at constant β and I_B is called* **stability factor** *i.e*:

$$\text{Stability factor, } S = \frac{dI_C}{dI_{CO}} \text{ at constant } I_B \text{ and } \beta$$

The stability factor indicates the change in collector current I_C due to the change in collector leakage current I_{CO}. Thus a stability factor 50 of a circuit means that I_C changes 50 times as much as any change in I_{CO}. In order to achieve greater thermal stability, it is desirable to have as low stability factor as possible. The ideal value of S is 1 but it is never possible to achieve it in practice. Experience shows that values of S exceeding 25 result in unsatisfactory performance.

The general expression of stability factor for a C.E. configuration can be obtained as under:

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

** Differentiating above expression w.r.t. I_C, we get,

$$1 = \beta \frac{dI_B}{dI_C} + (\beta + 1) \frac{dI_{CO}}{dI_C}$$

or
$$1 = \beta \frac{dI_B}{dI_C} + \frac{(\beta + 1)}{S} \qquad \left[\because \frac{dI_{CO}}{dI_C} = \frac{1}{S}\right]$$

or
$$S = \frac{\beta + 1}{1 - \beta \dfrac{(dI_B)}{(dI_C)}}$$

11.7 Methods of Transistor Biasing

In the transistor amplifier circuits drawn so far biasing was done with the aid of a battery V_{BB} which was separate from the battery V_{CC} used in the output circuit. However, in the interest of simplicity and economy, it is desirable that transistor circuit should have a single source of supply—the one in the output circuit (*i.e.* V_{CC}). The following are the most commonly used methods of obtaining transistor biasing from one source of supply (*i.e.* V_{CC}) :

(*i*) Base resistor method

(*ii*) Biasing with feedback resistor

(*iii*) Voltage-divider bias

In all these methods, the same basic principle is employed *i.e.* required value of base current (and hence I_C) is obtained from V_{CC} in the zero signal conditions. The value of collector load R_C is selected keeping in view that V_{CE} should not fall below 0.5 V for germanium transistors and 1 V for silicon transistors.

For example, if $\beta = 100$ and the zero signal collector current I_C is to be set at 1mA, then I_B is made equal to $I_C/\beta = 1/100 = 10\ \mu A$. Thus, the biasing network should be so designed that a base current of 10 μA flows in the zero signal conditions.

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* $I_{CBO} = I_{CO}$ = collector leakage current in CB arrangement

** Assuming β to be independent of I_C

11.8 Base Resistor Method

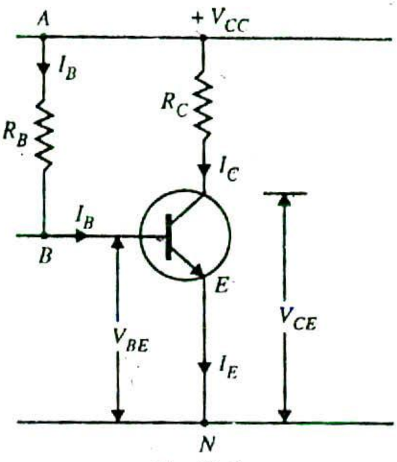


Fig. 11.6

In this method, a high resistance R_B (several hundred kΩ) is connected between the base and +ve end of supply for *npn* transistor (See Fig. 11.6) and between base and negative end of supply for *pnp* transistor. Here, the required zero signal base current is provided by V_{CC} and it flows through R_B. It is because now base is positive *w.r.t.* emitter *i.e.* base-emitter junction is forward biased. The required value of zero signal base current I_B (and hence $I_C = \beta I_B$) can be made to flow by selecting the proper value of base resistor R_B.

Circuit analysis. It is required to find the value of R_B so that required collector current flows in the zero signal conditions. Let I_C be the required zero signal collector current.

$$\therefore \quad I_B = \frac{I_C}{\beta}$$

Considering the closed circuit *ABENA* and applying Kirchhoff's voltage law, we get,

$$V_{CC} = I_B R_B + V_{BE}$$

or

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

$$\therefore \quad R_B = \frac{V_{CC} - V_{BE}}{I_B} \qquad \text{... } (i)$$

As V_{CC} and I_B are known and V_{BE} can be seen from the transistor manual, therefore, value of R_B can be readily found from exp. (*i*).

Since V_{BE} is generally quite small as compared to V_{CC}, the former can be neglected with little error. It then follows from exp. (*i*) that :

$$R_B = \frac{V_{CC}}{I_B}$$

It may be noted that V_{CC} is a fixed known quantity and I_B is chosen at some suitable value. Hence, R_B can always be found directly, and for this reason, this method is sometimes called *fixed-bias method*.

Stability factor. As shown in Art. 11.6,

$$\text{Stability factor, } S = \frac{\beta + 1}{1 - \beta \frac{(dI_B)}{(dI_C)}}$$

In fixed-bias method of biasing, I_B is independent of I_C so that $dI_B/dI_C = 0$. Putting the value of $dI_B / dI_C = 0$ in the above expression, we have,

$$\text{Stability factor, } S = \beta + 1$$

Thus the stability factor in a fixed bias is (β + 1). This means that I_C changes (β + 1) times as much as any change in I_{CO}. For instance, if $\beta = 100$, then $S = 101$ which means that I_C increases 10 times faster than I_{CO}. Due to the large value of S in a fixed bias, it has poor thermal stability.

Advantages :

(*i*) This biasing circuit is very simple as only one resistance R_B is required.

(*ii*) Biasing conditions can easily be set and the calculations are simple.

(*iii*) There is no loading of the source by the biasing circuit since no resistor is employed across base-emitter junction.

Disadvantages :

(*i*) This method provides poor stabilisation. It is because there is no means to stop a self-increase in collector current due to temperature rise and individual variations. For example, if β increases due to transistor replacement, then I_C also increases by the same factor as I_B is constant.

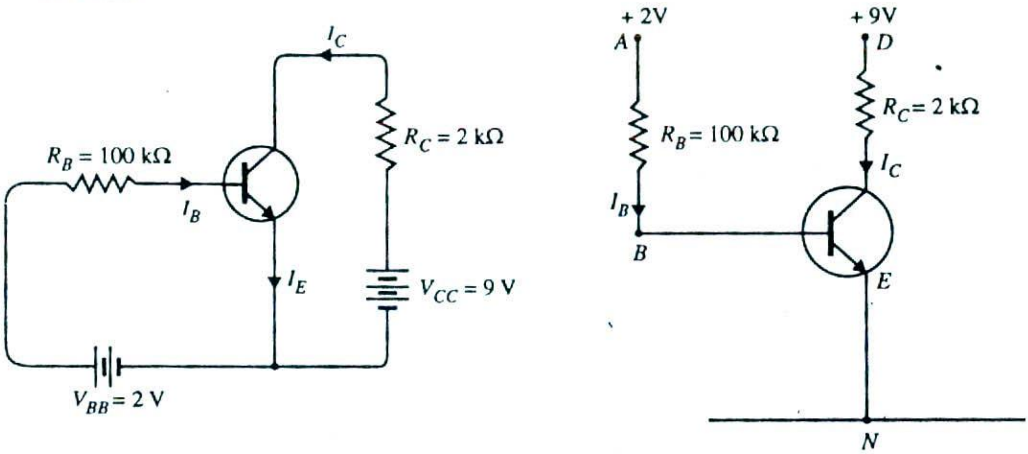
(*ii*) The stability factor is very high. Therefore, there are strong chances of thermal runaway.

Due to these disadvantages, this method of biasing is rarely employed.

Example 11.3. *Fig. 11.7 (i) shows biasing with base resistor method. (i) Determine the collector current I_C and collector-emitter voltage V_{CE}. Neglect small base-emitter voltage. Given that $\beta = 50$.*

(ii) If R_B in this circuit is changed to 50 kΩ, find the new operating point.

Solution.



(*i*) (*ii*)

Fig. 11.7

In the circuit shown in Fig. 11.7 (*i*), biasing is provided by a battery V_{BB} (= 2V) in the base circuit which is separate from the battery V_{CC} (= 9V) used in the output circuit. The same circuit is shown in a simplified way in Fig. 11.7 (*ii*). Here, we need show only the supply voltages, + 2V and + 9V. It may be noted that negative terminals of the power supplies are grounded to get a complete path of current.

(*i*) Referring to Fig. 11.7 (*ii*) and applying Kirchhoff's voltage law to the circuit *ABEN*, we get,

$$I_B R_B + V_{BE} = 2\text{V}$$

As V_{BE} is negligible,

$$\therefore \quad I_B = \frac{2\text{V}}{R_B} = \frac{2\text{V}}{100\text{ k}\Omega} = 20\ \mu\text{A}$$

$$\text{Collector current, } I_C = \beta I_B = 50 \times 20\ \mu\text{A} = 1000\ \mu\text{A} = \mathbf{1\ mA}$$

Applying Kirchhoff's voltage law to the circuit DEN, we get,

$$I_C R_C + V_{CE} = 9$$

or $$1\text{ mA} \times 2\text{ k}\Omega + V_{CE} = 9$$

or $$V_{CE} = 9 - 2 = \mathbf{7\ V}$$

(*ii*) When R_B is made equal to 50 kΩ, then it is easy to see that base current is doubled *i.e.* $I_B = 40\ \mu$A.

$$\therefore \quad \text{Collector current, } I_C = \beta I_B = 50 \times 40 = 2000\ \mu\text{A} = 2\text{ mA}$$

Collector-emitter voltage, $V_{CE} = V_{CC} - I_C R_C = 9 - 2 \text{ mA} \times 2 \text{ k}\Omega = 5 \text{ V}$

∴ New operating point is **5 V, 2 mA.**

Example 11.4. *Fig. 11.8 (i) shows that a silicon transistor with β = 100 is biased by base resistor method. Draw the d.c. load line and determine the operating point. What is the stability factor ?*

Solution. $V_{CC} = 6 \text{ V}, R_B = 530 \text{ k}\Omega, R_C = 2 \text{ k}\Omega$

D.C. load line. Referring to Fig. 11.8 (*i*),

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

When $I_C = 0$, $V_{CE} = V_{CC} = 6$ V. This locates the first point *B* (*OB* = 6V) of the load line on collector-emitter voltage axis as shown in Fig. 11.8 (*ii*).

When $V_{CE} = 0$, $I_C = V_{CC}/R_C = 6\text{V}/2 \text{ k}\Omega = 3 \text{ mA}$. This locates the second point *A* (*OA* = 3mA) of the load line on the collector current axis. By joining points *A* and *B*, d.c. load line *AB* is constructed [See Fig. 11.8 (*ii*)].

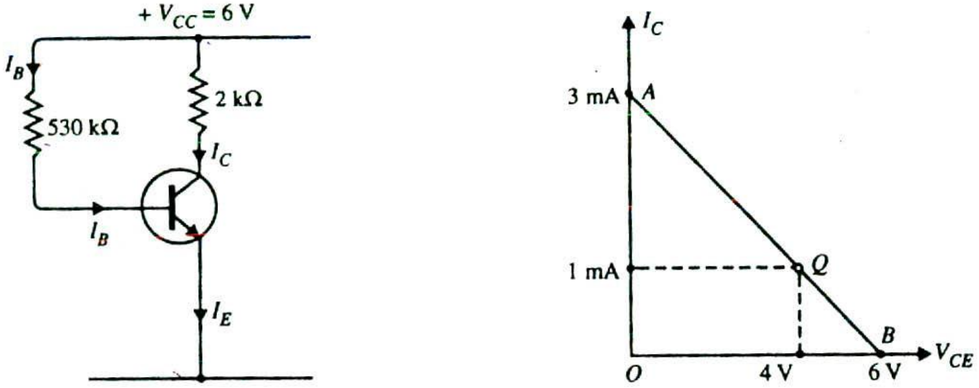


Fig. 11.8

Operating point Q. As it is a silicon transistor, therefore, $V_{BE} = 0.7$V. Referring to Fig. 11.8 (*i*), it is clear that :

$$I_B R_B + V_{BE} = V_{CC}$$

or
$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{(6 - 0.7) \text{ V}}{530 \text{ k}\Omega} = 10 \text{ μA}$$

∴ Collector current, $I_C = \beta I_B = 100 \times 10 = 1000 \text{ μA} = 1 \text{ mA}$

Collector-emitter voltage, $V_{CE} = V_{CC} - I_C R_C = 6 - 1 \text{ mA} \times 2 \text{ k}\Omega = 6 - 2 = 4 \text{ V}$

∴ Operating point is **4 V, 1 mA.**

Fig. 11.8 (*ii*) shows the operating point *Q* on the d.c. load line. Its co-ordinates are $I_C = 1$mA and $V_{CE} = 4$V.

Stability factor = β + 1 = 100 + 1 = **101**

Example 11.5. *(i) A germanium transistor is to be operated at zero signal I_C = 1mA. If the collector supply V_{CC} = 12V, what is the value of R_B in the base resistor method ? Take β = 100.*

(ii) If another transistor of the same batch with β = 50 is used, what will be the new value of zero signal I_C for the same R_B ?

Solution. $V_{CC} = 12$ V, $\beta = 100$

As it is a *Ge* transistor, therefore,

$$V_{BE} = 0.3 \text{ V}$$

(*i*) Zero signal $I_C = 1$ mA

∴ Zero signal $I_B = I_C/\beta = 1 \text{ mA}/100 = 0.01$ mA

Using the relation, $V_{CC} = I_B R_B + V_{BE}$

∴ $$R_B = \frac{V_{CC} - V_{BE}}{I_B} = \frac{12 - 0.3}{0.01 \text{ mA}}$$

$$= 11.7 \text{ V}/0.01 \text{ mA} = \mathbf{1170\ k\Omega}$$

(*ii*) Now $\beta = 50$

Again using the relation, $V_{CC} = I_B R_B + V_{BE}$

∴ $$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12 - 0.3}{1170 \text{ k}\Omega}$$

$$= 11.7 \text{ V}/1170 \text{ k}\Omega = 0.01 \text{ mA}$$

Zero signal $I_C = \beta I_B = 50 \times 0.01 = \mathbf{0.5\ mA}$

Comments. It is clear from the above example that with the change in transistor parameter β, the zero signal collector current has changed from 1mA to 0.5mA. Therefore, base resistor method cannot provide stabilisation.

Example 11.6. *Calculate the values of three currents in the circuit shown in Fig. 11.9.*

Solution. Applying Kirchhoff's voltage law to the base side and taking resistances in kΩ and currents in mA, we have,

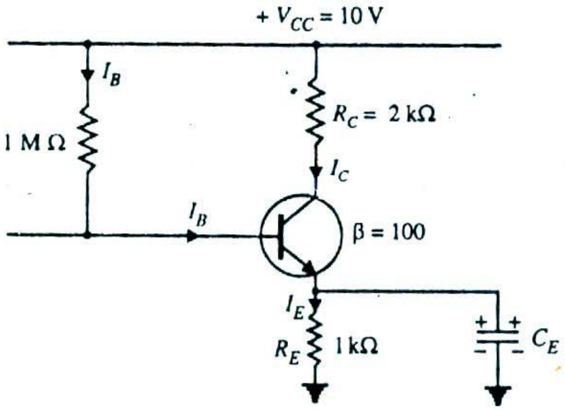


Fig. 11.9

$$V_{CC} = I_B R_B + V_{BE} + I_E \times 1$$

or $$10 = 1000\ I_B + {}^*0 + (I_C + I_B)$$

or $$10 = 1000\ I_B + (\beta\ I_B + I_B)$$

or $$10 = 1000\ I_B + (100\ I_B + I_B)$$

or $$10 = 1101\ I_B$$

∴ $$I_B = 10/1101 = \mathbf{0.0091\ mA}$$

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* Neglecting V_{BE} as it is generally very small.

$$I_C = \beta I_B = 100 \times 0.0091 = \mathbf{0.91\ mA}$$
$$I_E = I_C + I_B = 0.91 + 0.0091 = \mathbf{0.919\ mA}$$

Example 11.7. *Design base resistor bias circuit for a CE amplifier such that operating point is $V_{CE} = 8V$ and $I_C = 2$ mA. You are supplied with a fixed 15V d.c. supply and a silicon transistor with $\beta = 100$. Take base-emitter voltage $V_{BE} = 0.6V$. Calculate also the value of load resistance that would be employed.*

Solution. Fig. 11.10 shows *CE* amplifier using base resistor method of biasing.

$$V_{CC} = 15\text{ V};\ \beta = 100;\ V_{BE} = 0.6\text{V}$$
$$V_{CE} = 8\text{ V};\ I_C = 2\text{ mA};\ R_C = ?;\ R_B = ?$$
$$V_{CC} = V_{CE} + I_C R_C$$

or $$15\text{ V} = 8\text{ V} + 2\text{ mA} \times R_C$$

$$\therefore \quad R_C = \frac{(15-8)\text{ V}}{2\text{mA}} = \mathbf{3.5\ k\Omega}$$
$$I_B = I_C/\beta = 2/100 = 0.02\text{ mA}$$
$$V_{CC} = I_B R_B + V_{BE}$$
$$\therefore \quad R_B = \frac{V_{CC} - V_{BE}}{I_B} = \frac{(15-0.6)\text{ V}}{0.02\text{ mA}} = \mathbf{720\ k\Omega}$$

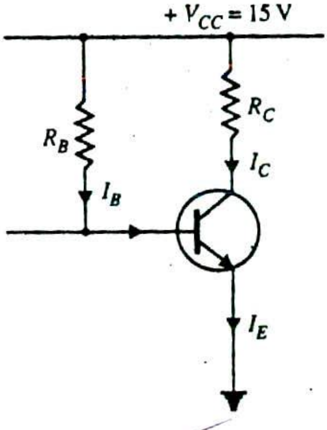

Fig. 11.10

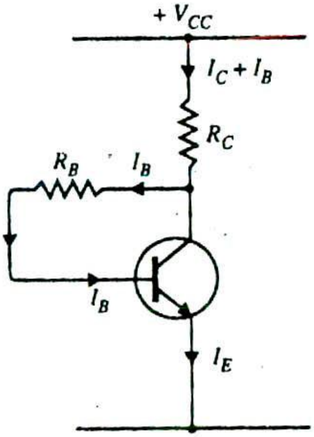

Fig. 11.11

11.9 Biasing with Feedback Resistor

In this method, one end of R_B is connected to the base and the other end to the collector as shown in Fig. 11.11. Here, the required zero signal base current is determined not by V_{CC} but by the collector-base voltage V_{CB}. It is clear that V_{CB} forward biases the base-emitter junction and hence base current I_B flows through R_B. This causes the zero signal collector current to flow in the circuit.

Circuit analysis. The required value of R_B needed to give the zero signal current I_C can be determined as follows. Referring to Fig. 11.11,

$$V_{CC} = {}^*I_C R_C + I_B R_B + V_{BE}$$

* Actually voltage drop across $R_C = (I_B + I_C) R_C$.
However, $I_B << I_C$. Therefore, as a reasonable approximation, we can say that drop across $R_C = I_C R_C$.

$$\text{or} \qquad R_B = \frac{V_{CC} - V_{BE} - I_C R_C}{I_B}$$

$$= \frac{V_{CC} - V_{BE} - \beta\, I_B R_C}{I_B} \qquad (\because I_C = \beta\, I_B)$$

$$\text{Alternatively,} \qquad V_{CE} = V_{BE} + V_{CB}$$

$$\text{or} \qquad V_{CB} = V_{CE} - V_{BE}$$

$$\therefore \qquad R_B = \frac{V_{CB}}{I_B} = \frac{V_{CE} - V_{BE}}{I_B}\,; \quad \text{where} \quad I_B = \frac{I_C}{\beta}$$

It can be shown mathematically that stability factor S for this method of biasing is less than $(\beta + 1)$ *i.e.*

$$\text{Stability factor, } S < (\beta + 1)$$

Therefore, this method provides better thermal stability than the fixed bias.

Advantages

(*i*) It is a simple method as it requires only one resistance R_B.

(*ii*) This circuit provides some stabilisation of the operating point as discussed below :

$$V_{CE} = V_{BE} + V_{CB}$$

Suppose the temperature increases. This will increase collector leakage current and hence the total collector current. But as soon as collector current increases, V_{CE} decreases due to greater drop across R_C. The result is that V_{CB} decreases *i.e.* lesser voltage is available across R_B. Hence the base current I_B decreases. The smaller I_B tends to decrease the collector current to original value.

Disadvantages

(*i*) The circuit does not provide good stabilisation because stability factor is fairly high, though it is lesser than that of fixed bias. Therefore, the operating point does change, although to lesser extent, due to temperature variations and other effects.

(*ii*) This circuit provides a negative feedback which reduces the gain of the amplifier as explained hereafter. During the positive half-cycle of the signal, the collector current increases. The increased collector current would result in greater voltage drop across R_C. This will reduce the base current and hence collector current.

Example 11.8. *Fig. 11.12 shows a silicon transistor biased by feedback resistor method. Determine the operating point. Given that $\beta = 100$.*

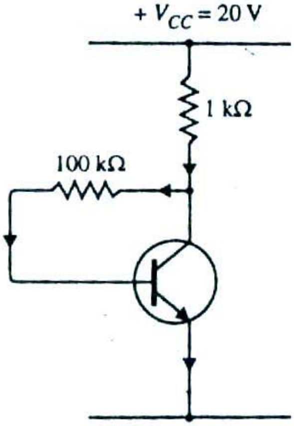

Fig. 11.12

Solution. $V_{CC} = 20\text{V}, R_B = 100\text{k}\Omega, R_C = 1\text{k}\Omega$

Since it is a silicon transistor, $V_{BE} = 0.7$ V.

Assuming I_B to be in mA and using the relation,

$$R_B = \frac{V_{CC} - V_{BE} - \beta\, I_B R_C}{I_B}$$

$$\text{or} \qquad 100 \times I_B = 20 - 0.7 - 100 \times I_B \times 1$$

$$\text{or} \qquad 200\, I_B = 19.3$$

$$\text{or} \qquad I_B = \frac{19.3}{200} = 0.096 \text{ mA}$$

$$\therefore \qquad \text{Collector current, } I_C = \beta\, I_B = 100 \times 0.096 = 9.6 \text{ mA}$$

Collector-emitter voltage is

$$V_{CE} = V_{CC} - I_C R_C$$
$$= 20 - 9.6 \text{ mA} \times 1 \text{ k}\Omega$$
$$= 10.4 \text{ V}$$

∴ Operating point is **10.4 V, 9.6 mA.**

Example 11.9. *(i) It is required to set the operating point by biasing with feedback resistor at $I_C = 1mA$, $V_{CE} = 8V$. If $\beta = 100$, $V_{CC} = 12V$, $V_{BE} = 0.3V$, how will you do it ?*

(ii) What will be the new operating point if $\beta = 50$, all other circuit values remaining the same ?

Solution.
$$V_{CC} = 12\text{V}, V_{CE} = 8\text{V}, I_C = 1\text{mA}$$
$$\beta = 100, V_{BE} = 0.3\text{V}$$

(*i*) To obtain the required operating point, we should find the value of R_B.

Now, collector load is

$$R_C = \frac{V_{CC} - V_{CE}}{I_C} = \frac{(12-8)\text{ V}}{1 \text{ mA}} = 4 \text{ k}\Omega$$

Also
$$I_B = \frac{I_C}{\beta} = \frac{1 \text{ mA}}{100} = 0.01 \text{ mA}$$

Using the relation, $$R_B = \frac{V_{CC} - V_{BE} - \beta I_B R_C}{I_B}$$
$$= \frac{12 - 0.3 - 100 \times 0.01 \times 4}{0.01} = \mathbf{770 \text{ k}\Omega}$$

(*ii*) Now $\beta = 50$, and other circuit values remain the same.

∴ $$V_{CC} = V_{BE} + I_B R_B + \beta I_B R_C$$
or $$12 = 0.3 + I_B (R_B + \beta R_C)$$
or $$11.7 = I_B (770 + 50 \times 4)$$
or $$I_B = \frac{11.7 \text{ V}}{970 \text{ k}\Omega} = 0.012 \text{ mA}$$

∴ Collector current, $I_C = \beta I_B = 50 \times 0.012 = 0.6 \text{ mA}$

∴ Collector-emitter voltage, $V_{CE} = V_{CC} - I_C R_C = 12 - 0.6 \text{ mA} \times 4 \text{ k}\Omega = 9.6 \text{ V}$

∴ New operating point is **9.6 V, 0.6 mA.**

Comments. It may be seen that operating point is changed when a new transistor with lesser β is used. Therefore, biasing with feedback resistor does not provide very good stabilisation. It may be noted, however, that change in operating point is less than that of base resistor method.

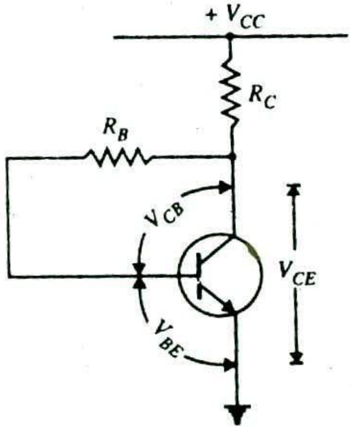

Fig. 11.13

Example 11.10. *It is desired to set the operating point at 2V, 1mA by biasing a silicon transistor with feedback resistor R_B. If $\beta = 100$, find the value of R_B.*

Solution.

For a silicon transistor,

$$V_{BE} = 0.7 \text{ V}$$
$$I_B = \frac{I_C}{\beta} = 1/100 = 0.01 \text{ mA}$$

Now $V_{CE} = V_{BE} + V_{CB}$

or $2 = 0.7 + V_{CB}$

∴ $V_{CB} = 2 - 0.7 = 1.3 \text{ V}$

$$R_B = \frac{V_{CB}}{I_B} = \frac{1.3\text{V}}{0.01 \text{ mA}} = \mathbf{130 \text{ k}\Omega}$$

11.10 Voltage Divider Bias Method

This is the most widely used method of providing biasing and stabilisation to a transistor. In this method, two resistances R_1 and R_2 are connected across the supply voltage V_{CC} (See Fig. 11.14) and provide biasing. The emitter resistance R_E provides stabilisation. The name "voltage divider" comes from the voltage divider formed by R_1 and R_2. The voltage drop across R_2 forward biases the base-emitter junction. This causes the base current and hence collector current flow in the zero signal conditions.

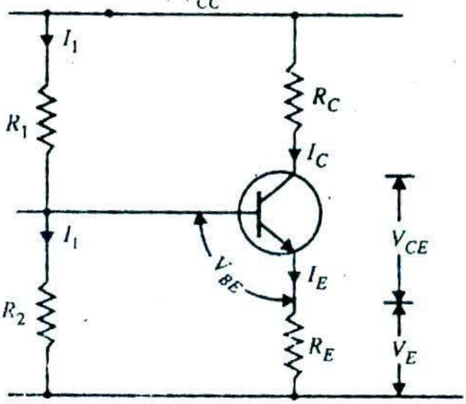

Fig. 11.14

Circuit analysis. Suppose that the current flowing through resistance R_1 is I_1. As base current I_B is very small, therefore, it can be assumed with reasonable accuracy that current flowing through R_2 is also I_1.

(*i*) **Collector current I_C:**

$$I_1 = \frac{V_{CC}}{R_1 + R_2}$$

∴ Voltage across resistance R_2 is

$$V_2 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2$$

Applying Kirchhoff's voltage law to the base circuit of Fig. 11.14,

$$V_2 = V_{BE} + V_E$$

or $$V_2 = V_{BE} + I_E R_E$$

or $$I_E = \frac{V_2 - V_{BE}}{R_E}$$

Since $I_E \simeq I_C$

∴ $$I_C = \frac{V_2 - V_{BE}}{R_E}$$

It is clear from exp. (*i*) above that I_C does not at all depend upon β. Though I_C depends upon V_{BE} but in practice $V_2 >> V_{BE}$ so that I_C is practically independent of V_{BE}. Thus I_C in this circuit is almost independent of transistor parameters and hence good stabilisation is ensured. It is due to this reason that potential divider bias has become universal method for providing transistor biasing.

(*ii*) **Collector-emitter voltage V_{CE}.** Applying Kirchhoff's voltage law to the collector side,

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E$$

$$= I_C R_C + V_{CE} + I_C R_E \qquad (\because I_E \simeq I_C)$$

$$= I_C (R_C + R_E) + V_{CE}$$

$$\therefore \quad V_{CE} = V_{CC} - I_C (R_C + R_E)$$

Stabilisation. In this circuit, excellent stabilisation is provided by R_E. Consideration of eq. (*i*) reveals this fact.

$$V_2 = V_{BE} + I_C R_E$$

Suppose the collector current I_C increases due to rise in temperature. This will cause the voltage drop across emitter resistance R_E to increase. As voltage drop across R_2 (*i.e.* V_2) is *independent of I_C, therefore, V_{BE} decreases. This in turn causes I_B to decrease. The reduced value of I_B tends to restore I_C to the original value.

Stability factor. It can be shown mathematically that stability factor of the circuit is given by ;

$$\text{Stability factor, } S = \frac{(\beta + 1)(R_T + R_E)}{R_T + R_E + \beta R_E}$$

$$= (\beta + 1) \times \frac{1 + \frac{R_T}{R_E}}{\beta + 1 + \frac{R_T}{R_E}} \qquad \text{where } R_T = \frac{R_1 R_2}{R_1 + R_2}$$

If the ratio R_T/R_E is very small, then R_T/R_E can be neglected as compared to 1 and the stability factor becomes :

$$\text{Stability factor} = (\beta + 1) \times \frac{1}{\beta + 1} = 1$$

This is the smallest possible value of S and leads to the maximum possible thermal stability. Due to design **considerations, R_T/R_E has a value that cannot be neglected as compared to 1. In actual practice, the circuit may have stability factor around 10.

Example 11.11. *Fig. 11.15 (i) shows the voltage divider bias method. Draw the d.c. load line and determine the operating point. Assume the transistor to be of silicon.*

Solution.

d.c. load line. The collector-emitter voltage V_{CE} is given by :

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

When $I_C = 0$, $V_{CE} = V_{CC} = 15\text{V}$. This locates the first point *B* (*OB* = 15V) of the load line on the collector-emitter voltage axis.

---

* Voltage drop across $R_2 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2$

** Low value of R_T can be obtained by making R_2 very small. But with low value of R_2, current drawn from V_{CC} will be large. This puts restrictions on the choice of R_T. Increasing the value of R_E requires greater V_{CC} in order to maintain the same value of zero signal collector current. Therefore, the ratio R_T/R_E cannot be made very small from design point of view.

When $V_{CE} = 0$, $I_C = \frac{V_{CC}}{R_C + R_E} = \frac{15 \text{ V}}{(1 + 2) \text{ k}\Omega} = 5 \text{ mA}$

This locates the second point A (OA = 5 mA) of the load line on the collector current axis. By joining points A and B, the d.c. load line AB is constructed as shown in Fig. 11.15 (*ii*).

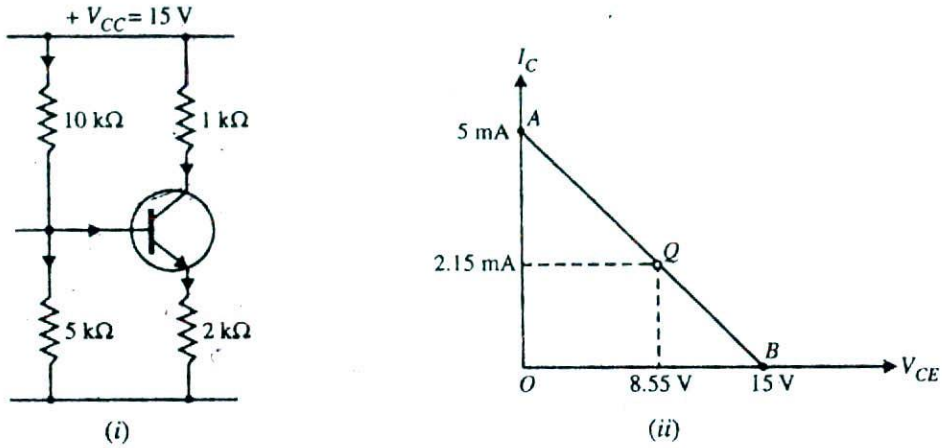

Fig. 11.15

Operating point. For silicon transistor,

$$V_{BE} = 0.7 \text{ V}$$

Voltage across 5 kΩ is

$$V_2 = \frac{V_{CC}}{10 + 5} \times 5 = \frac{15 \times 5}{10 + 5} = 5 \text{ V}$$

∴ Emitter current, $I_E = \frac{V_2 - V_{BE}}{R_E} = \frac{5 - 0.7}{2 \text{ k}\Omega} = \frac{4.3 \text{ V}}{2 \text{ k}\Omega} = 2.15 \text{ mA}$

∴ Collector current is

$$I_C \simeq I_E = 2.15 \text{ mA}$$

Collector-emitter voltage, $V_{CE} = V_{CC} - I_C (R_C + R_E)$

$$= 15 - 2.15 \text{ mA} \times 3 \text{ k}\Omega = 15 - 6.45 = 8.55 \text{ V}$$

∴ Operating point is **8.55 V, 2.15 mA.**

Fig. 11.15 (*ii*) shows the operating point Q on the load line. Its co-ordinates are I_C = 2.15 mA, V_{CE} = 8.55 V.

Example 11.12. *Determine the operating point of the circuit shown in the previous problem by using Thevenin's theorem.*

Solution. The circuit is redrawn and shown in Fig. 11.16 (*i*) for facility of reference. The d.c. circuit to the left of base terminal B can be replaced by Thevenin's equivalent circuit shown in Fig. 11.16 (*ii*). Looking to the left from the base terminal B [See Fig. 11.16 (*i*)], Thevenin's equivalent voltage E_0 is given by ;

$$E_0 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2 = \left(\frac{15}{10 + 5}\right) \times 5 = 5 \text{ V}$$

Again looking to the left from the base terminal B [See Fig. 11.16 (*i*)], Thevenin's equivalent resistance R_0 is given by ;

$$R_0 = \frac{R_1 R_2}{R_1 + R_2}$$

Fig. 11.16 (*ii*) shows the replacement of bias portion of the circuit of Fig. 11.16 (*i*) by its Thevenin's equivalent.

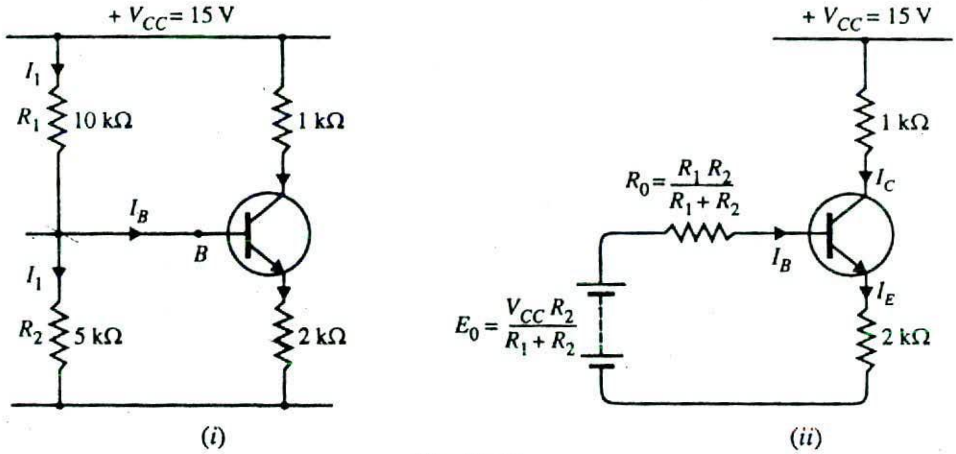

Fig. 11.16

Referring to Fig. 11.16 (*ii*), we have,

$$E_0 = I_B R_0 + V_{BE} + I_E R_E = I_B R_0 + V_{BE} + I_C R_E \qquad (\because I_E \simeq I_C)$$

$$= I_B R_0 + V_{BE} + \beta I_B R_E = I_B (R_0 + \beta R_E) + V_{BE}$$

or $$I_B = \frac{E_0 - V_{BE}}{R_0 + \beta R_E}$$

$\therefore$ Collector current, $$I_C = \beta I_B = \frac{\beta(E_0 - V_{BE})}{R_0 + \beta R_E}$$

Dividing the numerator and denominator of R.H.S. by β, we get,

$$I_C = \frac{E_0 - V_{BE}}{\frac{R_0}{\beta} + R_E}$$

As *$R_0/\beta << R_E$, therefore, R_0/β may be neglected as compared to R_E.

$$\therefore \quad I_C = \frac{E_0 - V_{BE}}{R_E} = \frac{5 - 0.7}{2\ \text{k}\Omega} = 2.15\ \text{mA}$$

$$V_{CE} = V_{CC} - I_C (R_C + R_E) = 15 - 2.15\ \text{mA} \times 3\ \text{k}\Omega$$

$$= 15 - 6.45 = 8.55\ \text{V}$$

$\therefore$ Operating point is **8.55 V, 2.15 mA.**

Example 11.13. *A transistor uses potential divider method of biasing.* $R_1 = 50\ k\Omega$, $R_2 = 10\ k\Omega$ *and* $R_E = 1 k\Omega$. *If* $V_{CC} = 12$ V, *find :*

(*i*) *the value of* I_C ; *given* $V_{BE} = 0.1V$

(*ii*) *the value of* I_C ; *given* $V_{BE} = 0.3V$. *Comment on the result.*

* In fact, this condition means that I_B is very small as compared to I_1, the current flowing through R_1 and R_2.

Solution. $R_1 = 50\text{ k}\Omega,\ R_2 = 10\text{ k}\Omega,\ R_E = 1\text{ k}\Omega,\ V_{CC} = 12\text{ V}$

(*i*) When $V_{BE} = 0.1$ V

$$\text{Voltage across } R_2,\ V_2 = \frac{R_2}{R_1 + R_2} V_{CC} = \frac{10}{50 + 10} \times 12 = 2\text{ V}$$

$$\therefore \quad \text{Collector current, } I_C = \frac{V_2 - V_{BE}}{R_E} = \frac{2 - 0.1}{1\text{ k}\Omega} = \mathbf{1.9\ mA}$$

(*ii*) When $V_{BE} = 0.3$ V

$$\text{Collector current, } I_C = \frac{V_2 - V_{BE}}{R_E} = \frac{2 - 0.3}{1\text{ k}\Omega} = \mathbf{1.7\ mA}$$

Comments. From the above example, it is clear that although V_{BE} varies by 300%, the value of I_C changes only by nearly 10%. This explains that in this method, I_C is almost independent of transistor parameter variations.

Example 11.14. *Calculate the emitter current in the voltage divider circuit shown in Fig. 11.17. Also find the value of V_{CE} and collector potential V_C.*

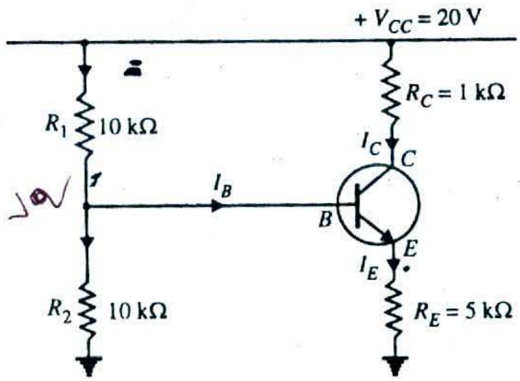

Fig. 11.17

Solution.

$$\text{Voltage across } R_2,\ V_2 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2 = \left(\frac{20}{10 + 10}\right) 10 = 10\text{ V}$$

Now $\quad V_2 = V_{BE} + I_E R_E$

As V_{BE} is generally small, therefore, it can be neglected.

$$\therefore \quad I_E = \frac{V_2}{R_E} = \frac{10\text{ V}}{5\text{ k}\Omega} = \mathbf{2\ mA}$$

Now $\quad I_C \simeq I_E = 2$ mA

$$\therefore \quad V_{CE} = V_{CC} - I_C (R_C + R_E) = 20 - 2\text{ mA } (6\text{ k}\Omega)$$

$$= 20 - 12 = \mathbf{8\ V}$$

$$\text{Collector potential, } V_C = V_{CC} - I_C R_C = 20 - 2\text{ mA} \times 1\text{ k}\Omega$$

$$= 20 - 2 = \mathbf{18\ V}$$

11.11 Design Of Transistor Biasing Circuits

(For low powered transistors)

In practice, the following steps are taken to design transistor biasing and stabilisation circuits :

Step 1. It is a common practice to take $R_E = 500 - 1000\Omega$. Greater the value of R_E, better is the stabilisation. However, if R_E is very large, higher voltage drop across it leaves reduced voltage drop across the collector load. Consequently, the output is decreased. Therefore, a compromise has to be made in the selection of the value of R_E.

Step 2. The zero signal current I_C is chosen according to the signal swing. However, in the initial stages of most transistor amplifiers, zero signal $I_C = 1$mA is sufficient. The major advantages of selecting this value are :

(*i*) The output impedance of a transistor is very high at 1mA. This increases the voltage gain.

(*ii*) There is little danger of overheating as 1mA is quite a small collector current.

It may be noted here that working the transistor below zero signal $I_C = 1$mA is not advisable because of strongly non-linear transistor characteristics.

Step 3. The values of resistances R_1 and R_2 are so selected that current I_1 flowing through R_1 and R_2 is atleast 10 times I_B *i.e.* $I_1 \geq 10\ I_B$. When this condition is satisfied, good stabilisation is achieved.

Step 4. The zero signal I_C should be a little more (say 20%) than the maximum collector current swing due to signal. For example, if collector current change is expected to be 3mA due to signal, then select zero signal $I_C \simeq 3.5$ mA. It is important to note this point. Selecting zero signal I_C below this value may cut off a part of negative half-cycle of a signal. On the other hand, selecting a value much above this value (say 15mA) may unnecessarily overheat the transistor, resulting in wastage of battery power. Moreover, a higher zero signal I_C will reduce the value of R_C (for same V_{CC}), resulting in reduced voltage gain.

Example 11.15. *In the circuit shown in Fig. 11.18, the operating point is chosen such that I_C = 2mA, V_{CE} = 3V. If R_C = 2.2 kΩ, V_{CC} = 9V and β = 50, determine the values of R_1, R_2 and R_E. Take V_{BE} = 0.3V and $I_1 = 10 I_B$.*

Solution.

$$R_C = 2.2\text{ k}\Omega, \quad V_{CC} = 9\text{V}, \quad \beta = 50$$
$$V_{BE} = 0.3\text{ V}, \quad I_1 = 10\, I_B$$

As I_B is very small as compared to I_1, therefore, we can assume with reasonable accuracy that I_1 flowing through R_1 also flows through R_2.

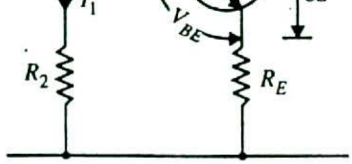

Fig. 11.18

$$\text{Base current, } I_B = \frac{I_C}{\beta} = \frac{2\ mA}{50} = 0.04\text{ mA}$$

Current through R_1 & R_2 is

$$I_1 = 10\, I_B = 10 \times 0.04 = 0.4\text{ mA}$$

Now
$$I_1 = \frac{V_{CC}}{R_1 + R_2}$$

$$\therefore \quad R_1 + R_2 = \frac{V_{CC}}{I_1} = \frac{9\text{ V}}{0.4\text{ mA}} = 22.5\text{ k}\Omega$$

Applying Kirchhoff's voltage law to the collector side of the circuit, we get,

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E\,.$$

or
$$V_{CC} = I_C R_C + V_{CE} + I_C R_E \qquad (\because I_C \simeq I_E)$$

or
$$9 = 2\text{ mA} \times 2.2\text{ k}\Omega + 3 + 2\text{ mA} \times R_E$$

$$\therefore \quad R_E = \frac{9 - 4.4 - 3}{2} = 0.8\text{ k}\Omega = \mathbf{800\ \Omega}$$

Voltage across R_2, $V_2 = V_{BE} + V_E = 0.3 + 2\text{ mA} \times 0.8\text{ k}\Omega$

$= 0.3 + 1.6 = 1.9\text{ V}$

$\therefore$ Resistance $R_2 = V_2/I_1 = 1.9\text{ V}/0.4\text{ mA} = \mathbf{4.75\text{ k}\Omega}$

and $R_1 = 22.5 - 4.75 = \mathbf{17.75\text{ k}\Omega}$

Example 11.16. *An npn transistor circuit (See Fig. 11.19) has α = 0.985 and V_{BE} = 0.3V. If V_{CC} = 16V, calculate R_1 and R_C to place Q point at I_C = 2mA, V_{CE} = 6 volts.*

Solution. $\alpha = 0.985, \quad V_{BE} = 0.3\text{ V}, \quad V_{CC} = 16\text{ V}$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.985}{1-0.985} = 66$$

Base current, $I_B = \frac{I_C}{\beta} = \frac{2\text{ mA}}{66} = 0.03\text{ mA}$

Voltage across R_2, $V_2 = V_{BE} + V_E = 0.3 + 2\text{ mA} \times 2\text{ k}\Omega$

$= 4.3\text{ V}$

$\therefore$ Voltage across $R_1 = V_{CC} - V_2 = 16 - 4.3 = 11.7\text{ V}$

$\therefore$ Current through R_1 & R_2 is

$$I_1 = \frac{V_2}{R_2} = \frac{4.3\text{ V}}{20\text{ k}\Omega} = 0.215\text{ mA}$$

$\therefore$ Resistance $R_1 = \frac{\text{Voltage across } R_1}{I_1} = \frac{11.7\text{ V}}{0.215\text{ mA}}$

$= \mathbf{54.4\text{ k}\Omega}$

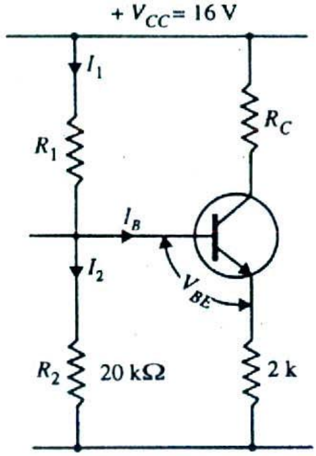

Fig. 11.19

Voltage across $R_C = V_{CC} - V_{CE} - V_E$

$= 16 - 6 - 2 \times 2 = 6\text{ V}$

$\therefore$ Collector resistance, $R_C = \frac{\text{Voltage across } R_C}{I_C} = \frac{6\text{ V}}{2\text{ mA}} = \mathbf{3\text{ k}\Omega}$

Example 11.17. *Calculate the exact value of emitter current in the circuit shown in Fig. 11.20 (i). Assume the transistor to be of silicon and β = 100.*

Solution. In order to obtain accurate value of emitter current I_E, we shall replace the bias portion of the circuit shown in Fig. 11.20 (*i*) by its Thevenin's equivalent. Fig. 11.20 (*ii*) shows the desired circuit.

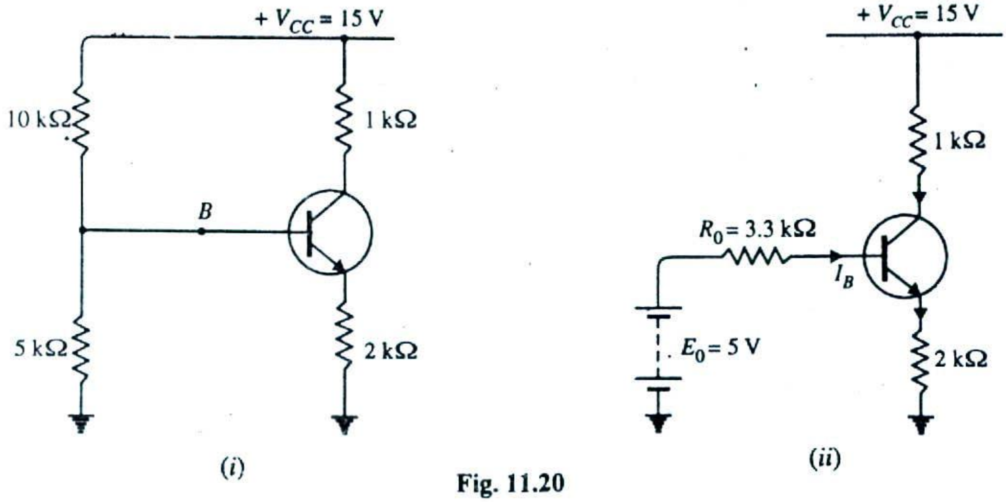

Fig. 11.20

Looking from the base terminal B to the left, Thevenin's voltage E_0 is given by ;

$$E_0 = \frac{R_2}{R_1 + R_2} V_{CC} = \frac{5}{10+5} \times 15 = 5 \text{ V}$$

Again looking from the base terminal B to the left, Thevenin's resistance R_0 is given by;

$$R_0 = \frac{R_1 R_2}{R_1 + R_2} = \frac{10 \times 5}{10+5} = \frac{50}{15} = 3.3 \text{ k}\Omega$$

Applying Kirchhoff's voltage law to the base-emitter loop [See Fig. 11.20 (*ii*)],

$$E_0 = I_B R_0 + V_{BE} + I_E R_E$$

Since $I_E \simeq I_C$, therefore, $I_B = I_E/\beta$.

$$\therefore \quad E_0 = \frac{I_E}{\beta} R_0 + V_{BE} + I_E R_E$$

$$= I_E \left(\frac{R_0}{\beta} + R_E \right) + V_{BE}$$

$$\therefore \quad I_E = \frac{E_0 - V_{BE}}{\frac{R_0}{\beta} + R_E} = \frac{5 - 0.7}{\frac{3.3}{100} + 2} \quad \text{(For } Si \text{ transistor, } V_{BE} = 0.7 \text{ V)}$$

$$= \frac{4.3 \text{ V}}{2.033 \text{ k}\Omega} = \mathbf{2.11 \text{ mA}}$$

Example 11.18. *The potential divider circuit shown in Fig. 11.21 has the values as follows: $I_E = 2mA$, $I_B = 50\mu A$, $V_{BE} = 0.2V$, $R_E = 1k\Omega$, $R_2 = 10\ k\Omega$ and $V_{CC} = 10V$. Find the value of R_1.*

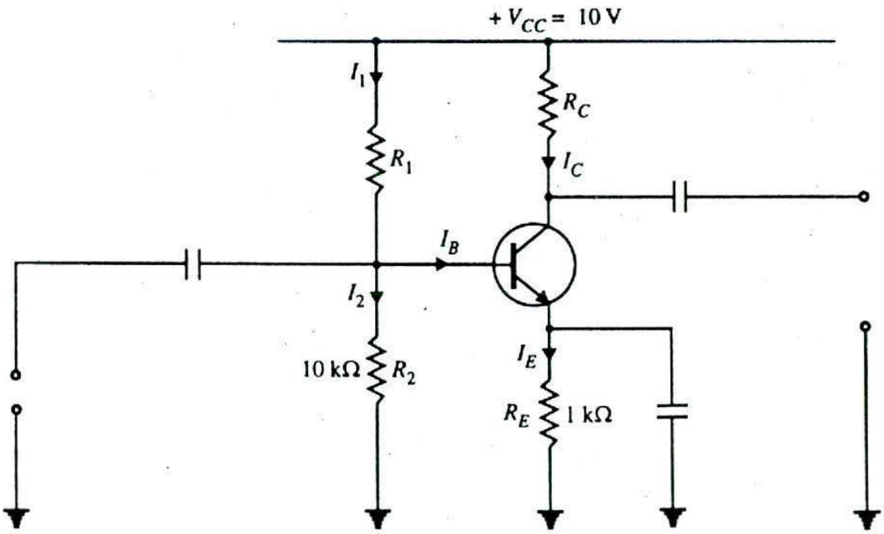

Fig. 11.21

Solution. In this problem, we shall consider that currents through R_1 and R_2 are different, although in practice this difference is very small.

$$\text{Voltage across } R_2,\ V_2 = V_{BE} + I_E R_E = 0.2 + 2 \text{ mA} \times 1 \text{ k}\Omega$$

$$= 0.2 + 2 = 2.2 \text{ V}$$

$$\text{Current through } R_2,\ I_2 = \frac{V_2}{R_2} = \frac{2.2 \text{ V}}{10 \text{ k}\Omega} = 0.22 \text{ mA}$$

$$\text{Current through } R_1, I_1 = I_2 + I_B = 0.22 + 0.05 = 0.27 \text{ mA}$$

$$\text{Voltage across } R_1, V_1 = V_{CC} - V_2 = 10 - 2.2 = 7.8 \text{ V}$$

$$\therefore \quad R_1 = \frac{V_1}{I_1} = \frac{7.8 \text{ V}}{0.27 \text{ mA}} = \mathbf{28.89 \text{ k}\Omega}$$

Example 11.19. *Fig. 11.22 shows the potential divider method of biasing. What will happen if*

(*i*) *resistance R_2 is shorted* (*ii*) *resistance R_2 is open-circuited*

(*iii*) *resistance R_1 is shorted* (*iv*) *resistance R_1 is open ?*

Solution. (*i*) If resistance R_2 is shorted, the base will be grounded. It will be left without forward bias and the transistor will be cut off *i.e.*, output will be zero.

(*ii*) If resistance R_2 is open, the forward bias will be very high. The collector current will be very high while collector-emitter voltage will be very low.

(*iii*) If resistance R_1 is shorted, the transistor will be in saturation due to excessive forward bias. The base will be at V_{CC} and emitter will be only slightly below V_{CC}.

(*iv*) If R_1 is open, the transistor will be without forward bias. Hence the transistor will be cut off *i.e.* output will be zero.

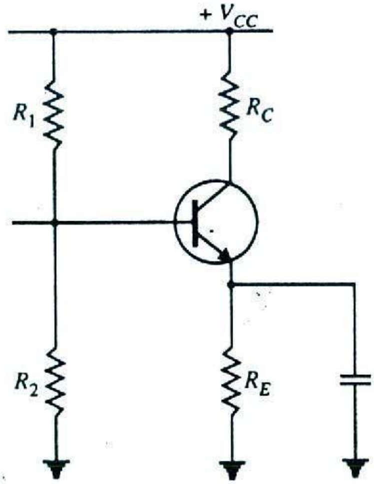

Fig. 11.22

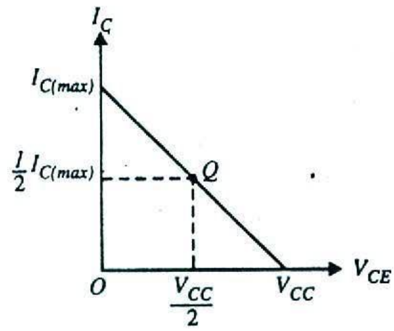

Fig. 11.23

11.12 Mid-Point Biasing

When an amplifier circuit is so designed that operating point Q lies at the centre of d.c. load line, the amplifier is said to be *midpoint biased.* When the amplifier is mid-point biased, the Q-point provides values of I_C and V_{CE} that are one-half of their maximum possible values. This is illustrated in Fig. 11.23. Since the Q-point is centred on the load line;

$$I_C = \frac{1}{2} I_{C\,(max)} \; ; \quad V_{CE} = \frac{V_{CC}}{2}$$

When a transistor is used as an amplifier, it is always designed for midpoint bias. The reason is that midpoint biasing allows optimum operation of the amplifier. In other words, midpoint biasing provides the largest possible output. This point is illustrated in Fig. 11.24 where Q-point is centred on the load line.

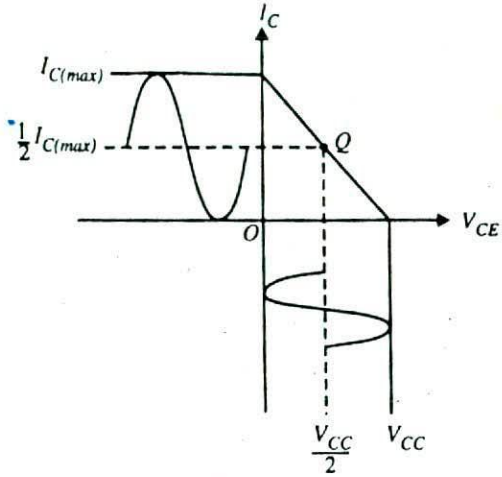

Fig. 11.24

When an ac signal is applied to the base of the transistor, collector current and collector- emitter voltage will both vary around their Q-point values. Since Q-point is centred, I_C and V_{CE} can both make the maximum possible transitions above and below their initial dc values. If Q-point is located above centre on the load line, the input may cause the transistor to saturate. As a result, a part of the output wave will be clipped off. Similarly, if Q-point is below midpoint on the load line, the input may cause the transistor to go into cut off. This can also cause a portion of the output to be clipped. It follows, therefore, that midpoint biased amplifier circuit allows the best possible ac operation of the circuit.

Example 11.20. *Determine whether or not the circuit shown in Fig. 11.25 (i) is midpoint biased.*

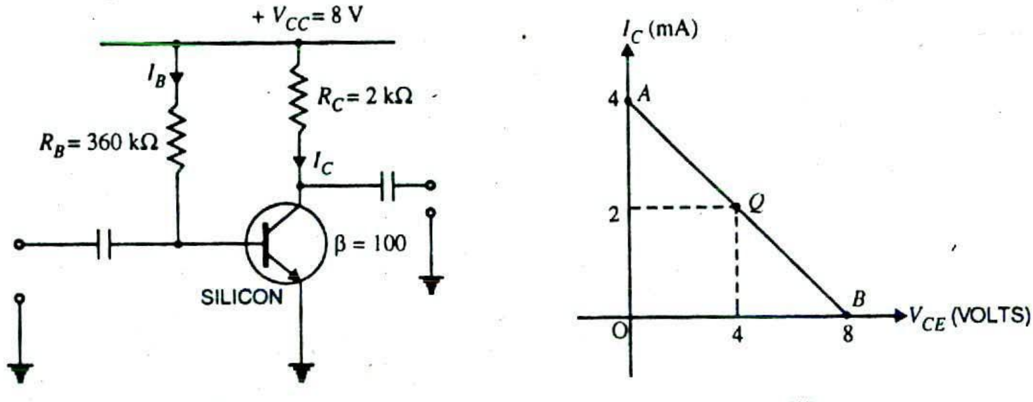

Fig. 11.25

Solution. Let us first construct the dc load line.

$$I_{C\,(max)} = \frac{V_{CC}}{R_C} = \frac{8\text{ V}}{2\text{ k}\Omega} = 4\text{ mA}$$

This locates the point A (OA = 4 mA) of the dc load line.

$$V_{CE(max)} = V_{CC} = 8\text{ V}$$

This locates the point B (OB = 8V) of the dc load line. By joining these two points, dc load line AB is constructed [See Fig. 11.25(*ii*)].

Operating point. Referring to Fig. 11.25 (*i*), we have,

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{8\text{ V} - 0.7\text{ V}}{360\text{ k}\Omega} = 20.28\ \mu\text{A}$$

$$\therefore \quad I_C = \beta I_B = 100\,(20.28\ \mu\text{A}) = 2.028\text{ mA}$$

Also $$V_{CE} = V_{CC} - I_C R_C = 8\text{ V} - (2.028\text{ mA})\,(2\text{ k}\Omega) = 3.94\text{ V}$$

Since V_{CE} is nearly one-half of V_{CC}, the amplifier circuit is midpoint biased.

Note. We can determine whether or not the circuit is midpoint biased without drawing the dc load line. By definition, a circuit is midpoint biased when the *Q*-point value of V_{CE} is one-half of V_{CC}. Therefore, all that you have to do is to find the operating point *Q* of the circuit. If the *Q*-point value of V_{CE} is one-half of V_{CC}, the circuit is midpoint biased.

Example 11.21. *Determine whether or not the circuit shown in Fig. 11.26 is midpoint biased.*

Solution. In order to determine whether the circuit is midpoint biased or not, we shall first find the operating point of the circuit.

Voltage across R_2 is

$$V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{10}{12 + 2.7} \times 2.7 = 1.84\text{ V}$$

$\therefore$ Emitter current is

$$I_E = \frac{V_2 - V_{BE}}{R_E} = \frac{1.84 - 0.7}{180} = 6.33\text{ mA}$$

$\therefore$ Collector current is

$$I_C \simeq I_E = \mathbf{6.33\ mA}$$

Collector-emitter voltage is

$$V_{CE} = V_{CC} - I_C\,(R_C + R_E)$$
$$= 10 - 6.33\,(0.62 + 0.18) = \mathbf{4.94\ V}$$

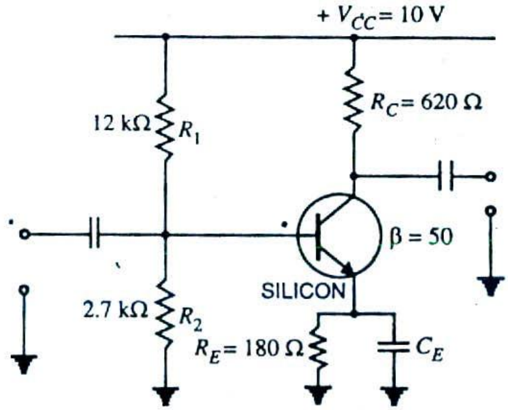

Fig. 11.26

Since *Q*-point value of V_{CE} is approximately one-half of V_{CC} (= 10 V), the circuit is midpoint biased. Note that answer has been obtained without the use of a dc load line.

11.13 Which Value of β to be used ?

While analysing a biasing circuit, we have to refer to the specification sheet for the transistor to obtain the value of β. Normally, the transistor specification sheet lists a minimum value (β_{min}) and maximum value (β_{max}) of β. In that case, the *geometric average of the two values* should be used.

$$\beta_{av} = \sqrt{\beta_{min} \times \beta_{max}}$$

Note. If only one value of β is listed on the specification sheet, we should then use that value.

Example 11.22. *Find the value of I_B for the circuit shown in Fig. 11.27. Given that β has a range of 100 to 400 when I_C = 10 mA.*

Solution. Voltage across R_2 is

$$V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{10}{1.5 + 0.68} \times 0.68 = 3.12\text{ V}$$

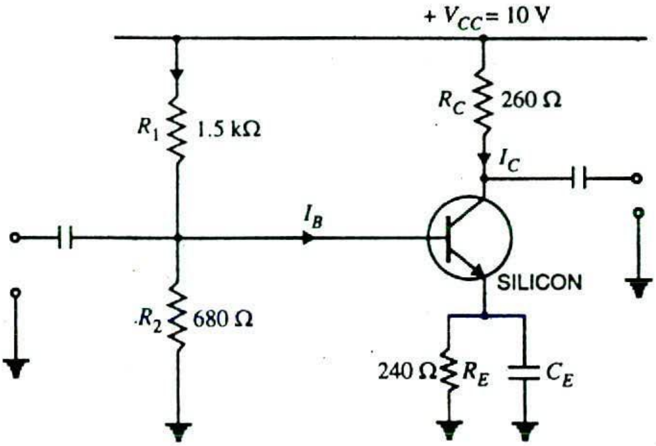

Fig.11.27

$$\therefore \quad \text{Emitter current, } I_E = \frac{V_2 - V_{BE}}{R_E} = \frac{3.12 - 0.7}{0.24} = 10 \text{ mA}$$

$$\therefore \quad \text{Collector current, } I_C \simeq I_E = 10 \text{ mA}$$

It is given that β has a range of 100 to 400 when Q-point value of I_C is 10mA.

$$\therefore \quad \beta_{av} = \sqrt{\beta_{min} \times \beta_{max}} = \sqrt{100 \times 400} = 200$$

$$\therefore \quad \text{Base current, } I_B = \frac{I_E}{\beta_{av} + 1} = \frac{10 \text{ mA}}{200 + 1} = \mathbf{49.75\ \mu A}$$

11.14 Silicon Versus Germanium

Although both silicon and germanium are used in semiconductor devices, the present day trend is to use silicon. The main reasons for this are :

(*i*) *Smaller* I_{CBO}. At room temperature, a silicon crystal has fewer free electrons than a germanium crystal. This implies that silicon will have much smaller collector cut off current (I_{CBO}) than that of germanium. In general, with germanium, I_{CBO} is 10 to 100 times greater than with silicon. The typical values of I_{CBO} at 25°C (the figures most often used for normal temperature) for small signal transistors are :

Silicon	0.01 μA to 1μA
Germanium	2 to 15 μA

(*ii*) *Smaller variation of* I_{CBO} *with temperature*. The variation of I_{CBO} with temperature is less in silicon as compared to germanium. A rough rule of thumb for germanium is that I_{CBO} approximately doubles with each 8 to 10°C rise while in case of silicon, it approximately doubles with each 12°C rise.

(*iii*) *Greater working temperature*. The structure of germanium will be destroyed at a temperature of approximately 100°C. The maximum normal working temperature of germanium is 70°C but silicon can be operated upto 150°C. Therefore, silicon devices are not easily damaged by excess heat.

Example 11.23. *A small signal germanium transistor operating at 25°C has* $I_{CBO} = 5\ \mu A$, $\beta = 40$ *and zero signal collector current = 2mA.*

(*i*) *Find the collector cut- off current i.e.* I_{CEO}

(ii) Find the percentage change in zero signal collector current if the temperature rises to 55°C. Assume I_{CBO} doubles with every 10°C rise.

(iii) What will be the percentage change in silicon transistor under the same conditions? Given that I_{CBO} for silicon is 0.1μA at 25°C and I_{CBO} doubles for every 10°C rise.

Solution.

(i) $I_{CEO} = (\beta + 1)\, I_{CBO} = (40 + 1)(5\ \mu A) = 205\ \mu A = \mathbf{0.205\ mA}$

(ii) Rise in temperature $= 55 - 25 = 30°C$

Since I_{CBO} doubles for every 10°C rise, the new I_{CBO} in Ge transistor at 55°C will be 8 times that at 25°C *i.e.*

Now $I_{CBO} = 8 \times 5 = 40\ \mu A$

$\therefore$ $I_{CEO} = (\beta + 1)\, I_{CBO} = (40 + 1)(40\ \mu A) = 1640\ \mu A = 1.64\ mA$

$\therefore$ Zero signal collector current at 55°C

$$= 2 + 1.64 = 3.64\ mA$$

Percentage change in zero signal collector current

$$= \frac{3.64 - 2}{2} \times 100 = \mathbf{82\ \%}$$

i.e., zero signal collector current rises 82% above its original value due to 30°C rise in temperature.

(*iii*) With silicon transistor,

$I_{CBO} = 0.1\ \mu A$ at 25°C and $\beta = 40$

$\therefore$ $I_{CEO} = (\beta + 1)\, I_{CBO} = (40 + 1)(0.1\ \mu A)$

$= 4.1\ \mu A = 0.0041\ mA$

A 30°C rise in temperature would cause I_{CEO} in silicon to increase 8 times.

Now $I_{CEO} = 8 \times 0.0041 = 0.0328\ mA$

$\therefore$ Zero signal collector current at 55°C

$$= 2 + 0.0328 = 2.0328\ mA$$

Percentage change in zero signal collector current

$$= \frac{2.0328 - 2}{2} \times 100 = \mathbf{1.6\ \%}$$

i.e., increase in zero signal collector current is 1.6%.

Comments. The above example shows that change in zero signal collector current with rise in temperature is very small in silicon as compared to germanium. In other words, temperature effects very slightly change the operating point of silicon transistors while they may cause a drastic change in germanium transistors. This is one of the reasons that silicon has become the main semiconductor material in use today.

Example 11.24. *A silicon transistor has I_{CBO} = 0.02μA at 27°C. The leakage current doubles for every 6°C rise in temperature. Calculate the base current at 57°C when the emitter current is 1mA. Given that α = 0.99.*

Solution. A 30°C (57 – 27 = 30) rise in temperature would cause I_{CBO} to increase 32 times.

$\therefore$ At 57°C, $I_{CBO} = 32 \times 0.02 = 0.64\ \mu A$

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

$= 0.99 \times 1 + 0.00064 = 0.9906\ mA$

$\therefore$ $I_B = I_E - I_C = 1 - 0.9906 = 0.0094\ mA = \mathbf{9.4\ \mu A}$

11.15 Instantaneous Current and Voltage Waveforms

It is worthwhile to show instantaneous current and voltage waveforms in an amplifier. Consider a *CE* amplifier biased by base resistor method as shown in Fig. 11.28. Typical circuit values have been assumed to make the treatment more illustrative. Neglecting V_{BE}, it is clear that zero signal base current $I_B = V_{CC}/R_B$ = 20 V/1 MΩ = 20 μA. The zero signal collector current $I_C = \beta I_B$ = 100 × 20 μA = 2mA. When signal of peak current 10 μA is applied, alternating current is superimposed on the d.c. base current. The collector current and collector-emitter voltage also vary as the signal changes. The instantaneous waveforms of currents and voltages are shown in Fig. 11.29. Note that base current, collector current and collector-emitter voltage waveforms are composed of (*i*) the d.c. component and (*ii*) the a.c. wave riding on the d.c.

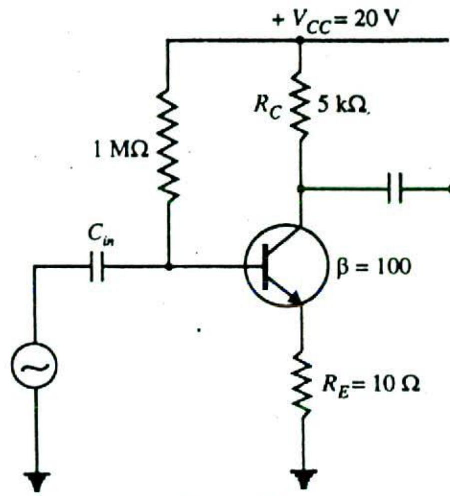

Fig. 11.28

(*i*) At π/2 radians, the base current is composed of 20 μA d.c. component plus 10 μA peak a.c. component, adding to 30 μA *i.e* i_B = 20 + 10 = 30 μA. The corresponding collector current i_C = 100 × 30 μA = 3 mA. The corresponding collector-emitter voltage is

$$v_{CE} = V_{CC} - i_C R_C = 20\text{ V} - 3\text{ mA} \times 5\text{ k}\Omega$$
$$= 20\text{ V} - 15\text{ V} = 5\text{ V}$$

Note that as the input signal goes positive, the collector current increases and collector-emitter voltage decreases. Moreover, during the positive half cycle of the signal (*i.e.* from 0 to π rad), the operating point moves from 20 μA to 20 + 10 = 30 μA and then back again *i.e.* operating point follows the path *Q* to *C* and back to *Q* on the load line.

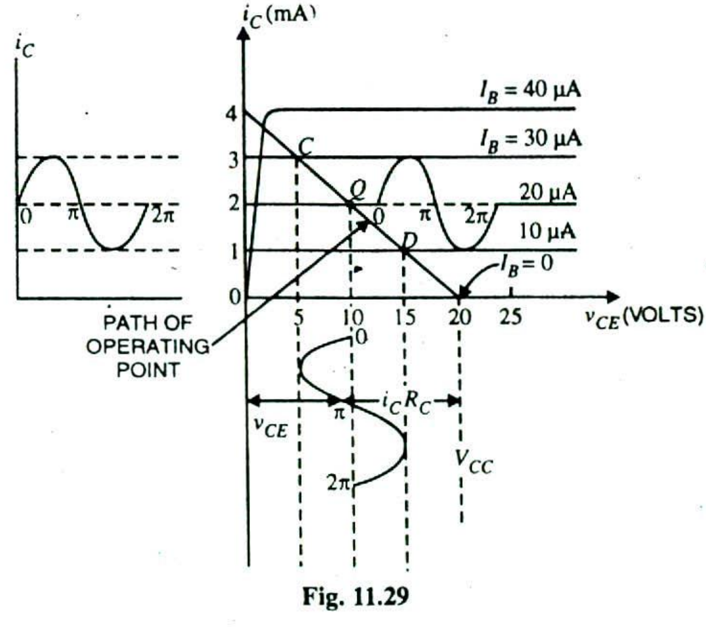

Fig. 11.29

(*ii*) During the negative half-cycle of the signal (from π to 2π rad.), the operating point goes from 20 μA to 20 – 10 = 10 μA and then back again *i.e.* the operating point follows the path *Q* to *D* and back to *Q* on the load line.

(*iii*) As the operating point moves along the path *CD* or *DC* due to the signal, the base current varies continuously. These variations in the base current cause both collector current and collector-emitter voltage to vary.

(*iv*) Note that when the input signal is maximum positive, the collector-emitter voltage is maximum negative. In other words, input signal voltage and output voltage have a phase difference of 180°. This is an important characteristic of *CE* arrangement.

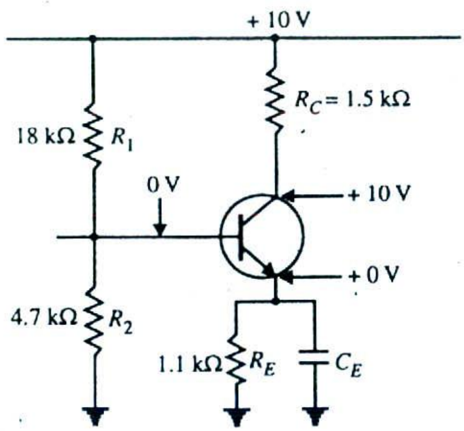

Fig. 11.30

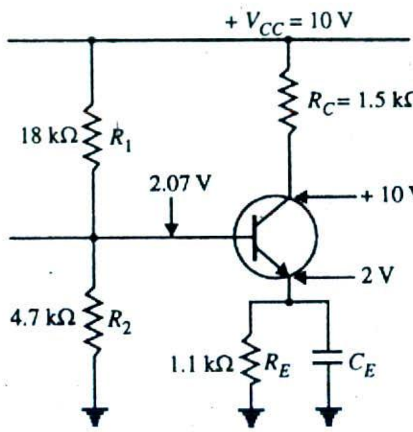

Fig. 11.31

Example 11.25. *What fault is indicated in Fig. 11.30 ? Explain your answer with reasons.*

Solution. Since V_B (*i.e.*, base voltage *w.r.t.* ground) is zero, it means that there is no path for current in the base circuit. The transistor will be biased off *i.e.*, $I_C = 0$ and $I_E = 0$. Therefore, V_C = 10 V ($\because I_C R_C = 0$) and $V_E = 0$. The obvious fault is that R_1 is open.

Example 11.26. *What fault is indicated in Fig. 11.31? Explain your answer with reasons.*

Solution. Based on the values of R_1, R_2 and V_{CC}, the voltage V_B at the base seems appropriate. In fact it is so as shown below :

$$\text{Voltage at base, } V_B = \text{Voltage across } R_2$$

$$= \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{10}{18 + 4.7} \times 4.7 = 2.07 \text{ V}$$

The fact that V_C = + 10 V and $V_E \simeq V_B$ reveals that $I_C = 0$ and $I_E = 0$. As a result, I_B drops to zero. The obvious fault is that R_E is open.

Multiple-Choice Questions

1. Transistor biasing represents .... conditions.
   (*i*) a.c.
   (*ii*) d.c.
   (*iii*) both a.c. and d.c.
   (*iv*) none of the above

2. Transistor biasing is done to keep .... in the circuit.
   (*i*) proper direct current
   (*ii*) proper alternating current
   (*iii*) the base current small
   (*iv*) collector current small

3. Operating point represents ....
   (i) values of I_C and V_{CE} when signal is applied
   (ii) the magnitude of signal
   (iii) zero signal values of I_C and V_{CE}
   (iv) none of the above
4. If biasing is not done in an amplifier circuit, it results in ....
   (i) decrease in base current
   (ii) unfaithful amplification
   (iii) excessive collector bias
   (iv) none of the above
5. Transistor biasing is generally provided by a ....
   (i) biasing circuit (ii) bias battery
   (iii) diode (iv) none of the above
6. For faithful amplification by a transistor circuit, the value of V_{BE} should .... for a silicon transistor.
   (i) be zero
   (ii) be 0.01 V
   (iii) not fall below 0.7 V
   (iv) be between 0 V and 0.1 V
7. For proper operation of the transistor, its collector should have ....
   (i) proper forward bias
   (ii) proper reverse bias
   (iii) very small size
   (iv) none of the above
8. For faithful amplification by a transistor circuit, the value of V_{CE} should .... for silicon transistor.
   (i) not fall below 1 V
   (ii) be zero
   (iii) be 0.2 V
   (iv) none of the above
9. The circuit that provides the best stabilisation of operating point is ....
   (i) base resistor bias
   (ii) collector feedback bias
   (iii) potential divider bias
   (iv) none of the above
10. The point of intersection of d.c. and a.c. load lines represents ....
   (i) operating point (ii) current gain
   (iii) voltage gain (iv) none of the above
11. An ideal value of stability factor is ....
   (i) 100 (ii) 200
   (iii) more than 200 (iv) 1
12. The zero signal I_C is generally ...... mA in the initial stages of a transistor amplifier.
   (i) 4 (ii) 1
   (iii) 3 (iv) more than 10
13. If the maximum collector current due to signal alone is 3 mA, then zero signal collector current should be atleast equal to ....
   (i) 6 mA (ii) 1.5 mA
   (iii) 3 mA (iv) 1 mA
14. The disadvantage of base resistor method of transistor biasing is that it ....
   (i) is complicated
   (ii) is sensitive to changes in β
   (iii) provides high stability
   (iv) none of the above
15. The biasing circuit has a stability factor of 50. If due to temperature change, I_{CBO} changes by 1 μA, then I_C will change by ....
   (i) 100 μA (ii) 25 μA
   (iii) 20 μA (iv) 50 μA
16. For good stabilisation in voltage divider bias, the current I_1 flowing through R_1 and R_2 should be equal to or greater than ....
   (i) $10\ I_B$ (ii) $3\ I_B$
   (iii) $2\ I_B$ (iv) $4\ I_B$
17. The leakage current in a silicon transistor is about .... the leakage current in a germanium transistor.
   (i) one hundredth (ii) one tenth
   (iii) one thousandth (iv) one millionth
18. The operating point is also called the ....
   (i) cut off point
   (ii) quiescent point
   (iii) saturation point
   (iv) none of the above
19. For proper amplification by a transistor cir-

cuit, the operating point should be located at .... of the d.c. load line.

(*i*) the end point
(*ii*) middle
(*iii*) the maximum current point
(*iv*) none of the above

20. The operating point .... on the a.c. load line.

(*i*) also lies (*ii*) does not lie
(*iii*) may or may not lie
(*iv*) data insufficient

21. The disadvantage of voltage divider bias is that it has ....

(*i*) high stability factor
(*ii*) low base current
(*iii*) many resistors
(*iv*) none of the above

22. Thermal runaway occurs when ....

(*i*) collector is reverse biased
(*ii*) transistor is not biased
(*iii*) emitter is forward biased
(*iv*) junction capacitance is high

23. The purpose of resistance in the emitter circuit of a transistor amplifier is to ....

(*i*) limit the maximum emitter current
(*ii*) provide base-emitter bias
(*iii*) limit the change in emitter current
(*iv*) none of the above

24. In a transistor amplifier circuit, $V_{CE} = V_{CB} +$ ....

(*i*) V_{BE} (*ii*) $2\ V_{BE}$
(*iii*) $1.5\ V_{BE}$ (*iv*) none of the above

25. The base resistor method is generally used in ....

(*i*) amplifier circuits
(*ii*) switching circuits
(*iii*) rectifier circuits
(*iv*) none of the above

26. For germanium transistor amplifier, V_{CE} should .... for faithful amplification.

(*i*) be zero
(*ii*) be 0.2 V
(*iii*) not fall below 0.7 V
(*iv*) none of the above

27. In a base resistor method, if the value of β changes by 50, then collector current will change by a factor of ....

(*i*) 25 (*ii*) 50
(*iii*) 100 (*iv*) 200

28. The stability factor of a collector feedback bias circuit is .... that of base resistor bias.

(*i*) the same as (*ii*) more than
(*iii*) less than (*iv*) none of the above

29. In the design of a biasing circuit, the value of collector load R_C is determined by ....

(*i*) V_{CE} consideration
(*ii*) V_{BE} consideration
(*iii*) I_B consideration
(*iv*) none of the above

30. If the value of collector current I_C increases, then value of V_{CE} ....

(*i*) remains the same
(*ii*) decreases
(*iii*) increases
(*iv*) none of the above

31. If the temperature increases, the value of V_{BE} ....

(*i*) remains the same
(*ii*) is increased
(*iii*) is decreased
(*iv*) none of the above

32. The stabilisation of operating point in potential divider method is provided by ....

(*i*) R_E consideration
(*ii*) R_C consideration
(*iii*) V_{CC} consideration
(*iv*) none of the above

33. The value of V_{BE} ....

(*i*) depends upon I_C to moderate extent
(*ii*) is almost independent of I_C
(*iii*) is strongly dependent on I_C
(*iv*) none of the above

34. When the temperature changes, the operating point is shifted due to ....

(i) change in I_{CBO}

(ii) change in V_{CC}

(iii) change in the values of circuit resistances

(iv) none of the above

35. The value of stability factor for a base-resistor bias is ....

(i) $R_B(\beta + 1)$ (ii) $(\beta + 1) R_B$

(iii) $(\beta + 1)$ (iv) $1 - \beta$

36. In a practical biasing circuit, the value of R_E is about ....

(i) 10 kΩ (ii) 1 MΩ

(iii) 100 kΩ (iv) 800 Ω

37. A silicon transistor is biased with base resistor method. If $\beta = 100$, $V_{BE} = 0.7$ V, zero signal collector current $I_C = 1$ mA and $V_{CC} = 6$ V, what is the value of base resistor R_B ?

(i) 105 kΩ (ii) 530 kΩ

(iii) 315 kΩ (iv) none of the above

38. In voltage divider bias, $V_{CC} = 25$ V ; $R_1 = 10$ kΩ; $R_2 = 2.2$ kΩ ; $R_C = 3.6$ kΩ and $R_E = 1$ kΩ. What is the emitter voltage ?

(i) 6.7 V (ii) 5.3 V

(iii) 4.9 V (iv) 3.8 V

39. In the above question, what is the collector voltage ?

(i) 11.3 V (ii) 14.8 V

(iii) 7.6 V (iv) 9.7 V

40. In voltage divider bias, operating point is 3 V, 2 mA. If $V_{CC} = 9$ V, $R_C = 2.2$ kΩ, what is the value of R_E ?

(i) 2000 Ω (ii) 1400 Ω

(iii) 800 Ω (iv) 1600 Ω

Answers to Multiple-Choice Questions

1. (ii)	**2.** (i)	**3.** (iii)	**4.** (ii)	**5.** (i)
6. (iii)	**7.** (ii)	**8.** (i)	**9.** (iii)	**10.** (i)
11. (iv)	**12.** (ii)	**13.** (iii)	**14.** (ii)	**15.** (iv)
16. (i)	**17.** (iii)	**18.** (ii)	**19.** (ii)	**20.** (i)
21. (iii)	**22.** (ii)	**23.** (iii)	**24.** (i)	**25.** (ii)
26. (iii)	**27.** (ii)	**28.** (iii)	**29.** (i)	**30.** (ii)
31. (iii)	**32.** (i)	**33.** (ii)	**34.** (i)	**35.** (iii)
36. (iv)	**37.** (ii)	**38.** (iv)	**39.** (i)	**40.** (iii)

Chapter Review Topics

1. What is faithful amplification ? Explain the conditions to be fulfilled to achieve faithful amplification in a transistor amplifier.
2. What do you understand by transistor biasing ? What is its need ?
3. What do you understand by stabilisation of operating point ?
4. Mention the essentials of a biasing circuit.
5. Describe the various methods used for transistor biasing. State their advantages and disadvantages.
6. Describe the potential divider method in detail. How stabilisation of operating point is achieved by this method ?
7. Mention the steps that are taken to design the transistor biasing and stabilisation circuits.
8. Write short notes on the following :

   (i) Operating point (ii) Stabilisation of operating point

Problems

1. An *npn* silicon transistor has $V_{CC} = 5$V and the collector load $R_C = 2$ kΩ. Find :

   (i) the maximum collector current that can be allowed during the application of signal for faithful amplification (*ii*) the minimum zero signal collector current required **[(*i*) 2mA (*ii*) 1mA]**

2. Fig. 11.32 shows biasing with base resistor method. Determine the operating point. Assume the transistor to be of silicon and take $\beta = 100$. **[$I_C = 0.93$ mA, $V_{CE} = 17.3$V]**
3. Fig. 11.33 shows biasing by base resistor method. If it is required to set the operating point at 1mA, 6 V, find the values of R_C and R_B. Given $\beta = 150$, $V_{BE} = 0.3$ V. **[$R_C = 3$ kΩ, $R_B = 0.3$ MΩ]**

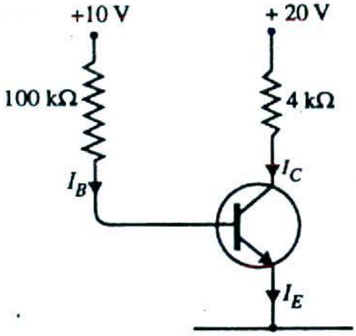

Fig. 11.32

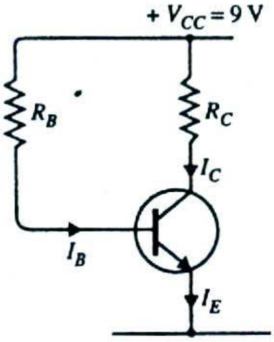

Fig. 11.33

4. A transistor amplifier is biased with feedback resistor R_B of 100 kΩ. If $V_{CC} = 25$ V, $R_C = 1$ kΩ and $\beta = 200$, find the values of zero signal I_C and V_{CE}. **[$I_C = 16.2$mA, $V_{CE} = 8.8$V]**

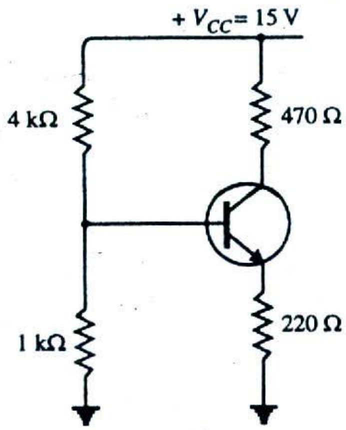

Fig. 11.34

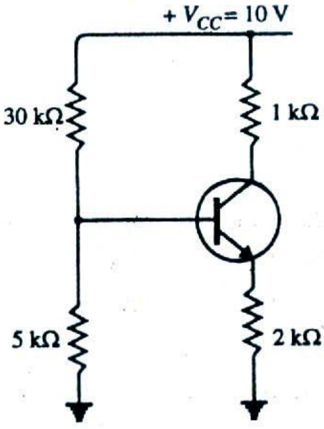

Fig. 11.35

5. Find the value of I_C for potential divider method if $V_{CC} = 9$V, $R_E = 1$kΩ, $R_1 = 39$ kΩ, $R_2 = 10$ kΩ, $R_C = 2.7$ kΩ, $V_{BE} = 0.15$ V and $\beta = 90$. **[1.5mA]**
6. In an *RC* coupled amplifier, the battery voltage is 16V and collector load $R_C = 4$ kΩ. It is required to set the operating point at $I_C = 1$ mA, $V_{CE} = 10$ V by potential divider method. If $V_{BE} = 0.2$ V and $I_1 = 10\ I_B$, $\beta = 100$, find the various circuit values.
7. In the transistor circuit shown in Fig. 11.34, find the operating point. Assume the transistor to be of silicon. **[$I_C = 10.5$mA, $V_{CE} = 7.75$V]**
8. In a transistor circuit shown in Fig. 11.35, find the operating point. Assume silicon transistor is used. **[$I_C = 0.365$mA, $V_{CE} = 8.9$V]**
9. Determine whether or not the circuit shown in Fig. 11.36 is midpoint biased. **[Yes]**
10. What fault is indicated in Fig. 11.37 ? Give reasons for your answer. **[R_C is open]**

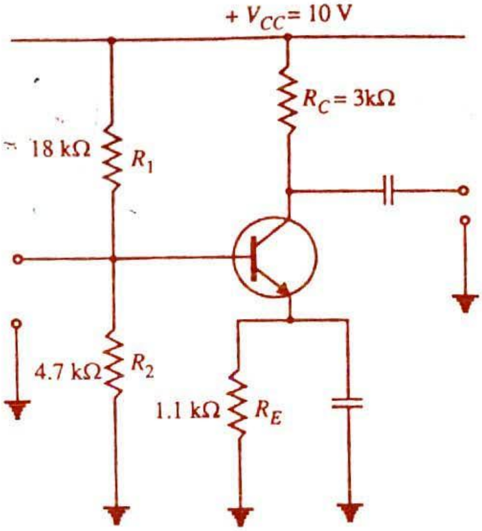

Fig. 11.36

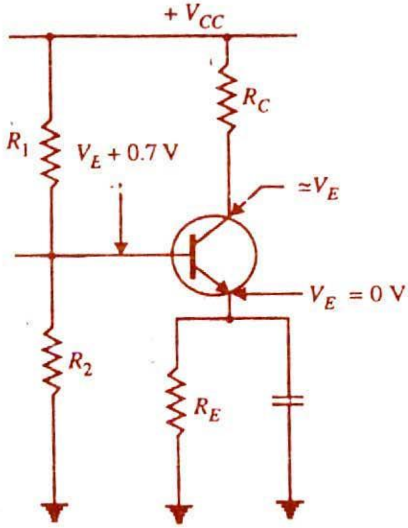

Fig. 11.37

Discussion Questions

1. Why are transistor amplifiers always operated above knee voltage region ?
2. What is the utility of d.c. load line ?
3. Why have transistors inherent variations of parameters ?
4. Why is $\beta_{d.c.}$ different from $\beta_{a.c.}$?
5. Why has potential divider method of biasing become universal ?

12

Single Stage Transistor Amplifiers

Introduction

In the previous chapter, it was discussed that a properly biased transistor raises the strength of a weak signal and thus acts as an amplifier. Almost all electronic equipments must include means for amplifying electrical signals. For instance, radio receivers amplify very weak signals—sometimes a few millionth of a volt at antenna–until they are strong enough to fill a room with sound. The transducers used in the medical and scientific investigations generate signals in the microvolt (μV) and millivolt (mV) range. These signals must be amplified thousands and millions times before they will be strong enough to operate indicating instruments. Therefore, electronic amplifiers are a constant and important ingredient of electronic systems.

Our purpose here will be to discuss *single stage* transistor amplifier. By a *stage* we mean a single transistor with its bias and auxiliary equipment. It may be emphasised here that a practical amplifier is always a multistage amplifier *i.e.* it has a number of stages of amplification. However, it is profitable to consider the multistage amplifier in terms of single stages that are connected together. In this chapter, we shall confine our attention to single stage transistor amplifiers.

12.1 Single Stage Transistor Amplifier

When only one transistor with associated circuitry is used for amplifying a weak signal, the circuit is known as **single stage transistor amplifier.**

A single stage transistor amplifier has one transistor, bias circuit and other auxiliary components. Although a practical amplifier consists of a number of stages, yet such a complex circuit can be conveniently split up into separate single stages. By analysing carefully only a single stage and using this single stage analysis repeatedly, we can effectively analyse the complex circuit. It follows, therefore, that single stage amplifier analysis is of great value in understanding the practical amplifier circuits.

12.2 How Transistor Amplifies ?

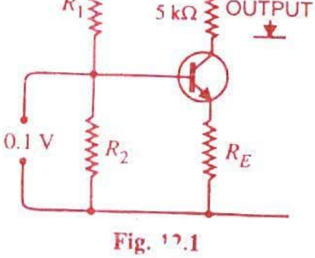

Fig. 12.1

Fig. 12.1 shows a single stage transistor amplifier. When a weak a.c. signal is given to the base of transistor, a small base current (which is a.c.) starts flowing. Due to transistor action, a much larger (β times the base current) a.c. current flows through the collector load R_C. As the value of R_C is quite high (usually 4-10 kΩ), therefore, a large voltage appears across R_C. Thus, a weak signal applied in the base circuit appears in amplified form in the collector circuit. It is in this way that a transistor acts as an amplifier.

The action of transistor amplifier can be beautifully explained by referring to Fig. 12.1. Suppose a change of 0.1V in signal voltage produces a change of 2 mA in the collector current. Obviously, a signal of only 0.1V applied to the base will give an output voltage = 2 mA × 5 kΩ = 10V. Thus, the transistor has been able to raise the voltage level of the signal from 0.1V to 10V *i.e.* voltage amplification or stage gain is 100.

12.3 Graphical Demonstration of Transistor Amplifier

The function of transistor as an amplifier can also be explained graphically. Fig. 12.2 shows the output characteristics of a transistor in *CE* configuration. Suppose the zero signal base current is 10 μA *i.e.* this is the base current for which the transistor is biased by the biasing network. When an a.c. signal is applied to the base, it makes the base, say positive in the first half-cycle and negative in the second half-cycle. Therefore, the base and collector currents will increase in the first half-cycle when base-emitter junction is more forward-biased. However, they will decrease in the second half-cycle when the base-emitter junction is less forward biased.

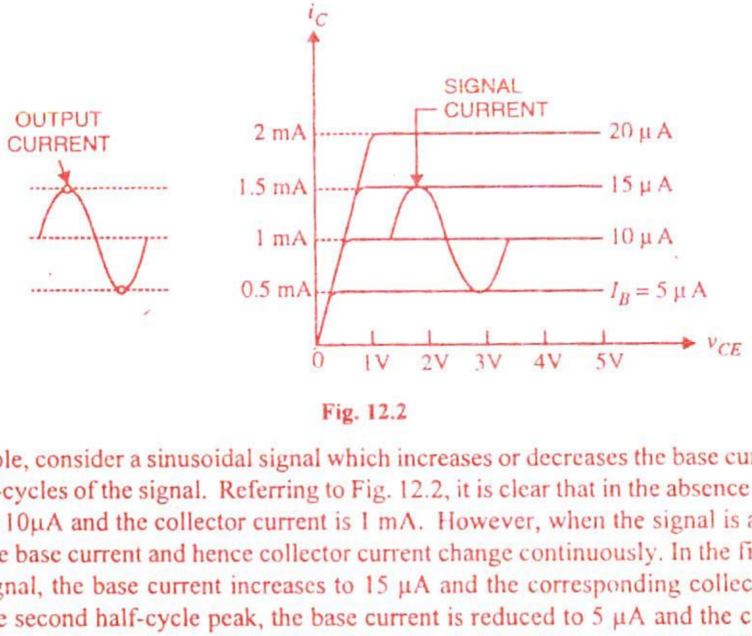

Fig. 12.2

For example, consider a sinusoidal signal which increases or decreases the base current by 5 μA in the two half-cycles of the signal. Referring to Fig. 12.2, it is clear that in the absence of signal, the base current is 10μA and the collector current is 1 mA. However, when the signal is applied in the base circuit, the base current and hence collector current change continuously. In the first half-cycle peak of the signal, the base current increases to 15 μA and the corresponding collector current is 1.5 mA. In the second half-cycle peak, the base current is reduced to 5 μA and the corresponding collector current is 0.5 mA. For other values of the signal, the collector current is inbetween these values *i.e.* 1.5 mA and 0.5 mA.

It is clear from Fig. 12.2 that 10 μA base current variation results in 1mA (1,000 μA) collector current variation *i.e.* by a factor of 100. This large change in collector current flows through collector resistance R_C. The result is that output signal is much larger than the input signal. Thus, the transistor has done amplification.

12.4 Practical Circuit of Transistor Amplifier

It is important to note that a transistor can accomplish faithful amplification only if proper associated circuitry is used with it. Fig. 12.3 shows a practical single stage transistor amplifier. The various circuit elements and their functions are described on the next page :

(*i*) **Biasing circuit.** The resistances R_1, R_2 and R_E form the biasing and stabilisation circuit. The biasing circuit must establish a proper operating point otherwise a part of the negative half-cycle of the signal may be cut off in the output.

(*ii*) **Input capacitor C_{in}.** An electrolytic capacitor C_{in} ($\simeq$ 10 μF) is used to couple the signal to the base of the transistor. If it is not used, the signal source resistance will come across R_2 and thus change the bias. The capacitor C_{in} allows only a.c. signal to flow but isolates the signal source from R_2.*

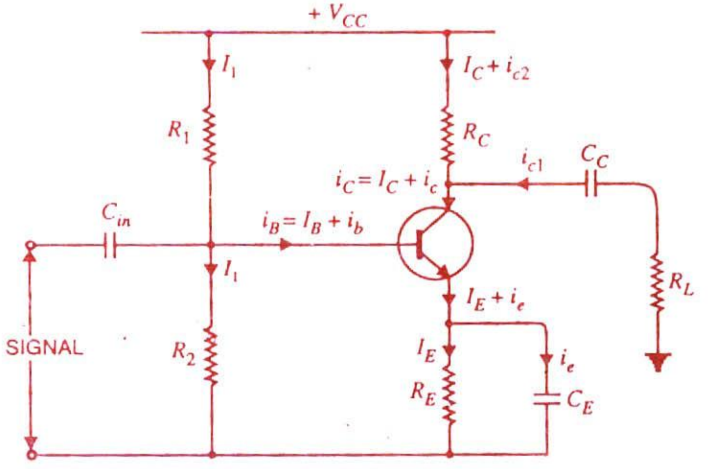

Fig. 12.3

(*iii*) **Emitter bypass capacitor C_E.** An emitter bypass capacitor C_E ($\simeq 100\mu F$) is used in parallel with R_E to provide a low reactance path to the amplified a.c. signal. If it is not used, then amplified a.c. signal flowing through R_E will cause a voltage drop across it, thereby reducing the output voltage.

(*iv*) **Coupling capacitor C_C.** The coupling capacitor C_C ($\simeq 10\mu F$) couples one stage of amplification to the next stage. If it is not used, the bias conditions of the next stage will be drastically changed due to the shunting effect of R_C. This is because R_C will come in parallel with the upper resistance R_1 of the biasing network of the next stage, thereby altering the biasing conditions of the latter. In short, the coupling capacitor C_C isolates the d.c. of one stage from the next stage, but allows the passage of a.c. signal.

Various circuit currents. It is useful to mention the various currents in the complete amplifier circuit. These are shown in the circuit of Fig. 12.3.

(*i*) **Base current.** When no signal is applied in the base circuit, d.c. base current I_B flows due to biasing circuit. When a.c. signal is applied, a.c. base current i_b also flows. Therefore, with the application of signal, total base current i_B is given by;

$$i_B = I_B + i_b$$

(*ii*) **Collector current.** When no signal is applied, a d.c. collector current I_C flows due to biasing circuit. When a.c. signal is applied, a.c. collector current i_c also flows. Therefore, the total collector current i_C is given by;

$$i_C = I_C + i_c$$

where $I_C = \beta I_B$ = zero signal collector current

* It may be noted that a capacitor offers infinite reactance to d.c. and blocks it completely whereas it allows a.c. to pass through it.

$$i_c = \beta\, i_b = \text{collector current due to signal.}$$

(*iii*) **Emitter current.** When no signal is applied, a d.c. emitter current I_E flows. With the application of signal, total emitter current i_E is given by ;

$$i_E = I_E + i_e$$

It is useful to keep in mind that :

$$I_E = I_B + I_C$$

$$i_e = i_b + i_c$$

Now base current is usually very small, therefore, as a reasonable approximation,

$$I_E \simeq I_C \quad \text{and} \quad i_e \simeq i_c$$

12.5 Phase Reversal

In common emitter connection, when the input signal voltage increases in the positive sense, the output voltage increases in the negative direction and *vice-versa*. In other words, there is a phase difference of 180° between the input and output voltage in *CE* connection. This is called phase reversal.*

The phase difference of 180° between the signal voltage and output voltage in a common emitter amplifier is known as **phase reversal.**

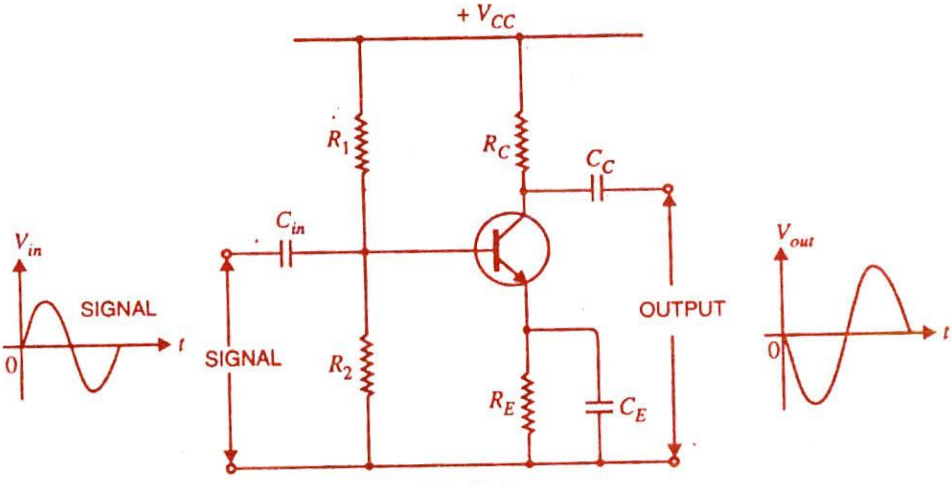

Fig. 12.4

Consider a common emitter amplifier circuit shown in Fig. 12.4. The signal is fed at the input terminals (*i.e.* between base and emitter) and output is taken from collector and emitter end of supply. The total instantaneous output voltage v_{CE} is given by;

$$^{**}v_{CE} = V_{CC} - i_C R_C \quad \text{...}(i)$$

When the signal voltage increases in the positive half-cycle, the base current also increases. The result is that collector current and hence voltage drop $i_C R_C$ increases. As V_{CC} is constant, therefore, output voltage v_{CE} decreases. In other words, as the signal voltage is increasing in the positive half-

---

* This is so if output is taken from collector and emitter end of supply as is always done. However, if the output is taken across R_C, it will be in phase with the input.

** Reactance of C_C (= 10μF) is negligible at ordinary signal frequencies. Therefore, it can be considered a short for the signal.

cycle, the output voltage is increasing in the negative sense *i.e.* output is 180° out of phase with the input. It follows, therefore, that in a common emitter amplifier, the positive half-cycle of the signal appears as amplified negative half-cycle in the output and *vice-versa*. It may be noted that amplification is not affected by this phase reversal.

The fact of phase reversal can be readily proved mathematically. Thus differentiating exp. (*i*), we get,

$$dv_{CE} = 0 - di_c R_C$$

or

$$dv_{CE} = -di_c R_C$$

The negative sign shows that output voltage is 180° out of phase with the input signal voltage.

Graphical demonstration. The fact of phase reversal in *CE* connection can be shown graphically with the help of output characteristics and load line (See Fig. 12.5).

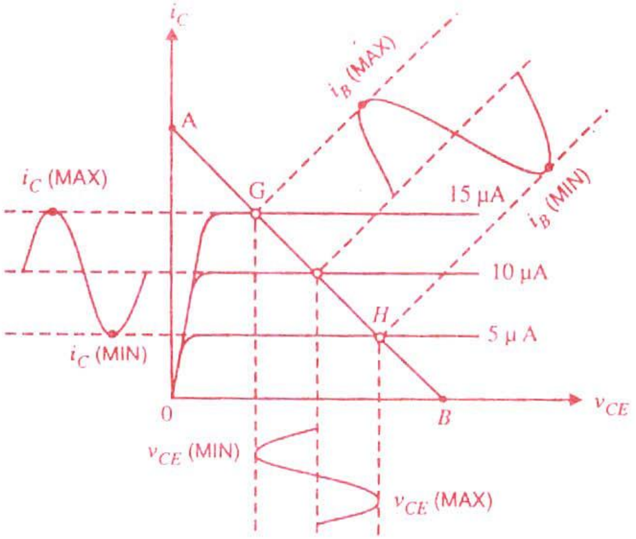

Fig. 12.5

In Fig. 12.5, *AB* is the load line. The base current fluctuates between, say ± 5 μA with 10μA as the zero signal base current. From the figure, it is clear that when the base current is maximum in the positive direction, v_{CE} becomes maximum in the negative direction (*point G* in Fig. 12.5). On the other hand, when the base current is maximum in the negative direction, v_{CE} is maximum in the positive sense (*point H* in Fig. 12.5). Thus, the input and output voltages are in *phase opposition* or equivalently, the transistor is said to produce a 180° phase reversal of output voltage *w.r.t.* signal voltage.

Note. No phase reversal of voltage occurs in common base and common collector amplifier. The a.c. output voltage is in phase with the a.c. input signal. For all three amplifier configurations; input and output currents are in phase.

Example 12.1. *Illustrate the phenomenon of phase reversal in CE amplifier assuming typical circuit values.*

Solution. In every type of amplifier, the input and output currents are in phase. However, common emitter amplifier has the unique property that input and output voltages are 180° out of phase, even though the input and output currents are in phase. This point is illustrated in Fig. 12.6.

Here it is assumed that Q-point value of $I_B = 10\ \mu A$, ac signal peak value is $5\ \mu A$ and $\beta = 100$. This means that input current varies by $5\ \mu A$ both above and below a $10\ \mu A$ dc level. At any instant, the output current will be 100 times the input current at that instant. Thus when the input current is $10\ \mu A$, output current is $i_C = 100 \times 10\ \mu A = 1$ mA. However, when the input current is $15\ \mu A$, then output current is $i_C = 100 \times 15\ \mu A = 1.5$ mA and so on. Note that input and output currents are in phase.

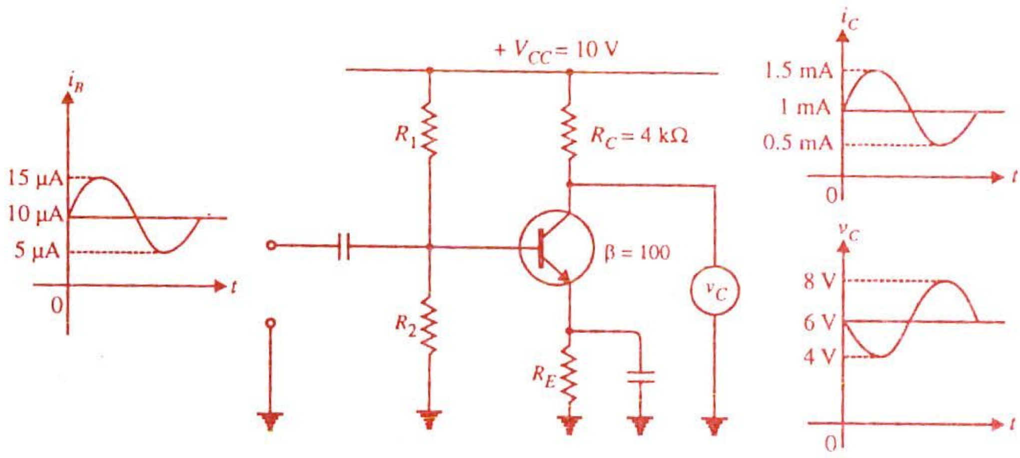

Fig. 12.6

The output voltage, $v_C = V_{CC} - i_C R_C$

(*i*) When signal current is zero (*i.e.*, in the absence of signal), $i_C = 1$ mA.

$\therefore \quad v_C = V_{CC} - i_C R_C = 10\text{ V} - 1\text{ mA} \times 4\text{ k}\Omega = 6\text{V}$

(*ii*) When signal reaches positive peak value, $i_C = 1.5$ mA.

$\therefore \quad v_C = V_{CC} - i_C R_C = 10\text{ V} - 1.5\text{ mA} \times 4\text{ k}\Omega = 4\text{ V}$

Note that as i_C increases from 1mA to 1.5 mA, v_C decreases from 6V to 4V. Clearly, output voltage is 180° out of phase from the input voltage as shown in Fig. 12.6.

(*iii*) When signal reaches negative peak, $i_C = 0.5$ mA.

$\therefore \quad v_C = V_{CC} - i_C R_C = 10\text{ V} - 0.5\text{ mA} \times 4\text{ k}\Omega = 8\text{ V}$

Note that as i_C decreases from 1.5 mA to 0.5 mA, v_C increases from 4 V to 8 V. Clearly, output voltage is 180° out of phase from the input voltage. The following points may be noted carefully about *CE* amplifier :

(*a*) The input voltage and input current are in phase.

(*b*) Since the input current and output current are in phase, input voltage and output current are in phase.

(*c*) Output current is 180° out of phase with the output voltage (v_C). *Therefore, input voltage and output voltage are 180° out of phase.*

12.6 D.C. And A.C. Equivalent Circuits

In a transistor amplifier, both d.c. and a.c. conditions prevail. The d.c. sources set up d.c. currents and voltages whereas the a.c. source (*i.e.* signal) produces fluctuations in the transistor currents and voltages. Therefore, a simple way to analyse the action of a transistor is to split the analysis into two parts *viz.* a d.c. analysis and an a.c. analysis. In the d.c. analysis, we consider all the d.c. sources at the same time and work out the d.c. currents and voltages in the circuit. On the other hand, for a.c. analysis, we consider all the a.c. sources at the same time and work out the a.c. currents and voltages. By adding the d.c. and a.c. currents and voltages, we get the total currents and voltages in the circuit. For example, consider the amplifier circuit shown in Fig. 12.7. This circuit can be easily analysed by splitting it into *d.c. equivalent circuit* and *a.c equivalent circuit.*

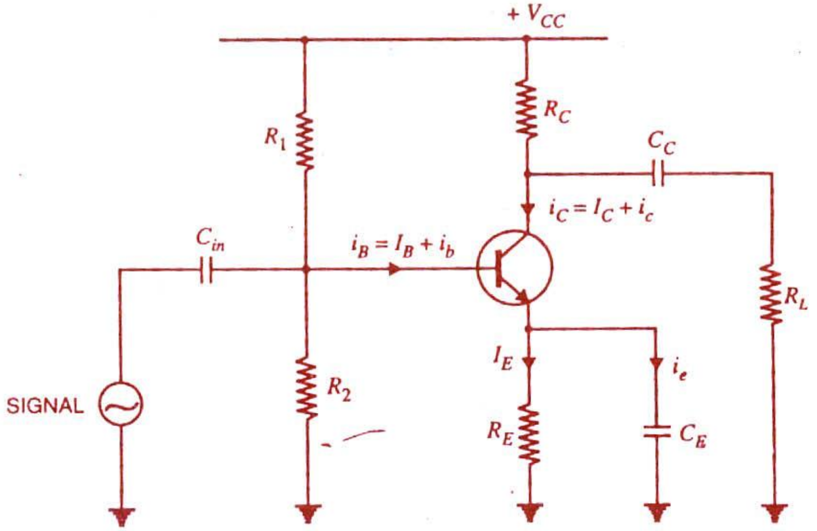

Fig. 12.7

(*i*) **D. C. equivalent circuit.** In the d.c. equivalent circuit of a transistor amplifier, only d.c. conditions are to be considered *i.e.* it is presumed that no signal is applied. As direct current cannot flow through a capacitor, therefore, *all the capacitors look like open circuits in the d.c. equivalent circuit.* It follows, therefore, that in order to draw the equivalent d.c. circuit, the following two steps are applied to the transistor circuit :

(*a*) Reduce all a.c. sources to zero.

(*b*) Open all the capacitors.

Applying these two steps to the circuit shown in Fig. 12.7, we get the d.c. equivalent circuit shown in Fig. 12.8. We can easily calculate the d.c. currents and voltages from this circuit.

Fig. 12.8

(*ii*) **A.C. equivalent circuit**. In the a.c. equivalent circuit of a transistor amplifier, only a.c. conditions are to be considered. Obviously, the d.c. voltage is not important for such a circuit and may be considered zero. The capacitors are generally used to couple or bypass the a.c. signal. The designer intentionally selects capacitors that are large enough to appear as *short* circuits to the a.c. signal. It follows, therefore, that in order to draw the a.c. equivalent circuit, the following two steps are applied to the transistor circuit :

(*a*) Reduce all d.c. sources to zero (*i.e.* $V_{CC} = 0$).

(*b*) Short all the capacitors.

Applying these two steps to the circuit shown in Fig. 12.7, we get the a.c. *equivalent circuit

* Note that R_1 is also in parallel with transistor input so far as signal is concerned. Since R_1 is connected from the base lead to V_{CC} and V_{CC} is at "ac ground", R_1 is effectively connected from the base lead to ground as far as signal is concerned.

shown in Fig. 12.9. We can easily calculate the a.c. currents and voltages from this circuit.

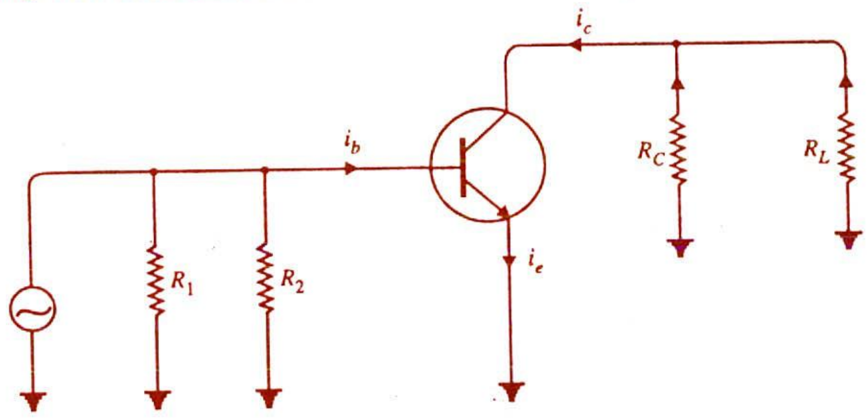

Fig. 12.9

It may be seen that total current in any branch is the sum of d.c. and a.c. currents through that branch. Similarly, the total voltage across any branch is the sum of d.c. and a.c. voltages across that branch.

Example 12.2. *For the transistor amplifier circuit shown in Fig. 12.7, determine :*

(i) d.c. load and a.c. load

(ii) maximum collector-emitter voltage and collector current under d.c. conditions

(iii) maximum collector-emitter voltage and collector current when a.c. signal is applied

Solution. Refer back to the transistor amplifier circuit shown in Fig. 12.7.

(*i*) The d.c. load for the transistor is Thevenin's equivalent resistance as seen by the collector and emitter terminals. Thus referring to the d.c. equivalent circuit shown in Fig. 12.8, Thevenin's equivalent resistance can be found by shorting the voltage source (*i.e.* V_{CC}) as shown in Fig. 12.10.

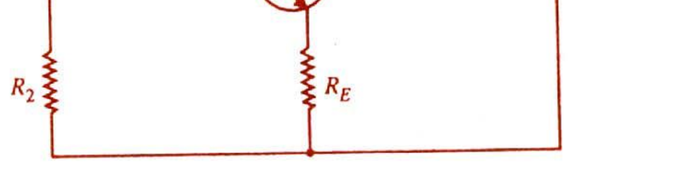

Fig. 12.10

Because a voltage source looks like a short, it will bypass all other resistances except R_C and R_E which will appear in series. Consequently, transistor amplifier will see a d.c. load of $R_C + R_E$ *i.e.*

$$\text{d.c. load} = \boldsymbol{R_C + R_E}$$

Referring to the a.c. equivalent circuit shown in Fig. 12.9, it is clear that as far as a.c. signal is concerned, resistance R_C appears in parallel with R_L. In other words, transistor amplifier sees an a.c. load equal to $R_C \parallel R_L$ *i.e.*

$$\text{a.c. load, } R_{AC} = R_C \parallel R_L = \frac{R_C\, R_L}{R_C + R_L}$$

(*ii*) Referring to d.c. equivalent circuit of Fig. 12.8,

$$V_{CC} = V_{CE} + I_C (R_C + R_E)$$

The maximum value of V_{CE} will occur when there is no collector current *i.e.* $I_C = 0$.

$$\therefore \quad \text{Maximum } V_{CE} = V_{CC}$$

The maximum collector current will flow when $V_{CE} = 0$.

$$\therefore \quad \text{Maximum } I_C = \frac{V_{CC}}{R_C + R_E}$$

(*iii*) When no signal is applied, V_{CE} and I_C are the collector-emitter voltage and collector current respectively. When a.c. signal is applied, it causes changes to take place above and below the operating point Q (*i.e.* V_{CE} and I_C).

Maximum collector current due to a.c. signal = *I_C

∴ Maximum positive swing of a.c. collector-emitter voltage

$$= I_C \times R_{AC}$$

Total maximum collector-emitter voltage

$$= V_{CE} + I_C R_{AC}$$

Maximum positive swing of a.c. collector current

$$= V_{CE}/R_{AC}$$

∴ Total maximum collector current

$$= I_C + V_{CE}/R_{AC}$$

12.7 Load Line Analysis

The output characteristics are determined experimentally and indicate the relation between V_{CE} and I_C. However, the same information can be obtained in a much simpler way by representing the mathematical relation between I_C and V_{CE} graphically. As discussed before, the relationship between V_{CE} and I_C is linear so that it can be represented by a straight line on the output characteristics. This is known as a *load line*. The points lying on the load line give the possible values of V_{CE} and I_C in the output circuit. As in a transistor circuit both d.c. and a.c. conditions exist, therefore, there are two types of load lines, namely ; d.c. load line and a.c. load line. The former determines the locus of I_C and V_{CE} in the zero signal conditions and the latter shows these values when the signal is applied.

(*i*) **d.c. load line.** *It is the line on the output characteristics of a transistor circuit which gives the values of I_C and V_{CE} corresponding to zero signal or d.c. conditions.*

Consider the transistor amplifier shown in Fig. 12.11. In the absence of signal, d.c. conditions prevail in the circuit as shown in Fig. 12.12 (*i*). Referring to this circuit and applying Kirchhoff's voltage law,

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

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* For faithful amplification.

or $$V_{CE} = V_{CC} - I_C (R_C + R_E) \quad ...(i)$$
$(\because I_E \simeq I_C)$

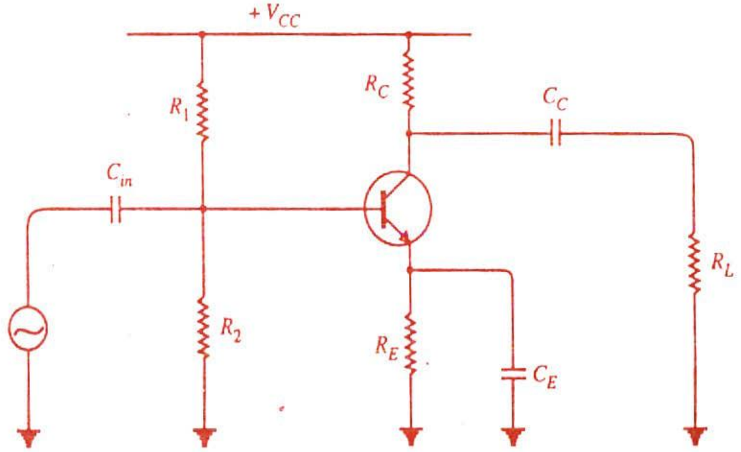


Fig 12.11

As for a given circuit, V_{CC} and $(R_C + R_E)$ are constant, therefore, it is a first degree *equation and can be represented by a straight line on the output characteristics. This is known as *d.c. load line* and determines the locus of V_{CE} and I_C points in the zero signal conditions. The d.c. load line can be readily plotted by locating two *end points* of the straight line.

The value of V_{CE} will be maximum when $I_C = 0$. Therefore, by putting $I_C = 0$ in exp. (*i*), we get,

$$\text{Max. } V_{CE} = V_{CC}$$

This locates the first point B ($OB = V_{CC}$) of the d.c. load line.

The value of I_C will be maximum when $V_{CE} = 0$.

$$\therefore \quad \text{Max. } I_C = \frac{V_{CC}}{R_C + R_E}$$

This locates the second point A ($OA = V_{CC}/R_C + R_E$) of the d.c. load line. By joining points A and B, d.c. load line AB is constructed [See Fig. 12.1 (*ii*)].

Alternatively. The two end points of the d.c. load line can also be determined in another way.

$$V_{CE} + I_C (R_C + R_E) = V_{CC}$$

Dividing throughout by V_{CC}, we have,

$$\frac{V_{CE}}{V_{CC}} + \frac{I_C}{(V_{CC} / R_C + R_E)} = 1 \quad ...(i)$$

The equation of a line having intercepts a and b on x-axis and y-axis respectively is given by ;

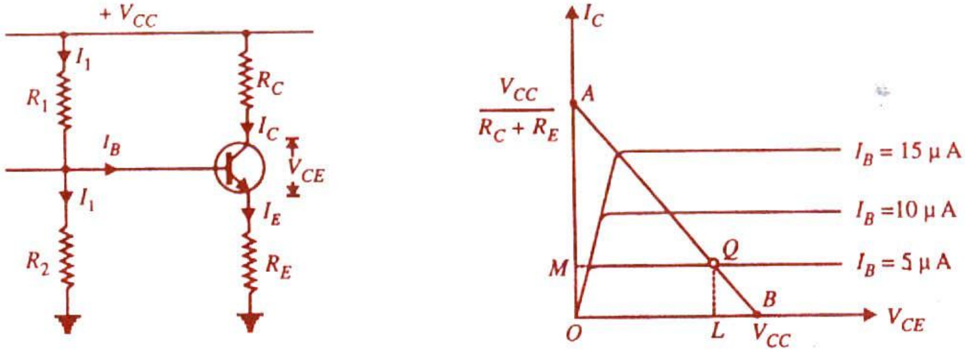
$$\frac{x}{a} + \frac{y}{b} = 1 \quad ...(ii)$$

Comparing eqs. (*i*) and (*ii*), we have,

$$\text{Intercept on } x\text{-axis} = V_{CC}$$

* This equation is known as **load line equation** since it relates the collector-emitter voltage (V_{CE}) to the collector current (I_C) flowing through the load.

$$\text{Intercept on } y\text{-axis} = \frac{V_{CC}}{R_C + R_E}$$



(*i*) (*ii*)

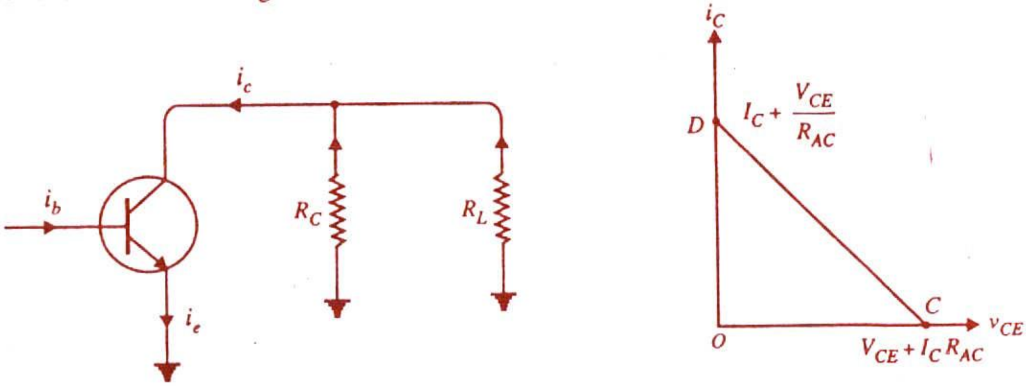
Fig. 12.12

With the construction of d.c. load line on the output characteristics, we get the complete information about the output circuit of transistor amplifier in the zero signal conditions. All the points showing zero signal I_C and V_{CE} will obviously lie on the d.c. load line. At the same time I_C and V_{CE} conditions in the circuit are also represented by the output characteristics. Therefore, actual operating conditions in the circuit will be represented by the point where d.c. load line intersects the base current curve under study. Thus, referring to Fig. 12.12 (*ii*), if $I_B = 5\ \mu A$ is set by the biasing circuit, then Q (*i.e.* intersection of 5 μA curve and load line) is the operating point.

(*ii*) **a.c. load line.** *This is the line on the output characteristics of a transistor circuit which gives the values of* i_C *and* v_{CE} *when signal is applied.*

Referring back to the transistor amplifier shown in Fig. 12.11, its a.c. equivalent circuit as far as output circuit is concerned is as shown in Fig. 12.13 (*i*). To add a.c. load line to the output characteristics, we again require two end points–one maximum collector-emitter voltage point and the other maximum collector current point. Under the application of a.c. signal, these values are (refer to example 12.2) :

Max. collector-emitter voltage $= V_{CE} + I_C R_{AC}$. This locates the point C of the a.c. load line on the collector-emitter voltage axis.



(*i*) (*ii*)

Fig. 12.13

Maximum collector current $= I_C + \dfrac{V_{CE}}{R_{AC}}$

where $R_{AC} = R_C \parallel R_L = \dfrac{R_C R_L}{R_C + R_L}$

This locates the point *D* of a.c. load line on the collector-current axis. By joining points *C* and *D*, the a.c.load line *CD* is constructed [See Fig. 12.13 (*ii*)].

Example 12.3. *For the transistor amplifier shown in Fig. 12.14, R_1 = 10 kΩ, R_2 = 5 kΩ, R_C = 1 kΩ, R_E = 2 kΩ and R_L = 1 kΩ.*

(i) Draw d.c. load line (ii) Determine the operating point (iii) Draw a.c. load line. Assume V_{BE} = 0.7 V.

Solution. (*i*) **d.c. load line :**

To draw d.c. load line, we require two end points *viz* maximum V_{CE} point and maximum I_C point.

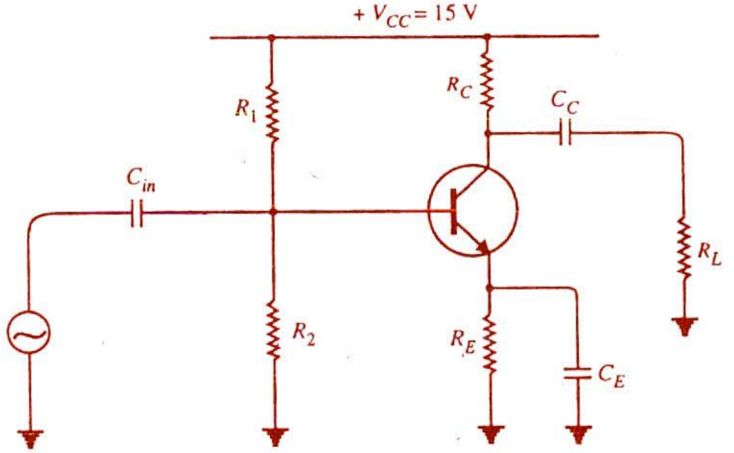


Fig. 12.14

Maximum V_{CE} = V_{CC} = 15 V [See Art. 12.7]

This locates the point *B* (*OB* = 15 V) of the d.c. load line.

Maximum $I_C = \dfrac{V_{CC}}{R_C + R_E} = \dfrac{15\,V}{(1+2)\,k\Omega} = 5$ mA [See Art. 12.7]

This locates the point *A* (*OA* = 5 mA) of the d.c. load line. Fig. 12.15 (*i*) shows the d.c. load line *AB*.

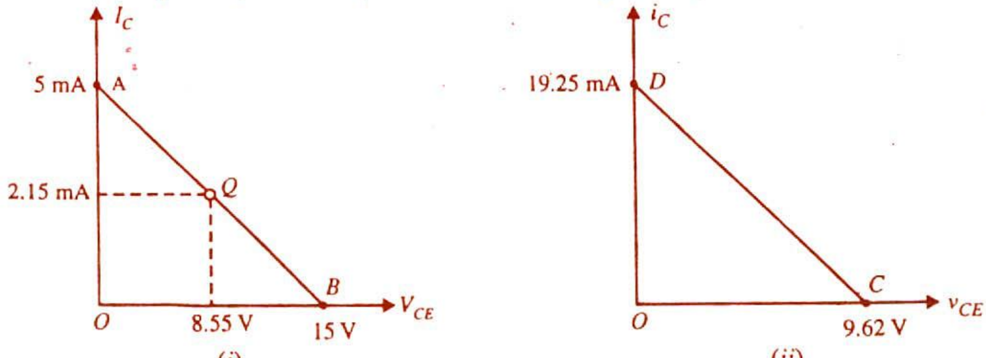


Fig. 12.15

(*ii*) **Operating point Q.** The voltage across R_2 (= 5 kΩ,) is *5 V *i.e.* V_2 = 5 V.

Now $$V_2 = V_{BE} + I_E R_E$$

∴ $$I_E = \frac{V_2 - V_{BE}}{R_E} = \frac{(5-0.7)\,V}{2\text{ k}\Omega} = 2.15\text{ mA}$$

∴ $$I_C = I_E = 2.15\text{ mA}$$

Now $$V_{CE} = V_{CC} - I_C(R_C + R_E) = 15 - 2.15\text{ mA} \times 3\text{ k}\Omega$$
$$= 8.55\text{ V}$$

∴ Operating point Q is **8.55 V, 2.15 mA.** This is shown on the d.c. load line.

(*iii*) **a.c. load line.** To draw a.c. load line, we require two end points *viz.* maximum collector-emitter voltage point and maximum collector current point when signal is applied.

$$\text{a.c. load, } R_{AC} = R_C \parallel R_L = \frac{1\times 1}{1+1} = 0.5\text{ k}\Omega$$

∴ Maximum collector-emitter voltage

$$= V_{CE} + i_C R_{AC}$$ [See example 12.2]

$$= 8.55 + 2.15\text{ mA} \times 0.5\text{ k}\Omega = 9.62\text{ volts}$$

This locates the point C (OC = 9.62 V) on the v_{CE} axis.

$$\text{Maximum collector current} = I_C + V_{CE}/R_{AC}$$
$$= 2.15 + (8.55\text{ V}/0.5\text{ k}\Omega) = 19.25\text{ mA}$$

This locates the point D (OD = 19 25mA) on the i_C axis. By joining points C and D, a.c. load line CD is constructed [See Fig. 12.15 (*ii*)].

Example 12.4. *In the transistor amplifier shown in Fig. 12.14, R_C = 10 kΩ, R_L = 30 kΩ and V_{CC} = 20V. The values R_1 and R_2 are such so as to fix the operating point at 10V, 1mA. Draw the d.c. and a.c. load lines. Assume R_E is negligible.*

Solution. d.c. load line. For drawing d.c. load line, two end points *viz.* maximum V_{CE} point and maximum I_C point are needed. Maximum V_{CE} = 20 V. This locates the point B (OB = 20V) of the d.c. load line on the V_{CE} axis.

$$\text{Maximum } I_C = \frac{V_{CC}}{R_C + R_E} = \frac{20\,V}{10\text{ k}\Omega} = 2\text{ mA}$$

This locates the point A (OA = 2 mA) on the I_C axis. By joining points A and B, the d.c. load line AB is constructed (See Fig. 12.16).

a.c. load line. To draw a.c. load line, we require two end points *viz* maximum collector-emitter voltage point and maximum collector current point when signal is applied.

$$\text{a.c. load, } R_{AC} = R_C \parallel R_L = \frac{10\times 30}{10+30} = 7.5\text{ k}\Omega$$

Maximum collector-emitter voltage

$$= V_{CE} + I_C R_{AC}$$
$$= 10 + 1\text{ mA} \times 7.5\text{ k}\Omega = 10 + 7.5 = 17.5\text{ V}$$

This locates the point D (OD = 17.5 V) on the v_{CE} axis.

---

* Voltage across series combination of R_1 and R_2 is 15 V. Applying voltage divider theorem, voltage across R_2 = 5 V.

Maximum collector current = $I_C + V_{CE}/R_{AC}$

$$= 1 \text{ mA} + 10 \text{ V}/7.5 \text{ k}\Omega = 1 \text{ mA} + 1.33 \text{ mA} = 2.33 \text{ mA}$$

This locates the point C (OC = 2.33 mA) on the i_C axis. By joining points C and D, a.c. load line CD is constructed (See Fig. 12.16).

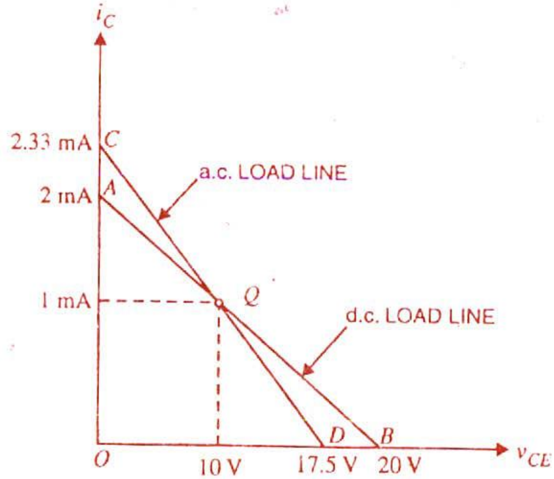


Fig. 12.16

Comments. The reader may see that the operating point lies on both a.c. and d.c. load lines. It is not surprising because signal is a.c. and it becomes zero after every half-cycle. When the signal is zero, we have the exact d.c. conditions. Therefore, key point to keep in mind is that the point of intersection of d.c. and a.c. load lines is the operating point Q.

Example 12.5. *In a transistor amplifier, the operating point Q is fixed at 8V, 1mA. When a.c. signal is applied, the collector current and collector-emitter voltage change about this point. During the positive peak of signal,* i_C = *1.5 mA and* v_{CE} = *7 V and during negative peak,* i_C = *0.5mA and* v_{CE} = *9V. Show this phenomenon with the help of a.c. load line.*

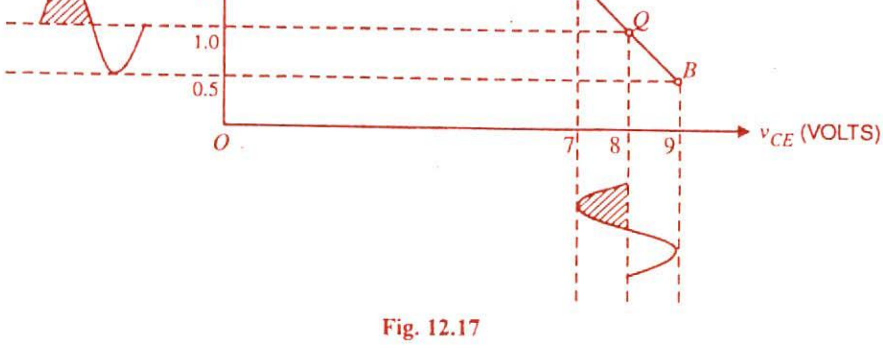


Fig. 12.17

Solution. Fig. 12.17 shows the whole process. When no signal is applied, v_{CE} = 8 V and i_C = 1mA. This is represented by the operating point Q on the a.c. load line. During the positive half-cycle of a.c. signal, i_C swings from 1 mA to 1.5 mA and v_{CE} swings from 8 V to 7 V. This is represented by point A on the a.c. load line. During the negative half-cycle of the signal, i_C swings from 1 mA to 0.5 mA and v_{CE} swings from 8 V to 9 V. This is represented by the point B on the a.c. load line.

The following points may be noted :

(*i*) When a.c. signal is applied, the collector current and collector-emitter voltage variations take place about the operating point Q.

(*ii*) When a.c. signal is applied, operating point moves along the a.c. load line. In other words, at any instant of a.c. signal, the co-ordinates of collector current and collector-emitter voltage are on the a.c. load line.

12.8 Voltage Gain

The basic function of an amplifier is to raise the strength of an a.c. input signal. The voltage gain of the amplifier is the ratio of a.c. output voltage to the a.c. input signal voltage. Therefore, in order to find the voltage gain, we should consider only the a.c. currents and voltages in the circuit. For this purpose, we should look at the a.c. equivalent circuit of transistor amplifier. For facility of reference,the a.c. equivalent circuit of transistor amplifier is redrawn in Fig. 12.18.

It is clear that as far as a.c. signal is concerned, load R_C appears in parallel with R_L. Therefore, effective load for a.c. is given by ;

$$\text{a.c. load, } R_{AC} = R_C \parallel R_L = \frac{R_C \times R_L}{R_C + R_L}$$

$$\text{Output voltage, } V_{out} = i_c R_{AC}$$

$$\text{Input voltage, } V_{in} = i_b R_{in}$$

$$\therefore \quad \text{Voltage gain, } A_v = V_{out}/V_{in}$$

$$= \frac{i_c R_{AC}}{i_b R_{in}} = \beta \times \frac{R_{AC}}{R_{in}} \qquad \left(\because \frac{i_c}{i_b} = \beta\right)$$

Incidentally, power gain is given by;

$$A_p = \frac{i_c^2 R_{AC}}{i_b^2 R_{in}} = \beta^2 \times \frac{R_{AC}}{R_{in}}$$

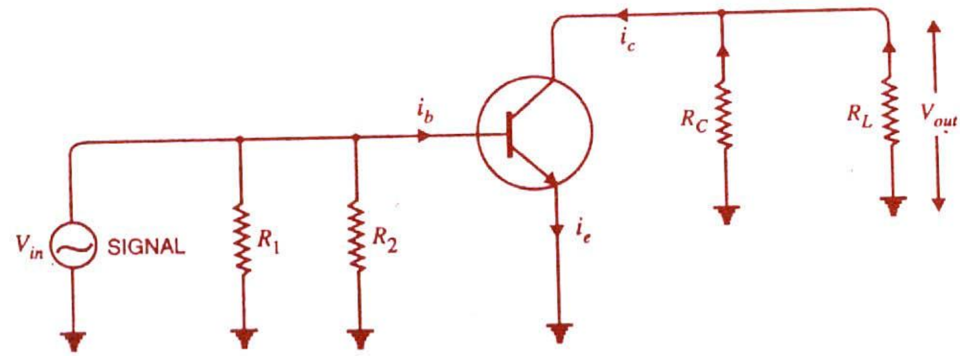


Fig. 12.18

Example 12.6. *In the circuit shown in Fig. 12.19, find the voltage gain. Given that $\beta = 60$ and input resistance $R_{in} = 1\ k\Omega$.*

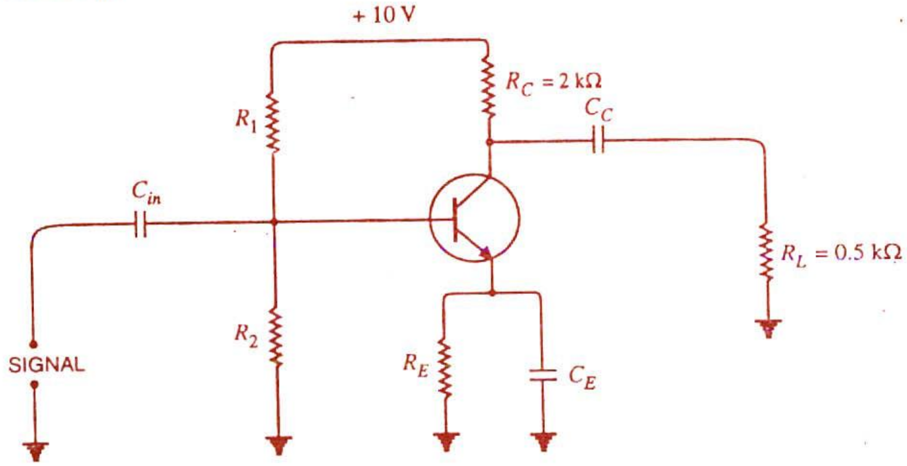


Fig. 12.19

Solution. So far as voltage gain of the circuit is concerned, we need only R_{AC}, β and R_{in}.

$$\text{Effective load, } R_{AC} = R_C \parallel R_L$$

$$= \frac{R_C \times R_L}{R_C + R_L} = \frac{2 \times 0.5}{2 + 0.5} = 0.4\ k\Omega$$

$$\text{Voltage gain} = \beta \times \frac{R_{AC}}{R_{in}} = \frac{6 \times 0.4\ k\Omega}{1\ k\Omega} = \mathbf{24}$$

Example 12.7. *In the circuit shown in Fig. 12.19, if $R_C = 10\ k\Omega$, $R_L = 10\ k\Omega$, $R_{in} = 2.5\ k\Omega$, $\beta = 100$, find the output voltage for an input voltage of 1mV r.m.s.*

Solution. Effective load, $R_{AC} = \frac{R_C \times R_L}{R_C + R_L} = \frac{10 \times 10}{10 + 10} = 5\ k\Omega$

$$\text{Voltage gain} = \beta \times \frac{R_{AC}}{R_{in}} = 100 \times \frac{5\ k\Omega}{2.5\ k\Omega} = 200$$

or
$$\frac{V_{out}}{V_{in}} = 200$$

$\therefore$
$$V_{out} = 200 \times V_{in} = 200 \times 1\ \text{mV} = \mathbf{200\ mV}$$

Example 12.8. *In a transistor amplifier, when the signal changes by 0.02V, the base current changes by 10 μA and collector current by 1mA. If collector load $R_C = 5\ k\Omega$ and $R_L = 10\ k\Omega$, find: (i) current gain (ii) input impedance (iii) a.c. load (iv) voltage gain (v) power gain.*

Solution. $\Delta I_B = 10\ \mu A$, $\Delta I_C = 1mA$, $\Delta V_{BE} = 0.02\ V$, $R_C = 5\ k\Omega$, $R_L = 10\ k\Omega$

(i) Current gain, $\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{1\ mA}{10\ \mu A} = \mathbf{100}$

(*ii*) Input impedance, $R_{in} = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{0.02\ V}{10\ \mu A}$ $= \mathbf{2\ k\Omega}$

(*iii*) a.c. load, $R_{AC} = \frac{R_C \times R_L}{R_C + R_L} = \frac{5 \times 10}{5 + 10}$ $= \mathbf{3.3\ k\Omega}$

(*iv*) Voltage gain, $A_v = \beta \times \frac{R_{AC}}{R_{in}} = 100 \times \frac{3.3}{2}$ $= \mathbf{165}$

(*v*) Power gain, A_p = current gain × voltage gain = 100 × 165 = **16500**

Example 12.9. *In Fig. 12.20, the transistor has β = 50. Find the output voltage if input resistance R_{in} = 0.5 kΩ.*

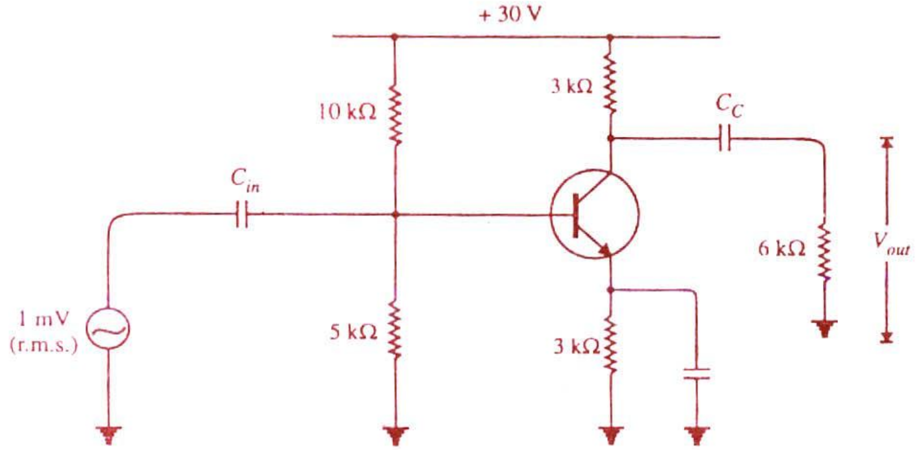


Fig. 12.20

Solution. $\beta = 50, \quad R_{in} = 0.5\ k\Omega$

$$\text{a.c. load, } R_{AC} = R_C \parallel R_L = \frac{R_C \times R_L}{R_C + R_L} = \frac{3 \times 6}{3 + 6} = 2\ k\Omega$$

∴ $$\text{Voltage gain} = \beta \times R_{AC}/R_{in} = 50 \times 2/0.5 = 200$$

or $$\frac{V_{out}}{V_{in}} = 200$$

∴ Output voltage, $V_{out} = 200 \times V_{in} = 200 \times (1\ mV) =$ **200 mV**

Example 12.10. *Fig. 12.21 shows a transistor circuit. The manufacturer of the circuit shows that collector potential is to be + 6V. The voltage measured at point B by a technician is found to be + 4V. Is the circuit operating properly ?*

Solution. The voltage at point *B* is equal to the voltage across R_1. Now total voltage V_T across the series combination of R_1 and R_2 is 6 V. Therefore, using voltage divider method, we have,

$$V_B = \text{Voltage across } R_1$$

$$= \frac{R_1}{R_1 + R_2} \times V_T = \frac{1}{1 + 2} \times 6 = 2\ V$$

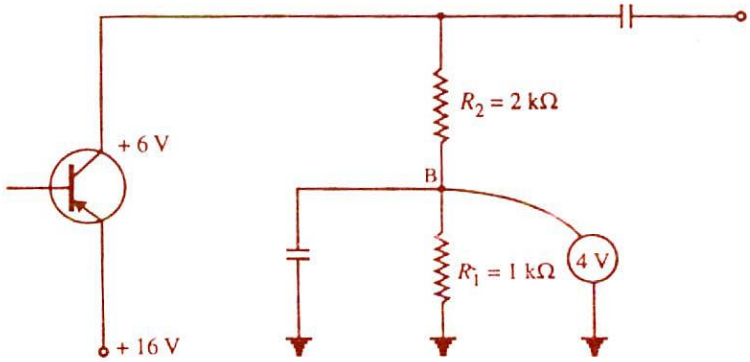


Fig. 12.21

The circuit is not operating properly. It is because the voltage at point B should be 2 V instead of 4 V.

12.9 A.C. Emitter Resistance

The ac or dynamic resistance of emitter-base junction diode of a transistor is called ac emitter resistance. It is defined as the change in base-emitter voltage divided by change in corresponding emitter current [See Fig. 12.22] *i.e.*

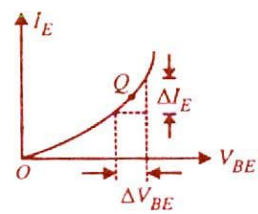


Fig. 12.22

$$R_{ac} = \frac{\Delta V_{BE}}{\Delta I_E}$$

For instance, suppose an ac base voltage change of 1 mV produces an ac emitter current change of 50 μA. Then emitter diode has an ac resistance of

$$R_{ac} = \frac{1\ mV}{50\ \mu A} = 20\ \Omega$$

12.10 Formula For AC Emitter Resistance

It can be shown mathematically that the ac resistance of emitter diode is given by ;

$$R_{ac} = \frac{25\ mV}{I_E}$$

where I_E = dc emitter current (= V_E/R_E) at Q point

Note the significance of this formula. It implies that ac emitter resistance can be found simply by substituting the quiescent value of emitter current into the equation. There is no need to have the characteristics available. It is important to keep in mind that this formula is accurate only for small signal operation. It is a usual practice to represent ac emitter resistance by r_e'.

$$\therefore \quad r_e' = \frac{25\ mV}{I_E}$$

The subscript e indicates emitter. The lower case r is used to indicate an ac resistance. The prime shows that it is an internal resistance.

Example 12.11. *Determine the ac emitter resistance for the transistor circuit shown in Fig. 12.23.*

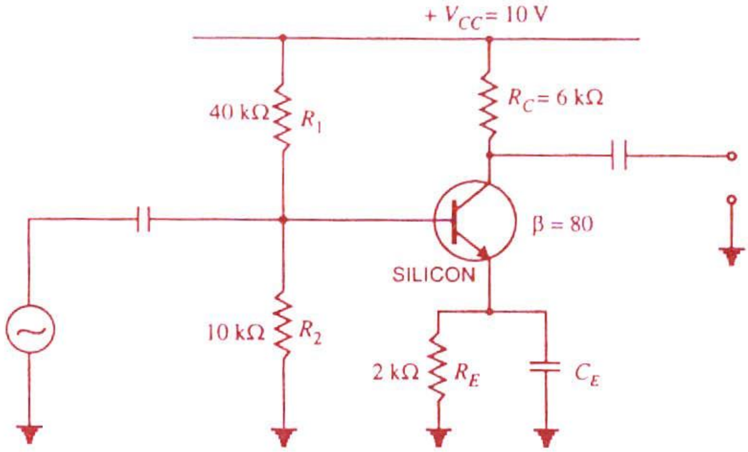


Fig. 12.23

Solution. Voltage across R_2, $V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{10}{40 + 10} \times 10 = 2$ V

Voltage across R_E, $V_E = V_2 - V_{BE} = 2 - 0.7 = 1.3$ V

Emitter current, $I_E = \frac{V_E}{R_E} = \frac{1.3\,V}{2\,k\Omega} = 0.65$ mA

$\therefore$ *AC* emitter resistance, $r_e' = \frac{25\,mV}{I_E} = \frac{25\,mV}{0.65\,mA} = \mathbf{38.46\,\Omega}$

12.11 Voltage Gain in terms of AC Emitter Resistance

It can be shown that for a common-emitter amplifier, the voltage gain is equal to the ratio of total *ac* collector resistance to total *ac* emitter resistance. Thus for the transistor amplifier shown in Fig. 12.24,

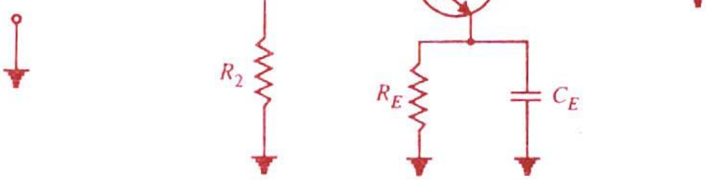


Fig. 12.24

Voltage gain, $A_v = \frac{R_C}{r_e'}$

where R_C = ac collector resistance

r_e' = ac emitter resistance = 25 mV/I_E

Derivation. Fig. 12.24 shows the common emitter amplifier. The ac equivalent circuit of the amplifier is shown in Fig. 12.25. (*i*). Replacing the transistor by its *equivalent circuit, we get the circuit shown in Fig. 12.25 (*ii*). Note that current source is still connected between the collector and base terminals while the diode between the base and emitter terminals. Further, the input current is the base current (i_b) while the output current is still i_c.

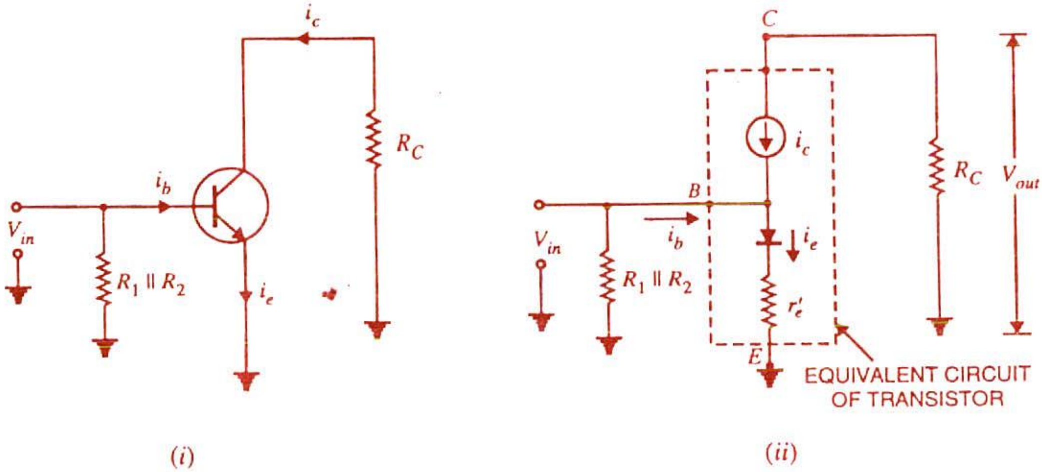


Fig. 12.25

Note that input voltage (V_{in}) is applied across the diode and r_e'. Assuming the diode to be ideal, the *ac* emitter current is given by;

$$i_e = \frac{V_{in}}{r_e'}$$

or $$V_{in} = i_e r_e' \quad ...(i)$$

Assuming $i_c = i_e$, we have,

$$V_{out} = i_e R_C$$

$\therefore$ $$\text{Voltage gain, } A_v = \frac{V_{out}}{V_{in}} = \frac{i_e R_C}{i_e r_e'} = \frac{R_C}{r_e'}$$

or $$A_v = \frac{R_C}{r_e'}$$

Example 12.12. *In the amplifier circuit shown in Fig. 12.24, R_1 = 150 kΩ, R_2 = 20 kΩ, R_C = 12 kΩ, R_E = 2.2 kΩ, V_{CC} = 20 V and β = 200. Determine the voltage gain of the amplifier.*

Solution. $$\text{Voltage gain, } A_v = \frac{R_C}{r_e'}$$

---

* The transistor equivalent circuit contains three components *viz.*,

(*i*) A resistor r_e' which represents ac emitter resistance.

(*ii*) A diode which represents the emitter-base junction of the transistor.

(*iii*) A current source which represents the current being supplied to R_C from the collector of the transistor.

where $$r_e' = \frac{25\ mV}{I_E}$$

In order to find I_E, we shall proceed as under :

$$\text{Voltage across } R_2,\ V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{20}{150 + 20} \times 20 = 2.35\ \text{V}$$

$$\text{Voltage across } R_E,\ V_E = V_2 - V_{BE} = 2.35 - 0.7 = 1.65\ \text{V}$$

$$\therefore \quad \text{Emitter current, } I_E = \frac{V_E}{R_E} = \frac{1.65\ V}{2.2\ \text{k}\Omega} = 0.75\ \text{mA}$$

$$\therefore \quad \text{AC emitter resistance, } r_e' = \frac{25\ \text{mV}}{I_E} = \frac{25\ \text{mV}}{0.75\ \text{mA}} = 33.3\ \Omega$$

$$\therefore \quad \text{Voltage gain, } A_v = \frac{R_C}{r_e'} = \frac{12\ \text{k}\Omega}{33.3\ \Omega} = \mathbf{360}$$

Example 12.13. *If in the above example, a load of 6 kΩ is connected to the collector terminal through a capacitor, what will be the voltage gain of the amplifier?*

Solution. Amplifiers are used to provide ac power to the load. When load R_L is connected to the collector terminal through a capacitor, the total ac resistance of collector changes to :

$$R_{AC} = R_C \parallel R_L = 12\ \text{k}\Omega \parallel 6\ \text{k}\Omega = \frac{12 \times 6}{12 + 6} = 4\ \text{k}\Omega\ .$$

The value of ac emitter resistance remains the same.

$$\therefore \quad \text{Voltage gain, } A_v = \frac{R_{AC}}{r_e'} = \frac{4\ \text{k}\Omega}{33.3\ \Omega} = \mathbf{120}$$

Thus voltage gain of the amplifier is reduced from 360 to 120 when load is connected to the circuit.

12.12 Input Impedance of An Amplifier

When one CE amplifier is being used to drive another, the input impedance of the second amplifier will serve as the load resistance of the first. Therefore, in order to calculate the voltage gain (A_v) of the first amplifier stage correctly, we must calculate the input impedance of the second stage.

The input impedance of an amplifier can be found by using the ac equivalent circuit of the amplifier as shown in Fig. 12.26.

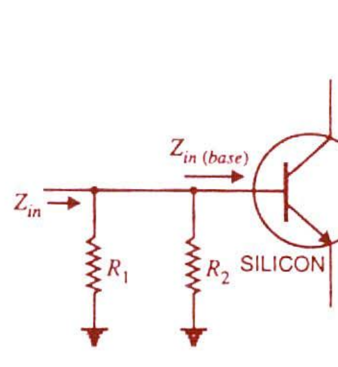


Fig. 12.26

$$Z_{in} = R_1 \parallel R_2 \parallel Z_{in\ (base)}$$

where Z_{in} = input impedance of the amplifier

$Z_{in\ (base)}$ = input impedance of transistor base

Now $Z_{in\ (base)}$ = *$\beta\, r_e'$

The input impedance [Z_{in}] is always less than the input impedance of the base [$Z_{in(base)}$].

* $Z_{in(base)} = \frac{V_{in}}{i_b} = \frac{i_e r_e'}{i_b}$. Since $\frac{i_e}{i_b}$ is approximately equal to β, $Z_{in\ (base)} = \beta\, r_e'$.

Example 12.14. *Determine the input impedance of the amplifier circuit shown in Fig. 12.27.*

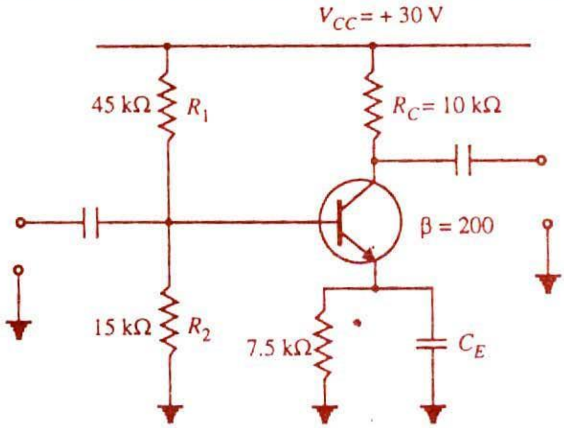


Fig. 12.27

Solution. Voltage across R_2,
$$V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{30}{45+15} \times 15 = 7.5 \text{ V}$$

$$\text{Voltage across } R_E,\ V_E = V_2 - V_{BE} = 7.5 - 0.7 \simeq 7.5 \text{ V}$$

$$\text{Emitter current, } I_E = \frac{V_E}{R_E} = \frac{7.5 \text{ V}}{7.5 \text{ k}\Omega} = 1 \text{ mA}$$

$$\text{AC emitter resistance, } r'_e = 25 \text{ mV}/I_E = 25 \text{ mV}/1 \text{ mA} = 25\ \Omega$$

$$Z_{in\,(base)} = \beta\, r'_e = 200 \times 25 = 5 \times 10^3\ \Omega = 5 \text{ k}\Omega$$

$$Z_{in} = R_1 \parallel R_2 \parallel Z_{in\,(base)}$$
$$= 45 \text{ k}\Omega \parallel 15 \text{ k}\Omega \parallel 5 \text{ k}\Omega = \mathbf{3.45\ k\Omega}$$

12.13. Classification Of Amplifiers

The transistor amplifiers may be classified as to their *usage, frequency capabilities, coupling methods and mode of operation.*

(*i*) *According to use.* The classifications of amplifiers as to usage are basically *voltage amplifiers* and *power amplifiers.* The former primarily increases the voltage level of the signal whereas the latter mainly increases the power level of the signal.

(*ii*) *According to frequency capabilities.* According to frequency capabilities, amplifiers are classified as *audio amplifiers, radio frequency amplifiers* etc. The former are used to amplify the signals lying in the audio range *i.e.* 20 Hz to 20 kHz whereas the latter are used to amplify signals having very high frequency.

(*iii*) *According to coupling methods.* The output from a single stage amplifier is usually insufficient to meet the practical requirements. Additional amplification is often necessary. To do this, the output of one stage is coupled to the next stage. Depending upon the coupling device used, the amplifiers are classified as *R-C coupled amplifiers, transformer coupled amplifiers* etc.

(*iv*) *According to mode of operation.* The amplifiers are frequently classified according to their mode of operation as *class A, class B* and *class C* amplifiers. This classification depends on the portion of the input signal cycle during which collector current is expected to flow. Thus, class *A* amplifier is one in which collector current flows for the entire a.c. signal. Class *B* amplifier is one in which collector current flows for half-cycle of input a.c. signal. Finally, class *C* amplifier is one in which collector current flows for less than half-cycle of a.c. signal.

Example 12.15. *What do you understand by following amplifiers:*

(i) Class A voltage amplifier *(ii) Audio voltage amplifier*

(iii) Class B power amplifier *(iv) Class A transformer coupled power amplifier ?*

Solution. (*i*) Class *A* voltage amplifier means that it raises the voltage level of the signal and its mode of operation is such that collector current flows for the whole input signal.

(*ii*) Audio voltage amplifier means that it raises the voltage level of audio signal (*i.e.* one having frequency range 20 Hz to 20 kHz) and its mode of operation is class *A*.

(*iii*) It means that this amplifier raises the power level of the signal and its mode of operation is such that collector current flows for half-cycle of the signal only.

(*iv*) It means that power amplification is being done, coupling is by transformer and mode of operation is class *A*.

12.14 Amplifier Equivalent Circuit

An amplifier can be replaced by an equivalent circuit for the purpose of analysis. Fig. 12.28 (*i*) shows the amplifier circuit while Fig. 12.28 (*ii*) shows its equivalent circuit.

V_1 = input signal voltage to the amplifier

I_1 = input signal current

R_{in} = input resistance of the amplifier

A_0 = voltage gain of the amplifier when no load is connected

I_2 = output current

V_2 = output voltage across load R_L

R_{out} = output resistance of the ampifier

R_L = load resistance

A_v = voltage gain when load R_L is connected

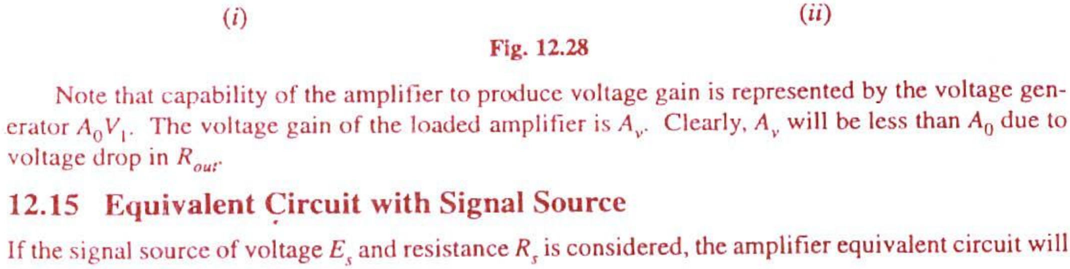


Fig. 12.28

Note that capability of the amplifier to produce voltage gain is represented by the voltage generator A_0V_1. The voltage gain of the loaded amplifier is A_v. Clearly, A_v will be less than A_0 due to voltage drop in R_{out}.

12.15 Equivalent Circuit with Signal Source

If the signal source of voltage E_s and resistance R_s is considered, the amplifier equivalent circuit will be as shown in Fig. 12.29.

Referring to Fig. 12.29, we have,

$$I_1 = \frac{E_S}{R_S + R_{in}}$$

$$\therefore \quad V_1 = I_1 R_{in} = \frac{E_S R_{in}}{R_S + R_{in}}$$

$$I_2 = \frac{A_0 V_1}{R_{out} + R_L} \quad ...(i)$$

$$= \frac{A_0 I_1 R_{in}}{R_{out} + R_L} \quad ...(ii)$$

$$\therefore \quad V_2 = I_2 R_L = \frac{A_0 V_1 R_L}{R_{out} + R_L} \quad ...(iii)$$

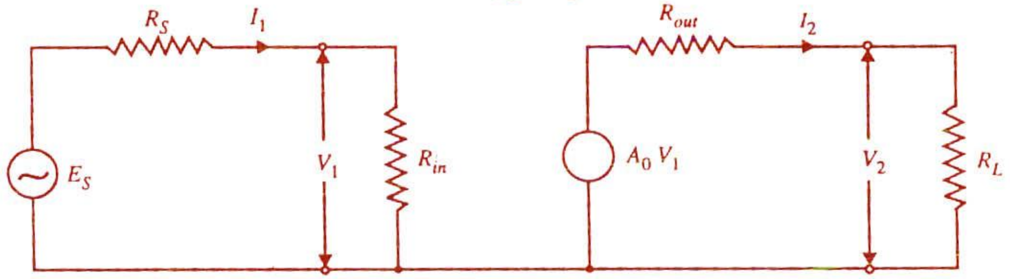


Fig. 12.29

$$\text{Voltage gain, } A_v = \frac{V_2}{V_1} = \frac{A_0 R_L}{R_{out} + R_L}$$

$$\text{Current gain, } A_i = \frac{I_2}{I_1} = \frac{A_0 R_{in}}{R_{out} + R_L}$$

$$\text{Power gain, } A_p = \frac{I_2^2 R_L}{I_1^2 R_{in}} = \frac{(I_2 R_L) I_2}{(I_1 R_{in}) I_1}$$

$$= \frac{V_2 I_2}{V_1 I_1} = \left(\frac{V_2}{V_1}\right) \times \left(\frac{I_2}{I_1}\right)$$

$$= A_v \times A_i$$

Note. The use of such equivalent circuit is restricted to the signal quantities only. Further, in drawing the equivalent circuit, it is assumed that exact linear relationship exists between input and output signals *i.e.* the amplifier produces no waveform distortion.

Example 12.16. *An amplifier has an open circuit voltage gain of 1000, an input resistance of 2 kΩ and an output resistance of 1Ω. Determine the input signal voltage required to produce an output signal current of 0.5A in 4Ω resistor connected across the output terminals.*

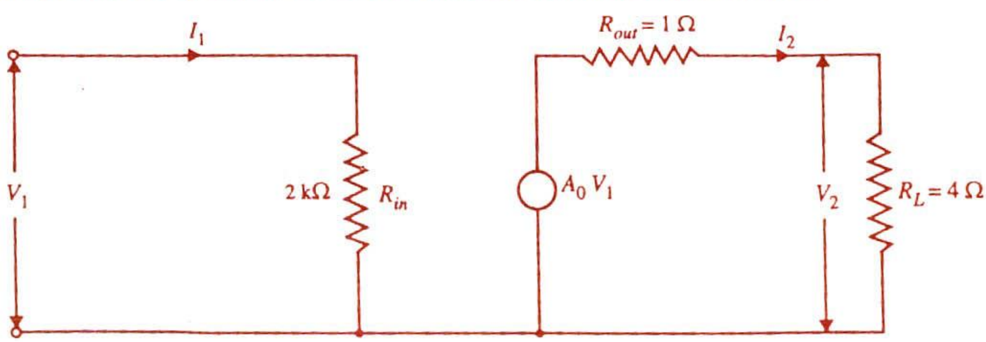


Fig. 12.30

Solution. Fig. 12.30 shows the equivalent circuit of the amplifier. Here $A_0 = 1000$.

$$\frac{I_2}{I_1} = \frac{A_0 R_{in}}{R_{out} + R_L} \quad \text{[See Art. 12.15]}$$

$$= \frac{1000 \times 2000}{1 + 4} = 4 \times 10^5$$

$$\therefore \quad I_1 = \frac{I_2}{4 \times 10^5} = \frac{0.5}{4 \times 10^5} = 1.25 \times 10^{-6} \text{ A}$$

Now $V_1 = I_1 R_{in} = (1.25 \times 10^{-6}) \times 2000 = 2.5 \times 10^{-3} \text{ V} = \mathbf{2.5 \text{ mV}}$

Example 12.17. *An amplifier has an open circuit voltage gain of 1000, an output resistance of 15Ω and an input resistance of 7kΩ. It is supplied from a signal source of e.m.f. 10mV and internal resistance 3kΩ. The amplifier feeds a load of 35 Ω. Determine (i) the magnitude of output voltage and (ii) power gain.*

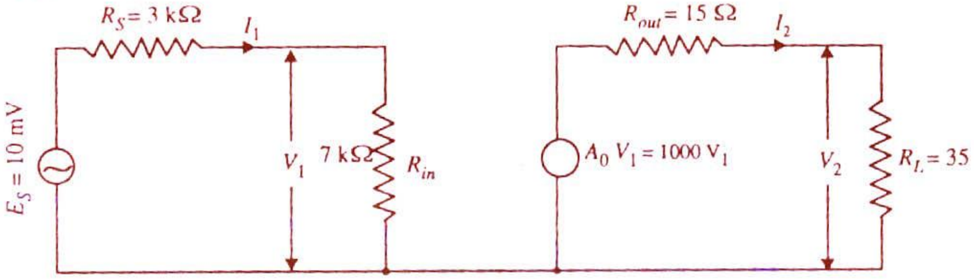


Fig. 12.31

Solution. (*i*) $$I_1 = \frac{E_S}{R_S + R_{in}} = \frac{10 \times 10^{-3}}{3000 + 7000} = 10^{-6} \text{ A}$$

$$V_1 = I_1 R_{in} = 10^{-6} \times 7000 = 7 \times 10^{-3} \text{ V}$$

$$A_v = \frac{V_2}{V_1} = \frac{A_0 R_L}{R_{out} + R_L} = \frac{1000 \times 35}{15 + 35} = 700$$

$$\therefore \quad V_2 = 700 V_1 = 700 \times 7 \times 10^{-3} = \mathbf{4.9 \text{ V}}$$

(*ii*) Output power, $$P_2 = \frac{V_2^2}{R_L} = \frac{(4.9)^2}{35} = 0.686 \text{ W}$$

Input power, $$P_1 = \frac{V_1^2}{R_{in}} = \frac{(7 \times 10^{-3})^2}{7000} = 7 \times 10^{-9} \text{ W}$$

Power gain, $$A_p = \frac{P_2}{P_1} = \frac{0.686}{7 \times 10^{-9}} = \mathbf{98 \times 10^6}$$

Example 12.18. *An amplifier, when loaded by 2 kΩ resistor, has a voltage gain of 80 and a current gain of 120. Determine the necessary signal voltage and current to give an output voltage of 1V. What is the power gain of the amplifier ?*

Solution. $$A_v = \frac{V_2}{V_1} = 80$$

$$\therefore \quad V_1 = V_2/80 = 1/80 = 0.0125 \text{ V} = \mathbf{12.5 \text{ mV}}$$

$$A_v = \frac{A_0 R_L}{R_{out} + R_L} \quad \text{...[See Art. 12.15]}$$

$$A_i = \frac{A_0 R_{in}}{R_{out} + R_L} \qquad \text{...[See Art. 12.15]}$$

$$\therefore \quad \frac{A_v}{A_i} = \frac{R_L}{R_{in}}$$

Fig. 12.32

$$\text{or} \quad \frac{80}{120} = \frac{2}{R_{in}}$$

$$\therefore \quad R_{in} = 120 \times 2/80 = 3 \text{ k}\Omega$$

$$I_1 = V_1/R_{in} = 12.5 \text{ mV}/3 \text{ k}\Omega = \mathbf{4.17\ \mu A}$$

$$\text{Power gain} = A_v \times A_i = 80 \times 120 = \mathbf{9600}$$

Multiple-Choice Questions

1. A single stage transistor amplifier contains .... and associated circuitry.
   (*i*) two transistors (*ii*) one transistor
   (*iii*) three transistors
   (*iv*) none of the above
2. The phase difference between the output and input voltages of a *CE* amplifier is ....
   (*i*) 180° (*ii*) 0°
   (*iii*) 90° (*iv*) 270°
3. It is generally desired that a transistor should have .... input impedance.
   (*i*) low (*ii*) very low
   (*iii*) high (*iv*) very high
4. When an a.c. signal is applied to an amplifier, the operating point moves along ....
   (*i*) d.c. load line (*ii*) a.c. load line
   (*iii*) both d.c. and a.c. load lines
   (*iv*) none of the above
5. If the collector supply is 10 V, then collector cut off voltage under d.c. conditions is ....
   (*i*) 20 V (*ii*) 5 V
   (*iii*) 2 V (*iv*) 10 V
6. In the zero signal conditions, a transistor sees .... load.
   (*i*) d.c. (*ii*) a.c.
   (*iii*) both d.c. and a.c
   (*iv*) none of the above
7. The input capacitor in an amplifier is the .... capacitor.
   (*i*) coupling (*ii*) bypass
   (*iii*) leakage (*iv*) none of the above
8. The point of intersection of d.c. and a.c. load lines is called ....
   (*i*) saturation point (*ii*) cut off point
   (*iii*) operating point (*iv*) none of the above
9. The slope of a.c. load line is .... that of d.c. load line.
   (*i*) the same as (*ii*) more than
   (*iii*) less than (*iv*) none of the above
10. If a transistor amplifier draws 2 mA when input voltage is 10 V, then its input impedance is ....
    (*i*) 20 kΩ (*ii*) 0.2 kΩ
    (*iii*) 10 kΩ (*iv*) 5 kΩ
11. When a transistor amplifier is operating, the current in any branch is ....
    (*i*) sum of a.c. and d.c.
    (*ii*) a.c. only (*iii*) d.c. only
    (*iv*) difference of a.c. and d.c.
12. The purpose of capacitors in a transistor amplifier is to ....
    (*i*) protect the transistor
    (*ii*) cool the transistor

(*iii*) couple or bypass a.c. component
(*iv*) provide biasing

13. In the d.c. equivalent circuit of a transistor amplifier, the capacitors are considered ....
(*i*) short (*ii*) open
(*iii*) partially short (*iv*) none of the above

14. In a *CE* amplifier, voltage gain = ... × $\frac{R_{AC}}{R_{in}}$
(*i*) α (*ii*) $(1 + \alpha)$
(*iii*) $(1 + \beta)$ (*iv*) β

15. In practice, the voltage gain of an amplifier is expressed ....
(*i*) as volts (*ii*) as a number
(*iii*) in *db* (*iv*) none of the above

16. If the power and current gains of a transistor amplifier are 16500 and 100 respectively, then voltage gain is ....
(*i*) 165 (*ii*) 165×10^4
(*iii*) 100 (*iv*) none of the above

17. If R_C and R_L represent the collector resistance and load resistance respectively in a single stage transistor amplifier, then a.c. load is ....
(*i*) $R_L + R_C$ (*ii*) $R_C \parallel R_L$
(*iii*) $R_L - R_C$ (*iv*) R_C

18. In a *CE* amplifier, the phase difference between voltage across collector load R_C and signal voltage is ....
(*i*) 180° (*ii*) 270°
(*iii*) 90° (*iv*) 0°

19. In the a.c. equivalent circuit of a transistor amplifier, the capacitors are considered ....
(*i*) short (*ii*) open
(*iii*) partially open (*iv*) none of the above

20. In a single stage transistor amplifier, R_C and R_L represent collector resistance and load resistance respectively. The transistor sees a d.c. load of ....
(*i*) $R_C + R_L$ (*ii*) $R_C \parallel R_L$
(*iii*) R_L (*iv*) R_C

21. The purpose of d.c. conditions in a transistor is to ....
(*i*) reverse bias the emitter
(*ii*) forward bias the collector
(*iii*) set up operating point
(*iv*) none of the above

22. An amplifier has a power gain of 100. Its *db* gain is........
(*i*) 10 *db* (*ii*) 20 *db*
(*iii*) 40 *db* (*iv*) none of the above

23. In order to get more voltage gain from a transistor amplifier, the transistor used should have ....
(*i*) thin base (*ii*) thin collector
(*iii*) wide emitter (*iv*) none of the above

24. The purpose of a coupling capacitor in a transistor amplifier is to ....
(*i*) increase the output impedance of transistor
(*ii*) protect the transistor
(*iii*) pass a.c. and block d.c.
(*iv*) provide biasing

25. The purpose of emitter capacitor (*i.e.* capacitor across R_E) is to ....
(*i*) avoid voltage gain drop
(*ii*) forward bias the emitter
(*iii*) reduce noise in the amplifier
(*iv*) none of the above

26. The ratio of output to input impedance of a *CE* amplifier is ....
(*i*) about 1 (*ii*) low
(*iii*) high (*iv*) moderate

27. If a transistor amplifier feeds a load of low resistance (*e.g.* speaker), then voltage gain will be ....
(*i*) high (*ii*) very high
(*iii*) moderate (*iv*) low

28. If the input capacitor of a transistor amplifier is short-circuited, then ....
(*i*) transistor will be destroyed
(*ii*) biasing conditions will change
(*iii*) signal will not reach the base
(*iv*) none of the above

29. The radio wave picked up by the receiving antenna is amplified about .... times to have reasonable sound output.
(*i*) 1000 (*ii*) a million
(*iii*) 100 (*iv*) 10000

30. A *CE* amplifier is also called .... circuit.
(*i*) grounded emitter

(ii) grounded base
(iii) grounded collector
(iv) none of the above

31. The d.c. load of a transistor amplifier is generally .... that of a.c. load.
(i) the same as (ii) less than
(iii) more than (iv) none of the above

32. The value of collector load R_C in a transistor amplifier is .... the output impedance of the transistor.
(i) the same as (ii) less than
(iii) more than (iv) none of the above

33. A single stage transistor amplifier with collector load R_C and emitter resistance R_E has a d.c. load of ....
(i) R_C (ii) $R_C \parallel R_E$
(iii) $R_C - R_E$ (iv) $R_C + R_E$

34. In transistor amplifiers, we generally use .... capacitors.
(i) electrolytic (ii) mica
(iii) paper (iv) air

35. A single stage transistor amplifier with no load sees an a.c. load of ....
(i) $R_C + R_E$ (ii) R_C
(iii) $R_C \parallel R_E$ (iv) R_C / R_E

36. The output power of a transistor amplifier is more than the input power because the additional power is supplied by ....
(i) transistor (ii) biasing circuit
(iii) collector supply V_{CC}
(iv) none of the above

37. A transistor converts ....
(i) d.c. power into a.c. power
(ii) a.c. power into d.c. power
(iii) high resistance into low resistance
(iv) none of the above

38. A transistor amplifier has high output impedance because ....
(i) emitter is heavily doped
(ii) collector has reverse bias
(iii) collector is wider than emitter or base
(iv) none of the above

39. For highest power gain, one would use .... configuration.
(i) CC (ii) CB
(iii) CE (iv) none of the above

40. CC configuration is used for impedance matching because its ....
(i) input impedance is very high
(ii) input impedance is low
(iii) output impedance is very low
(iv) none of the above

Answers to Multiple-Choice Questions

1. (ii)	**2.** (i)	**3.** (iii)	**4.** (ii)	**5.** (iv)
6. (i)	**7.** (i)	**8.** (iii)	**9.** (ii)	**10.** (iv)
11. (i)	**12.** (iii)	**13.** (ii)	**14.** (iv)	**15.** (iii)
16. (i)	**17.** (ii)	**18.** (iv)	**19.** (i)	**20.** (iv)
21. (iii)	**22.** (ii)	**23.** (i)	**24.** (iii)	**25.** (i)
26. (iv)	**27.** (iv)	**28.** (ii)	**29.** (ii)	**30.** (i)
31. (iii)	**32.** (ii)	**33.** (iv)	**34.** (i)	**35.** (ii)
36. (iii)	**37.** (i)	**38.** (ii)	**39.** (iii)	**40.** (i)

Chapter Review Topics

1. What do you understand by single stage transistor amplifiers ?
2. Explain with the help of output characteristics how the variations in base current affect collector current variations. Assume the base current varies sinusoidally.
3. Draw the circuit of a practical single stage transistor amplifier. Explain the function of each component.
4. Show the various currents and voltages in a single stage transistor amplifier.

5. Show that the output voltage of a single stage common emitter transistor amplifier is 180° out of phase with the input voltage.
6. What do you understand by d.c. and a.c. load lines ? How will you construct them on the output characteristics ?
7. Draw the d.c. and a.c. equivalent circuits of a transistor amplifier.
8. Derive an expression for the voltage gain of a transistor amplifier from its a.c. equivalent circuit.
9. Write short notes on the following :
   (*i*) phase reversal (*ii*) d.c. and a.c. load lines
   (*iii*) operating point (*iv*) classification of amplifiers.

Problems

1. In transistor amplifier, the collector current swings from 2 mA to 5 mA as the base current is changed from 5 μA to 15 μA. Find the current gain. **[300]**
2. A transistor amplifier employs a 4 kΩ as collector load. If the input resistance is 1 kΩ, determine the voltage gain. Given β = 100, g_m =10 mA/volt and signal voltage = 50 mV. **[1.04]**
3. Fig. 12.33 shows the transistor amplifier. If R_C = 4 kΩ, R_E = 5 kΩ and V_{CC} = 30 V, draw the d.c. load line.

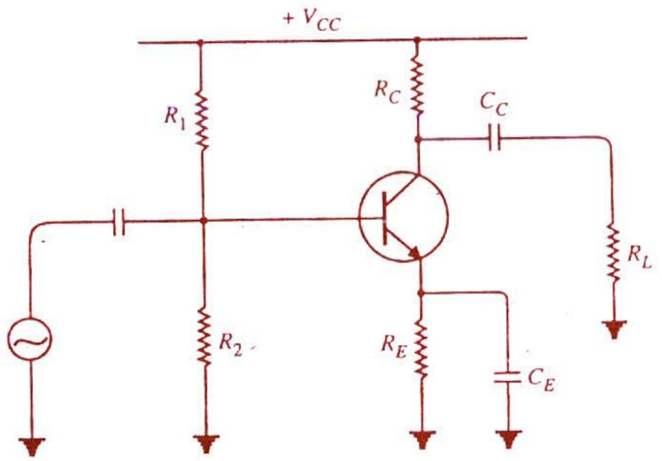


Fig. 12.33

4. Find the operating point for Fig. 12.33, V_{CC} = 30 V, R_1 = 20 kΩ, R_2 = 20 kΩ, R_C = 4 kΩ, R_E = 5 kΩ. **[13.2V, 1.85mA]**
5. For the circuit shown in Fig. 12.33, find the voltage gain if β = 100, R_C = 3 kΩ, R_L = 6 kΩ and R_{in} = 2 kΩ. **[100]**
6. In the circuit shown in Fig. 12.33, V_{CC} = 30 V, R_1 = 2 kΩ, R_2 = 1 kΩ, R_C = 2 kΩ, R_L = 2 kΩ, R_E = 1 kΩ. Draw the d.c. and a.c. load lines.
7. A voltage-divider biased circuit has an emitter voltage of 2 V and an emitter resistor of 4.7 kΩ. What is the ac resistance of emitter diode ? **[58.7 Ω]**
8. A transistor amplifier has a dc collector current of 5 mA. What is the ac resistance of the base if β = 200 ? **[1000 Ω]**
9. Determine the voltage gain for the amplifier circuit shown in Fig. 12.34.

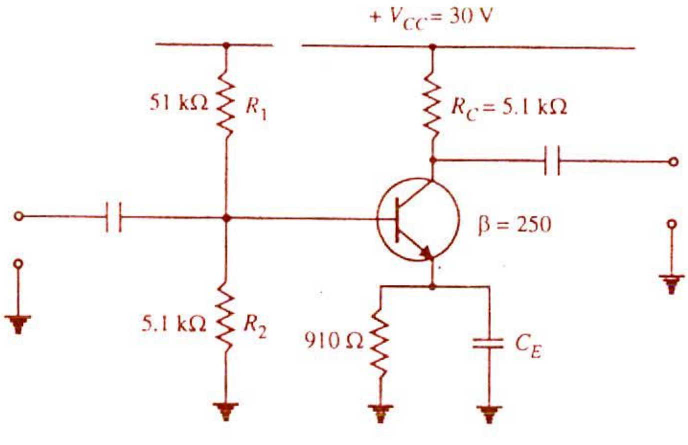


Fig. 12.34

10. What is the input impedance of the amplifier circuit shown in Fig. 12.34 ? **[1.75 kΩ]**

Discussion Questions

1. Does phase reversal affect amplification ?
2. Why does ac load differ from dc load ?
3. What is the importance of load line analysis ?
4. Why is ac load line steeper than dc load line?
5. What is the significance of operating point ?

13

Multitransistor Amplifiers

Introduction

The output from a single stage amplifier is usually insufficient to drive an output device. In other words, the gain of a single amplifier is inadequate for practical purposes. Consequently, additional amplification over two or three stages is necessary. To achieve this, the output of each amplifier stage is *coupled* in some way to the input of the next stage. The resulting system is referred to as multi-stage amplifier. It may be emphasised here that a practical amplifier is always a multistage amplifier. For example, in a transistor radio receiver, the number of amplification stages may be six or more. In this chapter, we shall focus our attention on the various multistage transistor amplifiers and their practical applications.

13.1 Multistage Transistor Amplifier

A transistor circuit containing more than one stage of amplification is known as **multistage transistor amplifier.**

In a multistage amplifier, a number of single amplifiers are connected in **cascade arrangement* *i.e.* output of first stage is connected to the input of the second stage through a suitable *coupling device* and so on. The purpose of coupling device (*e.g.* a capacitor, transformer etc.) is (*i*) to transfer a.c. output of one stage to the input of the next stage and (*ii*) to isolate the d.c. conditions of one stage from the next stage. Fig. 13.1 shows the block diagram of a 3-stage amplifier. Each stage consists of one transistor and associated circuitry and is coupled to the next stage through a coupling device. The name of the amplifier is usually given after the type of coupling used. *e.g.*

Name of coupling	*Name of multistage amplifier*
RC coupling	R-C coupled amplifier
Transformer coupling	Transformer coupled amplifier
Direct coupling	Direct coupled amplifier

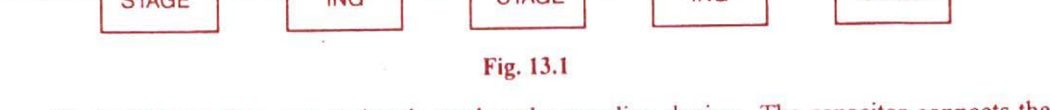


Fig. 13.1

(*i*) In *RC* coupling, a capacitor is used as the coupling device. The capacitor connects the

* The term cascaded means connected in series.

output of one stage to the input of the next stage in order to pass the a.c. signal on while blocking the d.c. bias voltages.

(*ii*) In transformer coupling, transformer is used as the coupling device. The transformer coupling provides the same two functions (*viz.* to pass the signal on and blocking d.c.) but permits in addition impedance matching.

(*iii*) In direct coupling or d.c. coupling, the individual amplifier stage bias conditions are so designed that the two stages may be directly connected without the necessity for d.c. isolation.

13.2 Important Terms

In the study of multistage amplifiers, we shall frequently come across the terms *gain, frequency response, decibel gain* and *bandwidth*. The terms stand discussed below :

(*i*) **Gain.** *The ratio of the output *electrical quantity to the input one of the amplifier is called its* **gain.**

The gain of a multistage amplifier is equal to the product of gains of individual stages. For instance, if G_1, G_2 and G_3 are the individual voltage gains of a three-stage amplifier, then total voltage gain G is given by ;

$$**G = G_1 \times G_2 \times G_3$$

It is worthwhile to mention here that in practice, total gain G is less than $G_1 \times G_2 \times G_3$ due to the loading effect of next stages.

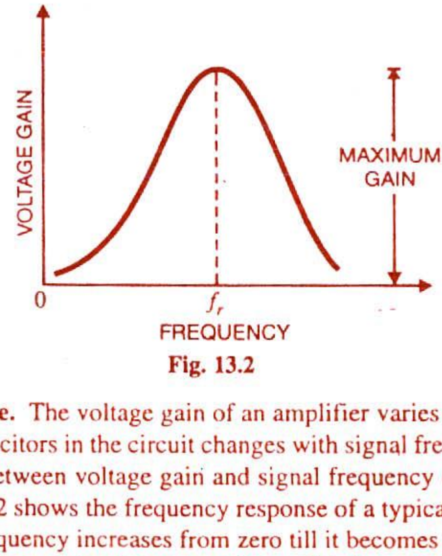


Fig. 13.2

(*ii*) **Frequency response.** The voltage gain of an amplifier varies with signal frequency. It is because reactance of the capacitors in the circuit changes with signal frequency and hence affect the output voltage. The curve between voltage gain and signal frequency of an amplifier is known as *frequency response*. Fig. 13.2 shows the frequency response of a typical amplifier. The gain of the amplifier increases as the frequency increases from zero till it becomes maximum at f_r, called *resonant frequency*. If the frequency of signal increases beyond f_r, the gain decreases.

* Accordingly, it can be current gain or voltage gain or power gain.

** This can be easily proved. Supporse the input to first stage is V.

$$\text{Output of first stage} = G_1 V$$

$$\text{Output of second stage} = (G_1 V)\, G_2 = G_1 G_2 V$$

$$\text{Output of third stage} = (G_1 G_2 V) G_3 = G_1 G_2 G_3 V$$

$$\text{Total gain, } G = \frac{\text{Output of third stage}}{V}$$

or $$G = \frac{G_1 G_2 G_3 V}{V} = G_1 \times G_2 \times G_3$$

The performance of an amplifier depends to a considerable extent upon its frequency response. While designing an amplifier, appropriate steps must be taken to ensure that gain is essentially uniform over some specified frequency range. For instance, in case of an audio amplifier, which is used to amplify speech or music, it is necessary that all the frequencies in the sound spectrum (*i.e.* 20 Hz to 20 kHz) should be uniformly amplified otherwise speaker will give a distorted sound output.

(*iii*) **Decibel gain.** Although the gain of an amplifier can be expressed as a number, yet it is of great practical importance to assign it a unit. The unit assigned is *bel or decibel* (*db*).

The common logarithm (log to the base 10) of power gain is known as **bel power gain** *i.e.*

$$\text{Power gain} = \log_{10} \frac{P_{out}}{P_{in}} \ bel$$

$$1 \text{ bel} = 10 \ db$$

$$\therefore \quad \text{Power gain} = 10 \log_{10} \frac{P_{out}}{P_{in}} \ db$$

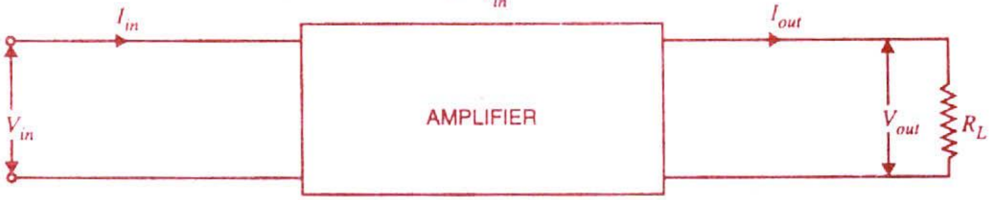


Fig. 13.3

If the two powers are developed in the same resistance or equal resistances, then,

$$P_1 = \frac{V_{in}^2}{R} = I_{in}^2 R$$

$$P_2 = \frac{V_{out}^2}{R} = I_{out}^2 R$$

$$\therefore \quad \text{Voltage gain in } db = 10 \log_{10} \frac{V_{out}^2 / R}{V_{in}^2 / R} = 20 \log_{10} \frac{V_{out}}{V_{in}}$$

$$\text{Current gain in } db = 10 \log_{10} \frac{I_{out}^2 R}{I_{in}^2 R} = 20 \log_{10} \frac{I_{out}}{I_{in}}$$

Advantages. The following are the advantages of expressing the gain in *db* :

(*a*) The unit *db* is a logarithmic unit. Our ear response is also logarithmic *i.e.* loudness of sound heard by ear is not according to the intensity of sound but according to the log of intensity of sound. Thus if the intensity of sound given by speaker (*i.e.* power) is increased 100 times, our ears hear a doubling effect ($\log_{10} 100 = 2$) *i.e.* as if loudness were doubled instead of made 100 times. Hence, this unit tallies with the natural response of our ears.

(*b*) When the gains are expressed in *db*, the overall gain of a multistage amplifier is the sum of gains of individual stages in *db*. Thus referring to Fig. 13.4,

$$\text{Gain as number} = \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$\text{Gain in } db = 20 \log_{10} \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$= 20 \log_{10} \frac{V_2}{V_1} + 20 \log_{10} \frac{V_3}{V_2}$$

= 1st stage gain in *db* + 2nd stage gain in *db*

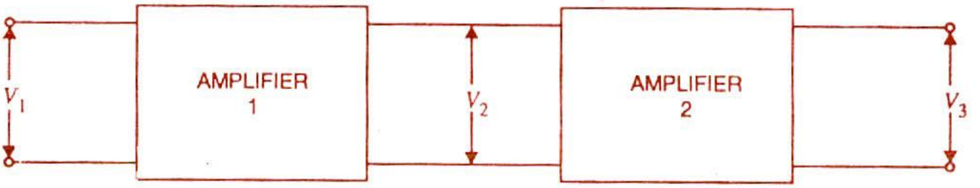


Fig. 13.4

However, absolute gain is obtained by multiplying the gains of individual stages. Obviously, it is easier to add than to multiply.

(*iv*) **Bandwidth.** *The range of frequency over which the gain is equal to or greater than *70.7% of the maximum gain is known as* **bandwidth.**

The voltage gain of an amplifier changes with frequency. Referring to the frequency response in Fig. 13.5, it is clear that for any frequency lying between f_1 and f_2, the gain is equal to or greater than 70.7% of the maximum gain. Therefore, $f_1 - f_2$ is the bandwidth. It may be seen that f_1 and f_2 are the limiting frequencies. The former (f_1) is called *lower cut-off frequency* and the latter (f_2) is known as *upper cut-off frequency*. For distortionless amplification, it is important that signal frequency range must be within the bandwidth of the amplifier.

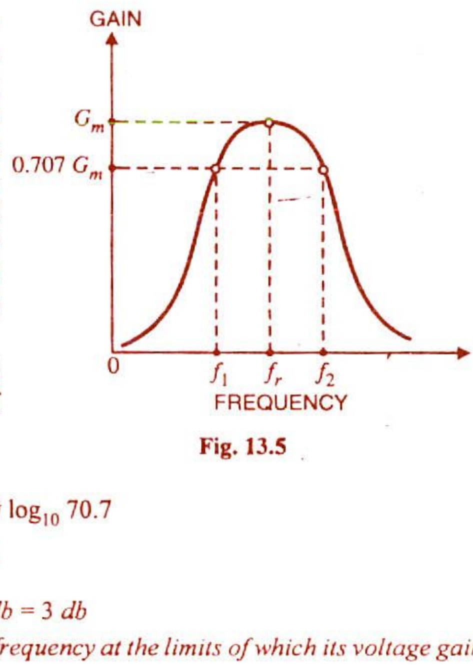


Fig. 13.5

The bandwidth of an amplifier can also be defined in terms of *db*. Suppose the maximum voltage gain of an amplifier is 100. Then 70.7% of it is 70.7.

∴ Fall in voltage gain from maximum gain

$$= 20 \log_{10} 100 - 20 \log_{10} 70.7$$

$$= 20 \log_{10} \frac{100}{70.7}\ db$$

$$= 20 \log_{10} 1.4142\ db = 3\ db$$

Hence **bandwidth** *of an amplifier is the range of frequency at the limits of which its voltage gain falls by 3 db from the maximum gain.*

The frequency f_1 or f_2 is also called *3-db frequency* or *half-power frequency.*

The 3-*db* designation comes from the fact that voltage gain at these frequencies is 3*db* below the maximum value. The term half-power is used because when voltage is down to 0.707 of its maximum value, the power (proportional to V^2) is down to $(0.707)^2$ or one-half of its maximum value.

Example 13.1. *Find the gain in db in the following cases :*

(*i*) *Voltage gain of 30* (*ii*) *Power gain of 100*

* The human ear is not a very sensitive hearing device. It has been found that if the gain falls to 70.7% of maximum gain, the ear cannot detect the change. For instance, if the gain of an amplifier is 100, then even if the gain falls to 70.7, the ear cannot detect the change in intensity of sound and hence no distortion will be heard. However, if the gain falls below 70.7, the ear will hear clear distortion.

Solution.

(*i*) Voltage gain $= 20 \log_{10} 30\ db = \mathbf{29.54\ db}$

(*ii*) Power gain $= 10 \log_{10} 100\ db = \mathbf{20\ db}$

Example 13.2. *Express the following gains as a number :*

(i) Power gain of 40 db *(ii) Power gain of 43 db*

Solution.

(*i*) Power gain = 40 *db* = 4 *bel*

If we want to find the gain as a number, we should work from logarithm back to the original number.

$\therefore$ Gain $=$ Antilog $4 = 10^4 = \mathbf{10{,}000}$

(*ii*) Power gain $= 43\ db = 4.3\ bel$

$\therefore$ Power gain $=$ Antilog $4.3 = 2 \times 10^4 = \mathbf{20{,}000}$

Alternatively. $$10 \log_{10} \frac{P_2}{P_1} = 43\ db$$

or $$\log_{10} \frac{P_2}{P_1} = 43/10 = 4.3$$

$$\therefore \quad \frac{P_2}{P_1} = (10)^{4.3} = \mathbf{20{,}000}$$

In general, we have,

$$\frac{V_2}{V_1} = (10)^{gain\ in\ db/20}$$

$$\frac{P_2}{P_1} = (10)^{gain\ in\ db/10}$$

Example 13.3. *A three-stage amplifier has a first stage voltage gain of 100, second stage voltage gain of 200 and third stage voltage gain of 400. Find the total voltage gain in db .*

Solution.

First-stage voltage gain in *db* $= 20 \log_{10} 100 = 20 \times 2 = 40$

Second-stage voltage gain in *db* $= 20 \log_{10} 200 = 20 \times 2.3 = 46$

Third-stage voltage gain in *db* $= 20 \log_{10} 400 = 20 \times 2.6 = 52$

$\therefore$ Total voltage gain $= 40 + 46 + 52 = \mathbf{138\ db}$

Example 13.4. (*i*) *A multistage amplifier employs five stages each of which has a power gain of 30. What is the total gain of the amplifier in db ?*

(*ii*) *If a negative feedback of 10 db is employed, find the resultant gain.*

Solution. Absolute gain of each stage = 30

No. of stages = 5

(*i*) Power gain of one stage in *db* $= 10 \log_{10} 30 = 14.77$

$\therefore$ Total power gain $= 5 \times 14.77 = \mathbf{73.85\ db}$

(*ii*) Resultant power gain with negative feedback

$= 73.85 - 10 = \mathbf{63.85\ db}$

It is clear from the above example that by expressing the gain in *db*, calculations have become very simple.

Example 13.5. *In an amplifier, the output power is 1.5 watts at 2 kHz and 0.3 watt at 20 Hz, while the input power is constant at 10 mW. Calculate by how many decibels gain at 20 Hz is below that at 2 kHz ?*

Solution.

db power gain at 2 kHz. At 2 kHz, the output power is 1.5 W and input power is 10 mW.

$$\therefore \quad \text{Power gain in } db = 10 \log_{10} \frac{1.5 \text{ W}}{10 \text{ mW}} = 21.76$$

db power gain at 20 Hz. At 20Hz, the output power is 0.3 W and input power is 10 mW.

$$\therefore \quad \text{Power gain in } db = 10 \log_{10} \frac{0.3 \text{ W}}{10 \text{ mW}} = 14.77$$

$$\text{Fall in gain from 2 kHz to 20 Hz} = 21.76 - 14.77 = \mathbf{6.99\ db}$$

Example 13.6. *A certain amplifier has voltage gain of 15 db. If the input signal voltage is 0.8V, what is the output voltage ?*

Solution.

$$db \text{ voltage gain} = 20 \log_{10} V_2/V_1$$

or $$15 = 20 \log_{10} V_2/V_1$$

or $$15/20 = \log_{10} V_2/V_1$$

or $$0.75 = \log_{10} V_2/0.8$$

Taking antilogs, we get

$$\text{Antilog } 0.75 = \text{Antilog } (\log_{10} V_2/0.8)$$

or $$10^{0.75} = V_2/0.8$$

$$\therefore \quad V_2 = 10^{0.75} \times 0.8 = \mathbf{4.5\ V}$$

Example13.7. *An amplifier has an open-circuit voltage gain of 70 db and an output resistance of 1.5 kΩ. Determine the minimum value of load resistance so that voltage gain is not more than 67db.*

Solution.

$$A_0 = 70\ db \quad ; \quad A_v = 67\ db$$

$$A_0 \text{ in } db - A_v \text{ in } db = 70 - 67 = 3\ db$$

or $$20 \log_{10} A_0 - 20 \log_{10} A_v = 3$$

or $$20 \log_{10} \frac{A_0}{A_v} = 3$$

or $$\frac{A_0}{A_v} = (10)^{3/20} = 1.41$$

But $$\frac{A_v}{A_0} = \frac{R_L}{R_{out} + R_L}$$ [See Art. 12.15]

$$\therefore \quad \frac{1}{1.41} = \frac{R_L}{1.5 + R_L}$$

or $$R_L = \mathbf{3.65\ k\Omega}$$

Example 13.8. *An amplifier feeding a resistive load of 1kΩ has a voltage gain of 40 db. If the input signal is 10 mV, find (i) output voltage (ii) load power.*

Solution.

(i) $$\frac{V_{out}}{V_{in}} = (10)^{db\ gain/20} = (10)^{40/20} = 100$$

$\therefore$ $$V_{out} = 100 \times V_{in} = 100 \times 10\ \text{mV} = 1000\ \text{mV} = \mathbf{1\ V}$$

(ii) $$\text{Load power} = \frac{V_{out}^2}{R_L} = \frac{(1)^2}{1000} = 10^{-3}\ \text{W} = \mathbf{1\ mW}$$

Example 13.9. *In an amplifier, the maximum voltage gain is 2000 and occurs at 2 kHz. It falls to 1414 at 10 kHz and 50 Hz. Find :*

(i) Bandwidth (ii) Lower cut-off frequency (iii) Upper cut-off frequency.

Solution.

(i) Referring to the frequency response in Fig. 13.6, the maximum gain is 2000. Then 70.7% of this gain is 0.707 × 2000 = 1414. It is given that gain is 1414 at 50 Hz and 10 kHz. As bandwidth is the range of frequency over which gain is equal or greater than 70.7% of maximum gain,

$\therefore$ Bandwidth = **50 Hz to 10 kHz**

(ii) The frequency (on lower side) at which the voltage gain of the amplifier is exactly 70.7% of the maximum gain is known as *lower cut-off frequency*. Referring to Fig. 13.6, it is clear that :

Lower cut-off frequency = **50 Hz**

(iii) The frequency (on the higher side) at which the voltage gain of the amplifier is exactly 70.7% of the maximum gain is known as *upper cut-off frequency*. Referring to Fig. 13.6, it is clear that:

Upper cut-off frequency = **10 kHz**

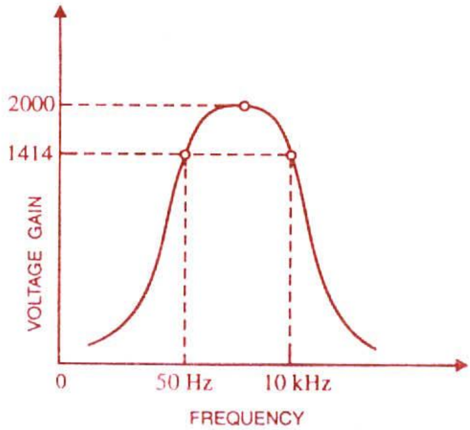


Fig. 13.6

Comments. As bandwidth of the amplifier is 50 Hz to 10 kHz, therefore, it will amplify the signal frequencies lying in this range without any distortion. However, if the signal frequency is not in this range, then there will be distortion in the output.

13.3 RC Coupled Transistor Amplifier

This is the most popular type of coupling because it is cheap and provides excellent audio fidelity over a wide range of frequency. It is usually employed for voltage amplification. Fig. 13.7 shows two stages of an *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 and so on. As the coupling from one stage to next is achieved by a coupling capacitor followed by a connection to a shunt resistor, therefore, such amplifiers are called *resistance - capacitance coupled amplifiers*.

The resistances R_1, R_2 and R_E form the biasing and stabilisation network. The emitter bypass capacitor offers low reactance path to the signal. Without it, the voltage gain of each stage would be lost. The coupling capacitor C_C transmits a.c. signal but blocks d.c. This prevents d.c. interference between various stages and the shifting of operating point.

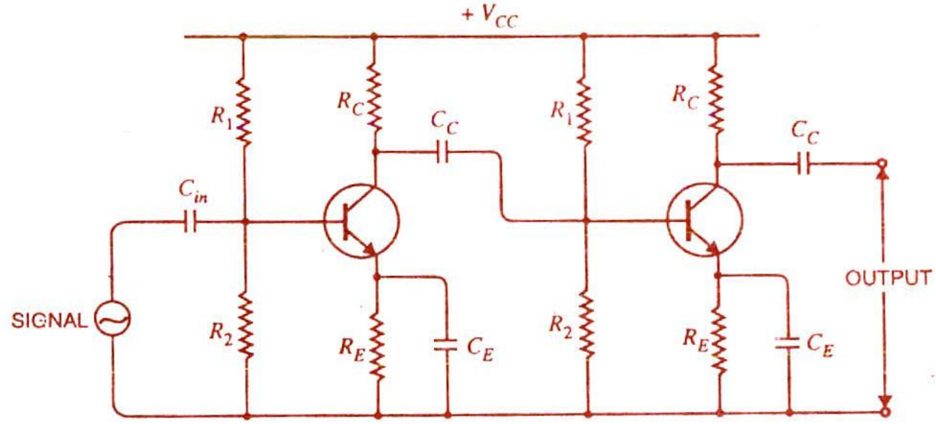


Fig. 13.7

Operation. When a.c. 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 base of next stage through coupling capacitor C_C. The second stage does further amplification of the signal. In this way, the *cascaded* (one after another) stages amplify the signal and the overall gain in considerably increased.

It may be mentioned here that total gain is less than the product of the gains of individual stages. It is because when a second stage is made to follow the first stage, the *effective load resistance* of first stage is reduced due to the shunting effect of the input resistance of second stage. This reduces the gain of the stage which is loaded by the next stage. For instance, in a 3-stage amplifier, the gain of first and second stages will be reduced due to loading effect of next stage. However, the gain of the third stage which has no loading effect of subsequent stage, remains unchanged. The overall gain shall be equal to the product of the gains of three stages.

Frequency response. Fig.13.8 shows the frequency response of a typical *RC* coupled amplifier. It is clear that voltage gain drops off at low (< 50 Hz) and high (> 20 kHz) frequencies whereas it is uniform over *mid-frequency* range (50 Hz to 20 kHz). This behaviour of the amplifier is briefly explained below :

(*i*) *At low frequencies* (< 50 Hz), the reactance of coupling capacitor C_C is quite high and hence very small part of signal will pass from one stage to the next stage. Moreover, C_E cannot shunt the emitter resistance R_E effectively because of its large reactance at low frequencies. These two factors cause a falling of voltage gain at low frequencies.

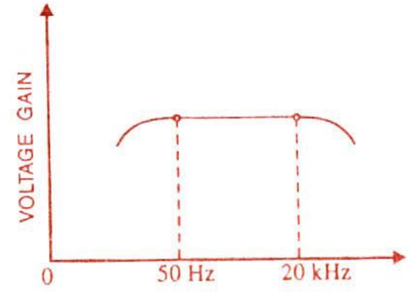


Fig. 13.8

(*ii*) *At high frequencies* (> 20 kHz), the reactance of C_C is very small and it behaves as a short circuit. This increases the loading effect of next stage and serves to reduce the voltage gain. Moreover, at high frequency, capacitive reactance of base-emitter junction is low which increases the base current. This reduces the current amplification factor β. Due to these two reasons, the voltage gain drops off at high frequency.

(*iii*) *At mid-frequencies* (50 Hz to 20 kHz), the voltage gain of the amplifier is constant. The effect of coupling capacitor in this frequency range is such so as to maintain a uniform voltage gain. Thus, as the frequency increases in this range, reactance of C_C decreases which tends to increase the gain. However, at the same time, lower reactance means higher loading of first stage and 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. The gain is constant over the audio frequency range which is the region of most importance for speech, music etc.

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

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

Disadvantages

(*i*) The *RC* coupled amplifiers have low voltage and power gain. It is because the low resistance presented by the input of each stage to the preceding stage decreases the effective load resistance (R_{AC}) and hence the gain.

(*ii*) They have the tendency to become noisy with age, particularly in moist climates.

(*iii*) Impedance matching is poor. It is because the output impedance of *RC* coupled amplifier is several hundred ohms whereas the input impedance of a speaker is only a few ohms. Hence, little power will be transferred to the speaker.

Applications.

The *RC* coupled amplifiers have excellent audio fidelity over a wide range of frequency. Therefore, they are widely used as voltage amplifiers *e.g.* in the initial stages of public address system. If other type of coupling (*e.g.* transformer coupling) is employed in the initial stages, this results in frequency distortion which may be amplified in next stages. However, because of poor impedance matching, *RC* coupling is rarely used in the final stages.

Example 13.10. *A single stage amplifier has a voltage gain of 60. The collector load R_C = 500 Ω and the input impedance is 1kΩ. Calculate the overall gain when two such stages are cascaded through R-C coupling. Comment on the result.*

Solution. The gain of second stage remains 60 because it has no loading effect of any stage. However, the gain of first stage is less than 60 due to the loading effect of the input impedance of second stage.

$$\therefore \quad \text{Gain of second stage} = 60$$

$$\text{Effective load of first stage} = R_C \parallel R_{in} = \frac{500 \times 1000}{500 + 1000} = 333\ \Omega$$

$$\text{Gain of first stage} = 60 \times 333/500 = 39.96$$

$$\text{Total gain} = 60 \times 39.96 = \mathbf{2397}$$

Comments. The gain of individual stage is 60. But when two stages are coupled, the gain is *not* 60 × 60 = 3600 as might be expected rather it is less and is equal to 2397 in this case. It is because the first stage has a loading effect of the input impedance of second stage and consequently its gain is reduced. However, the second stage has no loading effect of any subsequent stage. Hence, the gain of second stage remains 60.

Example 13.11. *Fig. 13.9 shows two-stage RC coupled amplifier. If the input resistance R_{in} of each stage is 1kΩ, find : (i) voltage gain of first stage (ii) voltage gain of second stage (iii) total voltage gain.*

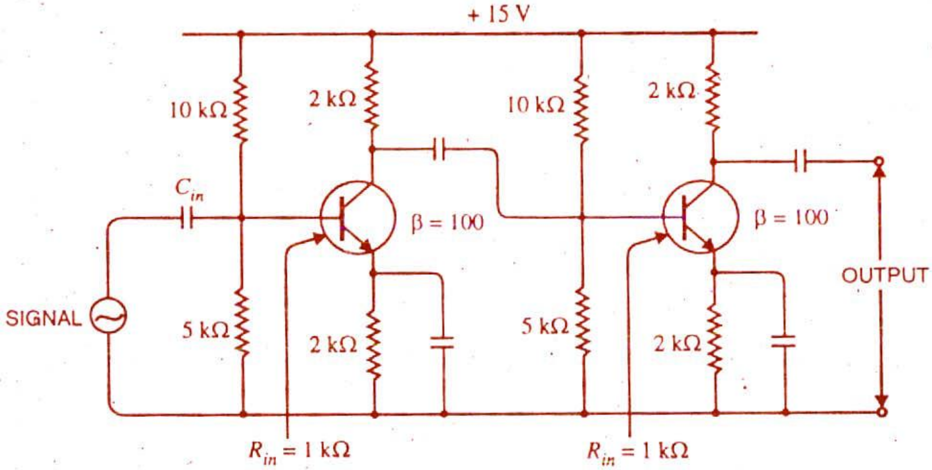


Fig. 13.9

Solution.

$$R_{in} = 1\text{ k}\Omega;\quad \beta = 100;\quad R_C = 2\text{ k}\Omega$$

(*i*) The first stage has a loading of input resistance of second stage.

∴ Effective load of first stage, $R_{AC} = R_C \parallel R_{in} = \dfrac{2 \times 1}{2 + 1} = 0.66\text{ k}\Omega$

∴ Voltage gain of first stage $= \beta \times R_{AC} / R_{in} = 100 \times 0.66/1 = \mathbf{66}$

(*ii*) The collector of the second stage sees a load of only R_C (= 2 kΩ) as there is no loading effect of any subsequent stage.

∴ Voltage gain of second stage

$$= \beta \times R_C / R_{in} = 100 \times 2/1 = \mathbf{200}$$

(*iii*) Total voltage gain $= 66 \times 200 = \mathbf{13200}$

Example 13.12. *A single stage amplifier has collector load R_C = 10 kΩ; input resistance R_{in} = 1kΩ and β = 100. If load R_L = 100Ω, find the voltage gain. Comment on the result.*

Solution. Effective collector load, $R_{AC} = R_C \parallel R_L = 10\text{ k}\Omega \parallel 100\ \Omega = {}^*100\ \Omega$

∴ $$\text{Voltage gain} = \beta \times \frac{R_{AC}}{R_{in}} = 100 \times \frac{100}{1000} = \mathbf{10}$$

Comments. As the load (*e.g.* speaker) is only of 100 ohms, therefore, effective load of the amplifier is too much reduced. Consequently, voltage gain is quite small. Under such situations, we can use a *transformer* to improve the voltage gain and signal handling capability. For example, if the output to 100 Ω load is delivered through a step-down transformer, the effective collector load and hence voltage gain can be increased.

Example 13.13. *Fig. 13.10 shows a 2-stage RC coupled amplifier. What is the biasing potential for the second stage ? If the coupling capacitor C_C is replaced by a wire, what would happen to the circuit ?*

* 10 kΩ ∥ 100 Ω is essentially 100 Ω.

Solution. Referring to Fig. 13.10, we have,

$$\text{Voltage across } R_4,\ V_B = \frac{V_{CC}}{R_3 + R_4} \times R_4 = \frac{20}{10 + 2.2} \times 2.2 = \mathbf{3.6\ V}$$

Thus biasing potential for the second stage is 3.6 V.

When the coupling capacitor C_C is replaced by a wire, this changes the entire picture. It is because now R_C of the first stage is in parallel with R_3 of the second stage as shown in Fig. 13.11(*i*). The total resistance of R_C (= 3.6 kΩ) and R_3 (= 10 kΩ) is given by;

$$R_{eq} = \frac{R_3\ R_C}{R_3 + R_C} = \frac{10 \times 3.6}{10 + 3.6} = 2.65\ \text{k}\Omega$$

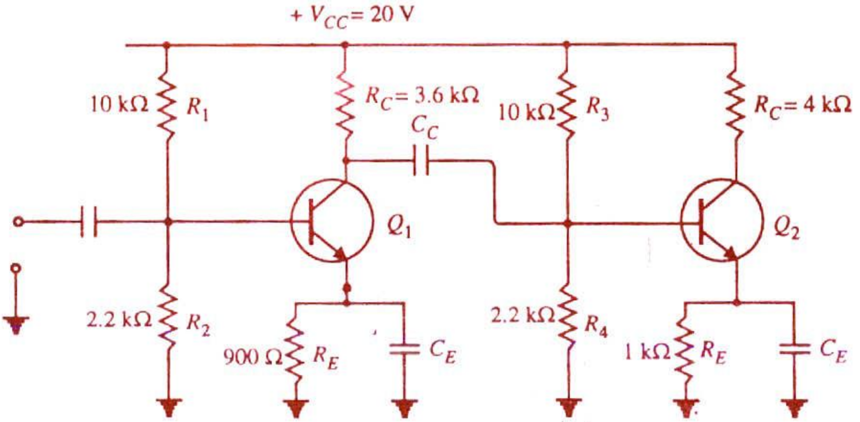


Fig. 13.10

The circuit shown in Fig. 13.11 (*i*) then reduces to the one shown in Fig. 13.11 (*ii*). Referring to Fig. 13.11 (*ii*), we have,

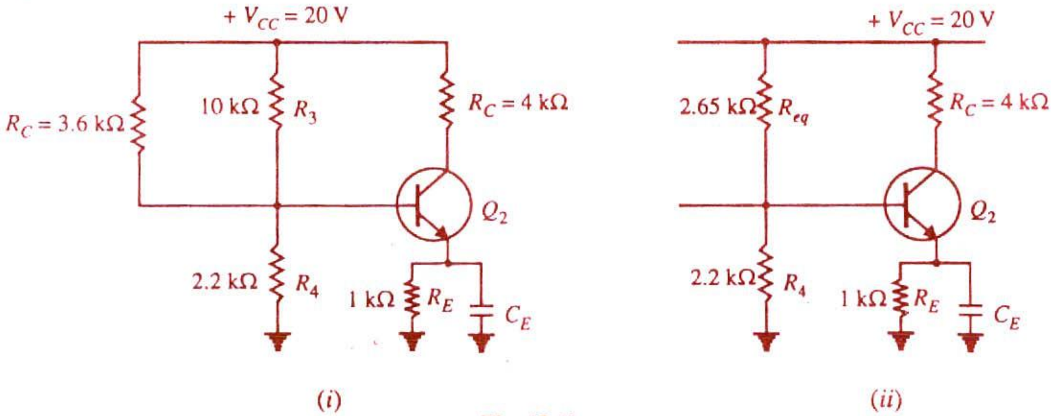


Fig. 13.11

$$\text{Voltage across } R_4,\ V_B = \frac{V_{CC}}{R_{eq} + R_4} \times R_4 = \frac{20}{2.65 + 2.2} \times 2.2 = 9.07\ \text{V}$$

Thus the biasing potential of second stage is drastically changed. The 9.07 V at the base of Q_2 would undoubtedly cause the transistor to saturate and the device would be rendered useless as an amplifier. This example explains the importance of dc isolation in a multistage amplifier. The use of coupling capacitor allows each amplifier stage to maintain its independent biasing potential while allowing the ac output from one stage to pass on to the next stage.

Example 13.14. *Fig. 13.12 shows a 2-stage RC coupled amplifier. Find the voltage gain of (i) first stage (ii) second stage and (iii) overall voltage gain.*

Solution. (*i*) **Voltage gain of First stage.** The input impedance of the second stage is the load for the first stage. In order to find input impedance of second stage, we shall first find r'_e (*ac* emitter resistance) for the second stage.

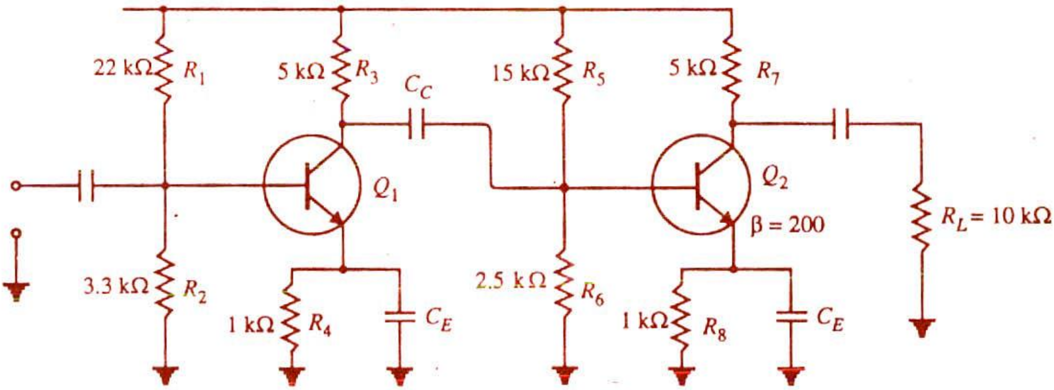


Fig. 13.12

$$\text{Voltage across } R_6 = \frac{V_{CC}}{R_5 + R_6} \times R_6 = \frac{15}{15 + 2.5} \times 2.5 = 2.14 \text{ V}$$

$$\text{Voltage across } R_8 = 2.14 - 0.7 = 1.44 \text{ V}$$

$$\text{Emitter current in } R_8,\ I_E = \frac{1.44 \text{ V}}{R_8} = \frac{1.44 \text{ V}}{1 \text{ k}\Omega} = 1.44 \text{ mA}$$

$$r'_e \text{ for second stage} = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{1.44 \text{ mA}} = 17.4\ \Omega$$

Similarly, it can be shown that r'_e for the first stage is 19.8 Ω.

$$Z_{in(base)} \text{ for second stage} = \beta \times r'_e \text{ for second stage} = 200 \times (17.4\ \Omega) = 3.48 \text{ k}\Omega$$

Input impedance of the second stage, $Z_{in} = R_5 \parallel R_6 \parallel Z_{in(base)}$

$$= 15 \text{ k}\Omega \parallel 2.5 \text{ k}\Omega \parallel 3.48 \text{ k}\Omega = 1.33 \text{ k}\Omega$$

∴ Effective collector load for first stage is

$$R_{AC} = R_3 \parallel Z_{in} = 5 \text{ k}\Omega \parallel 1.33 \text{ k}\Omega = 1.05 \text{ k}\Omega$$

$$\text{Voltage gain of first stage} = \frac{R_{AC}}{r'_e \text{ for first stage}} = \frac{1.05 \text{ k}\Omega}{19.8\ \Omega} = \mathbf{53}$$

(*ii*) **Voltage gain of second stage.** The load R_L (= 10 kΩ) is the load for the second stage.

∴ Effective collector load for second stage is

$$R_{AC} = R_7 \parallel R_L = 5 \text{ k}\Omega \parallel 10 \text{ k}\Omega = 3.33 \text{ k}\Omega$$

$$\therefore \quad \text{Voltage gain of second stage} = \frac{R_{AC}}{r'_e \text{ for second stage}} = \frac{3.33 \text{ k}\Omega}{17.4\ \Omega} = \mathbf{191.4}$$

(*iii*) **Overall voltage gain.** Overall voltage gain = First stage gain × Second stage gain

$$= 53 \times 191.4 = \mathbf{10144}$$

13.4 Transformer-Coupled Amplifier

The main reason for low voltage and power gain of *RC* coupled amplifier is that the effective load (R_{AC}) of each stage is *decreased due to the low resistance presented by the input of each stage to the preceding stage. If the effective load resistance of each stage could be increased, the voltage and power gain could be increased. This can be achieved by transformer coupling. By the use of **impedance-changing properties of transformer, the low resistance of a stage (or load) can be reflected as a high load resistance to the previous stage.

Transformer coupling is generally employed when the load is small. It is mostly used for power amplification. Fig. 13.13 shows two stages of transformer coupled amplifier. 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.

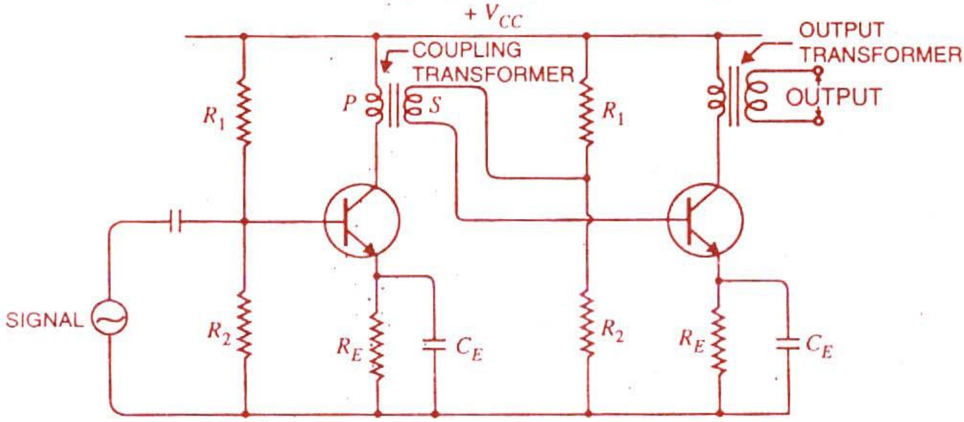


Fig. 13.13

Operation. When an 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 as shown in Fig.13.13. The second stage renders amplification in an exactly similar manner.

Frequency response. The frequency response of a transformer coupled amplifier is shown in Fig.13.14. It is clear that frequency response is rather poor *i.e.* gain is constant only over a small range of frequency. The output voltage is equal to the collector current multiplied by reactance of primary. At low frequencies, the reactance of primary begins to fall, resulting in decreased gain. At high frequencies, the capacitance between turns of windings acts as a bypass condenser to reduce the output voltage and hence gain. It follows, therefore, that there will be disproportionate amplification of frequencies in a complete sig-

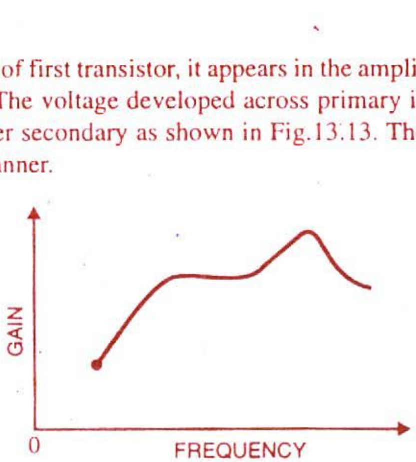


Fig. 13.14

* The input impedance of an amplifier is low while its output impedance is very high. When they are coupled to make a multistage amplifier, the high output impedance of one stage comes in parallel with the low input impedance of next state. Hence effective load (R_{AC}) is decreased.

** The resistance on the secondary side of a transformer reflected on the primary depends upon the turn ratio of the transformer.

nal such as music, speech etc. Hence, transformer-coupled amplifier introduces *frequency distortion.*

It may be added here that in a properly designed transformer, it is possible to achieve a fairly constant gain over the audio frequency range. But a transformer that achieves a frequency response comparable to *RC* coupling may cost 10 to 20 times as much as the inexpensive *RC* coupled amplifier.

Advantages

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

(*ii*) An excellent impedance matching can be achieved in a transformer coupled amplifier. It is easy to make the inductive reactance of primary equal to the output impedance of the transistor and inductive reactance of secondary equal to the input impedance of next stage.

(*iii*) Due to excellent impedance matching, transformer coupling provides higher gain. As a matter of fact, a single stage of properly designed transformer coupling can provide the gain of two stages of *RC* coupling.

Disadvantages

(*i*) It has a poor frequency response *i.e.* the gain varies considerably with frequency.

(*ii*) The coupling transformers are bulky and fairly expensive at audio frequencies.

(*iii*) Frequency distortion is higher *i.e.* low frequency signals are less amplified as compared to the high frequency signals.

(*iv*) Transformer coupling tends to introduce **hum* in the output.

Applications. Transformer coupling is mostly employed for *impedance matching*. In general, the last stage of a multistage amplifier is the *power stage*. Here, a concentrated effort is made to transfer maximum power to the output device *e.g.* a loudspeaker. For maximum power transfer, the impedance of power source should be equal to that of load. Usually, the impedance of an output device is a few ohms whereas the output impedance of transistor is several hundred times this value. In order to match the impedance, a step-down transformer of proper turn ratio is used. The impedance of secondary of the transformer is made equal to the load impedance and primary impedance

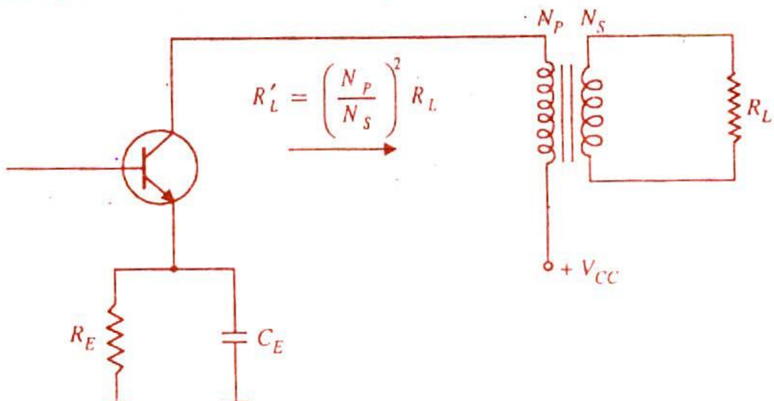


Fig. 13.15

equal to the output impedance of transistor. Fig. 13.15 illustrates the impedance matching by a step-down transformer. The output device (*e.g.* speaker) connected to the secondary has a small resistance

* There are hundreds of turns of primary and secondary. These turns will multiply an induced e.m.f. from nearby power wiring. As the transformer is connected in the base circuit, therefore, the induced hum voltage will appear in amplified form in the output.

R_L. The load R'_L appearing on the primary side will be:

$$^*R'_L = \left(\frac{N_P}{N_S}\right)^2 R_L$$

For instance, suppose the transformer has turn ratio $N_P : N_S :: 10 : 1$. If $R_L = 100\ \Omega$, then load appearing on the primary is :

$$R'_L = \left(\frac{10}{1}\right)^2 \times 100\ \Omega = 10\ \text{k}\Omega$$

Thus the load on the primary side is comparable to the output impedance of the transistor. This results in maximum power transfer from transistor to the primary of transformer. This shows that low value of load resistance (*e.g.* speaker) can be "stepped-up" to a more favourable value at the collector of transistor by using appropriate turn ratio.

Example 13.15. *A transformer coupling is used in the final stage of a multistage amplifier. If the output impedance of transistor is 1kΩ and the speaker has a resistance of 10Ω, find the turn ratio of the transformer so that maximum power is transferred to the load.*

Solution.

For maximum power transfer, the impedance of the primary should be equal to the output impedance of transistor and impedance of secondary should be equal to load impedance *i.e.*

$$\text{Primary impedance} = 1\ \text{k}\Omega = 1000\ \Omega$$

Let the turn ratio of the transformer be $n\ (= N_P/N_S)$.

$$\text{Primary impedance} = \left(\frac{N_P}{N_S}\right)^2 \times \text{Load impedance}$$

$$\therefore \quad \left(\frac{N_P}{N_S}\right)^2 = \frac{\text{Primary impedance}}{\text{Load impedance}}$$

or $$n^2 = 1000/10 = 100$$

$$\therefore \quad n = \sqrt{100} = \mathbf{10}$$

A step-down transformer with turn ratio 10 : 1 is required.

Example 13.16. *Determine the necessary transformer turn ratio for transferring maximum power to a 16Ω load from a source that has an output impedance of 10 kΩ. Also calculate the voltage across the external load if the terminal voltage of the source is 10V r.m.s.*

Solution.

For maximum power transfer, the impedance of the primary should be equal to the output impedance of the source.

$$\text{Primary impedance, } R'_L = 10\ \text{k}\Omega = 10{,}000\ \Omega$$

$$\text{Load impedance, } R_L = 16\ \Omega$$

Let the turn ratio of the transformer be $n\ (= N_P/N_S)$.

---

* Suppose primary and secondary of transformer carry currents I_P and I_S respectively. The secondary load R_L can be transferred to primary as R'_L provided the power loss remains the same *i.e.*,

$$I_P^2 R'_L = I_S^2 R_L$$

or $$R'_L = \left(\frac{I_S}{I_P}\right)^2 \times R_L = \left(\frac{N_P}{N_S}\right)^2 \times R_L \quad \left(\because \frac{I_S}{I_P} = \frac{N_P}{N_S}\right)$$

$$\therefore \quad R'_L = \left(\frac{N_P}{N_S}\right)^2 R_L$$

or $$\left(\frac{N_P}{N_S}\right)^2 = \frac{R'_L}{R_L} = \frac{10{,}000}{16} = 625$$

or $$n^2 = 625$$

or $$n = \sqrt{625} = 25$$

Now $$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

$$\therefore \quad V_S = \left(\frac{N_S}{N_P}\right) \times V_P = \frac{1}{25} \times 10 = \mathbf{0.4\ V}$$

Example 13.17. *The output resistance of the transistor shown in Fig. 13.16 is 3kΩ. The primary of the transformer has a d.c. resistance of 300 Ω and the load connected across secondary is 3Ω. Calculate the turn ratio of the transformer for transferring maximum power to the load.*

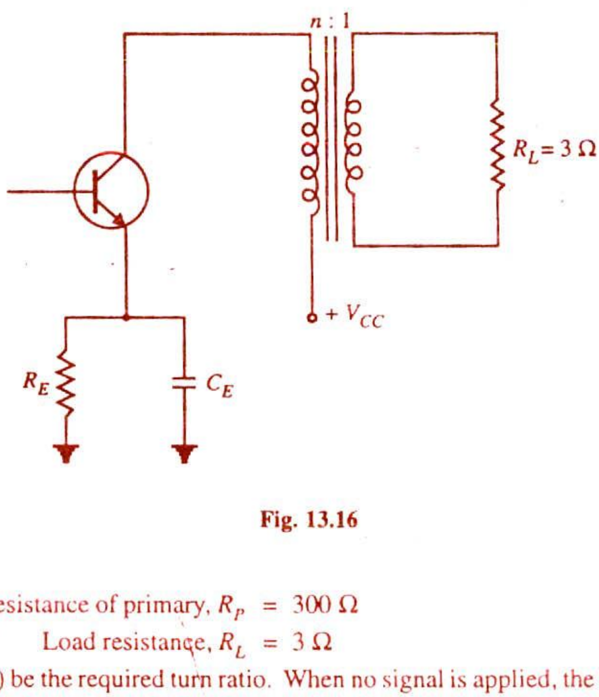


Fig. 13.16

Solution.

D.C. resistance of primary, $R_P = 300\ \Omega$

Load resistance, $R_L = 3\ \Omega$

Let $n\ (= N_P/N_S)$ be the required turn ratio. When no signal is applied, the transistor 'sees' a load of R_P (= 300 Ω) only. However, when a.c. signal is applied, the load R_L in the secondary is reflected in the primary as $n^2 R_L$. Consequently, the transistor now 'sees' a load of R_P in series with $n^2 R_L$.

For transference of maximum power,

$$\text{Output resistance of transistor} = R_P + n^2 R_L$$

or $$3000 = 300 + n^2 \times 3$$

or $$n^2 = \frac{3000 - 300}{3} = 900$$

$$\therefore \quad n = \sqrt{900} = \mathbf{30}$$

Example 13.18. *A transistor uses transformer coupling for amplification. The output impedance of transistor is 10 kΩ while the input impedance of next stage is 2.5 kΩ. Determine the inductance of primary and secondary of the transformer for perfect impedance matching at a frequency of 200 Hz.*

Solution. Frequency, $f = 200\text{Hz}$

Output impedance of transistor = $10\ \text{k}\Omega = 10^4\ \Omega$

Input impedance of next stage = $2.5\ \text{k}\Omega = 2.5 \times 10^3\ \Omega$

Primary inductance. Consider the primary side of the transformer. For perfect impedance matching,

Output impedance of transistor = Primary impedance

or $10^4 = 2\pi f L_P$

$\therefore$ Primary inductance, $L_P = \dfrac{10^4}{2\pi \times 200} = \mathbf{8\ H}$

Secondary inductance. Consider the secondary side of transformer. For impedance matching,

Input impedance of next stage = Impedance of secondary

or $2.5 \times 10^3 = 2\pi f L_S$

$\therefore$ Secondary inductance, $L_S = \dfrac{2.5 \times 10^3}{2\pi \times 200} = \mathbf{2\ H}$

Example 13.19. *In the above example, find the number of primary and secondary turns. Given that core section of the transformer is such that 1 turn gives an inductance of 10μH.*

Solution.

We know that inductance of a coil is directly proportional to the square of number of turns of the coil *i.e.*

$$L \propto N^2$$

or $L = K N^2$

Now $L = 10\ \mu H = 10^{-5}\ \text{H}, \quad N = 1$ turn

$\therefore$ $10^{-5} = K(1)^2$

or $K = 10^{-5}$

Primary inductance $= K N_P^2$

or $8 = 10^{-5} N_P^2$

$\therefore$ Primary turns, $N_P = \sqrt{8 \times 10^5} = \mathbf{894}$

Similarly, secondary turns, $N_S = \sqrt{2 \times 10^5} = \mathbf{447}$

13.5 Direct-Coupled Amplifier

There are many applications in which extremely low frequency (< 10 Hz) signals are to be amplified *e.g.* amplifying photo-electric current, thermo-couple current etc. The coupling devices such as capacitors and transformers cannot be used because the electrical sizes of these components become very large at extremely low frequencies. Under such situations, one stage is *directly* connected to the next stage without any intervening coupling device. This type of coupling is known as *direct coupling*.

Circuit details. Fig. 13.17 shows the circuit of a three-stage direct-coupled amplifier. It uses *complementary transistor. Thus, the first stage uses *npn* transistor, the second stage uses *pnp* transistor and so on. This arrangement makes the design very simple. The output from the collector of first transistor T_1 is fed to the input of the second transistor T_2 and so on.

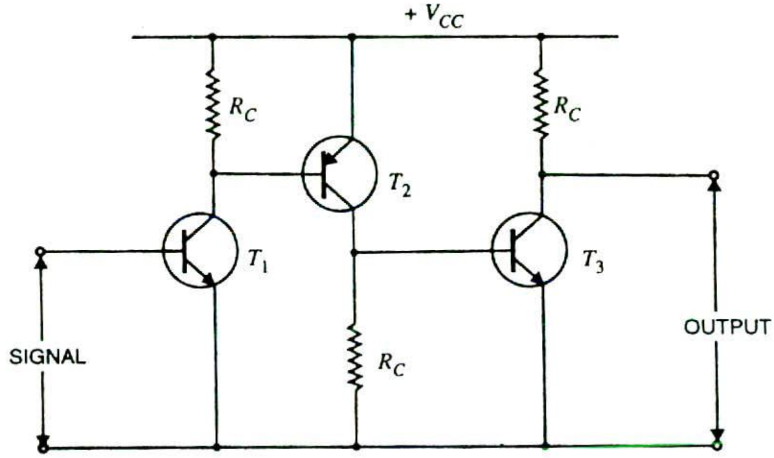


Fig. 13.17

The weak signal is applied to the input of first transistor T_1. Due to transistor action, an amplified output is obtained across the collector load R_C of transistor T_1. This voltage drives the base of the second transistor and amplified output is obtained across its collector load. In this way, direct coupled amplifier raises the strength of weak signal.

Advantages

(*i*) The circuit arrangement is simple because of minimum use of resistors.

(*ii*) The circuit has low cost because of the absence of expensive coupling devices.

Disadvantages

(*i*) It cannot be used for amplifying high frequencies.

(*ii*) The operating point is shifted due to temperature variations.

13.6 Comparison of Different Types of Coupling

S. No	Particular	R_C coupling	Transformer coupling	Direct coupling
1.	*Frequency response*	Excellent in the audio frequency range	Poor	Best
2.	*Cost*	Less	More	Least
3.	*Space and weight*	Less	More	Least
4.	*Impedance matching*	Not good	Excellent	Good
5.	*Use*	For voltage amplification	For power amplification	For amplifiying extremely low frequencies

* This makes the circuit stable w.r.t. temperature changes. In this connection (*i.e.*, *npn* followed by *pnp*), the direction of collector current increase β, when the temperature rises, is opposite for the two transistors. Thus the variation in one transistor tends to cancel that in the other.

13.7 Difference Between Transistor And Tube Amplifiers

Although both transistors and grid-controlled tubes (*e.g.* triode, tetrode and pentode) can render the job of amplification, they differ in the following respects :

(*i*) The electron tube is a voltage driven device while transistor is a current operated device.

(*ii*) The input and output impedances of the electron tubes are generally quite large. On the other hand, input and output impedances of transistors are relatively small.

(*iii*) Voltages for transistor amplifiers are much smaller than those of tube amplifiers.

(*iv*) Resistances of the components of a transistor amplifier are generally smaller than the resistances of the corresponding components of the tube amplifier.

(*v*) The capacitances of the components of a transistor amplifier are usually larger than the corresponding components of the tube amplifier.

Multiple-Choice Questions

1. A radio receiver has .... of amplification.
(*i*) one stage (*ii*) two stages
(*iii*) three stages
(*iv*) more than three stages

2. *RC* coupling is used for .... amplification.
(*i*) voltage (*ii*) current
(*iii*) power (*iv*) none of the above

3. In an *RC* coupled amplifier, the voltage gain over mid-frequency range ....
(*i*) changes abruptly with frequency
(*ii*) is constant
(*iii*) changes uniformly with frequency
(*iv*) none of the above

4. In obtaining the frequency response curve of an amplifier, the ....
(*i*) amplifier level output is kept constant
(*ii*) amplifier frequency is held constant
(*iii*) generator frequency is held constant
(*iv*) generator output level is held constant

5. An advantage of *RC* coupling scheme is the ....
(*i*) good impedance matching
(*ii*) economy
(*iii*) high efficiency (*iv*) none of the above

6. The best frequency response is of .... coupling.
(*i*) *RC* (*ii*) transformer
(*iii*) direct (*iv*) none of the above

7. Transformer coupling is used for .... amplification.
(*i*) power (*ii*) voltage
(*iii*) current (*iv*) none of the above

8. In an *RC* coupling scheme, the coupling capacitor C_C must be large enough ....
(*i*) to pass d.c. between the stages
(*ii*) not to attenuate the low frequencies
(*iii*) to dissipate high power
(*iv*) none of the above

9. In *RC* coupling, the value of coupling capacitor is about ....
(*i*) 100 pF (*ii*) 0.1 μF
(*iii*) 0.01 μF (*iv*) 10 μF

10. The noise factor of an ideal amplifier expressed in *db* is ....
(*i*) 0 (*ii*) 1
(*iii*) 0.1 (*iv*) 10

11. When a multistage amplifier is to amplify d.c. signal, then one must use .... coupling.
(*i*) *RC* (*ii*) transformer
(*iii*) direct (*iv*) none of the above

12. .... coupling provides the maximum voltage gain.
(*i*) *RC* (*ii*) transformer
(*iii*) direct (*iv*) impedance

13. In practice, voltage gain is expressed ....
(*i*) in *db* (*ii*) in volts
(*iii*) as a number (*iv*) none of the above

14. Transformer coupling provides high effi-

14. Transformer coupling provides high efficiency because ....
(*i*) collector voltage is stepped up
(*ii*) d.c. resistance is low
(*iii*) collector voltage is stepped down
(*iv*) none of the above

15. Transformer coupling is generally employed when load resistance is ....
(*i*) large (*ii*) very large
(*iii*) small (*iv*) none of the above

16. If a three-stage amplifier has individual stage gains of 10 *db*, 5 *db* and 12 *db*, then total gain in *db* is ....
(*i*) 600 *db* (*ii*) 24 *db*
(*iii*) 14 *db* (*iv*) 27 *db*

17. The final stage of a multistage amplifier uses ....
(*i*) *RC* coupling
(*ii*) transformer coupling
(*iii*) direct coupling
(*iv*) impedance coupling

18. The ear is not sensitive to........
(*i*) frequency distortion
(*ii*) amplitude distortion
(*iii*) frequency as well as amplitude distortion
(*iv*) none of the above

19. *RC* coupling is not used to amplify extremely low frequencies because ....
(*i*) there is considerable power loss
(*ii*) there is hum in the output
(*iii*) electrical size of coupling capacitor becomes very large
(*iv*) none of the above

20. In transistor amplifiers, we use .... transformer for impedance matching.
(*i*) step up (*ii*) step down
(*iii*) same turn ratio (*iv*) none of the above

21. The lower and upper cut off frequencies are also called .... frequencies.
(*i*) sideband (*ii*) resonant
(*iii*) half-resonant
(*iv*) half-power

22. A gain of 1,000,000 times in power is expressed by ....
(*i*) 30 *db* (*ii*) 60 *db*
(*iii*) 120 *db* (*iv*) 600 *db*

23. A gain of 1000 times in voltage is expressed by ....
(*i*) 60 *db* (*ii*) 30 *db*
(*iii*) 120 *db* (*iv*) 600 *db*

24. 1 *db* corresponds to .... change in power level.
(*i*) 50% (*ii*) 35%
(*iii*) 26% (*iv*) 22%

25. 1 *db* corresponds to .... change in voltage or current level.
(*i*) 40% (*ii*) 80%
(*iii*) 20% (*iv*) 25%

26. The frequency response of transformer coupling is ....
(*i*) good (*ii*) very good
(*iii*) excellent (*iv*) poor

27. In the initial stages of a multistage amplifier, we use ....
(*i*) *RC* coupling
(*ii*) transformer coupling
(*iii*) direct coupling (*iv*) none of the above

28. The total gain of a multistage amplifier is less than the product of the gains of individual stages due to ....
(*i*) power loss in the coupling device
(*ii*) loading effect of next stage
(*iii*) the use of many transistors
(*iv*) the use of many capacitors

29. The gain of an amplifier is expressed in *db* because ....
(*i*) it is a simple unit
(*ii*) calculations become easy
(*iii*) human ear response is logarithmic
(*iv*) none of the above

30. If the power level of an amplifier reduces to half, the *db* gain will fall by ....
(*i*) 0.5 *db* (*ii*) 2 *db*

(iii) 10 db (iv) 3 db

31. A current amplification of 2000 is a gain of ....
   (i) 3 db (ii) 66 db
   (iii) 20 db (iv) 200 db

32. An amplifier receives 0.1 W of input signal and delivers 15 W of signal power. What is the power gain is db ?
   (i) 21.8 db (ii) 13.6 db
   (iii) 9.5 db (iv) 17.4 db

33. The power output of an audio system is 18 W. For a person to notice an increase in the output (loudness or sound intensity) of the system, what must the output power be increased to ?
   (i) 14.2 W (ii) 11.6 W
   (iii) 22.68 W (iv) none of the above

34. The output of a microphone is rated at – 52 db. The reference level is 1 V under specified sound conditions. What is the output voltage of this microphone under the same sound conditions ?
   (i) 1.5 mV (ii) 6.2 mV
   (iii) 3.8 mV (iv) 2.5 mV

35. *RC* coupling is generally confined to low power applications because of ....
   (i) large value of coupling capacitor
   (ii) low efficiency
   (iii) large number of components
   (iv) none of the above

36. The number of stages that can be directly coupled is limited because ....
   (i) changes in temperature cause thermal instability
   (ii) circuit becomes heavy and costly
   (iii) it becomes difficult to bias the circuit
   (iv) none of the above

37. The purpose of RC or transformer coupling is to ....
   (i) block a.c.
   (ii) separate bias of one stage from another
   (iii) increase thermal stability
   (iv) none of the above

38. The upper or lower cut off frequency is also called .... frequency.
   (i) resonant (ii) sideband
   (iii) 3 db (iv) none of the above

39. The bandwidth of a single stage amplifier is .... that of a multistage amplifier.
   (i) more than (ii) the same as
   (iii) less than (iv) data insufficient

40. The value of emitter capacitor C_E in a multistage amplifier is about ....
   (i) 0.1 μF (ii) 100 pF
   (iii) 0.01 μF (iv) 50 μF

Answers to Multiple-Choice Questions

1. (iv)	**2.** (i)	**3.** (ii)	**4.** (iv)	**5.** (ii)
6. (iii)	**7.** (i)	**8.** (ii)	**9.** (iv)	**10.** (i)
11. (iii)	**12.** (ii)	**13.** (i)	**14.** (ii)	**15.** (iii)
16. (iv)	**17.** (ii)	**18.** (i)	**19.** (iii)	**20.** (ii)
21. (iv)	**22.** (ii)	**23.** (i)	**24.** (iii)	**25.** (i)
26. (iv)	**27.** (i)	**28.** (ii)	**29.** (iii)	**30.** (iv)
31. (ii)	**32.** (i)	**33.** (iii)	**34.** (iv)	**35.** (ii)
36. (i)	**37.** (ii)	**38.** (iii)	**39.** (i)	**40.** (iv)

Chapter Review Topics

1. What do you understand by multistage transistor amplifier ? Mention its need.
2. Explain the following terms : (i) Frequency response (ii) Decibel gain (iii) Bandwidth.
3. Explain transistor *RC* coupled amplifier with special reference to frequency response, advantages, disadvantages and applications.

4. With a neat circuit diagram, explain the working of transformer-coupled transistor amplifier.
5. How will you achieve impedance matching with transformer coupling ?
6. Explain direct coupled transistor amplifier.

Problems

1. The absolute voltage gain of an amplifier is 73. Find its decibel gain. [37db]
2. The input power to an amplifier is 15mW while output power is 2W. Find the decibel gain of the amplifier. [21.25db]
3. What is the *db* gain for an increase of power level from 12W to 24W ? [3 db]
4. What is the *db* gain for an increase of voltage from 4mV to 8mV ? [6 db]
5. A two-stage amplifier has first-stage voltage gain of 20 and second stage voltage gain of 400. Find the total decibel gain. [78db]
6. A multistage amplifier consists of three stages ; the voltage gain of stages are 60, 100 and 160. Calculate the overall gain in *db*. [119.64db]
7. A multistage amplifier consists of three stages ; the voltage gains of the stages are 30, 50 and 60. Calculate the overall gain in *db*. [99.1db]
8. In an *RC* coupled amplifier, the mid-frequency gain is 2000. What will be its value at upper and lower cut-off frequencies? [1414]
9. A three-stage amplifier employs *RC* coupling. The voltage gain of each stage is 50 and $R_C = 5\ k\Omega$ for each stage. If input impedance of each stage is 2 kΩ, find the overall decibel voltage gain. [80db]
10. We are to match a 16Ω speaker load to an amplifier so that the effective load resistance is 10 kΩ. What should be the transformer turn ratio ? [25]
11. Determine the necessary transformer turn ratio for transferring maximum power to a 50 ohm load from a source that has an output impedance of 5 kΩ. Also find the voltage across the external load if the terminal voltage of the source is 10V r.m.s. [10, 1V]
12. We are to match an 8Ω speaker load to an amplifier so that the effective load resistance is 8 kΩ. What should be the transformer turn ratio ? [10]

Discussion Questions

1. Why does *RC* coupling give constant gain over mid-frequency range ?
2. Why does transformer coupling give poor frequency response ?
3. How will you get frequency response comparable to *RC* coupling in a transformer coupling ?
4. Why is transformer coupling used in the final stage of a multistage amplifier ?
5. Why do you avoid *RC* or transformer coupling for amplifying extremely low frequency signals ?
6. Why do you prefer to express the gain in *db* ?

14

Transistor Audio Power Amplifiers

Introduction

A practical amplifier always consists of a number of stages that amplify a weak signal until sufficient power is available to operate a loudspeaker or other output device. The first few stages in this multistage amplifier have the function of only voltage amplification. However, the last stage is designed to provide maximum power. This final stage is known as *power stage.*

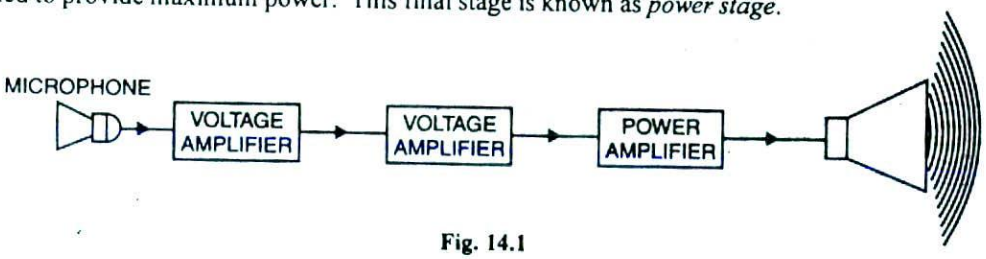


Fig. 14.1

The term audio means the range of frequencies which our ears can hear. The range of human hearing extends from 20 Hz to 20 kHz. Therefore, audio amplifiers amplify electrical signals that have a frequency range corresponding to the range of human hearing *i.e.* 20 Hz to 20 kHz. Fig. 14.1 shows the block diagram of an audio amplifier. The early stages build up the voltage level of the signal while the last stage builds up power to a level sufficient to operate the loudspeaker. In this chapter, we shall talk about the final stage in a multistage amplifier—the power amplifier.

14.1 Transistor Audio Power Amplifier

A transistor amplifier which raises the power level of the signals that have audio frequency range is known as **transistor audio power amplifier.**

In general, the last stage of a multistage amplifier is the *power stage.* The power amplifier differs from all the previous stages in that here a concentrated effort is made to obtain maximum output power. A transistor that is suitable for power amplification is generally called a *power transistor.* It differs from other transistors mostly in size ; it is considerably larger to provide for handling the great amount of power.

14.2 Difference Between Voltage and Power Amplifiers

The distinction between voltage and power amplifiers is somewhat artificial since useful power (*i.e.* product of voltage and current) is always developed in the load resistance through which current flows. The difference between the two types is really one of degree; it is a question of how much voltage and how much power. A voltage amplifier is designed to achieve maximum voltage amplification. It is, however, not important to raise the power level. On the other hand, a power amplifier is designed to obtain maximum output power.

1. Voltage amplifier. The voltage gain of an amplifier is given by ;

$$A_v = \beta \times \frac{R_C}{R_{in}}$$

In order to achieve high voltage amplification, the following features are incorporated in such amplifiers :

(*i*) The transistor with high β (>100) is used in the circuit. In other words, those transistors are employed which have thin base.

(*ii*) The input resistance R_{in} of the transistor is sought to be quite low as compared to the collector load R_C.

(*iii*) A relatively high load R_C is used in the collector. To permit this condition, voltage amplifiers are always operated at low collector currents (≃ 1 mA). If the collector current is small, we can use large R_C in the collector circuit.

2. Power amplifier. A power amplifier is required to deliver a large amount of power and as such it has to handle large current. In order to achieve high power amplification, the following features are incorporated in such amplifiers :

(*i*) The size of power transistor is made considerably larger in order to dissipate the heat produced in the transistor during operation.

(*ii*) The base is made thicker to handle large currents. In other words, transistors with comparatively smaller β are used.

(*iii*) Transformer coupling is used for impedance matching.

The comparison between voltage and power amplifiers is given below in the tabular form :

S. No.	Particular	Voltage amplifier	Power amplifier
1.	β	High (> 100)	low (5 to 20)
2.	R_C	High (4 – 10 kΩ)	low (5 to 20 Ω)
3.	*Coupling*	usually *R – C* coupling	Invariably transformer coupling
4.	*Input voltage*	low (a few mV)	High (2 – 4 V)
5.	*Collector current*	low (≃ 1 mA)	High (> 100 mA)
6.	*Power output*	low	high
7.	*Output impedance*	High (≃ 12 kΩ)	low (200 Ω)

Example 14.1. *A power amplifier operated from 12V battery gives an output of 2W. Find the maximum collector current in the circuit.*

Solution.

Let I_C be the maximum collector current.

$$\text{Power} = \text{battery voltage} \times \text{collector current}$$

$$2 = 12 \times I_C$$

$$\therefore \quad I_C = \frac{2}{12} = \frac{1}{6}\text{A} = \mathbf{166.7\ mA}$$

This example shows that a power amplifier handles large power as well as large current.

Example 14.2. *A voltage amplifier operated from a 12 V battery has a collector load of 4 kΩ. Find the maximum collector current in the circuit.*

Solution.

The maximum collector current will flow when the whole battery voltage is dropped across R_C.

$$\therefore \quad \text{Max. collector current} = \frac{\text{battery voltage}}{\text{collector load}} = \frac{12\text{ V}}{4\text{ k}\Omega} = \mathbf{3\text{ mA}}$$

This example shows that a voltage amplifier handles small current.

Example 14.3. *A power amplifier supplies 50W to an 8-ohm speaker. Find (i) a.c. output voltage (ii) a.c. output current.*

Solution.

(*i*) $$P = V^2/R$$

$$\therefore \quad \text{a.c. output voltage, } V = \sqrt{PR} = \sqrt{50 \times 8} = \mathbf{20\text{ V}}$$

(*ii*) $$\text{a.c. output current, } I = V/R = 20/8 = \mathbf{2.5\text{ A}}$$

14.3 Performance Quantities of Power Amplifiers

As mentioned previously, the prime objective for a power amplifier is to obtain maximum output power. Since a transistor, like any other electronic device has voltage, current and power dissipation limits, therefore, the criteria for a power amplifier are : *collector efficiency, distortion* and *power dissipation capability*.

(*i*) **Collector efficiency.** The main criterion for a power amplifier is not the power gain rather it is the maximum a.c. power output. Now, an amplifier converts d.c. power from supply into a.c. power output. Therefore, the ability of a power amplifier to convert d.c. power from supply into a.c. output power is a measure of its effectiveness. This is known as collector efficiency and may be defined as under :

The ratio of a.c. output power to the zero signal power (i.e. d.c. power) supplied by the battery of a power amplifier is known as **collector efficiency.**

Collector efficiency means as to how well an amplifier converts d.c. power from the battery into a.c. output power. For instance, if the d.c. power supplied by the battery is 10W and a.c. output power is 2W, then collector efficiency is 20%. The greater the collector efficiency, the larger is the a.c. power output. It is obvious that for power amplifiers, maximum collector efficiency is the desired goal.

(*ii*) **Distortion.** *The change of output wave shape from the input wave shape of an amplifier is known as* **distortion.**

A transistor like other electronic devices, is essentially a nonlinear device. Therefore, whenever a signal is applied to the input of the transistor, the output signal is not exactly like the input signal *i. e.* distortion occurs. Distortion is not a problem for small signals (*i.e.* voltage amplifiers) since transistor is a linear device for small variations about the operating point. However, a power amplifier handles large signals and, therefore, the problem of distortion immediately arises. For the comparison of two power amplifiers, the one which has the less distortion is the better. We shall discuss the method of reducing distortion in amplifiers in the chapter of negative feedback in amplifiers.

(*iii*) **Power dissipation capability.** *The ability of a power transistor to dissipate heat is known as* **power dissipation capability.**

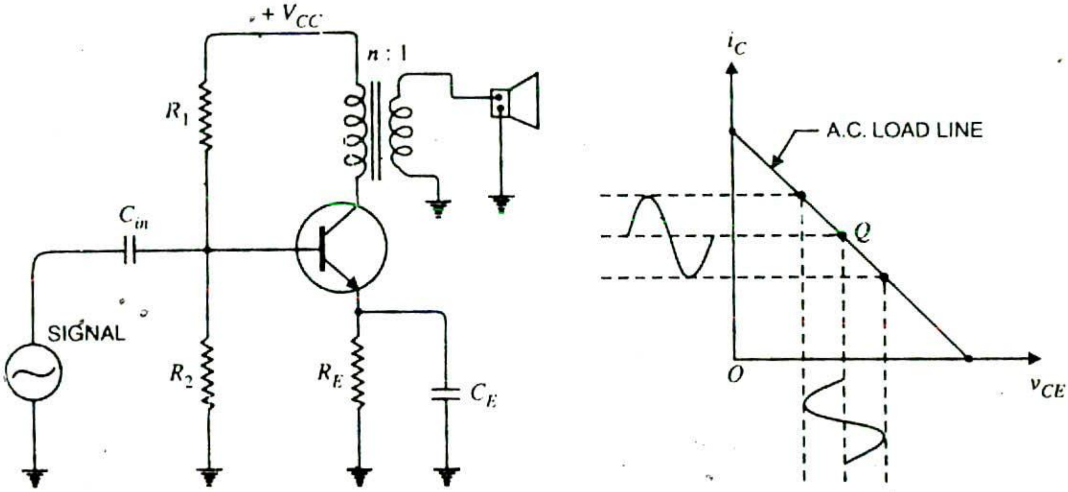
As stated before, a power transistor handles large currents and heats up during operation. As any temperature change influences the operation of transistor, therefore, the transistor must dissipate this heat to its surroundings. To achieve this, generally a *heat sink* (a metal case) is attached to a power transistor case. The increased surface area allows heat to escape easily and keeps the case temperature of the transistor within permissible limits.

14.4 Classification of Power Amplifiers

Transistor power amplifiers handle large signals. Many of them are driven so hard by the input large signal that collector current is either cut-off or is in the saturation region during a large portion of the input cycle. Therefore, such amplifiers are generally classified according to their mode of operation *i.e.* the portion of the input cycle during which the collector current is expected to flow. On this basis, they are classified as :

(*i*) class *A* power amplifier (*ii*) class *B* power amplifier (*iii*) class *C* power amplifier

(*i*) **Class *A* power amplifier.** *If the collector current flows at all times during the full cycle of the signal, the power amplifier is known as* **class A power amplifier.**



(*i*) (*ii*)

Fig. 14.2

Obviously, for this to happen, the power amplifier must be biased in such a way that no part of the signal is cut off. Fig. 14.2 (*i*) shows circuit of class *A* power amplifier. Note that collector has a transformer as the load which is most common for all classes of power amplifiers. The use of transformer permits impedance matching, resulting in the transference of maximum power to the load *e.g.* loudspeaker.

Fig. 14.2 (*ii*) shows the class *A* operation in terms of *a.c.* load line. The operating point *Q* is so selected that collector current flows at all times throughout the full cycle of the applied signal. As the output wave shape is exactly similar to the input wave shape, therefore, such amplifiers have least distortion. However, they have the disadvantage of low power output and low collector efficiency (about 35%).

(*ii*) **Class B power amplifier.** *If the collector current flows only during the positive half-cycle of the input signal, it is called a* **class B power amplifier.**

In class *B* operation, the transistor bias is so adjusted that zero signal collector current is zero *i.e.* no biasing circuit is needed at all. During the positive half-cycle of the signal, the input circuit is forward biased and hence collector current flows. However, during the negative half-cycle of the signal, the input circuit is reverse biased and no collector current flows. Fig. 14.3 shows the class *B* operation in terms of a.c. load line. Obviously, the operating point *Q* shall be located at collector cut off voltage. It is easy to see that output from a class *B* amplifier is amplified half-wave rectification.

In a class *B* amplifier, the negative half-cycle of the signal is cut off and hence a severe distortion occurs. However, class B amplifiers provide higher power output and collector efficiency (50 – 60%). Such amplifiers are mostly used for power amplification in push-pull arrangement. In such an arrangement, 2 transistors are used in class B operation. One transistor amplifies the positive half-cycle of the signal while the other amplifies the negative half-cycle.

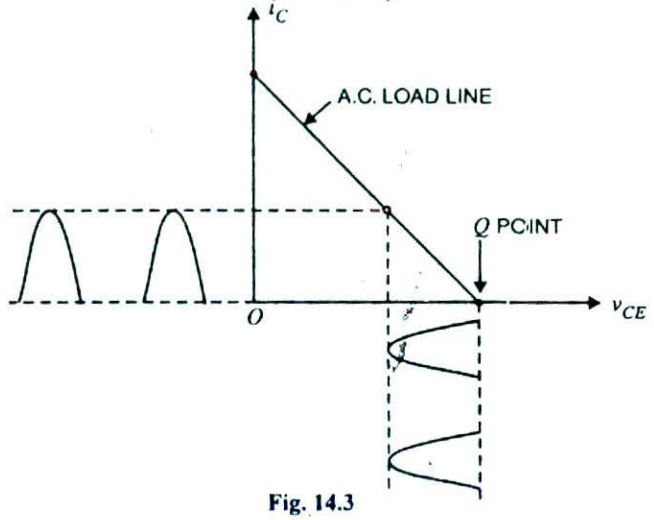


Fig. 14.3

(*iii*) **Class C power amplifier.** *If the collector current flows for less than half-cycle of the input signal, it is called* **class C power amplifier.**

In class C amplifier, the base is given some negative bias so that collector current does not flow just when the positive half-cycle of the signal starts. Such amplifiers are never used for power amplification. However, they are used as tuned amplifiers *i.e.* to amplify a narrow band of frequencies near the resonant frequency.

14.5 Expression for Collector Efficiency

For comparing power amplifiers, collector efficiency is the main criterion. The greater the collector efficiency, the better is the power amplifier.

Now Collector efficiency, $\eta = \dfrac{\text{a.c. power output}}{\text{d.c. power input}}$

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

where $^{*}P_{dc} = V_{CC} I_C$

$$P_{ac} = V_{ce} I_c$$

where V_{ce} is the *r.m.s.* value of signal output voltage and I_c is the *r.m.s.* value of output signal current. In terms of peak-to-peak values (which are often convenient values in load-line work), the a.c. power output can be expressed as :

$$^{**}P_{ac} = [(0.5 \times 0.707)\, v_{ce}\,(p-p)]\,[(0.5 \times 0.707)\, i_c\,(p-p)]$$

* Note that d.c. input power to the collector circuit of power amplifier is the product of collector supply V_{CC} (and not the collector-emitter voltage) and the average (*i.e.* d.c.) collector current I_C.

** $$r.m.s.\ \text{value} = \frac{1}{2}\left[\frac{\text{peak-to-peak value}}{\sqrt{2}}\right]$$

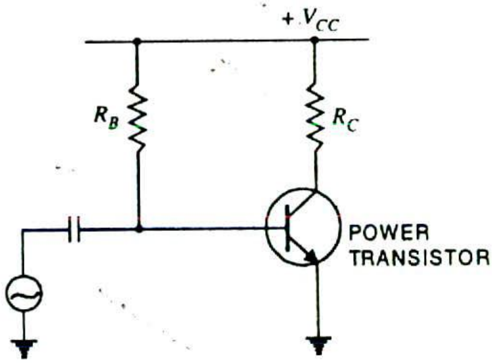
$$= 0.5 \times 0.707 \times \text{peak-to-peak value}$$

$$= \frac{v_{ce(p-p)} \times i_{c(p-p)}}{8}$$

$$\therefore \quad \text{Collector } \eta = \frac{v_{ce(p-p)} \times i_{c(p-p)}}{8 V_{CC} I_C}$$

14.6. Maximum Collector Efficiency of Series – Fed Class A Amplifier

Fig. 14.4 (*i*) shows a †series – fed class *A* amplifier. This circuit is seldom used for power amplification due to its poor collector efficiency. Nevertheless, it will help the reader to understand the class *A* operation. The d.c. load line of the circuit is shown in Fig. 14.4 (*ii*). When an *ac* signal is applied to the amplifier, the output current and voltage will vary about the operating point *Q*. In order to achieve the maximum symmetrical swing of current and voltage (to achieve maximum output power), the *Q* point should be located at the centre of the *dc* load line. In that case, operating point is $I_C = V_{CC}/2R_C$ and $V_{CE} = V_{CC}/2$.



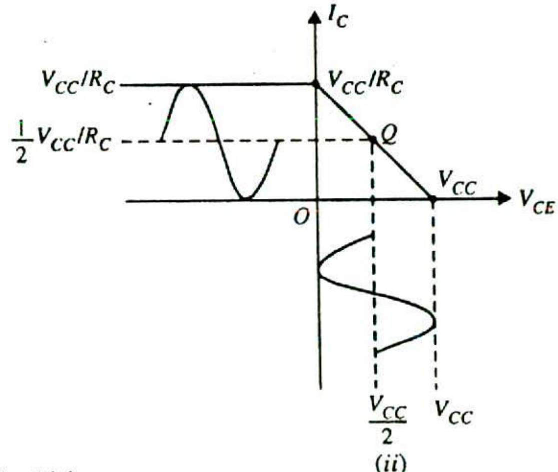


Fig. 14.4

$$\text{Maximum } v_{ce(p-p)} = V_{CC}$$

$$\text{Maximum } i_{C(p-p)} = V_{CC}/R_C$$

$$\text{Max. } ac \text{ output power, } P_{o(max)} = \frac{v_{ce(p-p)} \times i_{c(p-p)}}{8} = \frac{V_{CC} \times V_{CC}/R_C}{8} = \frac{V_{CC}^2}{8R_C}$$

$$\text{D.C. power supplied, } P_{dc} = V_{CC} I_C = V_{CC}\left(\frac{V_{CC}}{2R_C}\right) = \frac{V_{CC}^2}{2R_C}$$

$$\therefore \quad \text{Maximum collector } \eta = \frac{P_{o(max)}}{P_{dc}} \times 100 = \frac{V_{CC}^2/8R_C}{V_{CC}^2/2R_C} \times 100 = 25\%$$

Thus the maximum collector efficiency of a class *A* series-fed amplifier is 25%. In actual practice, the collector efficiency is far less than this value.

Example 14.4. *Calculate the (i) output power (ii) input power and (iii) collector efficiency of the amplifier circuit shown in Fig. 14.5 (i). It is given that input voltage results in a base current of 10 mA peak.*

† Note that the input to this circuit is a large signal and that transistor used is a power transistor.

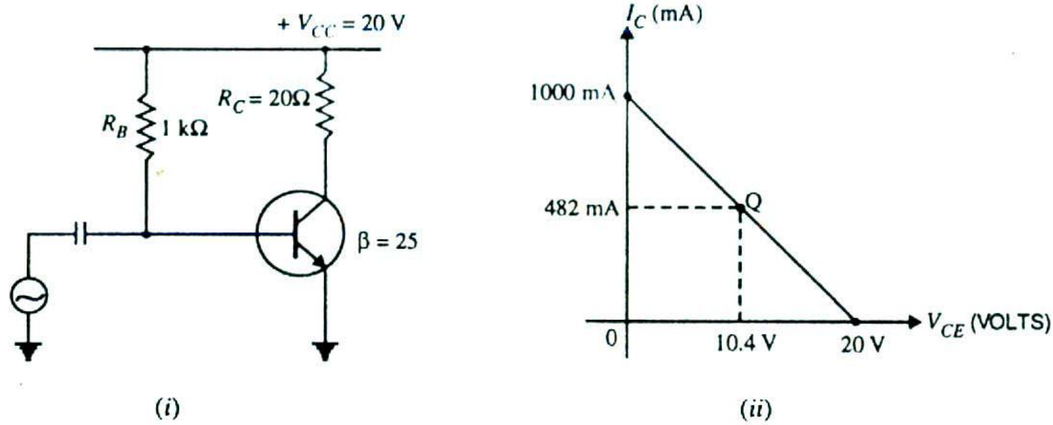


Fig. 14.5

Solution. First draw the *d.c.* load line by locating the two end points *viz.*, $I_{C\,(sat)} = V_{CC}/R_C = 20\text{ V}/20\ \Omega = 1\text{ A} = 1000\text{ mA}$ and $V_{CE} = V_{CC} = 20$ V as shown in Fig. 14.5 (*ii*). The operating point Q of the circuit can be located as under :

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{20 - 0.7}{1\text{ k}\Omega} = 19.3\text{ mA}$$

$$\therefore \quad I_C = \beta I_B = 25\,(19.3\text{ mA}) = 482\text{ mA}$$

Also $$V_{CE} = V_{CC} - I_C R_C = 20\text{ V} - (482\text{ mA})\,(20\ \Omega) = 10.4\text{ V}$$

The operating point Q (10.4 V, 482 mA) is shown on the d.c. load line.

(*i*) $i_c\,(peak) = \beta\, i_b\,(peak) = 25 \times (10\text{ mA}) = 250\text{ mA}$

$$\therefore \quad P_{o\,(ac)} = \frac{i_c^2\,(peak)}{2} R_C = \frac{(250 \times 10^{-3})^2}{2} \times 20 = \mathbf{0.625\ W}$$

(*ii*) $P_{dc} = V_{CC} I_C = (20\text{ V})\,(482 \times 10^{-3}) = \mathbf{9.6\ W}$

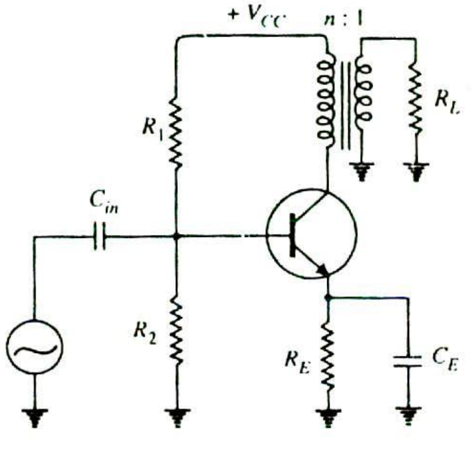
(*iii*) $$\text{Collector } \eta = \frac{P_o(ac)}{P_{dc}} \times 100 = \frac{0.625}{9.6} \times 100 = \mathbf{6.5\ \%}$$

14.7. Maximum Collector Efficiency of Transformer Coupled Class A Power Amplifier

In class *A* power amplifier, the load can be either connected directly in the collector or it can be transformer coupled. The latter method is often preferred for two main reasons. First, transformer coupling permits impedance matching and secondly it keeps the d.c. power loss small because of the small resistance of the transformer primary winding.

Fig. 14.6 (*i*) shows the transformer coupled class *A* power amplifier. In order to determine maximum collector efficiency, refer to the output characteristics shown in Fig. 14.6 (*ii*). Under zero signal conditions, the effective resistance in the collector circuit is that of the primary winding of the transformer. The primary resistance has a very small value and is assumed zero. Therefore, d.c. load line is a vertical line rising from V_{CC} as shown in Fig. 14.6 (*ii*). When signal is applied, the collector current will vary about the operating point Q.

In order to get maximum a.c. power output (and hence maximum collector η), the peak value of collector current due to signal alone should be equal to the zero signal collector current I_C. In terms of a.c. load line, the operating point Q should be located at the centre of a.c. load line.



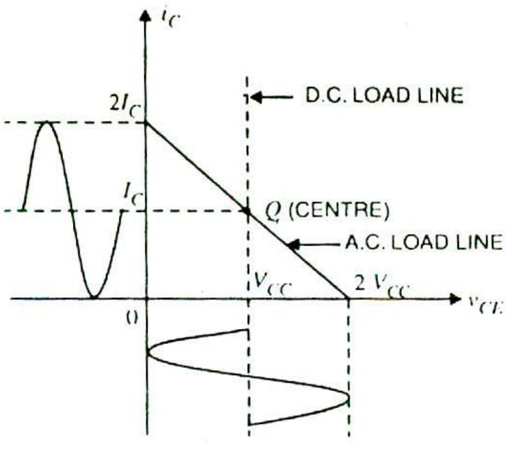


Fig. 14.6

During the peak of the positive half-cycle of the signal, the total collector current is $2I_C$ and v_{ce} = 0. During the negative peak of the signal, the collect or current is zero and *$v_{ce} = 2V_{CC}$.

∴ Peak-to-peak collector-emitter voltage is

$$v_{ce\,(p-p)} = 2V_{CC}$$

Peak-to-peak collector current, $i_{c\,(p-p)} = 2I_C$

$$= \frac{v_{ce(p-p)}}{R'_L} = \frac{2V_{CC}}{R'_L}$$

where R'_l is the reflected value of load R_l and appears in the primary of the transformer. If n (= N_p/N_s) is the turn ratio of the transformer, then, $R'_L = n^2 R_L$.

$$\text{d.c. power input, } P_{dc} = V_{CC} I_C$$

$$= I_C^2 R'_L \qquad (\because \; V_{CC} = I_C R'_L)$$

$$\text{Max.a.c. output power, } P_{ac\,(max)} = \frac{v_{ce\,(p-p)} \times i_{c\,(p-p)}}{8}$$

$$= \frac{2V_{CC} \times 2I_C}{8}$$

$$= \frac{1}{2} V_{CC} I_C \qquad ...(i)$$

$$= \frac{1}{2} I_C^2 R'_L \qquad (\because \; V_{CC} = I_C R'_L)$$

$$\text{Max. collector } \eta = \frac{P_{ac\,(max)}}{P_{dc}} \times 100$$

$$= \frac{(1/2)\, I_C^2 R'_L}{I_C^2 R'_L} \times 100 = 50\%$$

* This occurs at the negative peak of the signal. Under such conditions, the voltage across transformer primary is V_{CC} but in such a direction so as to reinforce the supply.

∴ $$v_{ce} = 2V_{CC}$$

14.8 Important Points About Class A Power Amplifier

(*i*) A *transformer coupled class *A* power amplifier has a maximum collector efficiency of 50% *i.e.*, maximum of 50% d.c. supply power is converted into a.c. power output. In practice, the efficiency of such an amplifier is less than 50% (about 35%) due to power losses in the output transformer, power dissipation in the transistor etc.

(*ii*) The power dissipated by a transistor is given by ;

$$P_{dis} = P_{dc} - P_{ac}$$

where P_{dc} = available d.c. power

P_{ac} = available a.c. power

Clearly, in class *A* operation, the transistor must dissipate less heat when signal is applied and therefore runs cooler.

(*iii*) When no signal is applied to a class *A* power amplifier, $P_{ac} = 0$.

$$\therefore \quad P_{dis} = P_{dc}$$

Thus in class *A* operation, maximum power dissipation in the transistor occurs under zero signal conditions. Therefore, the power dissipation capability of a power transistor (for class *A* operation) must be atleast equal to the zero signal rating. For example, if the zero signal power dissipation of a transistor is 1 W, then transistor needs a rating of atleast 1 W. If the power rating of the transistor is less than 1 W, it is likely to be damaged.

(*iv*) When a class *A* power amplifier is used in the final stage, it is called **single ended class *A* power amplifier.**

Example 14.5. *A power transistor working in class A operation has zero signal power dissipation of 10 watts. If the a.c. output power is 4 watts, find :*

(*i*) *collector efficiency* (*ii*) *power rating of transistor*

Solution.

Zero signal power dissipation, P_{dc} = 10 W

a.c. power output, P_o = 4 W

(*i*) collector efficiency $= \dfrac{P_o}{P_{dc}} \times 100 = \dfrac{4}{10} \times 100 = \mathbf{40\%}$

(*ii*) The zero signal power represents the worst case *i.e.* maximum power dissipation in a transistor occurs under zero signal conditions.

$\therefore$ Power rating of transistor = **10 W**

It means to avoid damage, the transistor must have a power rating of atleast 10 W.

Example 14.6. *A class A power amplifier has a transformer as the load. If the transformer has a turn ratio of 10 and the secondary load is 100 Ω, find the maximum a.c. power output. Given that zero signal collector current is 100 mA.*

Solution.

Secondary load, R_L = 100 Ω

Transformer turn ratio, n = 10

Zero signal collector current, I_C = 100 mA

Load as seen by the primary of the transformer is

$$R'_L = n^2 R_L = (10)^2 \times 100 = 10{,}000\ \Omega$$

---

* However, resistance coupled class *A* power amplifier has a maximum collector efficiency of 25%.

$\therefore$ Max. a.c. power output $= \frac{1}{2} I_C^2 R'_L = \frac{1}{2}\left(\frac{100}{1000}\right)^2 \times 10,000$

$= \mathbf{50\ W}$

Example 14.7. *A class A transformer coupled power amplifier has zero signal collector current of 50 mA. If the collector supply voltage is 5 V, find (i) the maximum a.c. power output (ii) the power rating of transistor (iii) the maximum collector efficiency.*

Solution.

(*i*) Max. a.c. power output, $P_{ac\,(max)} = \frac{V_{CC}\, I_C}{2}$ ...See Art. 14.7

$= \frac{(5\ V) \times (50\ mA)}{2} = \mathbf{125\ mW}$

(*ii*) D.C input power, $P_{dc} = V_{CC} I_C$

$= (5\ V) \times (50\ mA) = 250\ mW$

Since the maximum power is dissipated in the zero signal conditions,

$\therefore$ Power rating of transistor $= \mathbf{250\ mW}$

The reader may note that in class *A* operation :

$$P_{ac\,(max)} = \frac{P_{dis}}{2}$$

or

$$P_{dis} = 2\, P_{ac\,(max)}$$

It means that power rating of the transistor is twice as great as the maximum a.c. output power. For example, if a transistor dissipates 3 W under no signal conditions, then maximum a.c. output power it can deliver is 1.5 W.

(*iii*) Max. collector $\eta = \frac{P_{ac\,(max)}}{P_{dc}} \times 100 = \frac{125\ mW}{250\ mW} \times 100 = \mathbf{50\%}$

Example 14.8. *A power transistor working in class A operation is supplied from a 12-volt battery. If the maximum collector current change is 100 mA, find the power transferred to a 5 Ω loudspeaker if it is :*

(*i*) *directly connected in the collector*

(*ii*) *transformer-coupled for maximum power transference*

Find the turn ratio of the transformer in the second case.

Solution.

Max. collector current change, $\Delta I_C = 100\ mA$

Max. collector-emitter voltage change is

$\Delta V_{CE} = 12\ V$

Loudspeaker resistance, $R_L = 5\ \Omega$

(*i*) **Loudspeaker directly connected.** Fig. 14.7 (*i*) shows the circuit of class *A* power amplifier with loudspeaker directly connected in the collector.

Max. voltage across loudspeaker $= \Delta I_C \times R_L = 100\ mA \times 5\ \Omega = 0.5\ V$

Power developed in the loudspeaker $= 0.5\ V \times 100\ mA$

$= 0.05\ W = \mathbf{50\ mW}$

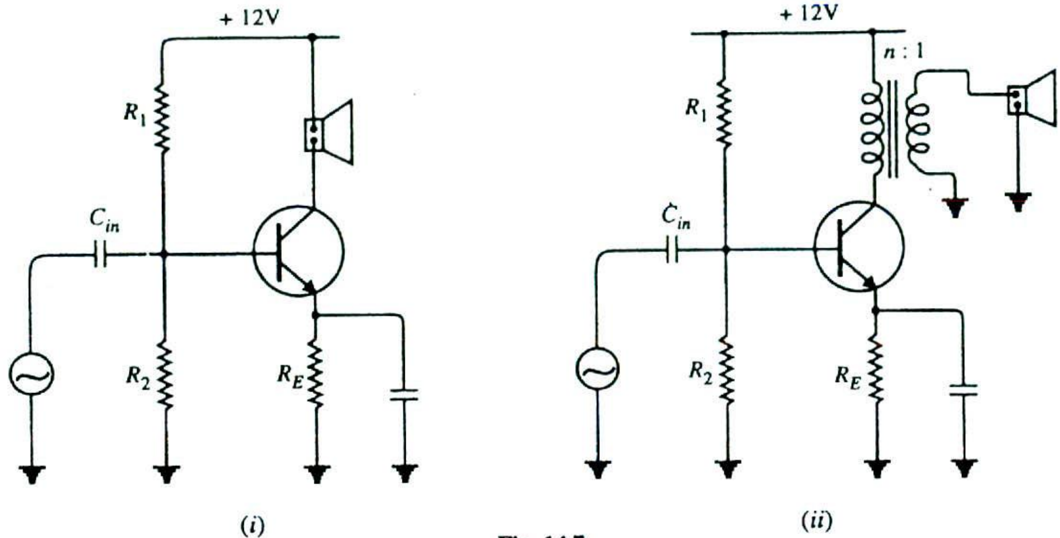


Fig. 14.7

Therefore, when loudspeaker is directly connected in the collector, only 50 mW of power is transferred to the loudspeaker.

(*ii*) **Loudspeaker transformer coupled.** Fig. 14.7 (*ii*) shows the class *A* power amplifier with speaker transformer coupled. As stated before, for impedance matching, step-down transformer is used.

$$\text{Output impedance of transistor} = \frac{\Delta V_{CE}}{\Delta I_C} = 12\text{ V}/100\text{ mA} = 120\,\Omega$$

In order to transfer maximum power, the primary resistance should be 120 Ω.

Now, load R'_L as seen by the primary is

$$R'_L = n^2 R_L$$

or $$120 = n^2 R_L$$

or $$n^2 = \frac{120}{5}$$

∴ $$\text{Turn ratio, } n = \sqrt{\frac{120}{5}} = \mathbf{4.9}$$

Transformer secondary voltage

$$= \frac{\text{Primary voltage}}{n} = 12/4.9 = 2.47\text{ V}$$

$$\text{Load current, } I_L = \frac{2.47\text{ V}}{5\,\Omega} = 0.49\text{ A}$$

Power transferred to the loudspeaker

$$= I_L^2 R_L$$

$$= (0.49)^2 \times 5 = 1.2\text{ W} = \mathbf{1200\text{ mW}}$$

It is clear that by employing transformer coupling, we have been able to transfer a large amount of power (1200 mW) to the speaker. The main consideration in power amplifiers is the maximum power output and, therefore, transformer coupling is invariably used.

Example 14.9. *A common emitter class A transistor power amplifier uses a transistor with* β = *100. The load has a resistance of 81.6 Ω, which is transformer coupled to the collector circuit. If the peak values of collector voltage and current are 30 V and 35 mA respectively and the corresponding minimum values are 5 V and 1 mA respectively, determine :*

(*i*) *the approximate value of zero signal collector current*

(*ii*) *the zero signal base current*

(*iii*) P_{dc} *and* P_{ac} (*iv*) *collector efficiency* (*v*) *turn ratio of the transformer.*

Solution.

In an ideal case, the minimum values of $v_{ce\,(min)}$ and $i_{c\,(min)}$ are zero. However, in actual practice, such ideal conditions cannot be realised. In the given problem, these minimum values are 5 V and 1mA respectively as shown in Fig. 14.8.

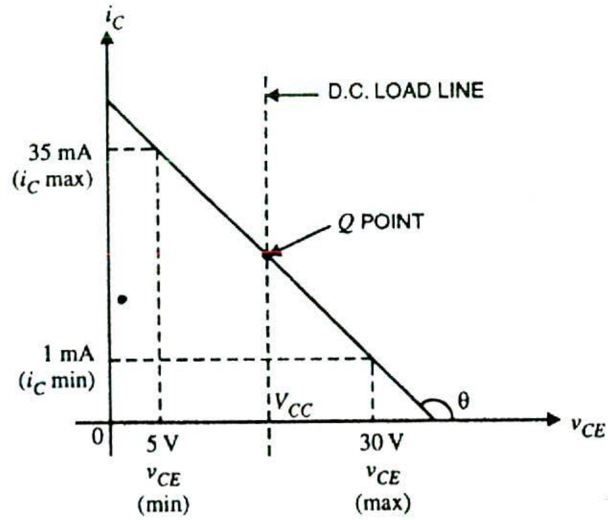


Fig. 14.8

(*i*) The zero signal collector current is approximately half-way between the maximum and minimum values of collector current *i.e.*

$$\text{Zero signal } I_C = \frac{35-1}{2}+1 = \mathbf{18\ mA}$$

(*ii*)
$$\text{Zero signal } I_B = I_C/\beta = 18/100 = \mathbf{0.18\ mA}$$

(*iii*)
$$\text{Zero signal } V_{CE} = \frac{30-5}{2}+5 = 17.5\text{ V}$$

Since the load is transformer coupled, $V_{CC} \simeq 17.5$ V.

$$\text{d.c. input power, } P_{dc} = V_{CC} I_C = 17.5\text{ V} \times 18\text{ mA} = \mathbf{315\ mW}$$

$$\text{a.c. output voltage, } V_{ce} = \frac{30-5}{2\sqrt{2}} = 8.84\text{ V}$$

$$\text{a.c. output current, } I_c = \frac{35-1}{2\sqrt{2}} = 12\text{ mA}$$

$\therefore$
$$\text{a.c. output power, } P_{ac} = V_{ce} \times I_c = 8.84\text{ V} \times 12\text{ mA} = \mathbf{106\ mW}$$

(*iv*)
$$\text{Collector } \eta = \frac{P_{ac}}{P_{dc}} \times 100 = \frac{106}{315} \times 100 = \mathbf{33.7\%}$$

(v) The a.c. resistance R'_L in the collector is determined from the slope of the line.

$$\text{Slope} = -\frac{1}{R'_L} = \frac{35-1}{5-30} = \frac{-34}{25}\ \text{mho}$$

$$\therefore \quad R'_L = \frac{25}{34}\ \text{k}\Omega = \frac{25}{34} \times 1000 = 735\ \Omega$$

$$\therefore \quad \text{Turn ratio, } n = \sqrt{\frac{R'_L}{R_L}} = \sqrt{\frac{735}{81.6}} = 3$$

14.9 Thermal Runaway

All semiconductor devices are very sensitive to temperature variations. If the temperature of a transistor exceeds the permissible limit, the transistor may be *permanently damaged. Silicon transistors can withstand temperatures upto 250°C while the germanium transistors can withstand temperatures upto 100°C.

There are two factors which determine the operating temperature of a transistor *viz.* (*i*) surrounding temperature and (*ii*) power dissipated by the transistor.

When the transistor is in operation, almost the entire heat is produced at the collector-base junction. This power dissipation causes the junction temperature to rise. This in turn increases the collector current since more electron-hole pairs are generated due to the rise in temperature. This produces an increased power dissipation in the transistor and consequently a further rise in temperature. Unless adequate cooling is provided or the transistor has built-in temperature compensation circuits to prevent excessive collector current rise, the junction temperature will continue to increase until the maximum permissible temperature is exceeded. If this situation occurs, the transistor will be permanently damaged.

The unstable condition where, owing to rise in temperature, the collector current rises and continues to increase is known as **thermal runaway.**

Thermal runaway must always be avoided. If it occurs, permanent damage is caused and the transistor must be replaced.

14.10. Heat Sink

As power transistors handle large currents, they always heat up during operation. Since transistor is a temperature dependent device, the heat generated must be dissipated to the surroundings in order to keep the temperature within permissible limits. Generally, the transistor is fixed on a metal sheet (usually aluminium) so that additional heat is transferred to the *Al* sheet.

The metal sheet that serves to dissipate the additional heat from the power transistor is known as **heat sink.**

Most of the heat within the transistor is produced at the **collector junction. The heat sink increases the surface area and allows heat to escape from the collector junction easily. The result is that temperature of the transistor is sufficiently lowered. Thus heat sink is a direct practical means of combating the undesirable thermal effects *e.g.* thermal runaway. It may be noted that the ability of any heat sink to transfer heat to the surroundings depends upon its material, volume, area, shape, contact between case and sink and movement of air around the sink. Finned aluminium heat sinks yield the best heat transfer per unit cost.

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* Almost the entire heat in a transistor is produced at the collector-base junction. If the temperature exceeds the permissible limit, this junction is destroyed and the transistor is rendered useless.

** Most of power is dissipated at the collector-base junction. This is because collector-base voltage is much greater than the base-emitter voltage, although currents through the two junctions are almost the same.

It should be realised that the use of heat sink alone may not be sufficient to prevent thermal runaway under all conditions. In designing a transistor circuit, consideration should also be given to the choice of (*i*) operating point (*ii*) ambient temperatures which are likely to be encountered and (*iii*) the type of transistor *e.g.* metal case transistors are more readily cooled by conduction than plastic ones. Circuits may also be designed to compensate automatically for temperature changes and thus stabilise the operation of the transistor components.

14.11. Mathematical Analysis

The permissible power dissipation of the transistor is very important item for power transistors. The permissible power rating of a transistor is calculated from the following relation :

$$P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta}$$

where P_{total} = total power dissipated within the transistor

$T_{J\,max}$ = maximum junction temperature. It is 90°C for *germanium* transistors and 150°C for *silicon* transistors.

T_{amb} = ambient temperature *i.e.* temperature of surrounding air

θ = *thermal resistance *i.e.* resistance to heat flow from the junction to the surrounding air

The unit of θ is °C/ watt and its value is always given in the transistor manual. A low thermal resistance means that it is easy for heat to flow from the junction to the surrounding air. The larger the transistor case, the lower is the thermal resistance and *vice-versa*. It is then clear that by using heat sink, the value of θ can be decreased considerably, resulting in increased power dissipation.

Example 14.10. *A power transistor dissipates 4 W. If T_{Jmax} = 90°C, find the maximum ambient temperature at which it can be operated. Given θ = 10°C/W.*

Solution.

$$P_{total} = 4\text{ W}$$

$$T_{J\,max} = 90°\text{C}$$

$$\theta = 10°\text{C/W}$$

Now $$P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta}$$

or $$4 = \frac{90 - T_{amb}}{10}$$

∴ Ambient temperature, $T_{amb} = 90 - 40 = \mathbf{50°C}$

The above example shows the effect of ambient temperature on the permissible power dissipation in a transistor. The lower the ambient temperature, the greater is the permissible power dissipation. Thus, a transistor can pass a higher collector current in winter than in summer.

Example 14.11. (*i*) *A power transistor has thermal resistance θ = 300°C/W. If the maximum junction temperature is 90°C and the ambient temperature is 30°C, find the maximum permissible power dissipation.*

(*ii*) *If a heat sink is used with the above transistor, the value of θ is reduced to 60°C/W. Find the maximum permissible power dissipation.*

* The path of heat flow generated at the collector-base junction is from junction to case, from case to sink and from sink to atmosphere.

Solution.

(i) *Without heat sink*

$$T_{J\,max} = 90°C$$

$$T_{amb} = 30°C$$

$$\theta = 300°C/W$$

$$\therefore \quad P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta} = \frac{90-30}{300} = 0.2\ \text{W} = \mathbf{200\ mW}$$

(ii) *With heat sink*

$$T_{J\,max} = 90°C$$

$$T_{amb} = 30°C$$

$$\theta = 60°C/W$$

$$\therefore \quad P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta} = \frac{90-30}{60} = 1\ \text{W} = \mathbf{1000\ mW}$$

It is clear from the above example that permissible power dissipation with heat sink is 5 times as compared to the case when no heat sink is used.

Example 14.12. *The total thermal resistance of a power transistor and heat sink is 20°C/W. The ambient temperature is 25°C and $T_{J\,max}$ = 200°C. If V_{CE} = 4 V, find the maximum collector current that the transistor can carry without destruction. What will be the allowed value of collector current if ambient temperature rises to 75°C ?*

Solution.

$$P_{total} = \frac{T_{Jmax} - T_{amb}}{\theta} = \frac{200-25}{20} = 8.75\ \text{W}$$

This means that maximum permissible power dissipation of the transistor at ambient temperature of 25°C is 8.75 W *i.e.*

$$V_{CE} I_C = 8.75$$

$$\therefore \quad I_C = 8.75/4 = \mathbf{2.19\ A}$$

Again

$$P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta} = \frac{200-75}{20} = 6.25\ \text{W}$$

$$\therefore \quad I_C = 6.25/4 = \mathbf{1.56\ A}$$

This example clearly shows the effect of ambient temperature.

14.12 Stages Of A Practical Power Amplifier

The function of a practical power amplifier is to amplify a weak signal until sufficient power is available to operate a loudspeaker or other output device. To achieve this goal, a power amplifier has generally three stages *viz. voltage amplification stage*, ***driver stage*** and ***output stage***. Fig. 14.9 shows the block diagram of a practical power amplifier.

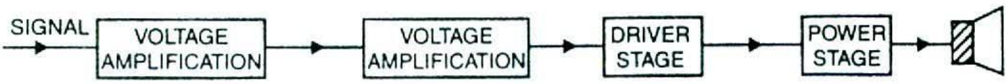


Fig. 14.9

(i) *Voltage amplification stage.* The signals found in practice have extremely low voltage level (< 10 mV). Therefore, the voltage level of the weak signal is raised by two or more voltage amplifiers. Generally, *RC* coupling is employed for this purpose.

(*ii*) *Driver stage.* The output from the last voltage amplification stage is fed to the driver stage. It supplies the necessary power to the output stage. The driver stage generally employs class *A* transformer coupled power amplifier. Here, concentrated effort is made to obtain *maximum power gain*.

(*iii*) *Output stage.* The output power from the driver stage is fed to the output stage. It is the final stage and feeds power directly to the speaker or other output device. The output stage is invariably transformer coupled and employs class *B* amplifiers in push-pull arrangement. Here, concentrated effort is made to obtain *maximum power output*.

14.13 Driver Stage

The stage that immediately precedes the output stage is called the *driver stage*. It operates as a class *A* power amplifier and supplies the drive for the output stage. Fig. 14.10 shows the driver stage. Note that transformer coupling is employed. The primary of this transformer is the collector load. The secondary is almost always centre-tapped so as to provide equal and opposite voltages to the input of push-pull amplifier (*i.e.* output stage). The driver transformer is usually a step-down transformer and facilitates impedance matching.

The output from the last voltage amplification stage forms the input to the driver stage. The driver stage renders power amplification in the usual way. It may be added that main consideration here is the maximum power gain. The output of the driver stage is taken from the centre-tapped secondary and is fed to the output stage.

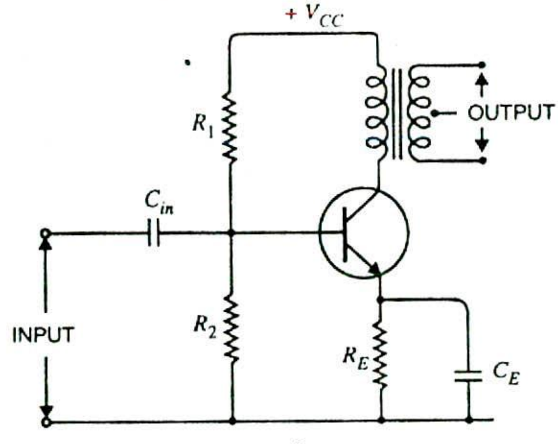


Fig. 14.10

14.14 Output Stage

The output stage essentially consists of a power amplifier and its purpose is to transfer maximum power to the output device. If a single transistor is used in the output stage, it can only be employed as class *A* amplifier for faithful amplification. Unfortunately, the power efficiency of a class *A* amplifier is very low ($\simeq$ 35%). As transistor amplifiers are operated from batteries, which is a costly source of power, therefore, such a low efficiency cannot be tolerated.

In order to obtain high output power at high efficiency, pushpull arrangement is used in the output stage. In this arrangement, we employ two transistors in class *B* operation. One transistor amplifies the positive half-cycle of the signal while the other transistor amplifies the negative half-cycle of the signal. In this way, output voltage is a complete sine wave. At the same time, the circuit delivers high output power to the load due to class *B* operation.

14.15 Push-Pull Amplifier

The push-pull amplifier is a power amplifier and is frequently employed in the output stages of electronic circuits. It is used whenever high output power at high efficiency is required. Fig. 14.11 shows the circuit of a push-pull amplifier. Two transistors T_{r1} and T_{r2} placed back to back are employed. Both transistors are operated in class *B* operation *i.e.* collector current is nearly zero in the absence of the signal. The centre-tapped secondary of driver transformer T_1 supplies equal and opposite voltages to the base circuits of two transistors.

The output transformer T_2 has the centre-tapped primary winding. The supply voltage V_{CC} is connected between the bases and this centre tap. The loudspeaker is connected across the secondary of this transformer.

Circuit operation. The input signal appears across the secondary *AB* of driver transformer. Suppose during the first half-cycle (marked 1) of the signal, end *A* becomes positive and end *B* negative. This will make the base-emitter junction of T_{r1} reverse biased and that of T_{r2} forward biased. The circuit will conduct current due to T_{r2} only and is shown by solid arrows. Therefore, this half-cycle of the signal is amplified by T_{r2} and appears in the lower half of the primary of output transformer. In the next half-cycle of the signal, T_{r1} is forward biased whereas T_{r2} is reverse biased. Therefore, T_{r1} conducts and is shown by dotted arrows. Consequently, this half-cycle of the signal is amplified by T_{r1} and appears in the upper half of the output transformer primary. The centre-tapped primary of the output transformer combines two collector currents to form a sine wave output in the secondary.

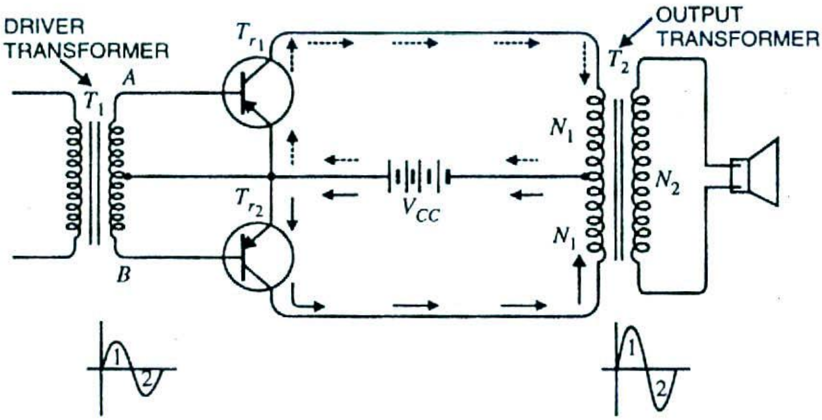


Fig. 14.11

It may be noted here that push-pull arrangement also permits a maximum transfer of power to the load through impedance matching. If R_L is the resistance appearing across secondary of output transformer, then resistance R'_L of primary shall become :

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

where N_1 = Number of turns between either end of primary winding and centre-tap

N_2 = Number of secondary turns

Advantages

(*i*) The efficiency of the circuit is quite high ($\simeq$ 75%) due to class *B* operation.

(*ii*) A high a.c. output power is obtained.

Disadvantages

(*i*) Two transistors have to be used.

(*ii*) It requires two equal and opposite voltages at the input. Therefore, push-pull circuit requires the use of driver stage to furnish these signals.

(*iii*) If the parameters of the two transistors are not the same, there will be unequal amplification of the two halves of the signal.

(*iv*) The circuit gives more distortion.

(*v*) Transformers used are bulky and expensive.

14.16 Complementary-Symmetry Amplifier

By complementary symmetry is meant a principle of assembling push-pull class *B* amplifier without requiring centre-tapped transformers at the input and output stages. Fig. 14.12 shows the transistor push-pull amplifier using complementary symmetry. It employs one *npn* and one *pnp* transistor and requires no centre-tapped transformers. The circuit action is as follows. During the positive-half of the input signal, transistor T_1 (the *npn* transistor) conducts current while T_2 (the *pnp* transistor) is cut off. During the negative half-cycle of the signal, T_2 conducts while T_1 is cut off. In this way, *npn* transistor amplifies the positive half-cycles of the signal while the *pnp* transistor amplifies the negative half-cycles of the signal. Note that we generally use an output transformer (not centre-tapped) for impedance matching.

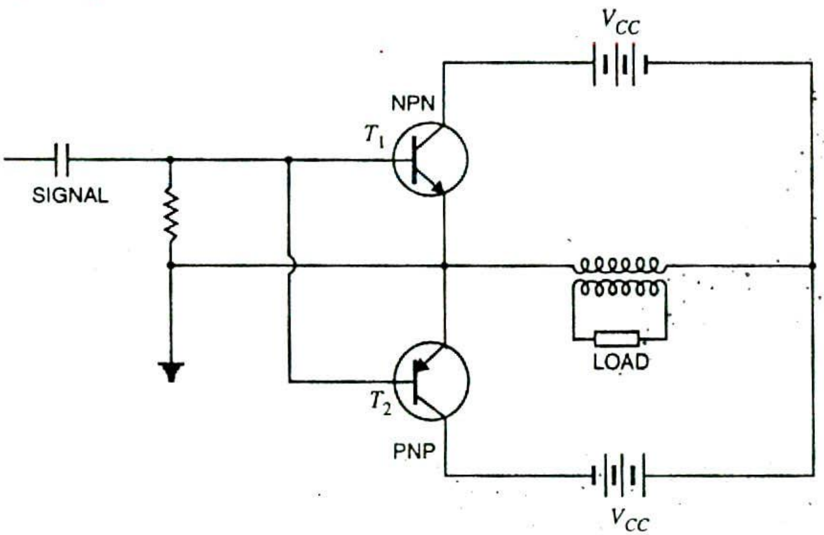


Fig.14.12

Advantages

(*i*) This circuit does not require transformer. This saves on weight and cost.

(*ii*) Equal and opposite input signal voltages are not required.

Disadvantages

(*i*) It is difficult to get a pair of transistors (*npn* and *pnp*) that have similar characteristics.

(*ii*) We require both positive and negative supply voltages.

Multiple-Choice Questions

1. The output stage of a multistage amplifier is also called ....
   (i) mixer stage (ii) power stage
   (iii) detector stage (iv) R.F. stage
2. .... coupling is generally employed in power amplifiers.
   (i) transformer (ii) *RC*
   (iii) direct (iv) impedance
3. A class *A* power amplifier uses ....
   (i) two transistors (ii) three transistors
   (iii) one transistor (iv) none of the above
4. The maximum efficiency of resistance loaded class *A* power amplifier is ....
   (i) 78.5% (ii) 50%
   (iii) 30% (iv) 25%
5. The maximum efficiency of transformer coupled class *A* power amplifier is ....
   (i) 30% (ii) 50%
   (iii) 80% (iv) 45%
6. Class .... power amplifier has the highest collector efficiency.
   (i) *C* (ii) *A*
   (iii) *B* (iv) *AB*
7. Power amplifiers handle .... signals compared to voltage amplifiers.
   (i) small (ii) very small
   (iii) large (iv) none of the above
8. In class *A* operation, the operating point is generally located .... of the d.c. load line.
   (i) at cut off point (ii) at the middle
   (iii) at saturation point
   (iv) none of the above
9. Class *C* amplifiers are used as ....
   (i) AF amplifiers (ii) detectors
   (iii) R.F. amplifiers (iv) none of the above
10. A power amplifier has comparatively ....β.
    (i) small (ii) large
    (iii) very large (iv) none of the above
11. The maximum collector efficiency of class *B* operation is ....
    (i) 50% (ii) 90%
    (iii) 60.5% (iv) 78.5%
12. A 2-transistor class *B* power amplifier is commonly called .... amplifier.
    (i) dual (ii) push-pull
    (iii) symmetrical (iv) differential
13. If a transistor is operated in such a way that output current flows for 60° of the input signal, then it is ...... operation.
    (i) class *A* (ii) class *B*
    (iii) class *C* (iv) none of the above
14. If the zero signal power dissipation of a transistor is 1 W, then power rating of the transistor should be atleast ....
    (i) 0.5 W (ii) 0.33 W
    (iii) 0.75 W (iv) 1 W
15. When a transistor is cut off, ...
    (i) maximum voltage appears across transistor
    (ii) maximum current flows
    (iii) maximum voltage appears across load
    (iv) none of the above
16. A class *A* power amplifier is sometimes called .... amplifier.
    (i) symmetrical (ii) single-ended
    (iii) reciprocating (iv) differential
17. Class .... operation gives the maximum distortion.
    (i) *A* (ii) *B*
    (iii) *C* (iv) *AB*
18. The output stage of a multistage amplifier usually employs ....
    (i) push-pull amplifier
    (ii) preamplifier
    (iii) class *A* power amplifier
    (iv) none of the above
19. The size of a power transistor is made considerably large to ....
    (i) provide easy handling
    (ii) dissipate heat
    (iii) facilitate connections
    (iv) none of the above

20. Low efficiency of a power amplifier results in ....

(*i*) low forward bias

(*ii*) less battery consumption

(*iii*) more battery consumption

(*iv*) none of the above

21. The driver stage usually employs ....

(*i*) class *A* power amplifier

(*ii*) push-pull amplifier

(*iii*) class *C* amplifier

(*iv*) none of the above

22. If the power rating of a transistor is 1 W and collector current is 100 mA, then maximum allowable collector voltage is ....

(*i*) 1 V (*ii*) 100 V

(*iii*) 20 V (*iv*) 10 V

23. When no signal is applied, the approximate collector efficiency of class *A* power amplifier is ....

(*i*) 10% (*ii*) 0%

(*iii*) 25% (*iv*) 50%

24. What will be the collector efficiency of a power amplifier having zero signal power dissipation of 5 watts and a.c. power output of 2 watts ?

(*i*) 20% (*ii*) 80%

(*iii*) 40% (*iv*) 50%

25. The output signal voltage and current of a power amplifier are 5 V and 200 mA ; the values being r.m.s. What is the power output ?

(*i*) 1 W (*ii*) 2 W

(*iii*) 4 W (*iv*) none of the above

26. The maximum a.c. power output from a class *A* power amplifier is 10 W. What should be the minimum power rating of the transistor used ?

(*i*) 10 W (*ii*) 15 W

(*iii*) 5 W (*iv*) 20 W

27. For the same a.c. power output as above, what should be the minimum power rating of transistor for class *B* operation ?

(*i*) 10 W (*ii*) 4 W

(*iii*) 8 W (*iv*) none of the above

28. The push-pull circuit must use ..... operation.

(*i*) class *A* (*ii*) class *C*

(*iii*) class *B* (*iv*) class *AB*

29. The class B push-pull circuit can deliver 100 W of a.c. output power. What should be the minimum power rating of each transistor ?

(*i*) 20 W (*ii*) 40 W

(*iii*) 10 W (*iv*) 80 W

30. What turn ratio (N_p/N_s) of transformer is required to match 4 Ω speaker to a transistor having an output impedance of 8000 Ω ?

(*i*) 35.2 (*ii*) 44.7

(*iii*) 54.3 (*iv*) none of the above

31. A transformer coupled class *A* power amplifier has a load of 100 Ω on the secondary. If the turn ratio is 10 : 1, what is the value of load appearing on the primary ?

(*i*) 5 kΩ (*ii*) 20 kΩ

(*iii*) 100 kΩ (*iv*) 10 kΩ

32. Power amplifiers generally use transformer coupling because transformer permits ....

(*i*) cooling of the circuit

(*ii*) impedance matching

(*iii*) distortionless output

(*iv*) good frequency response

33. Transformer coupling can be used in .... amplifiers.

(*i*) either power or voltage

(*ii*) only power

(*iii*) only voltage (*iv*) none of the above

34. The output transformer used in a power amplifier is a ...... transformer.

(*i*) 1 : 1 ratio (*ii*) step-up

(*iii*) step-down (*iv*) none of the above

35. The most important consideration in power amplifiers is......

(*i*) biasing the circuit

(*ii*) collector efficiency

(*iii*) to keep the transformer cool

(*iv*) none of the above

36. An *AF* amplifier is shielded to ....

(*i*) keep the amplifier cool

(*iii*) prevent induction due to stray magnetic fields
(*iv*) none of the above

37. The pulsating d.c. applied to power amplifier causes ....
(*i*) burning of transistor
(*ii*) hum in the circuit
(*iii*) excessive forward voltage
(*iv*) none of the above

38. The disadvantage of impedance matching is that it ....
(*i*) gives distorted output
(*ii*) gives low power output
(*iii*) requires a transformer
(*iv*) none of the above

39. If the gain versus frequency curve of a transistor amplifier is not flat, then there is .... distortion.
(*i*) amplitude (*ii*) intermodulation
(*iii*) frequency (*iv*) none of the above

40. The most costly coupling is .... coupling.
(*i*) *RC* (*ii*) direct
(*iii*) impedance (*iv*) transformer.

Answers to Multiple-Choice Questions

1. (*ii*)	**2.** (*i*)	**3.** (*iii*)	**4.** (*iv*)	**5.** (*ii*)
6. (*i*)	**7.** (*iii*)	**8.** (*ii*)	**9.** (*iii*)	**10.** (*i*)
11. (*iv*)	**12.** (*ii*)	**13.** (*iii*)	**14.** (*iv*)	**15.** (*i*)
16. (*ii*)	**17.** (*iii*)	**18.** (*i*)	**19.** (*ii*)	**20.** (*iii*)
21. (*i*)	**22.** (*iv*)	**23.** (*ii*)	**24.** (*iii*)	**25.** (*i*)
26. (*iv*)	**27.** (*ii*)	**28.** (*iii*)	**29.** (*i*)	**30.** (*ii*)
31. (*iv*)	**32.** (*ii*)	**33.** (*i*)	**34.** (*iii*)	**35.** (*ii*)
36. (*iii*)	**37.** (*ii*)	**38.** (*i*)	**39.** (*iii*)	**40.** (*iv*)

Chapter Review Topics

1. What is an audio power amplifier ? What is its need ?
2. Explain the difference between a voltage and a power amplifier.
3. What do you understand by class A, class B and class C power amplifiers ?
4. Define and explain the following terms as applied to power amplifiers.
   (*i*) collector efficiency (*ii*) distortion (*iii*) power dissipation capability
5. Show that maximum collector efficiency of class A transformer coupled power amplifier is 50%.
6. Draw the block diagram of a practical power amplifier.
7. Explain the push-pull circuit with a neat diagram.
8. Write short notes on the following :
   (*i*) Heat sink (*ii*) Driver stage
   (*iii*) Output stage (*iv*) Complementary-symmetry amplifier

Problems

1. The resistance of the secondary of an output transformer is 100 Ω. If the output impedance is 10 kΩ, find the turn ratio of the transformer for maximum power transference. **[$n = 10$]**
2. A power transistor working in class *A* operation has zero signal power dissipation of 5 watts. If a.c. output power is 2 watts, find (*i*) collector efficiency (*ii*) power rating of transistor. **[(*i*) 40% (*ii*) 5 watts]**
3. A class *A* power amplifier has a maximum a.c. power output of 30 W. Find the power rating of the transistor. **[60 W]**

4. The a.c. power output of a class *A* power amplifier is 2 W. If the collector efficiency is 40%, find the power rating of the transistor. **[5 W]**

5. In a class A transformer coupled amplifier, collector current alternates between 3 mA and 110 mA and its quiescent value is 58 mA. The load resistance is 15 Ω and when referred to primary winding is 325 Ω. The supply voltage is 20V. Find (*i*) transformer turn ratio (*ii*) a.c. power output (*iii*) power rating of transistor.

6. A transistor has thermal resistance θ = 80°C/W. If the maximum junction temperature is 90°C and the ambient temperature is 30°C, find the maximum permissible power dissipation. **[750 mW]**

7. A power transistor dissipates 4 W. If $T_{J\,max}$ = 90°C, find the maximum ambient temperature at which it can be operated. Given thermal resistance θ = 8°C/W. **[58 °C]**

Discussion Questions

1. Why does collector efficiency play important part in power amplifiers ?
2. Why does the problem of distortion arise in power amplifiers ?
3. Why are power amplifiers classified on the basis of mode of operation ?
4. Why does the output stage employ push-pull arrangement ?
5. Why is driver stage necessary for push-pull circuit ?
6. Why do we use transformer in the output stage ?

15

Amplifiers with Negative Feedback

Introduction

A practical amplifier has a gain of nearly one million *i.e.* its output is one million times the input. Consequently, even a casual disturbance at the input will appear in the amplified form in the output. There is a strong tendency in amplifiers to introduce *hum* due to sudden temperature changes or stray electric and magnetic fields. Therefore, every high gain amplifier tends to give noise along with signal in its output. The noise in the output of an amplifier is undesirable and must be kept to as small a level as possible.

The noise level in amplifiers can be reduced considerably by the use of *negative feedback i.e.* by injecting a fraction of output in phase opposition to the input signal. The object of this chapter is to consider the effects and methods of providing negative feedback in transistor amplifiers.

15.1 Feedback

The process of injecting a fraction of output energy of some device back to the input is known as **feedback**.

The principle of feedback is probably as old as the invention of first machine but it is only some 40 years ago that feedback has come into use in connection with electronic circuits. It has been found very useful in reducing noise in amplifiers and making amplifier operation stable. Depending upon whether the feedback energy aids or opposes the input signal, there are two basic types of feedback in amplifiers *viz positive feedback* and *negative feedback*.

(*i*) **Positive feedback.** When the feedback energy (voltage or current) is in phase with the input signal and thus aids it, it is called *positive feedback*. This is illustrated in Fig. 15.1. Both amplifier and feedback network introduce a phase shift of 180°. The result is a 360° phase shift around the loop, causing the *feedback voltage* V_f to be in phase with the input signal V_{in}.

The positive feedback increases the gain of the amplifier. However, it has the disadvantages of increased distortion and instability. Therefore, positive feedback is seldom employed in amplifiers. One important use of positive feedback is in oscillators. As we shall see in the next chapter, if positive feedback is sufficiently large, it leads to oscillations. As a matter of fact, an oscillator is a device that converts d.c. power into a.c. power of any desired frequency.

(*ii*) **Negative feedback.** When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called *negative feedback*. This is illustrated in Fig. 15.2. As you can see, the amplifier introduces a phase shift of 180° into the circuit while the feedback network is so designed that it introduces no phase shift (*i.e.*, 0° phase shift). The result is that the *feedback voltage* V_f is 180° out of phase with the input signal V_{in}.

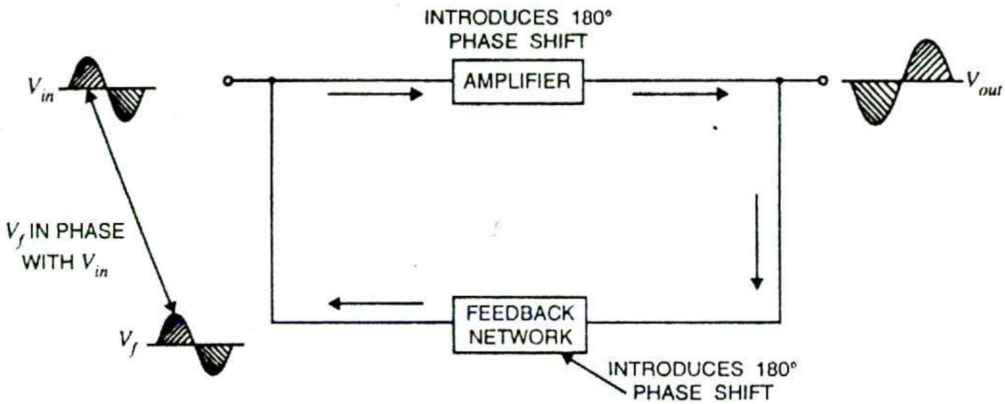


Fig. 15.1

Negative feedback reduces the gain of the amplifier. However, the advantages of negative feedback are: reduction is distortion, stability in gain, increased bandwidth and improved input and output impedances. It is due to these advantages that negative feedback is frequently employed in amplifiers.

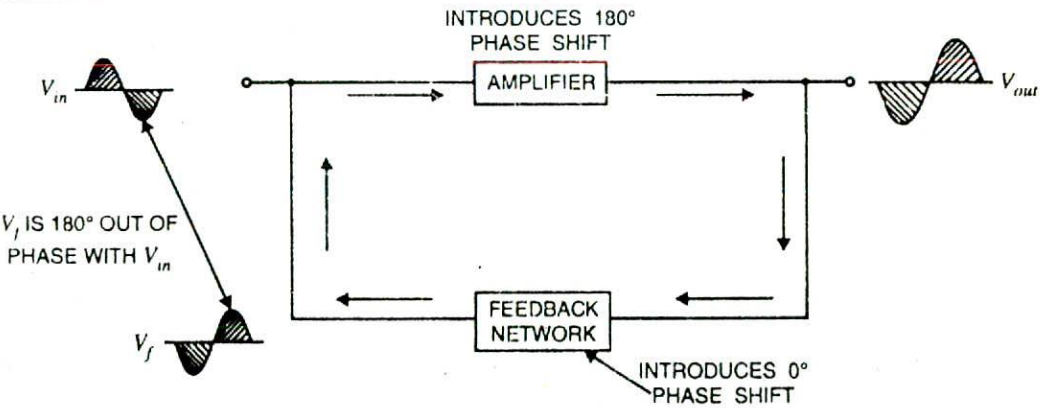


Fig. 15.2

15.2 Principles of Negative Voltage Feedback In Amplifiers

A feedback amplifier has two parts viz an amplifier and a feedback circuit. The feedback circuit usually consists of resistors and returns a fraction of output energy back to the input. Fig. 15.3 *shows the principles of negative voltage feedback in an amplifier. Typical values have been assumed to make the treatment more illustrative. The output of the amplifier is 10 V. The fraction m_v of this output *i.e.* 100 mV is fedback to the input where it is applied in series with the input signal of 101 mV. As the feedback is negative, therefore, only 1 mV appears at the input terminals of the amplifier.

Referring to Fig. 15.3, we have,

$$\text{Gain of amplifier without feedback, } A_v = \frac{10\text{ V}}{1\text{ mV}} = 10,000$$

* Note that amplifier and feedback circuits are connected in *series-parallel*. The inputs of amplifier and feedback circuits are in *series* but the outputs are in *parallel*. In practice, this circuit is widely used.

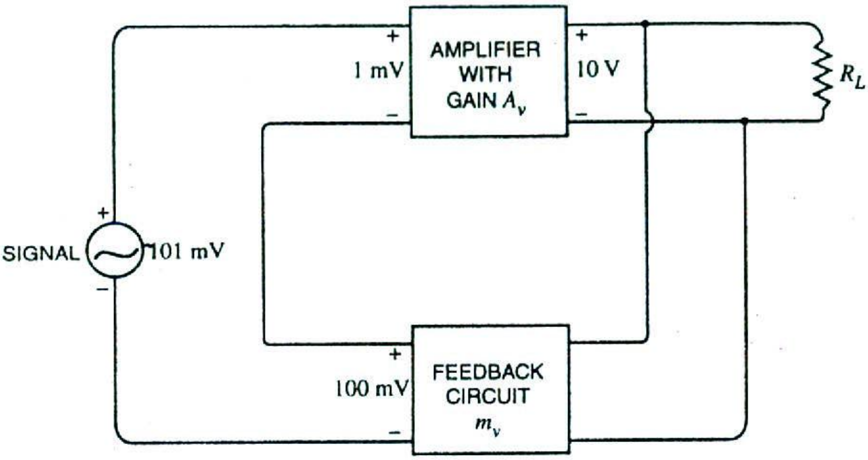


Fig. 15.3

$$\text{Fraction of output voltage fedback, } m_v = \frac{100 \text{ mV}}{10 \text{ V}} = 0.01$$

$$\text{Gain of amplifier with feedback, } A_{vf} = \frac{10 \text{ V}}{101 \text{ mV}} = 100$$

The following points are worth noting :

(*i*) When negative voltage feedback is applied, the gain of the amplifier is *reduced. Thus, the gain of above amplifier without feedback is 10,000 whereas with negative feedback, it is only 100.

(*ii*) When negative voltage feedback is employed, the voltage *actually* applied to the amplifier is extremely small. In this case, the signal voltage is 101 mV and the negative feedback is 100 mV so that voltage applied at the input of the amplifier is only 1 mV.

(*iii*) In a negative voltage feedback circuit, the feedback fraction m_v is always between 0 and 1.

(*iv*) The gain with feedback is sometimes called *closed-loop gain* while the gain without feedback is called *open-loop gain*. These terms come from the fact that amplifier and feedback circuits form a "loop". When the loop is "opened" by disconnecting the feedback circuit from the input, the amplifier's gain is A_v, the "open-loop" gain. When the loop is "closed" by connecting the feedback circuit, the gain decreases to A_{vf}, the "closed-loop" gain.

15.3 Gain of Negative Voltage Feedback Amplifier

Consider the negative voltage feedback amplifier shown in Fig. 15.4. The gain of the amplifier without feedback is A_v. Negative feedback is then applied by feeding a fraction m_v of the output voltage e_0 back to amplifier input. Therefore, the actual input to the amplifier is the signal voltage e_g *minus* feedback voltage $m_v e_0$ *i.e.*,

$$\text{Actual input to amplifier} = e_g - m_v e_0$$

The output e_0 must be equal to the input voltage $e_g - m_v e_0$ multiplied by gain A_v of the amplifier *i.e.*,

$$(e_g - m_v e_0) A_v = e_0$$

or

$$A_v e_g - A_v m_v e_0 = e_0$$

* Since with negative voltage feedback the voltage gain is decreased and current gain remains unaffected, the power gain A_p $(= A_v \times A_i)$ will decrease. However, the drawback of reduced power gain is offset by the advantage of increased bandwidth.

or $$e_0(1 + A_v m_v) = A_v e_g$$

or $$\frac{e_0}{e_g} = \frac{A_v}{1 + A_v m_v}$$

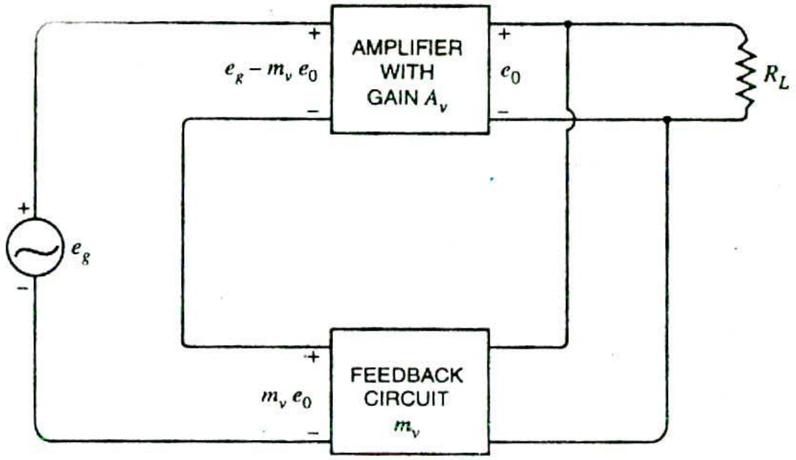


Fig. 15.4

But e_0/e_g is the voltage gain of the amplifier with feedback.

∴ Voltage gain with negative feedback is

$$A_{vf} = \frac{A_v}{1 + A_v m_v}$$

It may be seen that the gain of the amplifier without feedback is A_v. However, when negative voltage feedback is applied, the gain is reduced by a factor $1 + A_v m_v$. It may be noted that negative voltage feedback does not affect the current gain of the circuit.

Example 15.1. *The voltage gain of an amplifier without feedback is 3000. Calculate the voltage gain of the amplifier if negative voltage feedback is introduced in the circuit. Given that feedback fraction $m_v = 0.01$.*

Solution. $A_v = 3000, \quad m_v = 0.01$

∴ Voltage gain with negative feedback is

$$A_{vf} = \frac{A_v}{1 + A_v m_v} = \frac{3000}{1 + 3000 \times 0.01} = \frac{3000}{31} = \mathbf{97}$$

Example 15.2. *The overall gain of a multistage amplifier is 140. When negative voltage feedback is applied, the gain is reduced to 17.5. Find the fraction of the output that is fedback to the input.*

Solution. $A_v = 140, \quad A_{vf} = 17.5$

Let m_v be the feedback fraction. Voltage gain with negative feedback is

$$A_{vf} = \frac{A_v}{1 + A_v m_v}$$

or $$17.5 = \frac{140}{1 + 140\, m_v}$$

or $$17.5 + 2450\, m_v = 140$$

$$\therefore \qquad m_v = \frac{140 - 17.5}{2450} = \frac{1}{20}$$

Example 15.3. *When negative voltage feedback is applied to an amplifier of gain 100, the overall gain falls to 50.*

(i) Calculate the fraction of the output voltage fedback.

(ii) If this fraction is maintained, calculate the value of the amplifier gain required if the overall stage gain is to be 75.

Solution.

(*i*) Gain without feedback, $A_v = 100$

Gain with feedback, $A_{vf} = 50$

Let m_v be the fraction of the output voltage fedback.

Now $$A_{vf} = \frac{A_v}{1 + A_v\, m_v}$$

or $$50 = \frac{100}{1 + 100\, m_v}$$

or $$50 + 5000\, m_v = 100$$

or $$m_v = \frac{100 - 50}{5000} = \mathbf{0.01}$$

(*ii*) $A_{vf} = 75$; $m_v = 0.01$; $A_v = ?$

$$A_{vf} = \frac{A_v}{1 + A_v\, m_v}$$

or $$75 = \frac{A_v}{1 + 0.01\, A_v}$$

or $$75 + 0.75\, A_v = A_v$$

$$\therefore \qquad A_v = \frac{75}{1 - 0.75} = \mathbf{300}$$

Example 15.4. *With a negative voltage feedback, an amplifier gives an output of 10 V with an input of 0.5 V. When feedback is removed, it requires 0.25 V input for the same output. Calculate (i) gain without feedback (ii) feedback fraction m_v.*

Solution.

(*i*) Gain without feedback, $A_v = 10/0.25 = \mathbf{40}$

(*ii*) Gain with feedback, $A_{vf} = 10/0.5 = 20$

Now $$A_{vf} = \frac{A_v}{1 + A_v\, m_v}$$

or $$20 = \frac{40}{1 + 40\, m_v}$$

or $$20 + 800\, m_v = 40$$

or $$m_v = \frac{40 - 20}{800} = \mathbf{\frac{1}{40}}$$

Example 15.5. *The gain of an amplifier without feedback is 50 whereas with negative voltage feedback, it falls to 25. If due to ageing, the amplifier gain falls to 40, find the percentage reduction in stage gain (i) without feedback and (ii) with negative feedback.*

Solution. $$A_{vf} = \frac{A_v}{1 + A_v m_v}$$

or $$25 = \frac{50}{1 + 50 m_v}$$

or $$m_v = 1/50$$

(*i*) **Without feedback.** The gain of the amplifier without feedback is 50. However, due to ageing, it falls to 40.

$$\therefore \quad \text{\%age reduction in stage gain} = \frac{50 - 40}{50} \times 100 = \mathbf{20\%}$$

(*ii*) **With negative feedback.** When the gain without feedback was 50, the gain with negative feedback was 25. Now the gain without feedback falls to 40.

$$\therefore \quad \text{New gain with negative feedback} = \frac{A_v}{1 + A_v m_v} = \frac{40}{1 + (40 \times 1/50)} = 22.2$$

$$\therefore \quad \text{\%age reduction in stage gain} = \frac{25 - 22.2}{25} \times 100 = \mathbf{11.2\%}$$

Example 15.6. *An amplifier has a voltage amplification A_v and a fraction m_v of its output is fedback in opposition to the input. If $m_v = 0.1$ and $A_v = 100$, calculate the percentage change in the gain of the system if A_v falls 6db due to ageing.*

Solution. $$A_v = 100, \quad m_v = 0.1, \quad A_{vf} = ?$$

$$A_{vf} = \frac{A_v}{1 + A_v m_v} = \frac{100}{1 + 100 \times 0.1} = 9.09$$

$$\text{Fall in gain} = 6db$$

Let A_{v1} be the new absolute voltage gain without feedback.

Then, $$20 \log_{10} A_v/A_{v1} = 6$$

or $$\log_{10} A_v/A_{v1} = 6/20 = 0.3$$

or $$\frac{A_v}{A_{v1}} = \text{Antilog } 0.3 = 2$$

or $$A_{v1} = A_v/2 = 100/2 = 50$$

$$\therefore \quad \text{New } A_{vf} = \frac{A_{v1}}{1 + A_{v1} m_v} = \frac{50}{1 + 50 \times 0.1} = 8.33$$

$$\text{\% age change in system gain} = \frac{9.09 - 8.33}{9.09} \times 100 = \mathbf{8.36\%}$$

Example 15.7. *An amplifier with an open-circuit voltage gain of 1000 has an output resistance of 100 Ω and feeds a resistive load of 900 Ω. Negative voltage feedback is provided by connecting a resistive voltage divider across the output and one-fiftieth of the output voltage is fedback in series with the input signal. Determine the voltage gain with negative feedback.*

Solution. Fig. 15.5 shows the equivalent circuit of an amplifier along with the feedback circuit.

Voltage gain of the amplifier without feedback is

$$A_v = \frac{A_0 R_L}{R_{out} + R_L} \quad \text{...See Art. 12.15}$$

$$= \frac{1000 \times 900}{100 + 900} = 900$$

$$\therefore \quad A_{vf} = \frac{A_v}{1 + A_v m_v} = \frac{900}{1 + 900 \times (1/50)} = 47.4$$

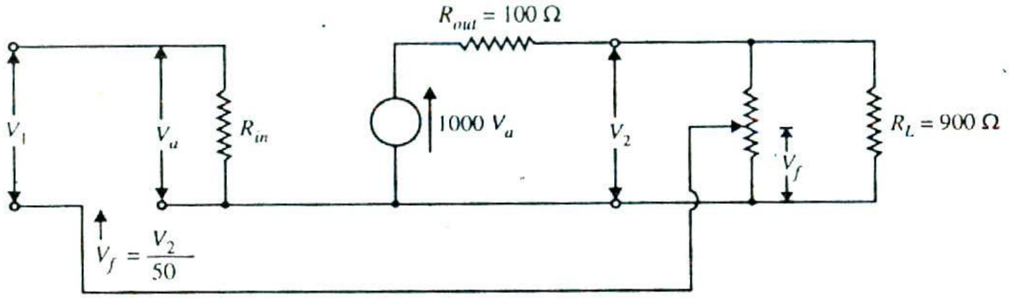


Fig. 15.5

15.4 Advantages of Negative Voltage Feedback

The following are the advantages of negative voltage feedback in amplifiers :

(*i*) **Gain stability.** An important advantage of negative voltage feedback is that the resultant gain of the amplifier can be made independent of transistor parameters or the supply voltage variations.

$$A_{vf} = \frac{A_v}{1 + A_v m_v}$$

For negative voltage feedback in an amplifier to be effective, the designer deliberately makes the product $A_v m_v$ much greater than unity. Therefore, in the above relation, 1 can be neglected as compared to $A_v m_v$ and the expression becomes :

$$A_{vf} = \frac{A_v}{A_v m_v} = \frac{1}{m_v}$$

It may be seen that the gain now depends only upon feedback fraction m_v *i.e.*, on the characteristics of feedback circuit. As feedback circuit is usually a voltage divider (a resistive network), therefore, it is unaffected by changes in temperature, variations in transistor parameters and frequency. Hence, the gain of the amplifier is extremely stable.

(*ii*) **Reduces non-linear distortion.** A large signal stage has non-linear distortion because its voltage gain changes at various points in the cycle. The negative voltage feedback reduces the non-linear distortion in large signal amplifiers. It can be proved mathematically that :

$$D_{vf} = \frac{D}{1 + A_v m_v}$$

where D = distortion in amplifier without feedback

D_{vf} = distortion in amplifier with negative feedback

It is clear that by applying negative voltage feedback to an amplifier, distortion is reduced by a factor $1 + A_v m_v$.

(*iii*) **Improves frequency response.** As feedback is usually obtained through a resistive network, therefore, voltage gain of the amplifier is *independent of signal frequency. The result is that

---

* $A_{vf} = 1/m_v$. Now m_v depends upon feedback circuit. As feedback circuit consists of resistive network, therefore, value of m_v is unaffected by change in signal frequency.

voltage gain of the amplifier will be substantially constant over a wide range of signal frequency. The negative voltage feedback, therefore, improves the frequency response of the amplifier.

(*iv*) **Increases circuit stability.** The output of an ordinary amplifier is easily changed due to variations in ambient temperature, frequency and signal amplitude. This changes the gain of the amplifier, resulting in distortion. However, by applying negative voltage feedback, voltage gain of the amplifier is stabilised or accurately fixed in value. This can be easily explained. Suppose the output of a negative voltage feedback amplifier has increased because of temperature change or due to some other reason. This means more negative feedback since feedback is being given from the output. This tends to oppose the increase in amplification and maintains it stable. The same is true should the output voltage decrease. Consequently, the circuit stability is considerably increased.

(*v*) **Increases input impedance and decreases output impedance.** The negative voltage feedback increases the input impedance and decreases the output impedance of amplifier. Such a change is profitable in practice as the amplifier can then serve the purpose of impedance matching.

(*a*) **Input impedance.** The increase in input impedance with negative voltage feedback can be explained by referring to Fig. 15.6. Suppose the input impedance of the amplifier is Z_{in} without feedback and Z'_{in} with negative feedback. Let us further assume that input current is i_1.

Referring to Fig. 15.6, we have,

$$e_g - m_v e_o = i_1 Z_{in}$$

Now

$$\begin{aligned} e_g &= (e_g - m_v e_o) + m_v e_o \\ &= (e_g - m_v e_o) + A_v m_v (e_g - m_v e_o) \qquad [\because e_o = A_v (e_g - m_v e_o)] \\ &= (e_g - m_v e_o)(1 + A_v m_v) \\ &= i_1 Z_{in} (1 + A_v m_v) \qquad [\because e_g - m_v e_o = i_1 Z_{in}] \end{aligned}$$

or

$$\frac{e_g}{i_1} = Z_{in}(1 + A_v m_v)$$

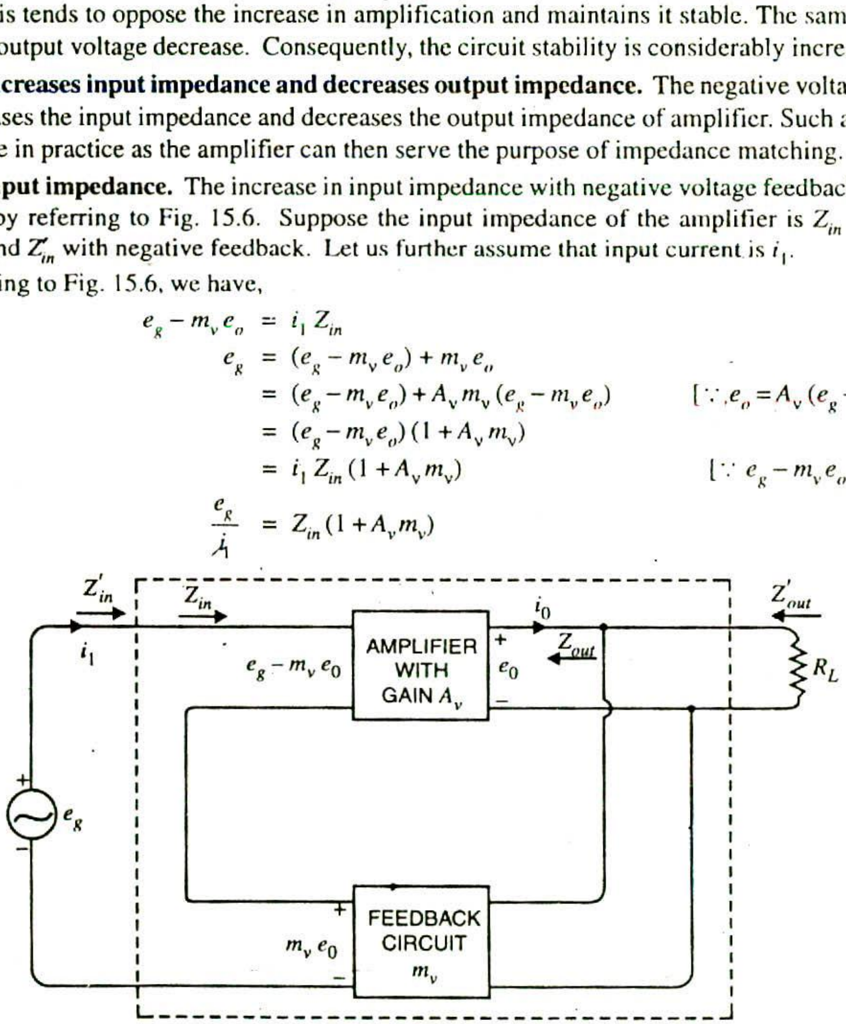


Fig. 15.6

But $e_g/i_1 = Z'_{in}$, the input impedance of the amplifier with negative voltage feedback.

$$\therefore \qquad Z'_{in} = Z_{in}(1 + A_v m_v)$$

It is clear that by applying negative voltage feedback, the input impedance of the amplifier is increased by a factor $1 + A_v m_v$. As $A_v m_v$ is much greater than unity, therefore, input impedance is increased considerably. This is an advantage, since the amplifier will now present less of a load to its source circuit.

(*b*) **Output impedance.** Following similar line, we can show that output impedance with negative voltage feedback is given by ;

$$Z'_{out} = \frac{Z_{out}}{1 + A_v\, m_v}$$

where Z'_{out} = output impedance with negative voltage feedback

Z_{out} = output impedance without feedback

It is clear that by applying negative feedback, the output impedance of the amplifier is decreased by a factor $1 + A_v\, m_v$. This is an added benefit of using negative voltage feedback. With lower value of output impedance, the amplifier is much better suited to drive low impedance loads.

15.5 Feedback Circuit

The function of the feedback circuit is to return a fraction of the output voltage to the input of the amplifier. Fig. 15.7 shows the feedback circuit of negative voltage feedback amplifier. It is essentially a potential divider consisting of resistances R_1 and R_2. The output voltage of the amplifier is fed to this potential divider which gives the feedback voltage to the input.

Referring to Fig. 15.7, it is clear that :

$$\text{Voltage across } R_1 = \left(\frac{R_1}{R_1 + R_2}\right) e_0$$

$$\text{Feedback fraction, } m_v = \frac{\text{Voltage across } R_1}{e_0} = \frac{R_1}{R_1 + R_2}$$

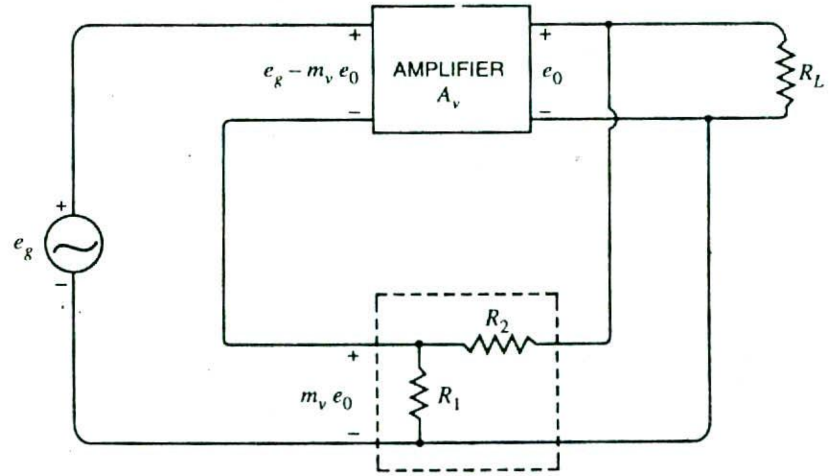


Fig. 15.7

Example 15.8. *Fig. 15.8 shows the negative voltage feedback amplifier. If the gain of the amplifier without feedback is 10,000, find :*

(i) feedback fraction (ii) overall voltage gain (iii) output voltage if input voltage is 1 mV.

Solution. $A_v = 10{,}000, \quad R_1 = 2\ k\Omega, \quad R_2 = 18\ k\Omega$

(*i*) Feedback fraction, $m_v = \dfrac{R_1}{R_1 + R_2} = \dfrac{2}{2 + 18} = \mathbf{0.1}$

(*ii*) Voltage gain with negative feedback is

$$A_{vf} = \frac{A_v}{1 + A_v m_v} = \frac{10,000}{1 + 10,000 \times 0.1} = \mathbf{10}$$

(*iii*) Output voltage $= A_{vf} \times$ input voltage

$= 10 \times 1 \text{ mV} = \mathbf{10\,mV}$

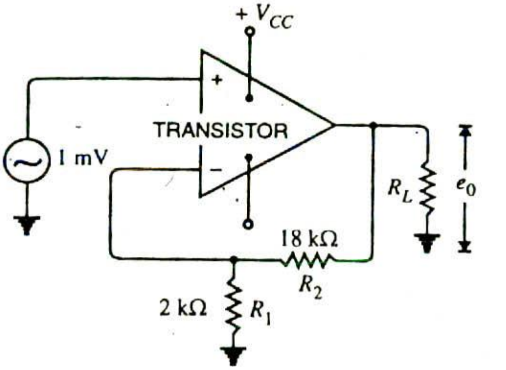


Fig. 15.8

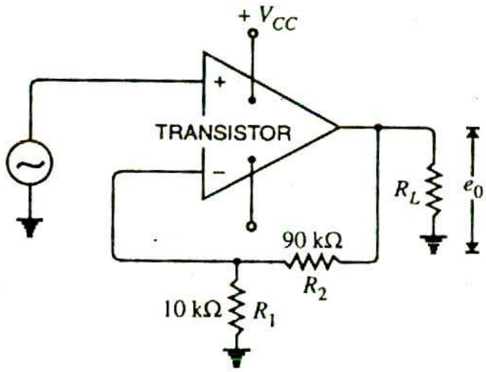


Fig. 15.9

Example 15.9. *Fig. 15.9 shows the circuit of a negative voltage feedback amplifier. If without feedback, A_v = 10,000, Z_{in} = 10 kΩ, Z_{out} = 100 Ω, find :*

(i) feedback fraction *(ii) gain with feedback*

(iii) input impedance with feedback *(iv) output impedance with feedback*

Solution.

(*i*) Feedback fraction, $m_v = \frac{R_1}{R_1 + R_2} = \frac{10}{10 + 90} = \mathbf{0.1}$

(*ii*) Gain with negative feedback is

$$A_{vf} = \frac{A_v}{1 + A_v m_v} = \frac{10,000}{1 + 10,000 \times 0.1} = \mathbf{10}$$

(*iii*) With negative voltage feedback, input impedance is increased and is given by ;

$$\underset{(feedback)}{Z'_{in}} = (1 + A_v m_v) Z_{in}$$

$= (1 + 10{,}000 \times 0.1)\ 10 \text{ k}\Omega$

$= 1001 \times 10 \text{ k}\Omega$

$= \mathbf{10\ M\Omega}$

(*iv*) With negative voltage feedback, output impedance is decreased and is given by ;

$$\underset{(feedback)}{Z'_{out}} = \frac{Z_{out}}{1 + A_v m_v} = \frac{100\ \Omega}{1 + 10,000 \times 0.1} = \frac{100}{1001} = \mathbf{0.1\ \Omega}$$

Example 15.10. *The gain and distortion of an amplifier are 150 and 5% respectively without feedback. If the stage has 10% of its output voltage applied as negative feedback, find the distortion of the amplifier with feedback*

Solution.

Gain without feedback, A_v = 150

Distortion without feedback, $D = 5\% = 0.05$

Feedback fraction, $m_v = 10\% = 0.1$

If D_{vf} is the distortion with negative feedback, then,

$$D_{vf} = \frac{D}{1 + A_v\, m_v} = \frac{0.05}{1 + 150 \times 0.1} = 0.00313 = \mathbf{0.313\%}$$

It may be seen that by the application of negative voltage feedback, the amplifier distortion is reduced from 5% to 0.313%.

Example 15.11. *An amplifier has a gain of 1000 without feedback and cut-off frequencies are $f_1 = 1.5$ kHz and $f_2 = 501.5$ kHz. If 1% of output voltage of the amplifier is applied as negative feedback, what are the new cut-off frequencies ?*

Solution. $A_v = 1000\,;\quad m_v = 0.01$

The new lower cut-off frequency with feedback is

$$f_{1(f)} = \frac{f_1}{1 + A_v\, m_v} = \frac{1.5 \text{ kHz}}{1 + 1000 \times 0.01} = \mathbf{136.4\ Hz}$$

The new upper cut-off frequency with feedback is

$$f_{2(f)} = f_2\,(1 + m_v A_v) = (501.5 \text{ kHz})\,(1 + 1000 \times 0.01) = \mathbf{5.52\ MHz}$$

Note the effect of negative voltage feedback on the bandwidth of the amplifier. The lower cut-off frequency is decreased by a factor $(1 + m_v A_v)$ while upper cut-off frequency is increased by a factor $(1 + m_v A_v)$. In other words, the bandwidth of the amplifier is increased approximately by a factor $(1 + m_v A_v)$.

$$BW_{(f)} \simeq BW\,(1 + m_v A_v)$$

where BW = Bandwidth of the amplifier without feedback

$BW_{(f)}$ = Bandwidth of the amplifier with negative feedback

15.6 Principles of Negative Current Feedback

In this method, a fraction of output current is fedback to the input of the amplifier. In other words, the feedback current (I_f) is proportional to the output current (I_{out}) of the amplifier. Fig. 15.10 shows the principles of negative current feedback. This circuit is called current-shunt feedback circuit. A feedback resistor R_f is connected between input and output of the amplifier. This amplifier has a current gain of A_i without feedback. It means that a current I_1 at the input terminals of the amplifier will appear as $A_i I_1$ in the output circuit *i.e.*, $I_{out} = A_i I_1$. Now a fraction m_i of this output current is fedback to the input through R_f. The fact that arrowhead shows the feed current being fed forward is because it is *negative* feedback.

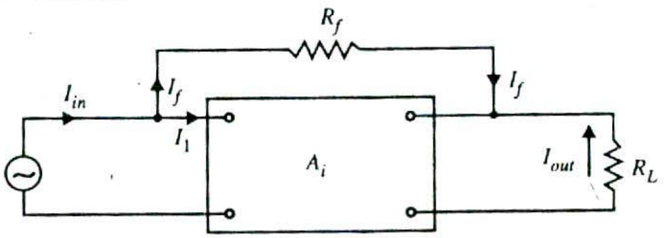


Fig. 15.10

Feedback current, $I_f = m_i\, I_{out}$

Feedback fraction, $m_i = \dfrac{I_f}{I_{out}} = \dfrac{\text{Feedback current}}{\text{Output current}}$

Note that negative current feedback reduces the input current to the amplifier and hence its current gain.

15.7 Current Gain with Negative Current Feedback

Referring to Fig. 15.10, we have,

$$I_{in} = I_1 + I_f = I_1 + m_i I_{out}$$

But $I_{out} = A_i I_1$, where A_i is the current gain of the amplifier without feedback.

$$\therefore \quad I_{in} = I_1 + m_i A_i I_1 \qquad (\because I_{out} = A_i I_1)$$

∴ Current gain with negative current feedback is

$$A_{if} = \frac{I_{out}}{I_{in}} = \frac{A_i I_1}{I_1 + m_i A_i I_1}$$

or

$$A_{if} = \frac{A_i}{1 + m_i A_i}$$

This equation looks very much like that for the voltage gain of negative voltage feedback amplifier. The only difference is that we are dealing with current gain rather than the voltage gain. The following points may be noted carefully :

(*i*) The current gain of the amplifier without feedback is A_i. However, when negative current feedback is applied, the current gain is reduced by a factor $(1 + m_i A_i)$.

(*ii*) The feedback fraction (or current attenuation) m_i has a value between 0 and 1.

(*iii*) The negative current feedback does not affect the voltage gain of the amplifier.

Example 15.12. *The current gain of an amplifier is 200 without feedback. When negative current feedback is applied, determine the effective current gain of the amplifier. Given that current attenuation m_i = 0.012.*

Solution.

$$A_{if} = \frac{A_i}{1 + m_i A_i}$$

Here $A_i = 200 \; ; \quad m_i = 0.012$

$$\therefore \quad A_{if} = \frac{200}{1 + (0.012)(200)} = \mathbf{58.82}$$

15.8 Effects of Negative Current Feedback

The negative current feedback has the following effects on the performance of amplifiers :

(*i*) **Decreases the input impedance.** The negative current feedback decreases the input impedance of most amplifiers.

Let Z_{in} = Input impedance of the amplifier without feedback

Z'_{in} = Input impedance of the amplifier with negative current feedback

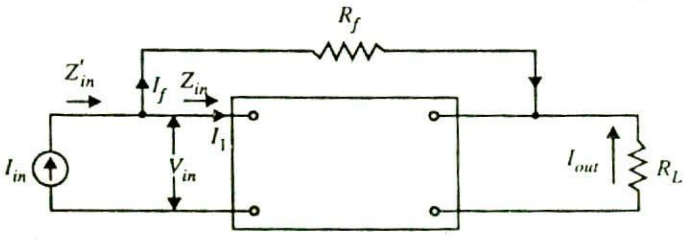


Fig. 15.11

Referring to Fig. 15.11, we have,

$$Z_{in} = \frac{V_{in}}{I_1}$$

and $$Z'_{in} = \frac{V_{in}}{I_{in}}$$

But $$V_{in} = I_1 Z_{in} \quad \text{and} \quad I_{in} = I_1 + I_f = I_1 + m_i I_{out} = I_1 + m_i A_i I_1$$

$$\therefore \quad Z'_{in} = \frac{I_1 Z_{in}}{I_1 + m_i A_i I_1} = \frac{Z_{in}}{1 + m_i A_i}$$

or $$Z'_{in} = \frac{Z_{in}}{1 + m_i A_i}$$

Thus the input impedance of the amplifier is decreased by the factor $(1 + m_i A_i)$. Note the primary difference between negative current feedback and negative voltage feedback. Negative current feedback *decreases* the input impedance of the amplifier while negative voltage feedback *increases* the input impedance of the amplifier.

(*ii*) **Increases the output impedance.** It can be proved that with negative current feedback, the output impedance of the amplifier is increased by a factor $(1 + m_i A_i)$.

$$Z'_{out} = Z_{out}(1 + m_i A_i)$$

where Z_{out} = output impedance of the amplifier without feedback

Z'_{out} = output impedance of the amplifier with negative current feedback

The reader may recall that with negative voltage feedback, the output impedance of the amplifier is decreased.

(*iii*) **Increases bandwidth.** It can be shown that with negative current feedback, the bandwidth of the amplifier is increased by the factor $(1 + m_i A_i)$.

$$BW' = BW(1 + m_i A_i)$$

where BW = Bandwidth of the amplifier without feedback

BW' = Bandwidth of the amplifier with negative current feedback

Example 15.13. *An amplifier has a current gain of 240 and input impedance of 15 kΩ without feedback. If negative current feedback (m_i = 0.015) is applied, what will be the input impedance of the amplifier ?*

Solution. $$Z'_{in} = \frac{Z_{in}}{1 + m_i A_i}$$

Here $Z_{in} = 15\ \text{k}\Omega$; $A_i = 240$; $m_i = 0.015$

$$\therefore \quad Z'_{in} = \frac{15}{1 + (0.015)(240)} = \mathbf{3.26\ k\Omega}$$

Example 15.14. *An amplifier has a current gain of 200 and output impedance of 3 kΩ without feedback. If negative current feedback (m_i = 0.01) is applied; what is the output impedance of the amplifier ?*

Solution. $$Z'_{out} = Z_{out}(1 + m_i A_i)$$

Here $Z_{out} = 3\ \text{k}\Omega$; $A_i = 200$; $m_i = 0.01$

$$\therefore \quad Z'_{out} = 3[1 + (0.01)(200)] = \mathbf{9\ k\Omega}$$

Example 15.15. *An amplifier has a current gain of 250 and a bandwidth of 400 kHz without feedback. If negative current feedback (m_i = 0.01) is applied, what is the bandwidth of the amplifier?*

Solution. $BW' = BW(1 + m_i A_i)$

Here $BW = 400\,\text{kHz}; \quad m_i = 0.01; \quad A_i = 250$

$\therefore \quad BW' = 400[1 + (0.01)250] = \mathbf{1400\,kHz}$

15.9 Emitter Follower

It is a negative current feedback circuit. The emitter follower is a current amplifier that has no voltage gain. Its most important characteristic is that it has high input impedance and low output impedance. This makes it an ideal circuit for impedance matching.

Circuit details. Fig. 15.12 shows the circuit of an emitter follower. As you can see, it differs from the circuitry of a conventional *CE* amplifier by the absence of collector load and emitter by–pass capacitor. The emitter resistance R_E itself acts as the load and a.c. output voltage (V_{out}) is taken across R_E. The biasing is generally provided by voltage-divider method or by base resistor method. The following points are worth noting about the emitter follower :

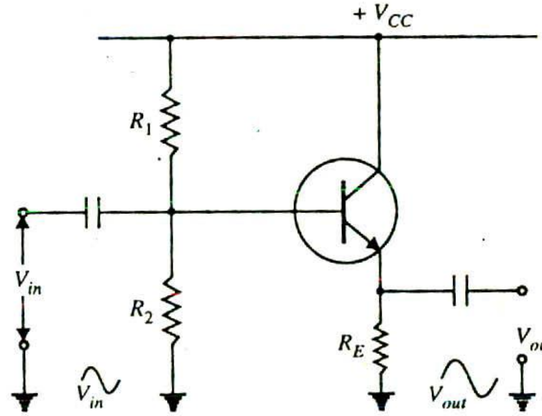


Fig. 15.12

(*i*) There is neither collector resistor in the circuit nor there is emitter by–pass capacitor. These are the two circuit recognition features of the emitter follower.

(*ii*) Since the collector is at *ac* ground, this circuit is also known as *common collector* (*CC*) *amplifier.*

Operation. The input voltage is applied between base and emitter and the resulting a.c. emitter current produces an output voltage $i_e R_E$ across the emitter resistance. This voltage opposes the input voltage, thus providing negative feedback. Clearly, it is a negative current feedback circuit since the voltage fedback is proportional to the emitter current *i.e.*, output current. It is called emitter follower because the output voltage follows the input voltage.

Characteristics. The major characteristics of the emitter follower are :

(*i*) No voltage gain. In fact, the voltage gain of an emitter follower is close to 1.

(*ii*) Relatively high current gain and power gain.

(*iii*) High input impedance and low output impedance.

(*iv*) Input and output *ac* voltages are in phase.

15.10 D.C. Analysis of Emitter Follower

The d.c. analysis of an emitter follower is made in the same way as the voltage divider bias circuit of a CE amplifier. Thus referring to Fig. 15.12 above, we have,

$$\text{Voltage across } R_2,\ V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2$$

$$\text{Emitter current, } I_E = \frac{V_E}{R_E} = \frac{V_2 - V_{BE}}{R_E}$$

$$\text{Collector-emitter voltage, } V_{CE} = V_{CC} - V_E$$

D.C. Load Line. The d.c. load line of emitter follower can be constructed by locating the two end points *viz.*, $I_{C(sat)}$ and $V_{CE(off)}$.

(*i*) When the transistor is saturated, $V_{CE} = 0$.

$$\therefore \quad I_{C(sat)} = \frac{V_{CC}}{R_E}$$

This locates the point A ($OA = V_{CC}/R_E$) of the d.c. load line as shown in Fig. 15.13.

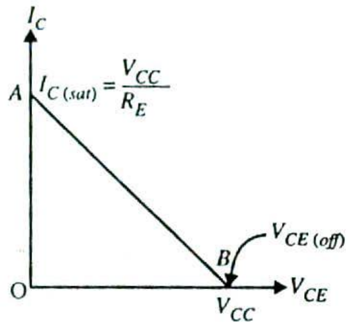


Fig. 15.13

(*ii*) When the transistor is cut off, $I_C = 0$. Therefore, $V_{CE(off)} = V_{CC}$. This locates the point B ($OB = V_{CC}$) of the d.c. load line.

By joining points A and B, d.c. load line AB is constructed.

Example 15.16. *For the emitter follower circuit shown in Fig. 15.14 (i), find V_E and I_E. Also draw the dc load line for this circuit.*

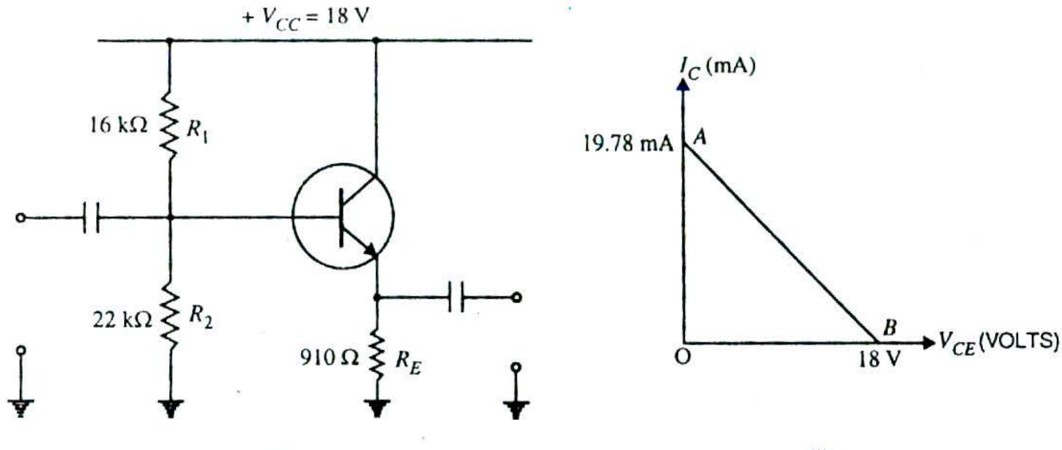


Fig. 15.14

Solution.

$$\text{Voltage across } R_2,\ V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{18}{16 + 22} \times 22 = 10.42 \text{ V}$$

$$\text{Voltage across } R_E,\ V_E = V_2 - V_{BE} = 10.42 - 0.7 = \mathbf{9.72\ V}$$

$$\text{Emitter current, } I_E = \frac{V_E}{R_E} = \frac{9.72 \text{ V}}{910\ \Omega} = \mathbf{10.68\ mA}$$

D.C. load line

$$I_{C\,(sat)} = \frac{V_{CC}}{R_E} = \frac{18 \text{ V}}{910\ \Omega} = 19.78 \text{ mA}$$

This locates the point A ($OA = 19.78$ mA) of the d.c. load line.

$$V_{CE(off)} = V_{CC} = 18 \text{ V}$$

This locates point B (OB = 18 V) of the d.c. load line.

By joining points A and B, d.c. load line AB is constructed [See Fig. 15.14 (*ii*)].

15.11 Voltage Gain of Emitter Follower

Fig. 15.15 shows the emitter follower circuit. Since the emitter resistor is not by-passed by a capacitor, the *a.c.* equivalent circuit of emitter follower will be as shown in Fig. 15.16. The ac resistance r_E of the emitter circuit is given by ;

$$r_E = r'_e + R_E \qquad \text{where } r'_e = \frac{25 \text{ mV}}{I_E}$$

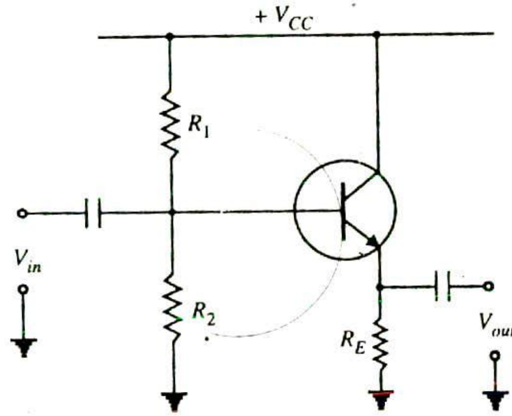


Fig. 15.15

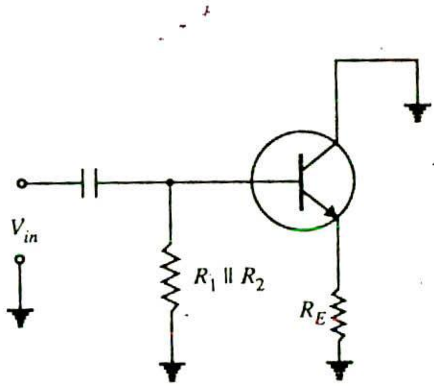


Fig. 15.16

In order to find the voltage gain of the emitter follower, let us replace the transistor in Fig. 15.16 by its equivalent circuit. The circuit then becomes as shown in Fig. 15.17.

Note that input voltage is applied across the *ac* resistance of the emitter circuit *i.e.*, $(r'_e + R_E)$. Assuming the emitter diode to be ideal,

$$\text{Output voltage, } V_{out} = i_e R_E$$

$$\text{Input voltage, } V_{in} = i_e (r'_e + R_E)$$

∴ Voltage gain of emitter follower is

$$A_v = \frac{V_{out}}{V_{in}} = \frac{i_e R_E}{i_e (r'_e + R_E)} = \frac{R_E}{r'_e + R_E}$$

or $$A_v = \frac{R_E}{r'_e + R_E}$$

In most practical applications, $R_E >> r'_e$ so that $A_v \simeq 1$.

In practice, the voltage gain of an emitter follower is between 0.8 and 0.999.

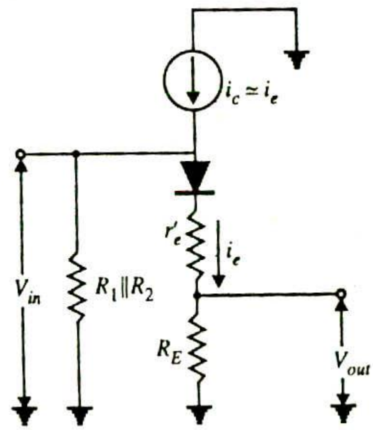


Fig. 15.17

Example 15.17. *Determine the voltage gain of the emitter follower circuit shown in Fig. 15.18.*

Solution.

$$\text{Voltage gain, } A_v = \frac{R_E}{r'_e + R_E}$$

Now $$r'_e = \frac{25 \text{ mV}}{I_E}$$

Voltage across R_2, $$V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{10}{10+10} \times 10 = 5 \text{ V}$$

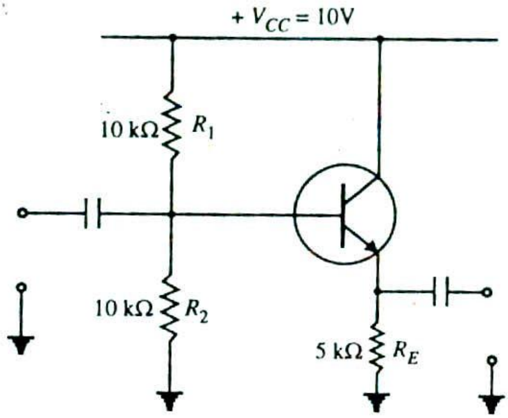


Fig. 15.18

Voltage across R_E, $$V_E = V_2 - V_{BE} = 5 - 0.7 = 4.3 \text{ V}$$

$\therefore$ Emitter current, $$I_E = \frac{V_E}{R_E} = \frac{4.3 \text{ V}}{5 \text{ k}\Omega} = 0.86 \text{ mA}$$

$\therefore$ $$r'_e = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{0.86 \text{ mA}} = 29.1 \ \Omega$$

$\therefore$ Voltage gain, $$A_v = \frac{R_E}{r'_e + R_E} = \frac{5000}{29.1 + 5000} = \mathbf{0.994}$$

Example 15.18. *If in the above example, a load of 5 kΩ is added to the emitter follower, what will be the voltage gain of the circuit ?*

Solution. When a load of 5 kΩ is added to the emitter follower; the circuit becomes as shown in Fig. 15.19. The coupling capacitor acts as a short for a.c. signal so that R_E and R_L are in parallel. Therefore, the external emitter resistance R_E changes to R'_E where

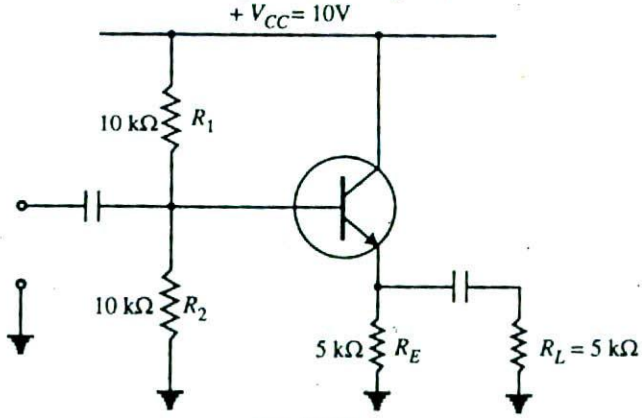


Fig. 15.19

$$R'_E = R_E \,||\, R_L = 5\text{ k}\Omega \,||\, 5\text{ k}\Omega = 2.5\text{ k}\Omega$$

$$\text{Voltage gain, } A_v = \frac{R'_E}{r'_e + R'_E} = \frac{2500}{29.1 + 2500} = \mathbf{0.988}$$

Comments. This is the same example as example 15.17 except that load is added. Note the loading effect on the voltage gain of an emitter follower. When load is added to the emitter follower, the voltage gain drops from 0.994 to 0.988. This is really a small change. On the other hand, when a CE amplifier is loaded, there is drastic change in voltage gain. This is yet another difference between the emitter follower and CE amplifier.

15.12 Input Impedance of Emitter Follower

Fig. 15.20 (*i*) shows the circuit of a loaded emitter follower. The a.c. equivalent circuit with T model is shown in Fig. 15.20 (*ii*).

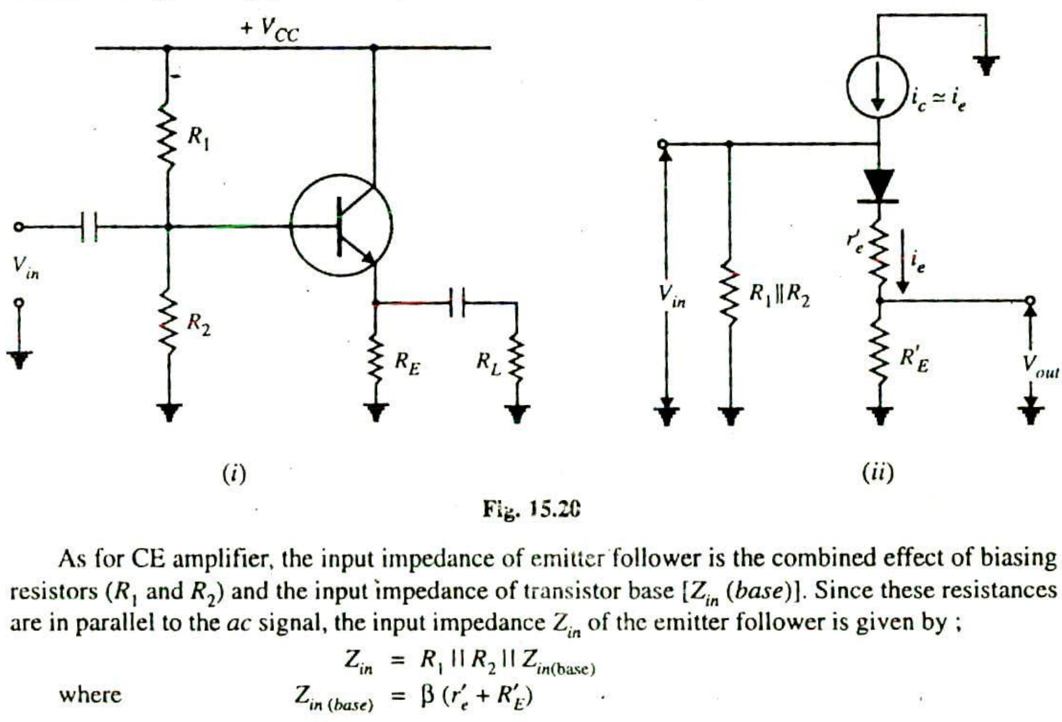


Fig. 15.20

As for CE amplifier, the input impedance of emitter follower is the combined effect of biasing resistors (R_1 and R_2) and the input impedance of transistor base [Z_{in} (*base*)]. Since these resistances are in parallel to the *ac* signal, the input impedance Z_{in} of the emitter follower is given by ;

$$Z_{in} = R_1 \,||\, R_2 \,||\, Z_{in(base)}$$

where $$Z_{in\,(base)} = \beta\,(r'_e + R'_E)$$

Now $$r'_e = \frac{25\text{ mV}}{I_E} \quad \text{and} \quad R'_E = R_E \,||\, R_L$$

Note. In an emitter follower, impedance of base [*i.e.*, Z_{in} (*base*)] is generally very large as compared to $R_1 \,||\, R_2$. Consequently, Z_{in} (*base*) can be ignored. As a result, approximate input impedance of the emitter follower is given by ;

$$Z_{in} = R_1 \,||\, R_2$$

Example 15.19. *For the emitter follower circuit shown in Fig. 15.21, find the input impedance.*

Solution.

$$\text{Voltage across } R_2,\ V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2 = \frac{10}{10 + 10} \times 10 = 5\text{ V}$$

$$\text{Voltage across } R_E,\ V_E = V_2 - V_{BE} = 5 - 0.7 = 4.3\text{ V}$$

$\therefore$ Emitter current, $I_E = \frac{V_E}{R_E} = \frac{4.3\text{ V}}{4.3\text{ k}\Omega} = 1\text{ mA}$

$\therefore$ A.C. emitter resistance, $r'_e = \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{1\text{ mA}} = 25\ \Omega$

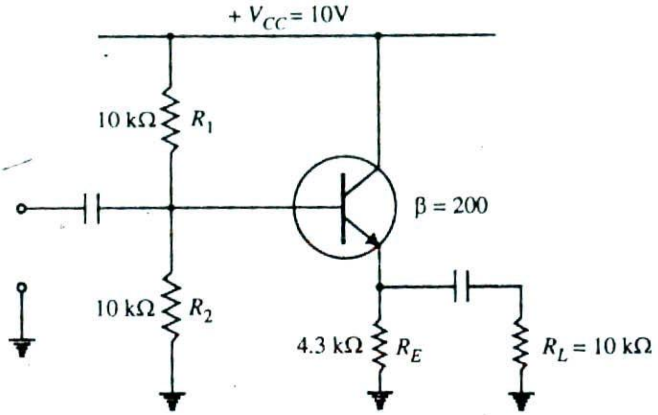


Fig. 15.21

Effective external emitter resistance is

$$R'_E = R_E \parallel R_L = 4.3\text{ k}\Omega \parallel 10\text{ k}\Omega = 3\text{ k}\Omega$$

$$\therefore \quad Z_{in\ (base)} = \beta\,(r'_e + R'_E) = 200\,(0.025 + 3) = 605\text{ k}\Omega$$

$\therefore$ Input impedance of the emitter follower is

$$Z_{in} = R_1 \parallel R_2 \parallel Z_{in\ (base)}$$
$$= 10\text{ k}\Omega \parallel 10\text{ k}\Omega \parallel 605\text{ k}\Omega$$
$$= 5\text{ k}\Omega \parallel 605\text{ k}\Omega \doteq \mathbf{4.96\text{ k}\Omega}$$

Note. Since 605 kΩ is much larger than $R_1 \parallel R_2$ (= 5kΩ), the former can be ignored. Therefore, approximate input impedance of emitter follower is given by ;

$$Z_{in} = R_1 \parallel R_2 = 10\text{ k}\Omega \parallel 10\text{ k}\Omega = 5\text{ k}\Omega$$

15.13 Output Impedance of Emitter Follower

The output impedance of a circuit is the impedance that the circuit offers to the load. When load is connected to the circuit, the output impedance acts as the source impedance for the load. Fig. 15.22 shows the circuit of emitter follower. Here R_s in the output resistance of amplifier voltage source.

It can be proved that the output impedance Z_{out} of the emitter follower is given by ;

$$Z_{out} = R_E \parallel \left(r'_e + \frac{R'_{in}}{\beta}\right)$$

where $R'_{in} = R_1 \parallel R_2 \parallel R_s$

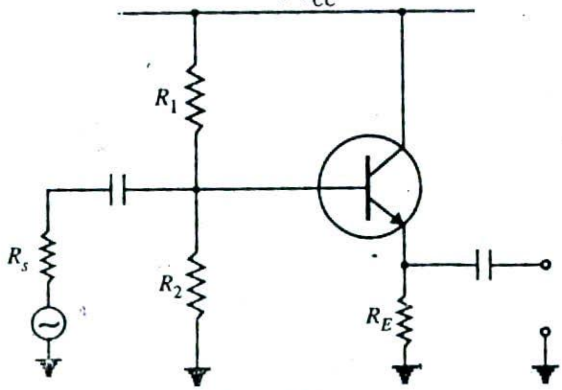


Fig. 15.22

In practical circuits, the value of R_E is large enough to be ignored. For this reason, the output impedance of emitter follower is approximately given by ;

$$Z_{out} = r'_e + \frac{R'_{in}}{\beta}$$

Example 15.20. *Determine the output impedance of the emitter follower shown in Fig. 15.23. Given that* $r'_e = 20\ \Omega$.

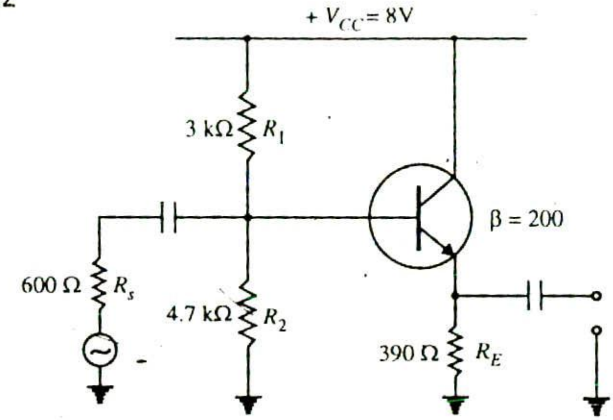


Fig. 15.23

Solution.

$$Z_{out} = r'_e + \frac{R'_{in}}{\beta}$$

Now

$$R'_{in} = R_1 \parallel R_2 \parallel R_s$$

$$= 3\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega \parallel 600\ \Omega = 452\ \Omega$$

∴

$$Z_{out} = 20 + \frac{452}{200} = 20 + 2.3 = \mathbf{22.3\ \Omega}$$

Note that output impedance of the emitter follower is very low. On the other hand, it has high input impedance. This property makes the emitter follower a perfect circuit for connecting a low impedance load to a high-impedance source.

15.14 Applications of Emitter Follower

The emitter follower has the following principal applications :

(*i*) To provide current amplification with no voltage gain.

(*ii*) Impedance matching.

(*i*) **Current amplification without voltage gain.** We know that an emitter follower is a current amplifier that has no voltage gain ($A_v \simeq 1$). There are many instances (especially in digital electronics) where an increase in current is required but no increase in voltage is needed. In such a situation, an emitter follower can be used. For example, consider the two stage amplifier circuit as shown in Fig. 15.24. Suppose this 2-stage amplifier has the desired voltage gain but current gain of this multistage amplifier is insufficient. In that case, we can use an emitter follower to increase the current gain without increasing the voltage gain.

Fig. 15.24

(*ii*) **Impedance matching.** We know that an emitter follower has high input impedance and low output impedance. This makes the emitter follower an ideal circuit for impedance matching. Fig. 15.25 shows the impedance matching by an emitter follower. Here the output impedance of the source is 120 kΩ while that of load is 20 Ω. The emitter follower has an input impedance of 120 kΩ and output impedance of 22 Ω. It is connected between high-impedance source and low impedance load. The net result of this arrangement is that maximum power is transferred from the original source to the original load. When an emitter follower is used for this purpose, it is called a *buffer amplifier.*

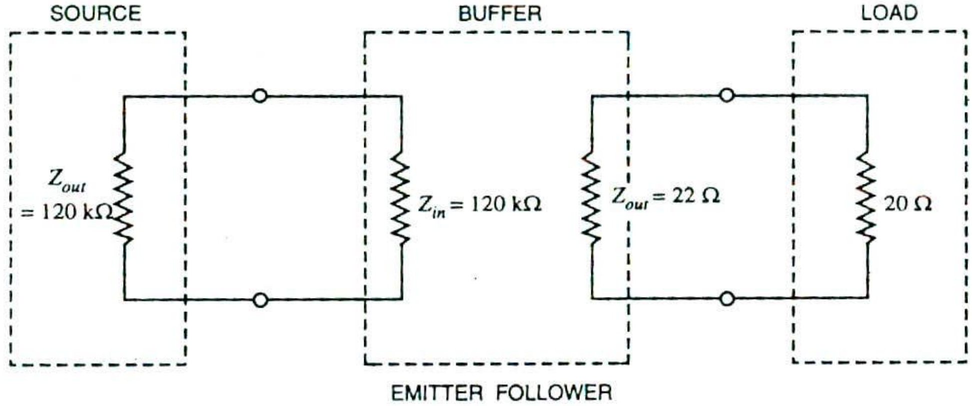


Fig. 15.25

It may be noted that the job of impedance matching can also be accomplished by a transformer. However, emitter follower is preferred for this purpose. It is because emitter follower is not only more convenient than a transformer but it also has much better frequency response *i.e.*, it works well over a large frequency range.

15.15 Darlington Amplifier

Sometimes, the current gain and input impedance of an emitter follower are insufficient to meet the requirement. In order to increase the overall values of circuit current gain (A_i) and input impedance, two transistors are connected in series in emitter follower configuration as shown in Fig. 15.26. Such a circuit is called *Darlington amplifier.* Note that emitter of first transistor is connected to the base of the second transistor and the collector terminals of the two transistors are connected together. The result is that emitter current of the first transistor is the base current of the second transistor. Therefore, the current gain of the pair is equal to product of individual current gains *i.e.*

$$\beta = \beta_1 \beta_2$$

Note that high current gain is achieved with a minimum use of components.

The biasing analysis is similar to that for one transistor except that two V_{BE} drops are to be considered. Thus referring to Fig. 15.26,

$$\text{Voltage across } R_2,\ V_2 = \frac{V_{CC}}{R_1 + R_2} \times R_2$$

$$\text{Voltage across } R_E,\ V_E = V_2 - 2V_{BE}$$

$$\text{Current through } R_E,\ I_{E2} = \frac{V_2 - 2V_{BE}}{R_E}$$

Since the transistors are directly coupled, $I_{E1} = I_{B2}$. Now $I_{B2} = I_{E2}/\beta_2$.

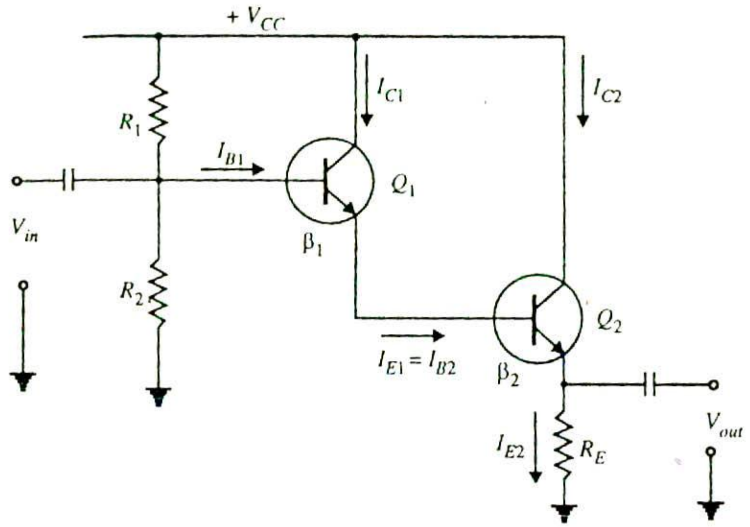


Fig. 15.26

$$\therefore \qquad I_{E1} = \frac{I_{E2}}{\beta_2}$$

In practice, the two transistors are put inside a single transistor housing and three terminals *E*, *B* and *C* are brought out as shown in Fig. 15.27. This three terminal device is known as a Darlington transistor. The Darlington transistor acts like a single transistor that has hight current gain and high input impedance.

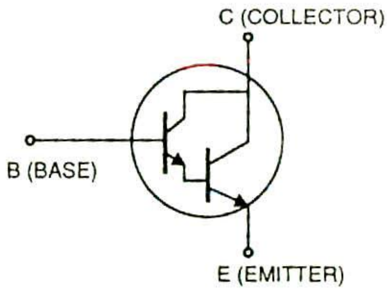


Fig. 15.27

Applications. When an emitter follower cannot provide the required high input impedance and current gain, the Darlington amplifier is used.

Multiple-Choice Questions

1. When negative voltage feedback is applied to an amplifier, its voltage gain ....
   (*i*) is increased (*ii*) is reduced
   (*iii*) remains the same
   (*iv*) none of the above

2. The value of negative feedback fraction is always ....
   (*i*) less than 1 (*ii*) more than 1
   (*iii*) equal to 1 (*iv*) none of the above

3. If the output of an amplifier is 10 V and 100 mV from the output is fed back to the input, then feedback fraction is ....
   (*i*) 10 (*ii*) 0.1
   (*iii*) 0.01 (*iv*) 0.15

4. The gain of an amplifier without feedback is 100 *db*. If a negative feedback of 3 *db* is applied, the gain of the amplifier will become ....
   (*i*) 101.5 *db* (*ii*) 300 *db*
   (*iii*) 103 *db* (*iv*) 97 *db*

5. If the feedback fraction of an amplifier is 0.01, then voltage gain with negative voltage feedback is approximately ....
   (*i*) 500 (*ii*) 100
   (*iii*) 1000 (*iv*) 5000

6. A feedback circuit usually employs .... network.
   (*i*) resistive (*ii*) capacitive

(iii) inductive (iv) none of the above

7. The gain of an amplifier with feedback is known as .... gain.
   (i) resonant (ii) open loop
   (iii) closed loop (iv) none of the above
8. When voltage feedback (negative) is applied to an amplifier, its input impedance ....
   (i) is decreased (ii) is increased
   (iii) remains the same
   (iv) none of the above
9. When current feedback (negative) is applied to an amplifier, its input impedance ....
   (i) is decreased (ii) is increased
   (iii) remains the same
   (iv) none of the above
10. Negative feedback is employed in ....
    (i) oscillators (ii) rectifiers
    (iii) amplifiers (iv) none of the above
11. Emitter follower is used for ....
    (i) current gain
    (ii) impedance matching
    (iii) voltage gain (iv) none of the above
12. The voltage gain of an emitter follower is ...
    (i) much less than 1
    (ii) approximately equal to 1
    (iii) greater than 1 (iv) none of the above
13. When current feedback (negative) is applied to an amplifier, its output impedance ......
    (i) is increased
    (ii) is decreased
    (iii) remains the same
    (iv) none of the above
14. Emitter follower is a .... circuit.
    (i) voltage feedback
    (ii) current feedback
    (iii) both voltage and current feedback
    (iv) none of the above
15. If voltage feedback (negative) is applied to an amplifier, its output impedance ....
    (i) remains the same
    (ii) is increased (iii) is decreased
    (iv) none of the above
16. When negative voltage feedback is applied to an amplifier, its bandwidth ....
    (i) is increased (ii) is decreased
    (iii) remains the same
    (iv) insufficient data
17. An emitter follower has ..... input impedance.
    (i) zero (ii) low
    (iii) high (iv) none of the above
18. If voltage gain without feedback and feedback fraction are A_v and m_v respectively, then gain with negative voltage feedback is ....
    (i) $\frac{A_v}{1 - A_v m_v}$ (ii) $\frac{A_v}{1 + A_v m_v}$
    (iii) $\frac{1 + A_v m_v}{A_v}$ (iv) $(1 + A_v m_v) A_v$
19. The output impedance of an emitter follower is ....
    (i) high (ii) very high
    (iii) almost zero (iv) low
20. The approximate voltage gain of an amplifier with negative voltage feedback (feedback fraction being m_v) is ....
    (i) $1/m_v$ (ii) m_v
    (iii) $\frac{1}{1 + m_v}$ (iv) $1 - m_v$
21. If A_v and A_{fb} are the voltage gains of an amplifier without feedback and with negative feedback respectively, then feedback fraction is ....
    (i) $\frac{1}{A_v} - \frac{1}{A_{fb}}$ (ii) $\frac{1}{A_v} + \frac{1}{A_{fb}}$
    (iii) $\frac{A_v}{A_{fb}} + \frac{1}{A_v}$ (iv) $\frac{1}{A_{fb}} - \frac{1}{A_v}$
22. In the expression for voltage gain with negative voltage feedback, the term $1 + A_m m_v$ is known as ....
    (i) gain factor (ii) feedback factor
    (iii) sacrifice factor (iv) none of the above
23. If the output impedance of an amplifier is Z_{out} without feedback, then with negative voltage feedback, its value will be ....
    (i) $\frac{Z_{out}}{1 + A_v m_v}$ (ii) $Z_{out}(1 + A_v m_v)$

(iii) $\frac{1 + A_v m_v}{Z_{out}}$ (iv) $Z_{out}(1 - A_v m_v)$

24. If the input impedance of an amplifier is Z_{in} without feedback, then with negative voltage feedback, its value will be ....

(i) $\frac{Z_{in}}{1 + A_v m_v}$ (ii) $Z_{in}(1 + A_v m_v)$

(iii) $\frac{1 + A_v m_v}{Z_{in}}$ (iv) $Z_{in}(1 - A_v m_v)$

25. Feedback circuit .... frequency.

(i) is independent of
(ii) is strongly dependent on
(iii) is moderately dependent on
(iv) none of the above

26. The basic purpose of applying negative voltage feedback is to ....

(i) increase voltage gain
(ii) reduce distortion
(iii) keep the temperature within limits
(iv) none of the above

27. If the voltage gain of an amplifier without feedback is 20 and with negative voltage feedback it is 12, then feedback fraction is ....

(i) 5/3 (ii) 3/5
(iii) 1/5 (iv) 0.033

28. In an emitter follower, we employ ...... negative current feedback.

(i) 50% (ii) 25%
(iii) 100% (iv) 75%

29. An amplifier has an open loop voltage gain of 1,00,000. With negative voltage feedback, the voltage gain is reduced to 100. What is the sacrifice factor ?

(i) 1000 (ii) 100
(iii) 5000 (iv) none of the above

30. In the above question, what will happen to circuit performance ?

(i) distortion is increased 1000 times
(ii) input impedance is increased 1000 times
(iii) output impedance is increased 1000 times
(iv) none of the above

31. The non-linear distortion of an amplifier is D without feedback. The amplifier has an open-loop voltage gain of A_v and feedback fraction is m_v. With negative voltage feedback, the non-linear distortion will be ....

(i) $D(1 + A_v m_v)$ (ii) $D(1 - A_v m_v)$

(iii) $\frac{1 + A_v m_v}{D}$ (iv) $\frac{D}{1 + A_v m_v}$

32. The output and input voltages of an emitter follower have a phase difference of ....

(i) 180° (ii) 90°
(iii) 0° (iv) 270°

33. It is most necessary to control signal-to-noise ratio at ....

(i) initial stage (ii) driver stage
(iii) output stage (iv) detector stage

34. In order to obtain good gain stability in a negative voltage feedback amplifier (A_v = voltage gain without feedback ; m_v = feedback fraction), ...

(i) $A_v m_v = 1$ (ii) $A_v m_v >> 1$
(iii) $A_v m_v < 1$ (iv) none of the above

35. Emitter follower is also known as ....

(i) grounded emitter circuit
(ii) grounded base circuit
(iii) grounded collector circuit
(iv) none of the above

Answers to Multiple-Choice Questions

1. (ii)	**2.** (i)	**3.** (iii)	**4.** (iv)	**5.** (ii)
6. (i)	**7.** (iii)	**8.** (ii)	**9.** (i)	**10.** (iii)
11. (ii)	**12.** (ii)	**13.** (i)	**14.** (ii)	**15.** (iii)
16. (i)	**17.** (iii)	**18.** (ii)	**19.** (iv)	**20.** (i)
21. (iv)	**22.** (iii)	**23.** (i)	**24.** (ii)	**25.** (i)
26. (ii)	**27.** (iv)	**28.** (iii)	**29.** (i)	**30.** (ii)
31. (iv)	**32.** (iii)	**33.** (i)	**34.** (ii)	**35.** (iii)

Chapter Review Topics

1. What do you understand by feedback ? Why is negative feedback applied in high gain amplifiers ?
2. Discuss the principles of negative voltage feedback in amplifiers with a neat diagram.
3. Derive an expression for the gain of negative voltage feedback amplifier.
4. What is a feedback circuit ? Explain how it provides feedback in amplifiers.
5. Describe the action of emitter follower with a neat diagram.
6. Derive the expressions for (*i*) voltage gain (*ii*) input impedance and (*iii*) output impedance of an emitter follower.

Problems

1. An amplifier has a gain of 2×10^5 without feedback. Determine the gain if negative voltage feedback is applied. Take feedback fraction $m_v = 0.02$. **[50]**
2. An amplifier has a gain of 10,000 without feedback. With negative voltage feedback, the gain is reduced to 50. Find the feedback fraction. **[$m_v = 0.02$]**
3. A feedback amplifier has an internal gain $A_v = 40db$ and feedback fraction $m_v = 0.05$. If the input impedance of this circuit is 12 kΩ, what would have been the input impedance if feedback were not present ? **[2k Ω]**
4. Calculate the gain of a negative voltage feedback amplifier with an internal gain $A_v = 75$ and feedback fraction $m_v = 1/15$. What will be the gain if A_v doubles ? **[12.5 ; 13.64]**
5. An amplifier with negative feedback has a voltage gain of 100. It is found that without feedback, an input signal of 50 mV is required to produce a given output, whereas with feedback, the input signal must be 0.6 V for the same output. Calculate (*i*) gain without feedback (*ii*) feedback fraction. **[(*i*) 1200 (*ii*) 0.009]**

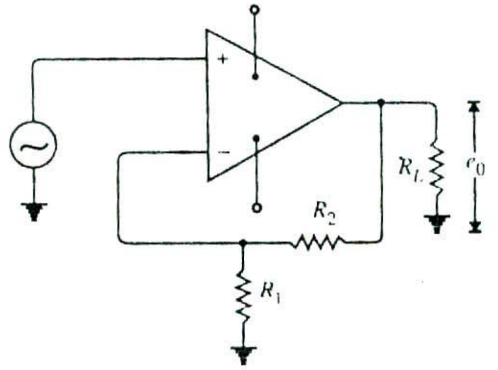


Fig. 15.28

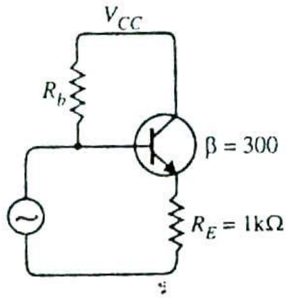


Fig. 15.29

6. Fig. 15.28 shows the negative feedback amplifier. If the gain of the amplifier without feedback is 10^5 and $R_1 = 100\ \Omega$, $R_2 = 100$ kΩ, find (*i*) feedback fraction (*ii*) gain with feedback. **[(*i*) 0.001(*ii*) 1000]**
7. In Fig. 15.29, if input and output impedances without feedback are 2 MΩ and 500 Ω respectively, find their values after negative voltage feedback. **[(*i*) 302MΩ (*ii*) 1.6]**
8. An amplifier has a current gain of 240 without feedback. When negative current feedback is applied, determine the effective current gain of the amplifier. Given that current attenuation $m_i = 0.015$. **[52.7]**
9. An amplifier has an open-loop gain and input impedance of 200 and 15 kΩ respectively. If negative current feedback is applied, what is the effective input impedance of the amplifier? Given that current attenuation $m_i = 0.012$. **[4.41 kΩ]**
10. An amplifier has $A_i = 200$ and $m_i = 0.012$. The open-loop output impedance of the amplifier is 2kΩ. If negative current feedback is applied, what is the effective output impedance of the amplifier ? **[6.8 kΩ]**

Discussion Questions

1. Why is negative voltage feedback employed in high gain amplifiers ?
2. How does negative voltage feedback increase bandwidth of an amplifier ?
3. Feedback for more than three stages is seldom employed. Explain why ?
4. Why is emitter follower preferred to transformer for impedance matching ?
5. Where is emitter follower employed practically and why ?
6. What are the practical applications of emitter follower ?

16

Sinusoidal Oscillators

Introduction

Many electronic devices require a source of energy at a specific frequency which may range from a few Hz to several MHz. This is achieved by an electronic device called an *oscillator*. Oscillators are extensively used in electronic equipment. For example, in radio and television receivers, oscillators are used to generate high frequency wave (called *carrier wave*) in the tuning stages. Audio frequency and radio-frequency signals are required for the repair of radio, television and other electronic equipment. Oscillators are also widely used in radar, electronic computers and other electronic devices.

Oscillators can produce sinusoidal or non-sinusoidal (*e.g.* square wave) waves. In this chapter, we shall confine our attention to sinusoidal oscillators *i.e.* those which produce sine-wave signals.

16.1 Sinusoidal Oscillator

An electronic device that generates sinusoidal oscillations of desired frequency is known as a ***sinusoidal oscillator.**

Although we speak of an oscillator as "generating" a frequency, it should be noted that it does not create energy, but merely acts as an energy converter. It receives d.c. energy and changes it into a.c. energy of desired frequency. The frequency of oscillations depends upon the constants of the device.

It may be mentioned here that although an alternator produces sinusoidal oscillations of 50Hz, it cannot be called an oscillator. Firstly, an alternator is a mechanical device having rotating parts whereas an oscillator is a non-rotating electronic device. Secondly, an alternator converts mechanical energy into a.c. energy while an oscillator converts d.c. energy into a.c. energy. Thirdly, an alternator cannot produce high frequency oscillations whereas an oscillator can produce oscillations ranging from a few Hz to several MHz.

Advantages

Although oscillations can be produced by mechanical devices (*e.g.* alternators), but electronic oscillators have the following advantages :

(*i*) An oscillator is a non-rotating device. Consequently, there is little wear and tear and hence longer life.

(*ii*) Due to the absence of moving parts, the operation of an oscillator is quite silent.

(*iii*) An oscillator can produce waves from small (20 Hz) to extremely high frequencies (> 100 MHz).

* Note that oscillations are produced without any external signal source. The only input power to an oscillator is the d.c. power supply.

(iv) The frequency of oscillations can be easily changed when desired.

(v) It has good frequency stability *i.e.* frequency once set remains constant for a considerable period of time.

(vi) It has very high efficiency.

16.2 Types of Sinusoidal Oscillations

Sinusoidal electrical oscillations can be of two types *viz damped oscillations* and *undamped oscillations*.

(i) **Damped oscillations.** The electrical oscillations whose amplitude goes on decreasing with time are called *damped oscillations.* Fig. 16.1 (i) shows waveform of damped electrical oscillations. Obviously, the electrical system in which these oscillations are generated has losses and some energy is lost during each oscillation. Further, no means are provided to compensate for the losses and consequently the amplitude of the generated wave decreases gradually. It may be noted that frequency of oscillations remains unchanged since it depends upon the constants of the electrical system.

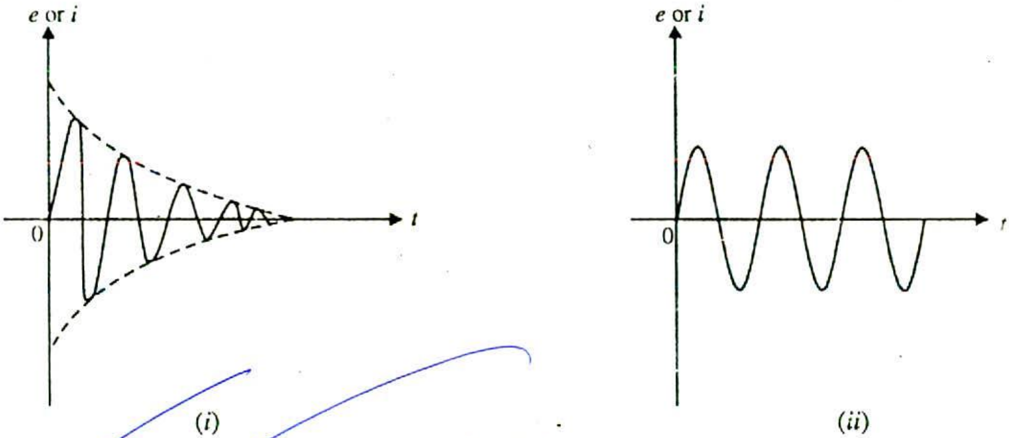


Fig. 16.1

(ii) **Undamped oscillations.** The electrical oscillations whose amplitude remains constant with time are called *undamped oscillations.* Fig. 16.1 (ii) shows waveform of undamped electrical oscillations. Although the electrical system in which these oscillations are being generated has also losses, but now right amount of energy is being supplied to overcome the losses. Consequently, the amplitude of the generated wave remains constant. It should be emphasised that an oscillator is required to produce undamped electrical oscillations for utilising in various electronics equipment.

16.3 Oscillatory Circuit

A circuit which produces electrical oscillations of any desired frequency is known as an **oscillatory circuit** *or* **tank circuit.**

A simple oscillatory circuit consists of a capacitor (C) and inductance coil (L) in parallel as shown in Fig. 16.2. This electrical system can produce electrical oscillations of frequency determined by the values of L and C. To understand how this comes about, suppose the capacitor is charged from a d.c. source with a polarity as shown in Fig. 16.2 (i).

(i) In the position shown in Fig. 16.2 (i), the upper plate of capacitor has deficit of electrons and the lower plate has excess of electrons. Therefore, there is a voltage across the capacitor and the capacitor has electrostatic energy.

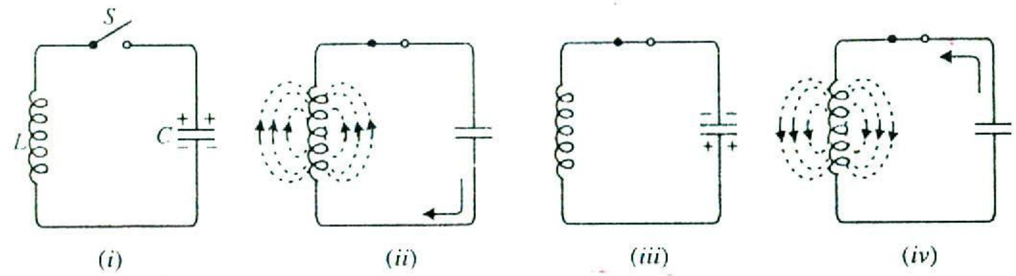


Fig. 16.2

(*ii*) When switch *S* is closed as shown in Fig. 16.2 (*ii*), the capacitor will discharge through inductance and the electron flow will be in the direction indicated by the arrow. This current flow sets up magnetic field around the coil. Due to the inductive effect, the current builds up slowly towards a maximum value. The circuit current will be maximum when the capacitor is fully discharged. At this instant, electrostatic energy is zero but because electron motion is greatest (*i.e.* maximum current), the magnetic field energy around the coil is maximum. This is shown in Fig. 16.2 (*ii*). Obviously, the electrostatic energy across the capacitor is completely converted into magnetic field energy around the coil.

(*iii*) Once the capacitor is discharged, the magnetic field will begin to collapse and produce a counter e.m.f. According to Lenz's law, the counter e.m.f. will keep the current flowing in the same direction. The result is that the capacitor is now charged with opposite polarity, making upper plate of capacitor negative and lower plate positive as shown in Fig. 16.2 (*iii*).

(*iv*) After the collapsing field has recharged the capacitor, the capacitor now begins to discharge; current now flowing in the opposite direction. Fig. 16.2 (*iv*) shows capacitor fully discharged and maximum current flowing.

The sequence of charge and discharge results in alternating motion of electrons or an oscillating current. The energy is alternately stored in the electric field of the capacitor (*C*) and the magnetic field of the inductance coil (*L*). This interchange of energy between *L* and *C* is repeated over and again resulting in the production of oscillations.

Waveform. If there were no losses in the tank circuit to consume the energy, the interchange of energy between *L* and *C* would continue indefinitely. In a practical tank circuit, there are resistive and radiation losses in the coil and dielectric losses in the capacitor. During each cycle, a small part of the originally imparted energy is used up to overcome these losses. The result is that the amplitude of oscillating current decreases gradually and eventually it becomes zero when all the energy is consumed as losses. Therefore, the tank circuit by itself will produce *damped oscillations* as shown in Fig. 16.3.

Fig. 16.3

Frequency of oscillations. The frequency of oscillations in the tank circuit is determined by the constants of the circuit *viz L* and *C*. The actual frequency of oscillations is the resonant frequency (or natural frequency) of the tank circuit given by :

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

It is clear that frequency of oscillations in the tank circuit is inversely proportional to L and C. This can be easily explained. If a large value of capacitor is used, it will take longer for the capacitor to charge fully and also longer to discharge. This will lengthen the period of oscillations in the tank circuit, or equivalently lower its frequency. With a large value of inductance, the opposition to change in current flow is greater and hence the time required to complete each cycle will be longer. Therefore, the greater the value of inductance, the longer is the period or the lower is the frequency of oscillations in the tank circuit.

16.4. Undamped Oscillations from Tank Circuit

As discussed before, a tank circuit produces damped oscillations. However, in practice, we need continuous undamped oscillations for the successful operation of electronics equipment. In order to make the oscillations in the tank circuit undamped, it is necessary to supply correct amount of energy to the tank circuit at the proper time intervals to meet the losses. Thus referring back to Fig. 16.2, any energy which would be applied to the circuit must have a polarity conforming to the existing polarity at the instant of application of energy. If the applied energy is of opposite polarity, it would oppose the energy in the tank circuit, causing stoppage of oscillations. Therefore, in order to make the oscillations in the tank circuit undamped, the following conditions must be fulfilled :

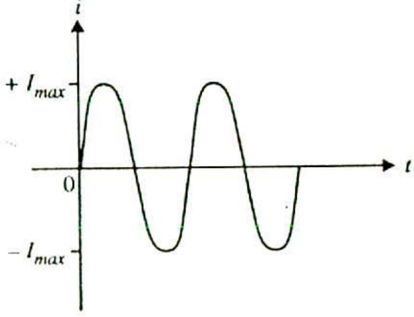


Fig. 16.4

(*i*) The amount of energy supplied should be such so as to meet the losses in the tank circuit and the a.c. energy removed from the circuit by the load. For instance, if losses in LC circuit amount to 5 mW and a.c. output being taken is 100 mW, then power of 105 mW should be continuously supplied to the circuit.

(*ii*) The applied energy should have the same frequency as that of the oscillations in the tank circuit.

(*iii*) The applied energy should be in phase with the oscillations set up in the tank circuit *i.e.* it should aid the tank circuit oscillations.

If these conditions are fulfilled, the circuit will produce continuous undamped output as shown in Fig. 16.4.

16.5. Positive Feedback Amplifier — Oscillator

A transistor amplifier with *proper* positive feedback can act as an oscillator *i.e.*, it can generate oscillations without any external signal source. Fig. 16.5 shows a transistor amplifier with positive

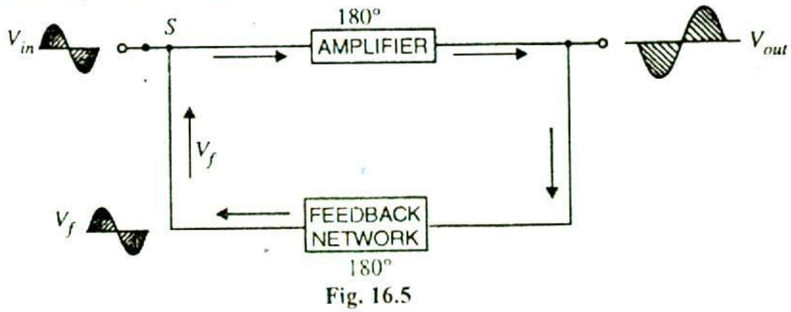


Fig. 16.5

feedback. Remember that a positive feedback amplifier is one that produces a feedback voltage (V_f) that *is in phase* with the original input signal. As you can see, this condition is met in the circuit shown in Fig. 16.5. A phase shift of 180° is produced by the amplifier and a further phase shift of 180° is introduced by feedback network. Consequently, the signal is shifted by 360° and fed to the input *i.e.*, feedback voltage is in phase with the input signal.

(*i*) We note that the circuit shown in Fig. 16.5 is producing oscillations in the output. However, this circuit has an input signal. This is inconsistent with our definition of an oscillator *i.e.*, an oscillator is a circuit that produces oscillations without any external signal source.

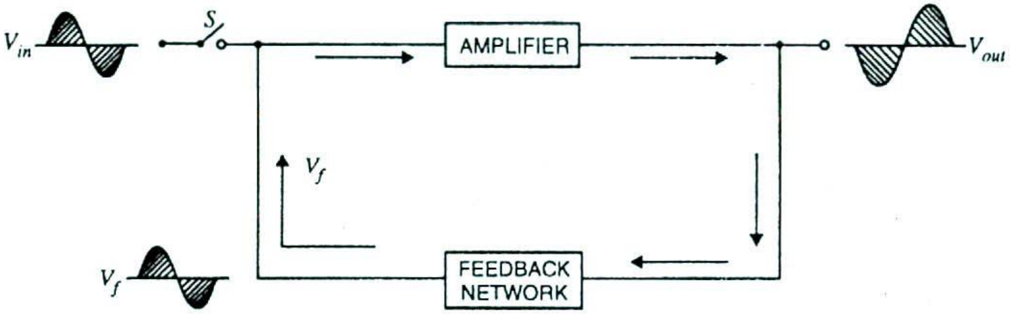


Fig. 16.6

(*ii*) When we open the switch *S* of Fig. 16.5, we get the circuit shown in Fig. 16.6. This means the input signal (V_{in}) is removed. However, V_f(which is in phase with the original signal) is still applied to the input signal. The amplifier will respond to this signal in the same way that it did to V_{in} *i.e.*, V_f will be amplified and sent to the output. The feedback network sends a portion of the output back to the input. Therefore, the amplifier receives another input cycle and another output cycle is produced. This process will continue so long as the amplifier is turned on. Therefore, the amplifer will produce sinusoidal output with no external signal source. The following points may be noted carefully :

(*a*) A transistor amplifer with proper *positive* feedback will work as an oscillator.

(*b*) The circuit needs only a quick trigger signal to start the oscillations. Once the oscillations have started, no external signal source is needed.

(*c*) In order to get continuous undamped output from the circuit, the following condition must be met :

$$m_v A_v = 1$$

where A_v = voltage gain of amplifer without feedback

m_v = feedback fraction

This relation is called *Barkhausen criterion*. This condition will be explained in the Art. 16.7.

16.6 Essentials of Transistor Oscillator

Fig. 16.7 shows the block diagram of an oscillator. Its essential components are :

(*i*) *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.

(*ii*) *Transistor amplifier*. The transistor amplifier receives d.c. power from the battery and changes it into a.c. power for supplying to the tank circuit. The oscillations occurring 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.

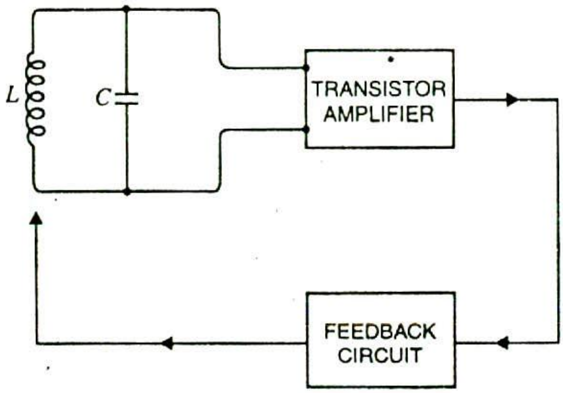


Fig. 16.7

This amplified output of oscillations is due to the d.c. power supplied by the battery. The output of the transistor can be supplied to the tank circuit to meet the losses.

(*iii*) *Feedback circuit.* The feedback circuit supplies a part of collector energy to the tank circuit in correct phase to aid the oscillations *i.e.* it provides positive feedback.

16.7 Explanation of 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 :

$$m_v A_v = 1$$

Once this condition is set in the positive feedback amplifier, continuous undamped oscillations can be obtained at the output immediately after connecting the necessary power supplies.

(*i*) **Mathematical explanation.** The voltage gain of a positive feedback amplifier is given by;

$$A_{vf} = \frac{A_v}{1 - m_v A_v}$$

$$\text{If } m_v A_v = 1, \quad \text{then} \quad A_{vf} \rightarrow \infty$$

We know that we cannot achieve infinite gain in an amplifier. So what does this result infer in physical terms ? It means that a vanishing small input voltage would give rise to finite (*i.e.*, a definite amount of) output voltage even when the input signal is zero. Thus once the circuit receives the input trigger, it would become an oscillator, generating oscillations with no external signal source.

(*ii*) **Graphical Explanation.** Let us discuss the condition $m_v A_v = 1$ graphically. Suppose the voltage gain of the amplifier without positive feedback is 100. In order to produce continuous

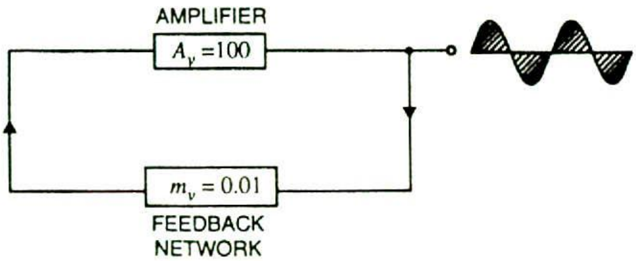


Fig. 16.8

undamped oscillations, $m_v A_v = 1$ or $m_v \times 100 = 1$ or $m_v = 0.01$. This is illustrated in Fig. 16.8. Since the condition $m_v A_v = 1$ is met in the circuit shown in Fig. 16.8, it will produce sustained oscillations.

Suppose the initial triggering voltage is 0.1V peak. Starting with this value, circuit ($A_v = 100$; $m_v = 0.01$) will progress as follows.

Cycle	V_{in}	V_{out}	V_f
1.	0.1Vpk	10Vpk	0.1Vpk
2.	0.1Vpk	10Vpk	0.1Vpk

The same thing will repeat for 3rd, 4th cycles and so on. Note that during each cycle, V_f = 0.1Vpk and V_{out} = 10 Vpk. Clearly, the oscillator is producing continuous undamped oscillations.

Note. The relation $m_v A_v = 1$ holds good for true ideal circuits. However, practical circuits need an $m_v A_v$ product that is slightly greater than 1. This is to compensate for power loss (*e.g.*, in resistors) in the circuit.

16.8 Different Types of Transistor Oscillators

A transistor can work as an oscillator to produce continuous undamped oscillations of any desired frequency if tank and feedback circuits are properly connected to it. All oscillators under different names have similar function *i.e.*, they produce continuous undamped output. However, the major difference between these oscillators lies in the method by which energy is supplied to the tank circuit to meet the losses. The following are the transistor oscillators commonly used at various places in electronic circuits :

(*i*) Tuned collector oscillator
(*ii*) Colpitt's oscillator
(*iii*) Hartley oscillator
(*iv*) Phase shift oscillator
(*v*) Wien Bridge oscillator
(*vi*) Crystal oscillator

16.9 Tuned Collector Oscillator

Fig. 16.9 shows the circuit of tuned collector oscillator. It contains tuned circuit L_1-C_1 in the collector and hence the name. The frequency of oscillations depends upon the values of L_1 and C_1 and is given by ;

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} \qquad ...(i)$$

The feedback coil L_2 in the base circuit is magnetically coupled to the tank circuit coil L_1. In practice, L_1 and L_2 form the primary and secondary of the transformer respectively. The biasing is provided by potential divider arrangement. The capacitor C connected in the base circuit provides low reactance path to the oscillations.

Circuit operation. 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 oscillations of frequency determined by exp. (*i*). These oscillations induce 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 and 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 occurring in the tank circuit. The number of turns of L_2 and coupling between L_1 and L_2 are so adjusted that oscillations across L_2 are amplified to a level just sufficient to supply losses to the tank circuit.

It may be noted that the phase of feedback is correct *i.e.* energy supplied to the tank circuit is in phase with the generated oscillations. 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 and collector circuit due to transistor properties. As a result, the energy fedback to the tank circuit is in phase with the generated oscillations.

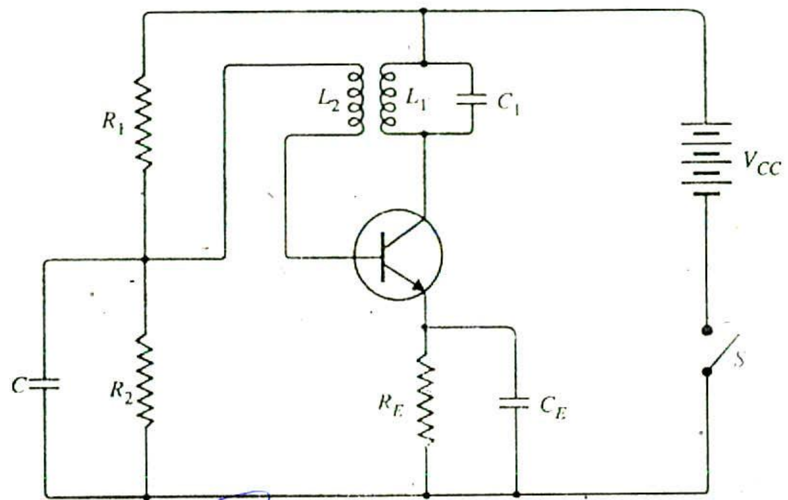


Fig. 16.9

Example 16.1. *The tuned collector oscillator circuit used in the local oscillator of a radio receiver makes use of an LC tuned circuit with L_1 = 58.6 μH and C_1 = 300 pF. Calculate the frequency of oscillations.*

Solution.

$$L_1 = 58.6\ \mu H = 58.6 \times 10^{-6}\ H$$

$$C_1 = 300\ pF = 300 \times 10^{-12}\ F$$

$$\text{Frequency of oscillations, } f = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

$$= \frac{1}{2\pi\sqrt{58.6 \times 10^{-6} \times 300 \times 10^{-12}}}\ Hz$$

$$= 1199 \times 10^3\ Hz = \mathbf{1199\ kHz}$$

16.10 Colpitt's Oscillator

Fig. 16.10 shows a Colpitt's oscillator. It uses two capacitors and placed across a common inductor L and the centre of the two capacitors is tapped. The tank circuit is made up of C_1, C_2 and L. The frequency of oscillations is determined by the values of C_1, C_2 and L and is given by ;

$$f = \frac{1}{2\pi\sqrt{LC_T}} \quad ....(i)$$

where $$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

**Note that $C_1 - C_2 - L$ is also the feedback circuit that produces a phase shift of 180°.

* All transformers introduce a phase shift of 180° between primary and secondary.

** The RF choke decouples any ac signal on the power lines from affecting the output signal.

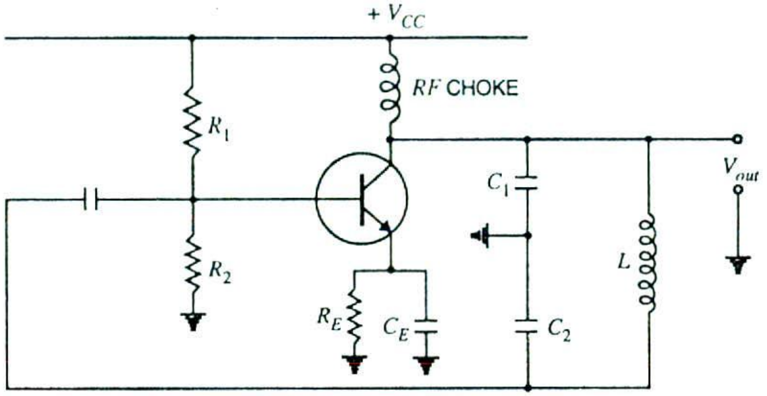


Fig. 16.10

Circuit operation. When the circuit is turned on, the capacitors C_1 and C_2 are charged. The capacitors discharge through L, setting up oscillations of frequency determined by exp* (*i*). The output voltage of the amplifier appears across C_1 and feedback voltage is developed across C_2. The voltage across is 180° out of phase with the voltage developed across C_1 (V_{out}) as shown in Fig. 16.11. It is easy to see that voltage fedback (voltage across C_2) to the transistor provides positive fedback. A phase shift of 180° is produced by the transistor and a further phase shift of 180° is produced by $C_1 - C_2$ voltage divider. In this way, feedback is properly phased to produce continuous undamped oscillation.

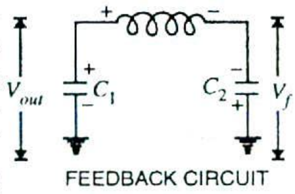


Fig. 16.11

Feedback fraction m_v. The amount of feedback voltage in Colpitt's oscillator depends upon feedback fraction m_v of the circuit. For this circuit,

$$\text{Feedback fraction, } m_v = \frac{V_f}{V_{out}} = \frac{X_{c2}}{X_{c1}} = \frac{{}^{**}C_1}{C_2}$$

or
$$m_v = \frac{C_1}{C_2}$$

Example 16.2. *Determine the (i) operating frequency and (ii) feedback fraction for Colpitt's oscillator shown in Fig. 16.12.*

Solution.

(*i*) **Operating Frequency.** The operating frequency of the circuit is always equal to the resonant frequency of the feedback network. As noted previously, the capacitors C_1 and C_2 are in series.

$$\therefore \quad C_T = \frac{C_1 C_2}{C_1 + C_2} = \frac{0.001 \times 0.01}{0.001 + 0.01} = 9.09 \times 10^{-4}\ \mu\text{F}$$
$$= 909 \times 10^{-12}\ \text{F}$$

---

* Referring to Fig. 16.11, it is clear that C_1 and C_2 are in series. Therefore, total capacitance C_T is given by;

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

** Referring to Fig. 16.11, the circulating current for the two capacitors is the same. Futher, capacitive reactance is inversely proportional to capacitance.

$$L = 15\ \mu F = 15 \times 10^{-6}\ H$$

$\therefore$ Operating frequency, $f = \dfrac{1}{2\pi\sqrt{LC_T}}$

$$= \frac{1}{2\pi\sqrt{15 \times 10^{-6} \times 909 \times 10^{-12}}}\ \text{Hz}$$

$$= 1361 \times 10^{3}\ \text{Hz} = \mathbf{1361\ kHz}$$

(*ii*) **Feedback fraction**

$$m_v = \frac{C_1}{C_2} = \frac{0.001}{0.01} = \mathbf{0.1}$$

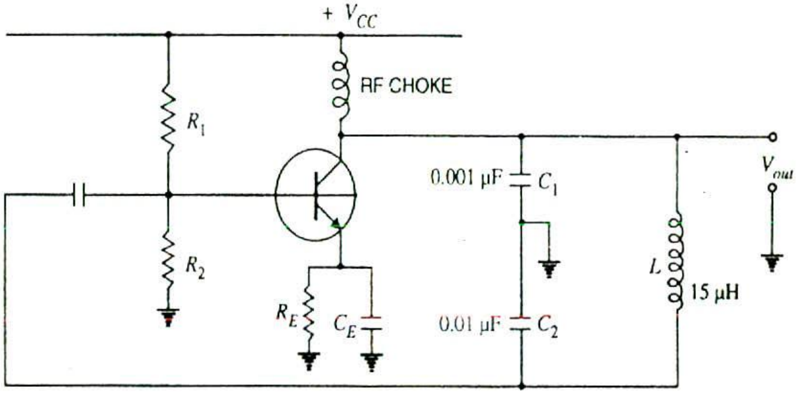


Fig. 16.12

16.11 Hartley Oscillator

The Hartley oscillator is similar to Colpitt's oscillator with minor modifications. Instead of using tapped capacitors, two inductors L_1 and L_2 are placed across a common capacitor C and the centre of the inductors is tapped as shown in Fig. 16.13. The tank circuit is made up of L_1, L_2 and C. The frequency of oscillations is determined by the values of L_1, L_2 and C and is given by ;

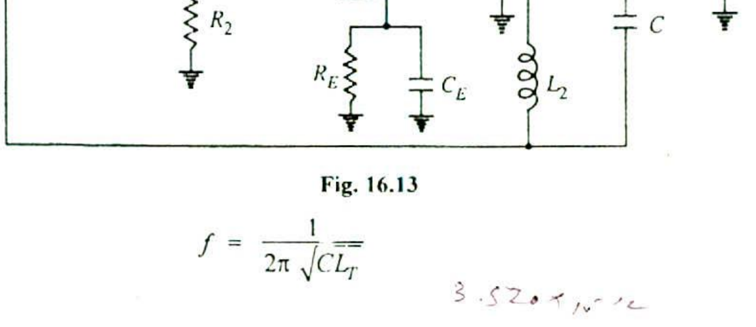


Fig. 16.13

$$f = \frac{1}{2\pi\sqrt{CL_T}} \quad ...(i)$$

where $L_T = L_1 + L_2 + 2M$

Here M = mutual inductance between L_1 and L_2.

Note that $L_1 - L_2 - C$ is also the feedback network that produces a phase shift of 180°.

Circuit operation. When the circuit is turned on, the capacitor is charged. When this capacitor is fully charged, it discharges through coils L_1 and L_2 setting up oscillations of frequency determined by *exp (*i*). The output voltage of the amplifier appears across L_1 and feedback voltage across L_2. The voltage across L_2 is 180° out of phase with the voltage developed across L_1 (V_{out}) as shown in Fig. 16.14. It is easy to see that voltage fedback (*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 $L_1 - L_2$ voltage divider. In this way, feedback is properly phased to produce continuous undamped oscillations.

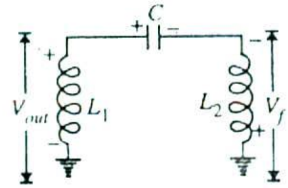


Fig. 16.14

Feedback fraction m_v. In Hartley oscillator, the feedback voltage is across L_2 and output voltage is across L_1.

$$\therefore \quad \text{Feedback fraction, } m_v = \frac{V_f}{V_{out}} = \frac{X_{L_2}}{X_{L_1}} = \frac{^{**}L_2}{L_1}$$

or
$$m_v = \frac{L_2}{L_1}$$

Example 16.3. *Calculate the (i) operating frequency and (ii) feedback fraction for Hartley oscillator shown in Fig. 16.15. The mutual inductance between the coils, M = 20 μH.*

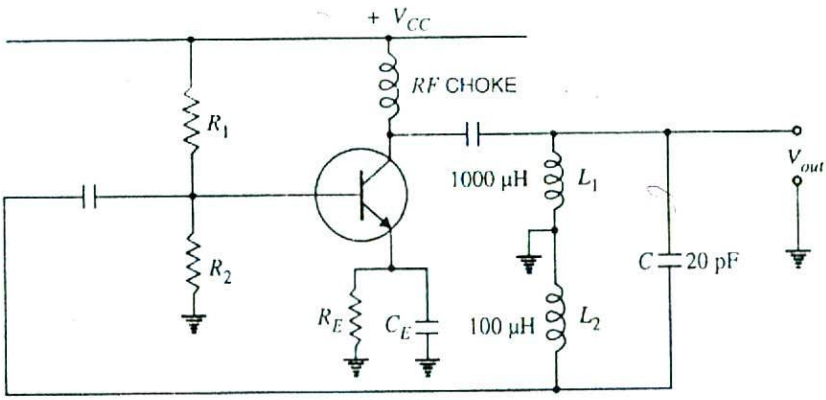


Fig. 16.15

Solution.

(*i*) L_1 = 1000 μH ; L_2 = 100 μH ; M = 20 μH

$\therefore$ Total inductance, $L_T = L_1 + L_2 + 2M$

$= 1000 + 100 + 2 \times 20 = 1140\ \mu H = 1140 \times 10^{-6} H$

---

* Refering to Fig. 16.14, it is clear that L_1 and L_2 are in series. Therefore, total inductance L_T is given by ; $L_T = L_1 + L_2 + 2M$

** Referring to Fig. 16.14, the circulating current for the two inductors is the same. Further, inductive reactance is directly proportional to inductance.

Capacitance, $C = 20\text{ pF} = 20 \times 10^{-12}\text{ F}$

$\therefore$ Operating frequency, $f = \dfrac{1}{2\pi\sqrt{L_T C}}$

$$= \frac{1}{2\pi\sqrt{1140 \times 10^{-6} \times 20 \times 10^{-12}}}\text{ Hz}$$

$$= 1052 \times 10^3\text{ Hz} = \mathbf{1052\ kHz}$$

(*ii*) Feedback fraction, $m_v = \dfrac{L_2}{L_1} = \dfrac{100\ \mu H}{1000\ \mu H} = \mathbf{0.1}$

16.12 Principle of Phase Shift Oscillators

One desirable feature of an oscillator is that it should feedback energy of correct phase to the tank circuit to overcome the losses occurring in it. In the oscillator circuits discussed so far, the tank circuit employed inductive (L) and capacitive (C) elements. In such circuits, a phase shift of 180° was obtained due to inductive or capacitive coupling and a further phase shift of 180° was obtained due to transistor properties. In this way, energy supplied to the tank circuit was in phase with the generated oscillations. The oscillator circuits employing L-C elements have two general drawbacks. Firstly, they suffer from frequency instability and poor waveform. Secondly, they cannot be used for very low frequencies because they become too much bulky and expensive.

Good frequency stability and waveform can be obtained from oscillators employing resistive and capacitive elements. Such amplifiers are called *R-C or phase shift oscillators* and have the additional advantage that they can be used for very low frequencies. In a phase shift oscillator, a phase shift of 180° is obtained with a phase shift circuit instead of inductive or capacitive coupling. A further phase shift of 180° is introduced due to the transistor properties. Thus, energy supplied back to the tank circuit is assured of correct phase.

Phase shift circuit. A phase-shift circuit essentially consists of an R-C network. Fig. 16.16 (*i*) shows a single section of RC network. From the elementary theory of electrical engineering, it can be shown that alternating voltage V_1' across R leads the applied voltage V_1 by ϕ°. The value of ϕ depends upon the values of R and C. If resistance R is varied, the value of ϕ also changes. If R were reduced to zero, V_1' will lead V_1 by 90° *i.e.* $\phi = 90°$. However, adjusting R to zero would be impracticable because it would lead to no voltage across R. Therefore, in practice, R is varied to such a value that makes V_1' to lead V_1 by 60°.

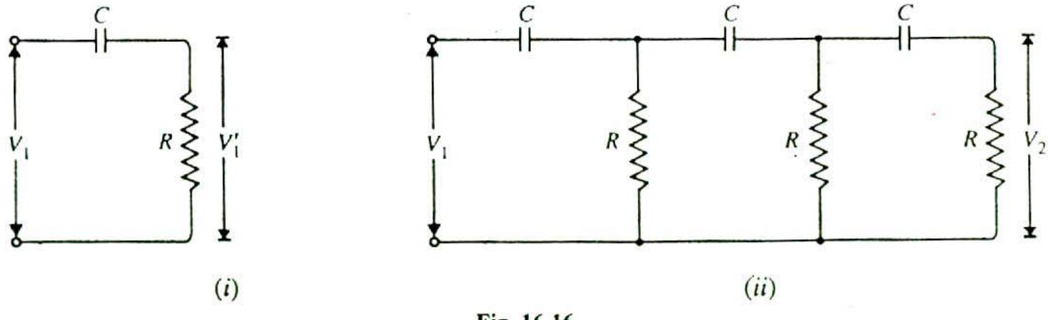


Fig. 16.16

Fig. 16.16 (*ii*) shows the three sections of RC network. Each section produces a phase shift of 60°. Consequently, a total phase shift of 180° is produced *i.e.* voltage V_2 leads the voltage V_1 by 180°.

16.13 Phase Shift Oscillator

Fig. 16.17 shows the circuit of a phase shift oscillator. It consists of a conventional single transistor amplifier and a RC phase shift network. The phase shift network consists of three sections R_1C_1, R_2C_2 and 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 ;

$$f_0 = \frac{1}{2\pi RC\sqrt{6}} \quad \text{...(i)}$$

where $R_1 = R_2 = R_3 = R$

$C_1 = C_2 = C_3 = C$

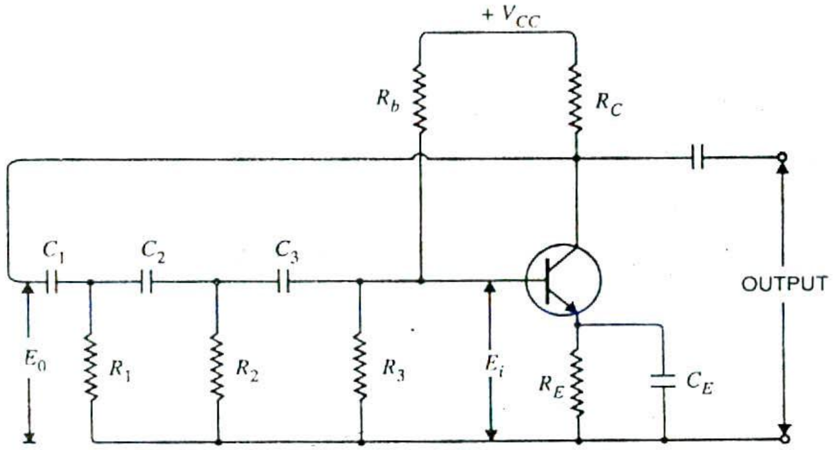


Fig. 16.17

Circuit operation. When the circuit is switched on, it produces oscillations of frequency determined by exp. (*i*). The output E_0 of the amplifier is fedback 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.

Obviously, the feedback fraction $m = E_i / E_0$. The feedback phase is correct. 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

(*i*) It does not require transformers or inductors.

(*ii*) It can be used to produce very low frequencies.

(*iii*) The circuit provides good frequency stability.

Disadvantages

(*i*) It is difficult for the circuit to start oscillations as the feedback is generally small.

(*ii*) The circuit gives small output.

Example 16.4. *In the phase shift oscillator shown in Fig. 16.17, $R_1 = R_2 = R_3 = 1 M\Omega$ and $C_1 = C_2 = C_3 = 68$ pF. At what frequency does the circuit oscillate ?*

Solution.

$$R_1 = R_2 = R_3 = R = 1\ M\Omega = 10^6\ \Omega$$

$$C_1 = C_2 = C_3 = C = 68\ pF = 68 \times 10^{-12}\ F$$

Frequency of oscillations is

$$f_o = \frac{1}{2\pi\ RC\ \sqrt{6}}$$

$$= \frac{1}{2\pi \times 10^6 \times 68 \times 10^{-12}\ \sqrt{6}}\ \text{Hz}$$

$$= \mathbf{954\ Hz}$$

16.14 Wien Bridge Oscillator

The Wien-bridge oscillator is the standard oscillator circuit for all frequencies in the range of 10 Hz to about 1 MHz. It is the most frequently used type of audio oscillator as the output is free from circuit fluctuations and ambient temperature. Fig. 16.18 shows the circuit of Wien bridge oscillator. It is essentially a two-stage amplifier with R-C bridge circuit. The bridge circuit has the arms R_1C_1, R_3, R_2C_2 and tungsten lamp L_p. Resistances R_3 and L_p are used to stabilise the amplitude of the output. The transistor T_1 serves as an oscillator and amplifier while the other transistor T_2 serves as an inverter (*i.e.* to produce a phase shift of 180°). The circuit uses positive and negative feedbacks. The positive feedback is through R_1C_1, C_2R_2 to the transistor T_1.- The negative feedback is through the voltage divider to the input of transistor T_2. The frequency of oscillations is determined by the series element R_1C_1 and parallel element R_2C_2 of the bridge.

$$f = \frac{1}{2\pi\sqrt{R_1\ C_1\ R_2\ C_2}}$$

If $R_1 = R_2 = R$

and $C_1 = C_2 = C$ then,

$$f = \frac{1}{2\pi\ RC} \quad ...(i)$$

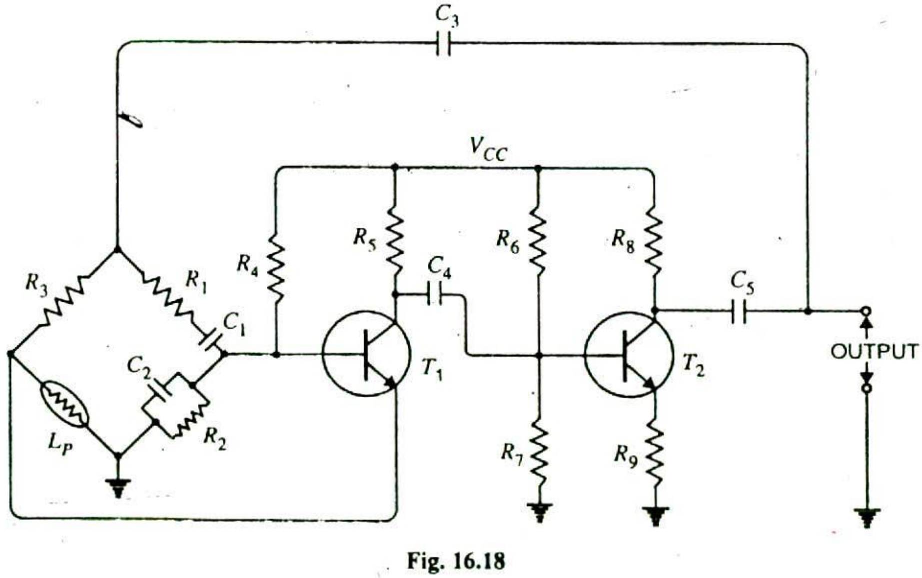


Fig. 16.18

When the circuit is started, bridge circuit produces oscillations of frequency determined by exp. (i). The two transistors produce a total phase shift of 360° so that proper positive feedback is ensured.

The negative feedback in the circuit ensures constant output. This is achieved by the temperature sensitive tungsten lamp L_p. Its resistance increases with current. Should the amplitude of output tend to increase, more current would provide more negative feedback. The result is that the output would return to original value. A reverse action would take place if the output tends to decrease.

Advantages

(*i*) It gives constant output.

(*ii*) The circuit works quite easily.

(*iii*) The overall gain is high because of two transistors.

(*iv*) The frequency of oscillations can be easily changed by using a potentiometer.

Disadvantages

(*i*) The circuit requires two transistors and a large number of components.

(*ii*) It cannot generate very high frequencies.

Example 16.5. *In the Wien bridge oscillator shown in Fig. 16.18, $R_1 = R_2 = 220\ k\Omega$ and $C_1 = C_2 = 250\ pF$. Determine the frequency of oscillations.*

Solution.

$$R_1 = R_2 = R = 220\ \text{k}\Omega = 220 \times 10^3\ \Omega$$
$$C_1 = C_2 = C = 250\ \text{pF} = 250 \times 10^{-12}\ \text{F}$$

Frequency of oscillations, $f = \dfrac{1}{2\pi RC}$

$$= \frac{1}{2\pi \times 220 \times 10^3 \times 250 \times 10^{-12}}\ \text{Hz}$$

$$= \mathbf{2892\ Hz}$$

16.15 Limitations of LC and RC Oscillators

The *LC* and *RC* oscillators discussed so far have their own limitations. The major problem in such circuits is that their operating frequency does not remain strictly constant. There are two principal reasons for it *viz.*,

(*i*) As the circuit operates, it will warm up. Consequently, the values of resistors and inductors, which are the frequency determining factors in these circuits, will change with temperature. This causes the change in frequency of the oscillator.

(*ii*) If any component in the feedback network is changed, it will shift the operating frequency of the oscillator.

However in many applications, it is desirable and necessary to maintain the frequency constant with extreme low tolerances. For example, the frequency tolerance for a broadcasting station should not exceed 0.002% *i.e.* change in frequency due to any reason should not be more than 0.002% of the specified frequency. The broadcasting stations have frequencies which are quite close to each other. In fact, the frequency difference between two broadcasting stations is less than 1%. It is apparent that if we employ *LC* or *RC* circuits, a change of temperature may cause the frequencies of adjacent broadcasting stations to overlap.

In order to maintain constant frequency, *piezoelectric crystals* are used in place of *LC* or *RC* circuits. Oscillators of this type are called *crystal oscillators*. The frequency of a crystal oscillator changes by less than 0.1% due to temperature and other changes. Therefore, such oscillators offer the most satisfactory method of stabilising the frequency and are used in great majority of electronic applications.

16.16 Piezoelectric Crystals

Certain crystalline materials, namely, Rochelle salt, quartz and tourmaline exhibit the *piezoelectric effect i.e.*, when we apply an a.c. voltage across them, they vibrate at the frequency of the applied voltage. Conversely, when they are compressed or placed under mechanical strain to vibrate, they produce an a.c. voltage. Such crystals which exhibit piezoelectric effect are called *piezoelectric crystals*. Of the various piezoelectric crystals, quartz is most commonly used because it is inexpensive and readily available in nature.

Quartz crystal. Quartz crystals are generally used in crystal oscillators because of their great mechanical strength and simplicity of manufacture. The natural shape of quartz crystal is hexagonal as shown in Fig. 16.19. The three axes are shown : the *z-axis* is called the *optical axis*, the *x-axis* is called the *electrical axis* and *y-axis* is called the *mechanical axis*. Quartz crystal can be cut in different ways. Crystal cut perpendicular to the *x-axis* is called *x-cut crystal* whereas that cut perpendicular to *y-axis* is called *y-cut crystal*. The piezoelectric properties of a crystal depend upon its cut.

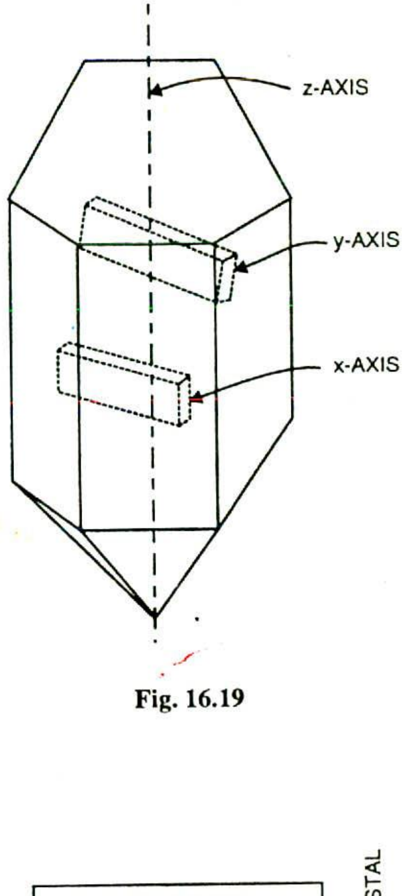


Fig. 16.19

Frequency of crystal. Each crystal has a natural frequency like a pendulum. The natural frequency f of a crystal is given by ;

$$f = \frac{K}{t}$$

where K is a constant that depends upon the cut and t is the thickness of the crystal. It is clear that frequency is inversely proportional to crystal thickness. The thinner the crystal, the greater is its natural frequency and *vice-versa*. However, extremely thin crystal may break because of vibrations. This puts a limit to the frequency obtainable. In practice, frequencies between *25 kHz* to *5 MHz* have been obtained with crystals.

16.17 Working of Quartz Crystal

In order to use crystal in an electronic circuit, it is placed between two metal plates. The arrangement then forms a capacitor with crystal as the dielectric as shown in Fig. 16.20. If an a.c. voltage is applied across the plates, the crystal will start vibrating at the frequency of applied voltage. However, if the frequency of the applied voltage is made equal to the natural frequency of the crystal, resonance takes place and crystal vibrations reach a maximum value. This natural frequency is almost constant. Effects of temperature change can be eliminated by mounting the crystal in a temperature-controlled oven as in radio and television transmitters.

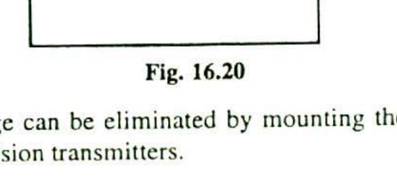


Fig. 16.20

16.18 Equivalent Circuit of Crystal

Although the crystal has electromechanical resonance, we can represent the crystal action by an equivalent electrical circuit.

(*i*) When the crystal is not vibrating, it is equivalent to capacitance C_m because it has two metal plates separated by a dielectric [See Fig. 16.21 (*i*)]. This capacitance is known as *mounting capacitance.*

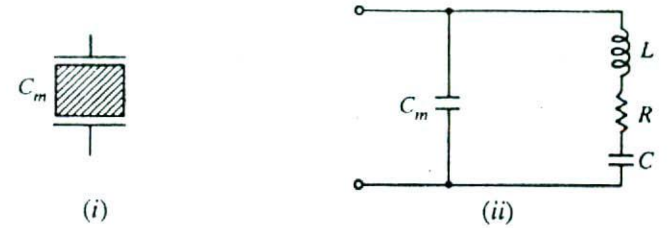


Fig. 16.21

(*ii*) When a crystal vibrates, *it is equivalent to $R - L - C$ series circuit. Therefore, the equivalent circuit of a vibrating crystal is $R - L - C$ series circuit shunted by the mounting capacitance C_m as shown in Fig. 16.21 (*ii*).

C_m = mounting capacitance

R–L–C = electrical equivalent of vibrational characteristic of the crystal

Typical values for a 4 MHz crystal are :

L = 100 mH ; R = 100 Ω

C = 0.015 pF ; C_m = 5 pF

$$\therefore \quad Q\text{-factor of crystal} = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{1}{100}\sqrt{\frac{100 \times 10^{-3}}{0.015 \times 10^{-12}}} = 26{,}000$$

Note that Q of crystal is very high. The extremely high Q of a crystal leads to frequency **stability.

16.19 Frequency Response of Crystal

When the crystal is vibrating, its equivalent electrical circuit is as shown in Fig. 16.22 (*i*). The capacitance values of C and C_m are relatively low (less than 1 pF for C and 4-40 pF for C_m). Note that the value of C is much lower than that of C_m.

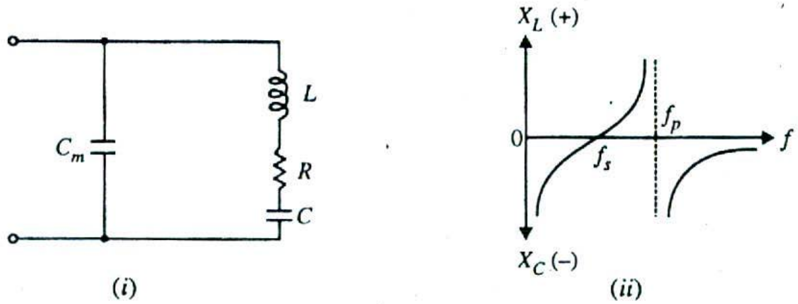


Fig. 16.22

* When the crystal is vibrating, L is the electrical equivalent of crystal mass, C is the electrical equivalent of elasticity and R is electrical equivalent of mechanical friction.

** When Q is high, frequency is primarily determined by L and C of the crystal. Since these values remain fixed for a crystal, the frequency is stable. However, in ordinary LC tank circuit, the values of L and C have large tolerances.

(*i*) At low frequencies, the impedance of the crystal is controlled by extremely high values of X_{C_m} and X_C. In other words, at low frequencies, the impedance of the network is high and capacitive as shown in Fig. 16.22 (*ii*).

(*ii*) As the frequency is increased, $R-L-C$ branch approaches its resonant frequency. At some definite frequency, the reactance X_L will be equal to X_C. The crystal now acts as a series-resonant circuit. For this condition, the impedance of the crystal is very low; being equal to R. The frequency at which the vibrating crystal behaves as a series-resonant circuit is called *series-resonant frequency* f_s. Its value is given by;

$$f_s = \frac{1}{2\pi\sqrt{LC}} \text{ Hz}$$

where L is in henry and C is in farad.

(*iii*) At a slightly higher frequency, the net reactance of branch $R-L-C$ becomes inductive and equal to X_{C_m}. The crystal now acts as a parallel-resonant circuit. For this condition, the crystal offers a very high impedance. The frequency at which the vibrating crystal behaves as a parallel-resonant circuit is called *parallel-resonant frequency* f_p.

$$f_p = \frac{1}{2\pi\sqrt{LC_T}}$$

where

$$C_T = \frac{C \times C_m}{C + C_m}$$

Since C_T is less than C, f_p is always greater than f_s. Note that frequencies f_s and f_p are very close to each other.

(*iv*) At frequencies greater than f_p, the value of X_{C_m} drops and eventually the crystal acts as a short circuit.

Conclusion. The above discussion leads to the following conclusions :

(*i*) At f_s, the crystal will acts as a series-resonant circuit.

(*ii*) At f_p, the crystal will act as a parallel-resonant circuit.

Therefore, we can use a crystal in place of a series LC circuit or in place of parallel LC circuit. If we use it in place of series LC circuit, the oscillator will operate at f_s. However if we use the crystal in place of parallel LC circuit, the oscillator will operate at f_p. In order to use the crystal properly, it must be connected in a cricuit so that its low impedance in the series resonant operating mode or high impedance in the parallel resonant operating mode is selected.

16.20 Transistor Crystal Oscillator

Fig. 16.23 shows the transistor crystal oscillator. Note that it is a Collpit's oscillator modified to act as a crystal oscillator. The only change is the addition of the crystal (Y) in the feedback network. The crystal will act as a parallel-tuned circuit. As you can see in this circuit that instead of resonance caused by L and $(C_1 + C_2)$, we have the parallel resonance of the crystal. At parallel resonance, the impedance of the crystal is maximum. This means that there is a maximum voltage drop across C_1. This in turn will allow the maximum energy transfer through the feedback network at f_p.

Note that feedback is positive. A phase shift of 180° is produced by the transistor. A further phase shift of 180° is produced by the capacitor voltage divider. This oscillator will oscillate only at f_p. Even the smallest deviation from f_p will cause the oscillator to act as an effective short. Consequently, we have an extremely stable oscillator.

Advantages

(*i*) They have a high order of frequency stability.

(*ii*) The quality factor (Q) of the crystal is very high. The Q factor of the crystal may be as high as 10,000 compared to about 100 of *L-C* tank.

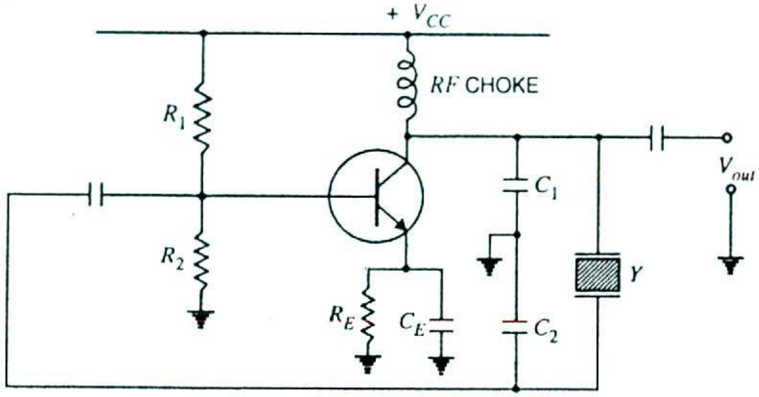


Fig. 16.23

Disadvantages

(*i*) They are fragile and consequently can only be used in low power circuits.

(*ii*) The frequency of oscillations cannot be changed appreciably.

Example 16.6. *A crystal has a thickness of t mm. If the thickness is reduced by 1%, what happens to frequency of oscillations ?*

Solution. Frequency, $f = \frac{K}{t}$

or $f \propto \frac{1}{t}$

If the thickness of the crystal is reduced by 1%, the frequency of oscillations will increase by 1%.

Example 16.7. *The ac equivalent circuit of a crystal has these values: L = 1H, C = 0.01 pF, R = 1000 Ω and C_m = 20 pF. Calculate f_s and f_p of the crystal.*

Solution.

$$L = 1\text{ H}$$

$$C = 0.01\text{ pF} = 0.01 \times 10^{-12}\text{ F}$$

$$C_m = 20\text{ pF} = 20 \times 10^{-12}\text{ F}$$

$$\therefore \quad f_s = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{1 \times 0.01 \times 10^{-12}}}\text{ Hz}$$

$$= 1589 \times 10^3\text{ Hz} = \mathbf{1589\text{ kHz}}$$

Now

$$C_T = \frac{C \times C_m}{C + C_m} = \frac{0.01 \times 20}{0.01 + 20} = 9.99 \times 10^{-3}\text{ pF}$$

$$= 9.99 \times 10^{-15}\text{ F}$$

$$\therefore \quad f_p = \frac{1}{2\pi\sqrt{LC_T}}$$

$$= \frac{1}{2\pi\sqrt{1 \times 9.99 \times 10^{-15}}}\text{ Hz}$$

$$= 1590 \times 10^3\text{ Hz} = \mathbf{1590\text{ kHz}}$$

If this crystal is used in an oscillator, the frequency of oscillations will lie between 1589 kHz and 1590 kHz.

Multiple-Choice Questions

1. An oscillator converts ....
   (*i*) a.c. power into d.c. power
   (*ii*) d.c. power into a.c. power
   (*iii*) mechanical power into a.c. power
   (*iv*) none of the above
2. In an LC transistor oscillator, the active device is ....
   (*i*) LC tank circuit (*ii*) biasing circuit
   (*iii*) transistor (*iv*) none of the above
3. In an LC circuit, when the capacitor energy is maximum, the inductor energy is ....
   (*i*) minimum (*ii*) maximum
   (*iii*) half-way between maximum and minimum
   (*iv*) none of the above
4. In an *LC* oscillator, the frequency of oscillator is .... *L* or *C*.
   (*i*) proportional to square
   (*ii*) directly proportional to
   (*iii*) independent of the values of
   (*iv*) inversely proportional to square root of
5. An oscillator produces .... oscillations.
   (*i*) damped (*ii*) undamped
   (*iii*) modulated (*iv*) none of the above
6. An oscillator employs .... feedback.
   (*i*) positive (*ii*) negative
   (*iii*) neither positive nor negative
   (*iv*) data insufficient
7. An LC oscillator cannot be used to produce .... frequencies.
   (*i*) high (*ii*) audio
   (*iii*) very low (*iv*) very high
8. Hartley oscillator is commonly used in ....
   (*i*) radio receivers (*ii*) radio transmitters
   (*iii*) TV receivers (*iv*) none of the above
9. In a phase shift oscillator, we use .... *RC* sections.
   (*i*) two (*ii*) three
   (*iii*) four (*iv*) none of the above
10. In a phase shift oscillator, the frequency determining elements are ....
    (*i*) L and C (*ii*) R, L and C
    (*iii*) R and C (*iv*) none of the above
11. A Wien bridge oscillator uses .... feedback.
    (*i*) only positive (*ii*) only negative
    (*iii*) both positive and negative
    (*iv*) none of the above
12. The piezoelectric effect in a crystal is ....
    (*i*) a voltage developed because of mechanical stress
    (*ii*) a change in resistance because of temperature
    (*iii*) a change of frequency because of temperature
    (*iv*) none of the above
13. If the crystal frequency changes with temperature, we say that crystal has .... temperature coefficient
    (*i*) positive (*ii*) zero
    (*iii*) negative (*iv*) none of the above
14. The crystal oscillator frequency is very stable due to .... of the crystal.
    (*i*) rigidity (*ii*) vibrations
    (*iii*) low *Q* (*iv*) high *Q*
15. The application where one would most likely find a crystal oscillator is ....
    (*i*) radio receiver (*ii*) radio transmitter
    (*iii*) AF sweep generator
    (*iv*) none of the above
16. An oscillator differs from an amplifer because it ....
    (*i*) has more gain
    (*ii*) requires no input signal
    (*iii*) requires no d.c. supply
    (*iv*) always has the same input

17. One condition for oscillation is ....
   (*i*) a phase shift around the feedback loop of 180°
   (*ii*) a gain around the feedback loop of one-third
   (*iii*) a phase shift around the feedback loop of 0°
   (*iv*) a gain around the feedback loop of less than 1
18. A second condition for oscillations is ....
   (*i*) a gain of 1 around the feedback loop
   (*ii*) no gain around the feedback loop
   (*iii*) the attenuation of the feedback circuit must be one-third
   (*iv*) the feedback circuit must be capacitive
19. In a certain oscillator, $A_v = 50$. The attenuation of the feedback circuit must be ....
   (*i*) 1 (*ii*) 0.01
   (*iii*) 10 (*iv*) 0.02
20. For an oscillator to properly start, the gain around the feedback loop must initially be ....
   (*i*) 1 (*ii*) greater than 1
   (*iii*) less than 1
   (*iv*) equal to attenuation of feedback circuit
21. In a Wien-bridge oscillator, if the resistances in the positive feedback circuit are decreased, the frequency ....
   (*i*) remains the same
   (*ii*) decreases
   (*iii*) increases
   (*iv*) insufficient data
22. In a Colpitt's oscillator, feedback is obtained ....
   (*i*) by magnetic induction
   (*ii*) by a tickler coil
   (*iii*) from the centre of split capacitors
   (*iv*) none of the above
23. The Q of a crystal is of the order of ....
   (*i*) 100 (*ii*) 1000
   (*iii*) 50 (*iv*) more than 10,000
24. Quartz crystal is most commonly used in crystal oscillators because ....
   (*i*) it has superior electrical properties
   (*ii*) it is easily available
   (*iii*) it is quite inexpensive
   (*iv*) none of the above
25. In LC oscillators, the frequency of oscillations is given by ....
   (*i*) $\frac{2\pi}{\sqrt{LC}}$ (*ii*) $\frac{1}{2\pi\sqrt{LC}}$
   (*iii*) $\frac{\sqrt{LC}}{2\pi}$ (*iv*) $\frac{2\pi L}{\sqrt{LC}}$
26. The operating frequency of a Wien-bridge oscillator is given by ....
   (*i*) $\frac{1}{2\pi\sqrt{LC}}$ (*ii*) $\frac{1}{4\pi\sqrt{LC}}$
   (*iii*) $\frac{1}{2\pi RC}$ (*iv*) $\frac{1}{29\, RC}$
27. .... is a fixed frequency oscillator.
   (*i*) Phase-shift oscillator
   (*ii*) Hartley oscillator
   (*iii*) Colpitt's oscillator
   (*iv*) Crystal oscillator
28. In an LC oscillator, if the value of L is increased four times, the frequency of oscillations is ....
   (*i*) increased 2 times
   (*ii*) decreased 4 times
   (*iii*) increased 4 times
   (*iv*) decreased 2 times
29. An important limitation of a crystal oscillator is ....
   (*i*) its low output (*ii*) its high Q
   (*iii*) less availability of quartz crystal
   (*iv*) its high output
30. The signal generator generally used in the laboratories is .... oscillator.
   (*i*) Wien-bridge (*ii*) Hartley
   (*iii*) Crystal (*iv*) Phase shift

Answers to Multiple-Choice Questions

1. (*ii*)	**2.** (*iii*)	**3.** (*i*)	**4.** (*iv*)	**5.** (*ii*)
6. (*i*)	**7.** (*iii*)	**8.** (*i*)	**9.** (*ii*)	**10.** (*iii*)
11. (*iii*)	**12.** (*i*)	**13.** (*i*)	**14.** (*iv*)	**15.** (*ii*)
16. (*ii*)	**17.** (*iii*)	**18.** (*i*)	**19.** (*iv*)	**20.** (*ii*)
21. (*iii*)	**22.** (*iii*)	**23.** (*iv*)	**24.** (*i*)	**25.** (*ii*)
26. (*iii*)	**27.** (*iv*)	**28.** (*iv*)	**29.** (*i*)	**30.** (*i*)

Chapter Review Topics

1. What is an oscillator ? What is its need ? Discuss the advantages of oscillators.
2. What do you understand by damped and undamped electrical oscillations ? Illustrate your answer with examples.
3. Explain the operation of a tank circuit with neat diagrams.
4. What is the nature of oscillations produced by tank circuit ?
5. How will you get undamped oscillations from a tank circuit ?
6. Discuss the essentials of an oscillator.
7. Discuss the circuit operation of tuned collector oscillator.
8. With a neat diagram, explain the action of Hartley and Colpitt's oscillators.
9. What are the drawbacks of LC oscillators ?
10. Write short notes on the following :
    (*i*) *RC* oscillators (*ii*) Wien bridge oscillators (*iii*) Crystal oscillator

Problems

1. Figure 16.24 shows the Colpitt's oscillator. Determine the (*i*) operating frequency and (*ii*) feedback fraction. [(*i*) **24.5 kHz** (*ii*) **0.1**]

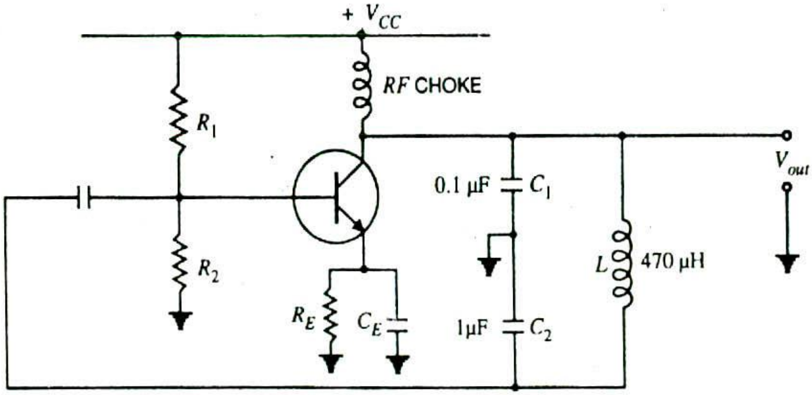


Fig. 16.24

2. Figure 16.25 shows the Hartley oscillator. If L_1 = 1000 μH, L_2 = 100 μH and C = 20 pF, find the (*i*) operating frequency and (*ii*) feedback fraction. [(*i*) **1052 kHz** (*ii*) **0.1**]
3. For the Colpitt's oscillator shown in Fig. 16.24, C_1= 750 pF, C_2 = 2500 pF and L = 40 μH. Determine (*i*) the operating frequency and (*ii*) feedback fraction. [(*i*) **1050 kHz** (*ii*) **0.3**]
4. For the Hartley oscillator shown in Fig. 16.25, C = 250 pF, L_1 = 1.5 mH, L_2 = 1.5 mH and M = 0.58 mH. Determine the operating frequency. [**159.2 kHz**]

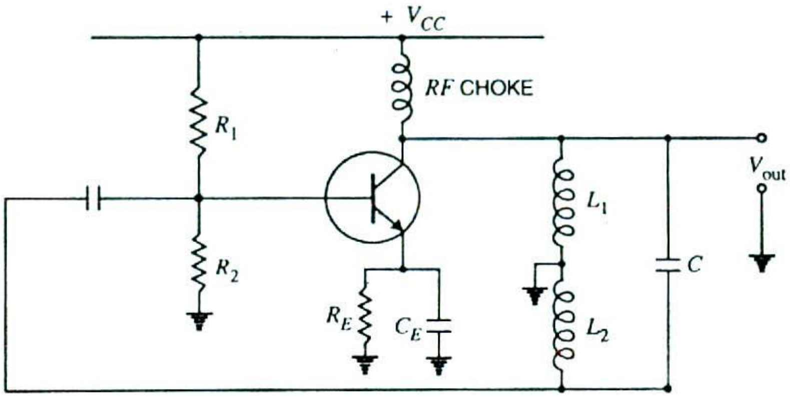


Fig. 16.25

5. A crystal has $L = 3H$, $C = 0.05$ pF, $R = 2$ kΩ and $C_m = 10$ pF. Calculate the series-resonant and parallel-resonant frequencies of the crystal. **[411 kHz ; 412 kHz]**

Discussion Questions

1. Why is amplifier circuit necessary in an oscillator ?
2. Why is crystal oscillator used in radio transmitter ?
3. Why do you use three *RC* sections in *RC* oscillator ?
4. Why is negative feedback provided in Wien bridge oscillators ?
5. Why is quartz crystal commonly used in crystal oscillators ?

17

Transistor Tuned Amplifiers

Introduction

Most of the audio amplifiers we have discussed in the earlier chapters will also work at radio frequencies *i.e.* above 50 kHz. However, they suffer from two major drawbacks. First, they become less efficient at radio frequency. Secondly, such amplifiers have mostly resistive loads and consequently their gain is independent of signal frequency over a large bandwidth. In other words, an audio amplifier amplifies a wide band of frequencies equally well and does not permit the selection of a particular desired frequency while rejecting all other frequencies.

However, sometimes it is desired that an amplifier should be selective *i.e.* it should select a desired frequency or narrow band of frequencies for amplification. For instance, radio and television transmission are carried on a specific radio frequency assigned to the broadcasting station. The radio receiver is required to pick up and amplify the radio frequency desired while discriminating all others. To achieve this, the simple resistive load is replaced by a parallel tuned circuit whose impedance strongly depends upon frequency. Such a tuned circuit becomes very selective and amplifies very strongly signals of resonant frequency and narrow band on either side. Therefore, the use of tuned circuits in conjunction with a transistor makes possible the selection and efficient amplification of a particular desired radio frequency. Such an amplifier is called a *tuned amplifier*. In this chapter, we shall focus our attention on transistor tuned amplifiers and their increasing applications in high frequency electronic circuits.

17.1 Tuned Amplifiers

Amplifiers which amplify a specific frequency or narrow band of frequencies are called **tuned amplifiers.**

Tuned amplifiers are mostly used for the amplification of high or radio frequencies. It is because radio frequencies are generally single and the tuned circuit permits their selection and efficient amplification. However, such amplifiers are not suitable for the amplification of audio frequencies as they are mixture of frequencies from 20 Hz to 20 kHz and not single. Tuned amplifiers are widely used in radio and television circuits where they are called upon to handle radio frequencies.

Fig. 17.1 shows the circuit of a simple transistor tuned amplifier. Here, instead of load resistor, we have a parallel tuned circuit in the collector. The impedance of this tuned circuit strongly depends upon frequency. It offers a very high impedance at *resonant frequency* and very small impedance at all other frequencies. If the signal has the same frequency as the resonant frequency of *LC* circuit, large amplification will result due to high impedance of *LC* circuit at this frequency. When signals of many frequencies are present at the input of tuned amplifier, it will select and strongly amplify the signals of resonant frequency while *rejecting all others. Therefore, such amplifiers are very useful in radio receivers to select the signal from one particular broadcasting station when signals of many other frequencies are present at the receiving aerial.

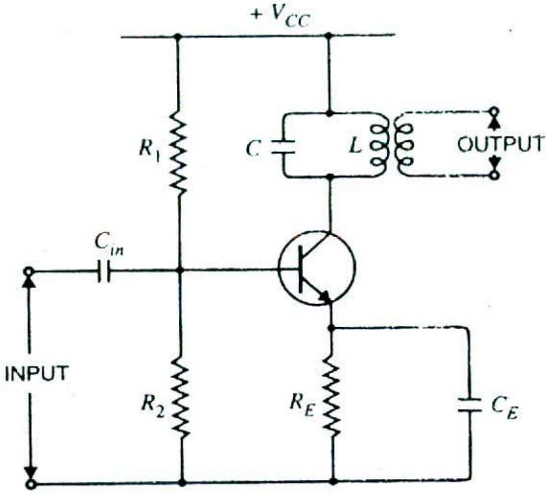


Fig. 17.1

17.2 Distinction between Tuned Amplifiers and other Amplifiers

We have seen that amplifiers (*e.g.*, voltage amplifier, power amplifier *etc*) provide the constant gain over a limited band of frequencies *i.e.*, from lower cut-off frequency f_1 to upper cut-off frequency f_2. Now bandwidth of the amplifier, $BW = f_2 - f_1$. The reader may wonder, then, what distinguishes a tuned amplifier from other amplifiers? The difference is that tuned amplifiers are designed to have specific, usually narrow bandwidth. This point is illustrated in in Fig. 17.2. Note that BW_S is the bandwidth of standard frequency response while BW_T is the bandwidth of the tuned amplifier. In many applications, the narrower the bandwidth of a tuned amplifier, the better it is.

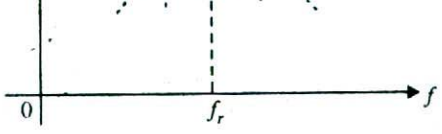


Fig. 17.2

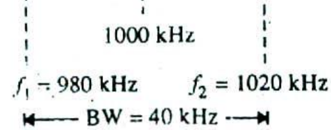


Fig. 17.3

Illustration. Consider a tuned amplifier that is designed to amplify only those frequencies that

* For all other frequencies, the impedance of LC circuit will be very small. Consequently, little amplification will occur for these frequencies.

are within ± 20 kHz of the central frequency of 1000 kHz (*i.e.*, f_r = 1000 kHz). Here [See Fig. 17.3],

f_1 = 980 kHz, f_r = 1000 kHz, f_2 = 1020 kHz, BW = 40 kHz

This means that so long as the input signal is within the range of 980 – 1020 kHz, it will be amplified. If the frequency of input signal goes out of this range, amplification will be drastically reduced.

17.3 Analysis of Parallel Tuned Circuit

A parallel tuned circuit consists of a capacitor C and inductor L in parallel as shown in Fig. 17.4 (*i*). In practice, some resistance R is always present with the coil. If an alternating voltage is applied across this parallel circuit, the frequency of oscillations will be that of the applied voltage. However, if the frequency of applied voltage is equal to the natural or resonant frequency of LC circuit, then *electrical resonance* will occur. Under such conditions, the impedance of the tuned circuit becomes maximum and the line current is minimum. The circuit then draws just enough energy from a.c. supply necessary to overcome the losses in the resistance R.

Parallel resonance. A parallel circuit containing reactive elements (L and C) is *resonant when the circuit power factor is unity *i.e.* applied voltage and the supply current are in phase. The phasor diagram of the parallel circuit is shown in Fig. 17. 4 (*ii*). The coil current I_L has two rectangular components *viz* active component $I_L \cos \phi_L$ and reactive component $I_L \sin \phi_L$. This parallel circuit will resonate when the circuit power factor is unity. This is possible only when the net reactive component of the circuit current is zero *i.e.*

$$I_C - I_L \sin \phi_L = 0$$

or

$$I_C = I_L \sin \phi_L$$

Resonance in parallel circuit can be obtained by changing the supply frequency. At some frequency f_r (called resonant frequency), $I_C = I_L \sin \phi_L$ and resonance occurs.

Resonant frequency. The frequency at which parallel resonance occurs (*i.e.* reactive component of circuit current becomes zero) is called the *resonant frequency* f_r.

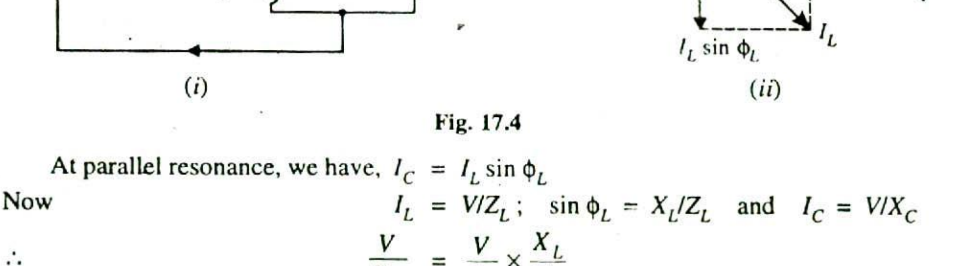


Fig. 17.4

At parallel resonance, we have, $I_C = I_L \sin \phi_L$

Now $I_L = V/Z_L$; $\sin \phi_L = X_L/Z_L$ and $I_C = V/X_C$

$$\therefore \quad \frac{V}{X_C} = \frac{V}{Z_L} \times \frac{X_L}{Z_L}$$

* Resonance means to be in step with. In an a.c. circuit if applied voltage and supply current are in phase (*i.e.*, in step with), resonance is said to occur. If this happens in a parallel a.c. circuit, it is called parallel resonance.

or $$X_L X_C = Z_L^2$$

or $$\frac{\omega L}{\omega C} = Z_L^2 = R^2 + X_L^2 \quad ...(i)$$

or $$\frac{L}{C} = R^2 + (2\pi f_r L)^2$$

or $$(2\pi f_r L)^2 = \frac{L}{C} - R^2$$

or $$2\pi f_r L = \sqrt{\frac{L}{C} - R^2}$$

or $$f_r = \frac{1}{2\pi L}\sqrt{\frac{L}{C} - R^2}$$

$\therefore$ $$\text{Resonant frequency, } f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}} \quad ...(ii)$$

If coil resistance R is small (as is generally the case), then,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad ...(iii)$$

The resonant frequency will be in Hz if R, L and C are in ohms, henry and farad respectively.

Note. If in the problem, the value of R is given, then eq. (*ii*) should be used to find f_r. However, if R is not given, then eq. (*iii*) may be used to find f_r.

17.4 Characteristics of Parallel Resonant Circuit

It is now desirable to discuss some important characteristics of parallel resonant circuit.

(*i*) **Impedance of tuned circuit.** The impedance offered by the parallel LC circuit is given by the supply voltage divided by the line current *i.e.*, V/I. Since at resonance, line current is minimum, therefore, impedance is maximum at resonant frequency. This fact is shown by the impedance-frequency curve of Fig. 17.5. It is clear from impedance-frequency curve that impedance rises to a steep peak at resonant frequency f_r. However, the impedance of the circuit decreases rapidly when the frequency is changed above or below the resonant frequency. This characteristic of parallel tuned circuit provides it the selective properties *i.e.* to select the resonant frequency and reject all others.

Line current, $I = I_L \cos\phi_L$

or $$\frac{V}{Z_r} = \frac{V}{Z_L} \times \frac{R}{Z_L}$$

or $$\frac{1}{Z_r} = \frac{R}{Z_L^2}$$

or $$\frac{1}{Z_r} = \frac{R}{L/C} = \frac{CR}{L} \quad \left[\because Z_L^2 = \frac{L}{C} \text{ from eq. } (i)\right]$$

$\therefore$ Circuit impedance, $$Z_r = \frac{L}{CR}$$

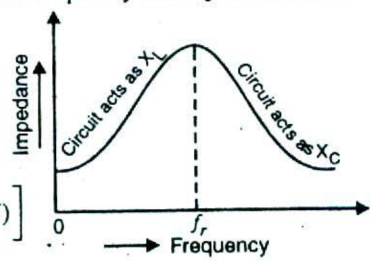


Fig. 17.5

Thus at parallel resonance, the circuit impedance is equal to *L/CR. It may be noted that Z_r will be in ohms if R, L and C are measured in ohms, henry and farad respectively.

(*ii*) **Circuit Current.** At parallel resonance, the circuit or line current I is given by the applied voltage divided by the circuit impedance Z_r *i.e.*,

* Two things are worth noting, First, Z_r (= L/CR) is a pure resistance because there is no frequency term present. Secondly, the value of Z_r is very high because the ratio L/C is very large at parallel resonance.

$$\text{Line current, } I = \frac{V}{Z_r} \qquad \text{where } Z_r = \frac{L}{CR}$$

Because Z_r is very high, the line current I will be very small.

(*iii*) **Quality factor Q.** It is desired that resonance curve of a parallel tuned circuit should be as sharp as possible in order to provide selectivity. The sharp resonance curve means that impedance falls rapidly as the frequency is varied from the resonant frequency. The smaller the resistance of coil, the more sharp is the resonance curve. This is due to the fact that a small resistance consumes less power and draws a relatively small line current. The ratio of inductive reactance and resistance of the coil at resonance, therefore, becomes a measure of the quality of the tuned circuit. This is called *quality factor* and may be defined as under :

The ratio of inductive reactance of the coil at resonance to its resistance is known as ***quality factor Q** *i.e.*,

$$Q = \frac{X_L}{R} = \frac{2\pi f_r L}{R}$$

The quality factor Q of a parallel tuned circuit is very important because the sharpness of resonance curve and hence selectivity of the circuit depends upon it. The higher the value of Q, the more selective is the tuned circuit. Fig. 17.6 shows the effect of resistance R of the coil on the sharpness of the resonance curve. It is clear that when the resistance is small, the resonance curve is very sharp. However, if the coil has large resistance, the resonance curve is less sharp. It may be emphasised that where high selectivity is desired, the value of Q should be very large.

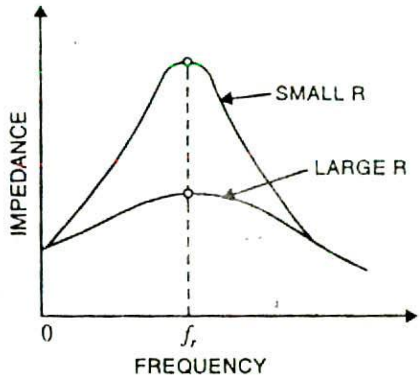


Fig. 17.6

Example 17.1. *A parallel resonant circuit has a capacitor of 250pF in one branch and inductance of 1.25mH plus a resistance of 10Ω in the parallel branch. Find (i) resonant frequency (ii) impedance of the circuit at resonance (iii) Q-factor of the circuit.*

Solution.

$R = 10\Omega$; $L = 1.25 \times 10^{-3}$H ; $C = 250 \times 10^{-12}$ F

(*i*) Resonant frequency of the circuit is

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{10^{12}}{1.25 \times 10^{-3} \times 250} - \frac{10^2}{(1.25 \times 10^{-3})^2}} \text{ Hz}$$

$$= 284.7 \times 10^3 \text{ Hz} = \mathbf{284.7\ kHz}$$

(*ii*) Impedance of the circuit at resonance is

* Strictly speaking, the Q of a tank circuit is defined as the ratio of the energy stored in the circuit to the energy lost in the circuit *i.e.*,

$$Q = \frac{\text{Energy stored}}{\text{Energy lost}} = \frac{\text{Reactive Power}}{\text{Resistive Power}} = \frac{I_L^2 X_L}{I_L^2 R} \quad \text{or} \quad Q = \frac{X_L}{R}$$

$$Z_r = \frac{L}{C\,R} = \frac{1.25 \times 10^{-3}}{250 \times 10^{-12} \times 10} = 500 \times 10^3\ \Omega$$

$$= \mathbf{500\ k\Omega}$$

(*iii*) Quality factor of the circuit is

$$Q = \frac{2\pi f_r L}{R} = \frac{2\pi\,(284.7 \times 10^3) \times 1.25 \times 10^{-3}}{10} = \mathbf{223.6}$$

Example 17.2. *A parallel resonant circuit has a capacitor of 100 pF in one branch and inductance of 100 μH plus a resistance of 10 Ω in parallel branch. If the supply voltage is 10 V, calculate (i) resonant frequency (ii) impedance of the circuit and line current at resonance.*

Solution.

$R = 10\ \Omega,\ L = 100 \times 10^{-6}\ \text{H};\ C = 100 \times 10^{-12}\ \text{F}$

(*i*) Resonant frequency of the circuit is

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{10^{12}}{100 \times 10^{-6} \times 100} - \frac{10^2}{(100 \times 10^{-6})^2}}\ \text{Hz}$$

$$= 1592.28 \times 10^3\ \text{Hz} = \mathbf{1592.28\ kHz}$$

(*ii*) Impedance of the circuit at resonance is

$$Z_r = \frac{L}{C\,R} = \frac{L}{C} \times \frac{1}{R} = \frac{100 \times 10^{-6}}{100 \times 10^{-12}} \times \frac{1}{R}$$

$$= 10^6 \times \frac{1}{R} = 10^6 \times \frac{1}{10} = 10^5\ \Omega = \mathbf{0.1\ M\Omega}$$

Note that the circuit impedance Z_r is very high at resonance. It is because the ratio L/C is very large at resonance.

Line current at resonance is

$$I = \frac{V}{Z_r} = \frac{10\ \text{V}}{10^5\ \Omega} = \mathbf{100\ \mu A}$$

17.5 Advantages of Tuned Amplifiers

In high frequency applications, it is generally required to amplify a single frequency, rejecting all other frequencies present. For such purposes, tuned amplifiers are used. These amplifiers use tuned parallel circuit as the collector load and offer the following advantages :

(*i*) **Small power loss.** A tuned parallel circuit employs reactive components L and C. Consequently, the power loss in such a circuit is quite low. On the other hand, if a resistive load is used in the collector circuit, there will be considerable loss of power. Therefore, tuned amplifiers are highly efficient.

(*ii*) **High selectivity.** A tuned circuit has the property of selectivity *i.e.* it can select the desired frequency for amplification out of a large number of frequencies simultaneously impressed upon it. For instance, if a mixture of frequencies including f_r is fed to the input of a tuned amplifier, then maximum amplification occurs for f_r. For all other frequencies, the tuned circuit offers very low impedance and hence these are amplified to a little extent and may be thought as rejected by the circuit. On the other hand, if we use resistive load in the collector, all the frequencies will be amplified equally well *i.e.* the circuit will not have the ability to select the desired frequency.

(*iii*) **Smaller collector supply voltage.** Because of little resistance in the parallel tuned circuit, it requires small collector supply voltage V_{CC}. On the other hand, if a high load resistance is used in the collector for amplifying even one frequency, it would mean large voltage drop across it due to zero signal collector current. Consequently, a higher collector supply will be needed.

17.6 Why not Tuned Circuits for Low Frequency Amplification ?

The tuned amplifiers are used to select and amplify a specific high frequency or narrow band of frequencies. The reader may be inclined to think as to why tuned circuits are not used to amplify low frequencies. This is due to the following reasons :

(*i*) *Low frequencies are never single.* A tuned amplifier selects and amplifies a single frequency. However, the low frequencies found in practice are the audio frequencies which are a mixture of frequencies from 20 Hz to 20 kHz and are not single. It is desired that all these frequencies should be equally amplified for proper reproduction of the signal. Consequently, tuned amplifiers cannot be used for the purpose.

(*ii*) *High values of L and C.* The resonant frequency of a parallel tuned circuit is given by;

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

For low frequency amplification, we require large values of L and C. This will make the tuned circuit bulky and expensive. It is worthwhile to mention here that R-C and transformer coupled amplifiers, which are comparatively cheap, can be conveniently used for low frequency applications.

17.7 Frequency Response of Tuned Amplifier

The voltage gain of an amplifier depends upon β, input impedance and effective collector load. In a tuned amplifier, tuned circuit is used in the collector. Therefore, voltage gain of such an amplifier is given by ;

$$\text{Voltage gain} = \frac{\beta Z_C}{Z_{in}}$$

where Z_C = effective collector load

Z_{in} = input impedance of the amplifier

The value of Z_C and hence gain strongly depends upon frequency in the tuned amplifier. As Z_C is maximum at resonant frequency, therefore, voltage gain will be maximum at this frequency. The value of Z_C and gain decrease as the frequency is varied above and below the resonant frequency. Fig. 17.7 shows the frequency response of a tuned amplifier. It is clear that voltage gain is maximum at resonant frequency and falls off as the frequency is varied in either direction from resonance.

Bandwidth. The range of frequencies at which the voltage gain of the tuned amplifier falls to 70.7 % of the maximum gain is called its *bandwidth*. Referring to Fig. 17.7, the bandwidth of tuned amplifier is $f_1 - f_2$. The amplifier will amplify nicely any signal in this frequency range. The bandwidth of tuned amplifier depends upon the value of Q of LC circuit *i.e.* upon the sharpness of the frequency response. The greater the value of Q of tuned circuit, the lesser is the bandwidth of the amplifier and *vice-versa*. In practice, the value of Q of LC circuit is made such so as to permit the amplification of desired narrow band of high frequencies.

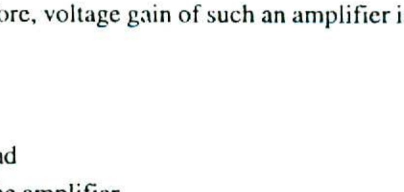


Fig. 17.7

The practical importance of bandwidth of tuned amplifiers is found in communication system. In radio and TV transmission, a very high frequency wave, called *carrier wave* is used to carry the audio or picture signal. In radio transmission, the audio signal has a frequency range of 10 kHz. If the carrier wave frequency is 710 kHz, then the resultant radio wave has a frequency range *between (710 –5) kHz and (710 +5) kHz. Consequently, the tuned amplifier must have a bandwidth of 705 kHz to 715 kHz (*i.e.* 10 kHz). The Q of the tuned circuit should be such that bandwidth of the amplifier lies in this range.

17.8 Relation between Q and Bandwidth

The quality factor Q of a tuned amplifier is equal to the ratio of resonant frequency (f_r) to bandwidth (BW) *i.e.*,

$$Q = \frac{f_r}{BW}$$

The Q of an amplifier is determined by the circuit component values. It may be noted here that Q of a tuned amplifier is generally greater than 10. When this condition is met, the resonant frequency at parallel resonance is approximately given by;

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Example 17.3. *The Q of a tuned amplifier is 60. If the resonant frequency for the amplifier is 1200 kHz, find (i) bandwidth and (ii) cut-off frequencies.*

Solution.

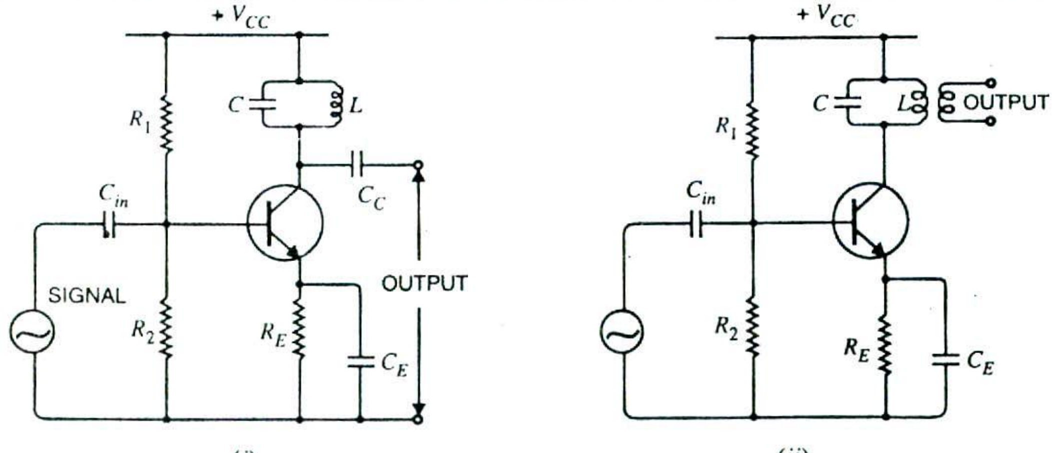
(*i*) $BW = \frac{f_r}{Q} = \frac{1200 \text{ kHz}}{60}$ = **20 kHz**

(*ii*) Lower cut-off frequency, f_1 = 1200 – 10 = **1190 kHz**

Upper cut-off frequency, f_2 = 1200 + 10 = **1210 kHz**

17.9 Single Tuned Amplifier

A single tuned amplifier consists of a transistor amplifier containing a parallel tuned circuit as the collector load. The values of capacitance and inductance of the tuned circuit are so selected that its



(*i*) (*ii*)

Fig. 17.8

* See chapter on modulation and demodulation.

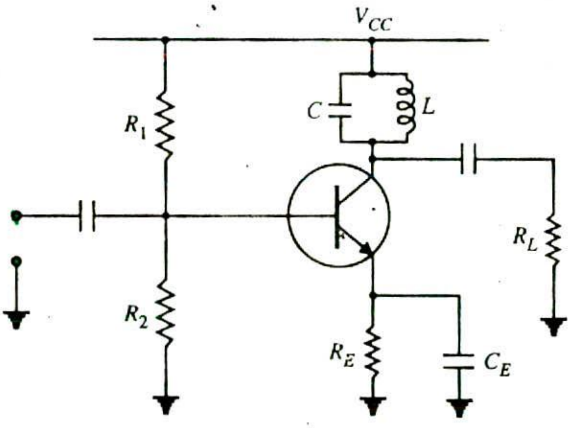
resonant frequency is equal to the frequency to be amplified. The output from a single tuned amplifier can be obtained either (*a*) by a coupling capacitor C_C as shown in Fig. 17.8 (*i*) or (*b*) by a secondary coil as shown in Fig. 17.8 (*ii*).

Operation. The high frequency signal to be amplified is given to the input of the amplifier. The resonant frequency of parallel tuned circuit is made equal to the frequency of the signal by changing the value of *C*. Under such conditions, the tuned circuit will offer very high impedance to the signal frequency. Hence a large output appears across the tuned circuit. In case the input signal is complex containing many frequencies, only that frequency which corresponds to the resonant frequency of the tuned circuit will be amplified. All other frequencies will be rejected by the tuned circuit. In this way, a tuned amplifier selects and amplifies the desired frequency.

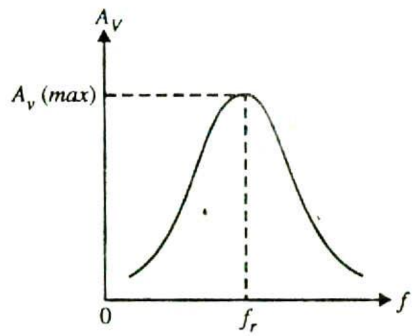
Note. The fundamental difference between *AF* and tuned (*RF*) amplifiers is the bandwidth they are expected to amplify. The *AF* amplifiers amplify a major portion of *AF* specturm (20 Hz to 20 kHz) equally well throughout. The tuned amplifiers amplify a relatively narrow portion of *RF* spectrum, rejecting all other frequencies.

17.10 Analysis of Tuned Amplifier

Fig. 17.9 (*i*) shows a single tuned amplifier. Note the presence of the parallel *LC* circuit in the collector circuit of the transistor. When the circuit has a high *Q*, the parallel resonance occurs at a frequency f_r given by;



(*i*)



(*ii*)

Fig. 17.9

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

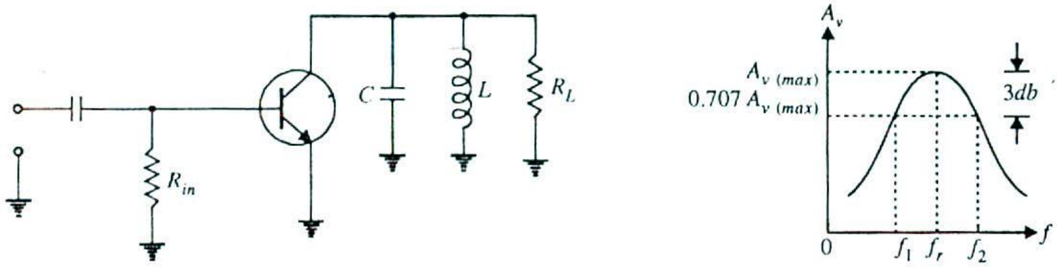
At the resonant frequency, the impedance of the parallel resonant circuit is very high and is purely resistive. Therefore, when the circuit is tuned to resonant frequency, the voltage across R_L is maximum. In other words, the voltage gain is maximum at f_r. However, above and below the resonant frequency, the voltage gain decreases rapidly. The higher the *Q* of the circuit, the faster the gain drops off on either side of resonance [See Fig. 17.9 (*ii*)].

17.11 A.C. Equivalent Circuit of Tuned Amplifier

Fig. 17.10 (*i*) shows the *ac* equivalent circuit of the tuned amplifier. Note the tank circuit components are not shorted. In order to completely understand the operation of this circuit, we shall see its behaviour at three frequency conditions *viz.*,

(*i*) $f_{in} = f_r$ (*ii*) $f_{in} < f_r$ (*iii*) $f_{in} > f_r$

(*i*) **When input frequency equals** f_r (*i.e.*, $f_{in} = f_r$). When the frequency of the input signal is equal to f_r, the parallel *LC* circuit offers a very high impedance *i.e.*, it acts as an open. Since R_L represents the only path to ground in the collector circuit, all the ac collector current flows through R_L. Therefore, voltage across R_L is maximum *i.e.*, the voltage gain is maximum as shown in Fig. 17.10 (*ii*).



(*i*) **Fig. 17.10** (*ii*)

(*ii*) **When input frequency is less than** f_r (*i.e.*, $f_{in} < f_r$). When the input signal frequency is less than f_r, the circuit is effectively* inductive. As the frequency decreases from f_r, a point is reached when $X_C - X_L = R_L$. When this happens, the voltage gain of the amplifier falls by 3 *db*. In other words, the lower cut-off frequency f_1 for the circuit occurs when $X_C - X_L = R_L$.

(*iii*) **When input frequency is greater than** f_r (*i.e.*, $f_{in} > f_r$). When the input signal frequency is greater than f_r, the circuit is effectively capacitive. As f_{in} is increased beyond f_r, a point is reached when $X_L - X_C = R_L$. When this happens, the voltage gain of the amplifier will again fall by 3*db*. In other words, the upper cut-off frequency for the circuit will occur when $X_L - X_C = R_L$.

Example 17.4. *For the tuned amplifier shown in Fig. 17.11, determine (i) the resonant frequency (ii) the Q of tank circuit and (iii) bandwidth of the amplifier.*

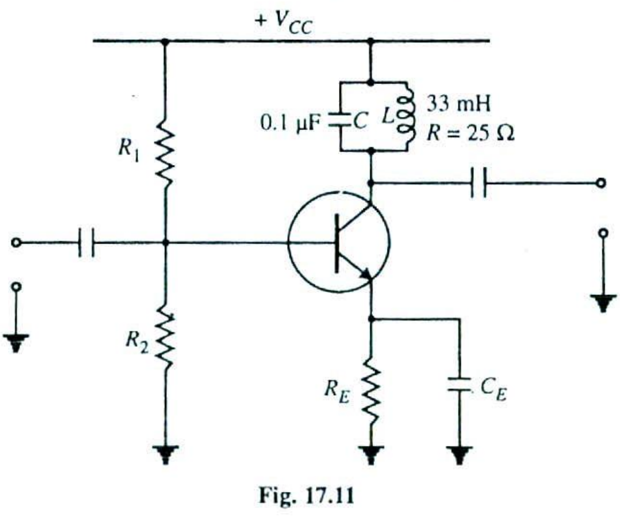


Fig. 17.11

* At frequencies below f_r, $X_C > X_L$ or $I_L > I_C$. Therefore, the circuit will be inductive.

Solution.

(*i*) Resonant frequency, $f_r = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{1}{2\pi\sqrt{33\times10^{-3}\times0.1\times10^{-6}}}$

$= 2.77\times10^3\text{ Hz} = \mathbf{2.77\ kHz}$

(*ii*) $X_L = 2\pi f_r L = 2\pi\times(2.77\times10^3)\times33\times10^{-3} = 574\ \Omega$

$\therefore \quad Q = \dfrac{X_L}{R} = \dfrac{574}{25} = \mathbf{23}$

(*iii*) $BW = \dfrac{f_r}{Q} = \dfrac{2.77\text{ kHz}}{23} = \mathbf{120\ Hz}$

17.12 Double Tuned Amplifier

Fig. 17.12 shows the circuit of a double tuned amplifier. It consists of a transistor amplifier containing two tuned circuits ; one (L_1C_1) in the collector and the other (L_2C_2) in the output as shown. The high frequency signal to be amplified is applied to the input terminals of the amplifier. The resonant frequency of tuned circuit L_1C_1 is made equal to the signal frequency. Under such conditions, the tuned circuit offers very high impedance to the signal frequency. Consequently, large output appears across the tuned circuit L_1C_1. The output from this tuned circuit is transferred to the second tuned circuit L_2C_2 through mutual induction. Double tuned circuits are extensively used for coupling the various circuits of radio and television receivers.

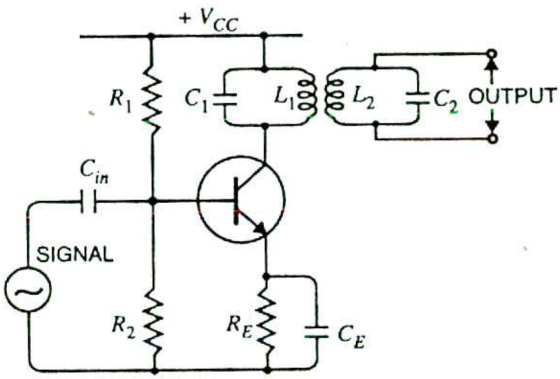


Fig. 17.12

Frequency response. The frequency response of a double tuned circuit depends upon the degree of coupling *i.e.* upon the amount of mutual inductance between the two tuned circuits. When coil L_2 is coupled to coil L_1 [See Fig. 17.13 (*i*)], a portion of load resistance is coupled into the primary tank circuit L_1C_1 and affects the primary circuit in exactly the same manner as though a resistor had been added in series with the primary coil L_1.

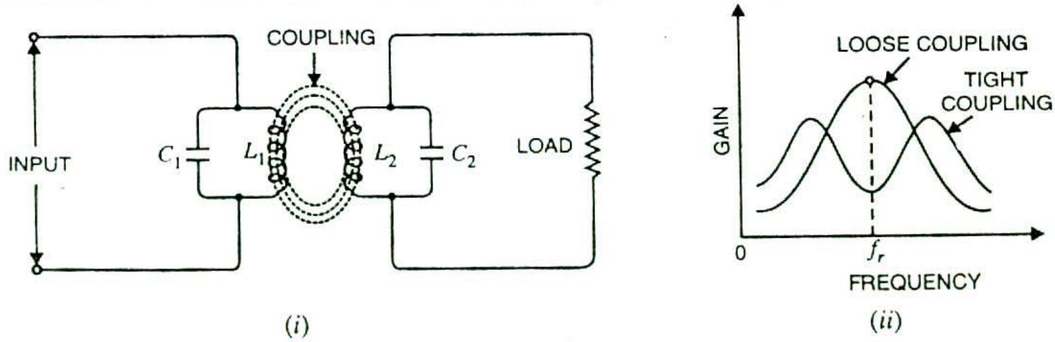


Fig.17.13

When the coils are spaced apart, all the primary coil L_1 flux will not link the secondary coil L_2.

The coils are said to have *loose coupling*. Under such conditions, the resistance reflected from the load (*i.e.* secondary circuit) is small. The resonance curve will be sharp and the circuit Q is high as shown in Fig. 17.13 (*ii*). When the primary and secondary coils are very close together, they are said to have *tight coupling*. Under such conditions, the reflected resistance will be large and the circuit Q is lower. Two positions of gain maxima, one above and the other below the resonant frequency, are obtained.

17.13 Bandwidth of Double–Tuned Circuit

If you refer to the frequency response of double-tuned circuit shown in Fig. 17.13 (*ii*), it is clear that bandwidth increases with the degree of coupling. Obviously, the determining factor in a double-tuned circuit is not Q but the coupling. For a given frequency, the tighter the coupling, the greater is the bandwidth.

$$BW_{dt} = k f_r$$

The subscript *dt* is used to indicate double-tuned circuit. Here *k* is coefficient of coupling.

Example 17.5. *It is desired to obtain a bandwidth of 200 kHz at an operating frequency of 10 MHz using a double tuned circuit. What value of co-efficient of coupling should be used ?*

Solution.

$$BW_{dt} = k f_r$$

$$\therefore \text{ Co-efficient of coupling, } k = \frac{BW_{dt}}{f_r} = \frac{200 \text{ kHz}}{10 \times 10^3 \text{ kHz}} = \mathbf{0.02}$$

17.14 Tuned Class C Amplifier

So far we have confined our attention to tuned class *A* amplifiers. Such amplifiers are used where *RF* signal has low power level *e.g.* in radio receivers, small signal applications in transmitters. However, owing to low efficiency of class *A* operation, these amplifiers are not employed where large *RF* (radio frequency) power is involved *e.g.* to excite transmitting antenna. In such situations, tuned class *C* power amplifiers are used. Since a class *C* amplifier has a very high efficiency, it can deliver more load power than a class *A* amplifier.

Class *C* operation means that collector current flows for less than 180°. In a practical tuned class *C* amplifier, the collector current flows for much less than 180° ; the current looks like narrow pulses as shown in Fig. 17.14. As we shall see later, when narrow current pulses like these drive a high-Q resonant (*i.e. LC*) circuit, the voltage across the circuit is almost a perfect sine wave. One very important advantage of class *C* operation is its *high efficiency. Thus 10 W supplied to a class *A* amplifier may produce only about 3.5 W of a.c. output (35 % efficiency). The same transistor biased to class *C* may be able to produce 7 W output (70 % efficiency). Class *C* power amplifiers normally use *RF* power transistors. The power ratings of such transistors range from 1 W to over 100 W.

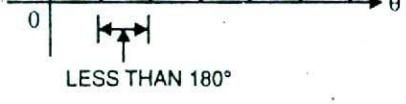


Fig. 17.14

* Class *C* amplifier has a relatively long duration between the pulses, allowing the transistor to rest for a major portion of each input cycle. In other words, very little power is dissipated by the transistor. For this reason, class *C* amplifier has high efficiency.

17.15. Class C Operation

Fig. 17.15 (*i*) shows the circuit of tuned class *C* amplifier. The circuit action is as under:

(*i*) When no a.c. input signal is applied, no collector current flows because the emitter diode (*i.e.* base-emitter junction) is unbiased.

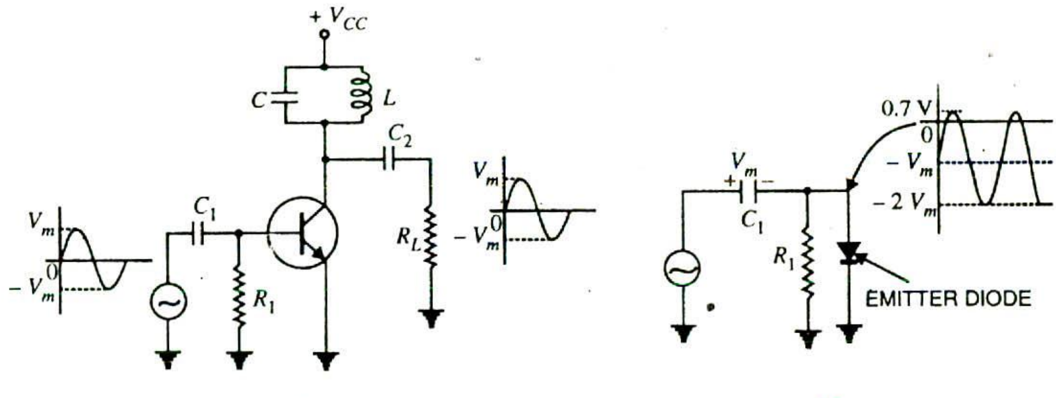


Fig. 17.15

(*ii*) When an a.c. signal is applied, *clamping action* takes place as shown in Fig. 17.15 (*ii*). The voltage across the emitter diode varies between + 0.7 V (during positive peaks of input signal) to about $-2V_m$ (during negative peaks of input signal). This means that conduction of the transistor occurs only for a short period during positive peaks of the signal. This results in the pulsed output *i.e.* collector current waveform is a train of narrow pulses (Refer back to Fig. 17.14).

(*iii*) When this pulsed output is fed to the *LC* circuit, *sine-wave output is obtained. This can be easily explained. Since the pulse is narrow, inductor looks like high impedance and the capacitor like a low impedance. Consequently, most of the current charges the capacitor as shown in Fig. 17.16. When the capacitor is fully charged, it will discharge through the coil and the load resistor, setting up oscillations just as an oscillatory circuit does. Consequently, sine-wave output is obtained.

(*iv*) If only a single current pulse drives the *LC* circuit, we will get damped sine-wave output. However, if a train of narrow pulses drive the *LC* circuit, we shall get undamped sine-wave output.

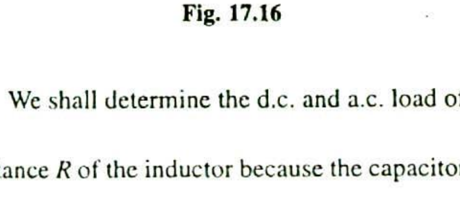


Fig. 17.16

17.16 D.C. and A.C. Loads

Fig. 17.17 shows the circuit of tuned class *C* amplifier. We shall determine the d.c. and a.c. load of the circuit.

(*i*) The d.c. load of the circuit is just the d.c. resistance *R* of the inductor because the capacitor looks like an open to d.c.

$\therefore$ D.C. load, R_{dc} = d.c. resistance of the inductor = R

* There is another explanation for it. The pulsed output is actually the sum of an infinite number of sine waves at frequencies in multiples of the input frequency. If the LC tank circuit is set up to resonate at the input frequency, it will result in sine-wave output of just the input frequency.

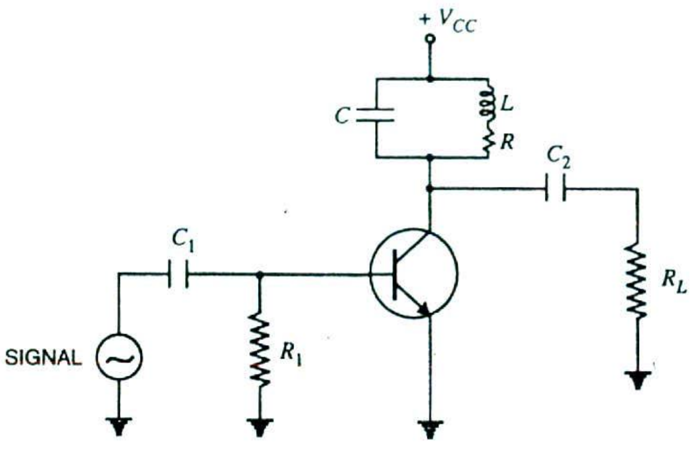


Fig. 17.17

(*ii*) The a.c. load is a parallel combination of capacitor, coil and load resistance R_L as shown in Fig. 17.18 (*i*). The series resistance R of the inductor can be replaced by its equivalent parallel resistance R_P as shown in Fig. 17.18 (*ii*) where

$$R_P = Q_{coil} \times X_L$$

The a.c. load resistance R_{AC} is the equivalent resistance of the parallel combination of R_P and R_L *i.e.*

$$R_{AC} = R_P \parallel R_L = \frac{R_P \times R_L}{R_P + R_L}$$

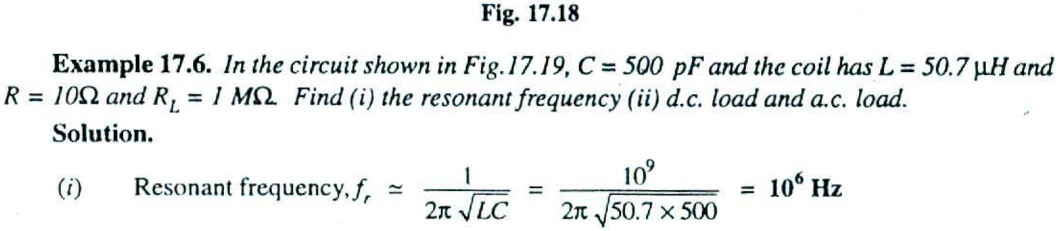


Fig. 17.18

Example 17.6. *In the circuit shown in Fig.17.19, C = 500 pF and the coil has L = 50.7 μH and R = 10Ω and R_L = 1 MΩ. Find (i) the resonant frequency (ii) d.c. load and a.c. load.*

Solution.

(*i*) Resonant frequency, $f_r \simeq \frac{1}{2\pi\sqrt{LC}} = \frac{10^9}{2\pi\sqrt{50.7 \times 500}} = \mathbf{10^6\ Hz}$

(*ii*) D.C. load, $R_{dc} = R = \mathbf{10\ \Omega}$

$$X_L = 2\pi f_r L = 2\pi \times (10^6) \times (50.7 \times 10^{-6}) = 318\ \Omega$$

$$Q_{coil} = \frac{X_L}{R} = \frac{318}{10} = 31.8$$

The series resistance R (= 10 Ω) of the inductor can be replaced by its equivalent parallel resistance R_P, where,

$$R_P = Q_{coil} \times X_L = 31.8 \times 318 = 10^4\ \Omega = 10\ \text{k}\Omega$$

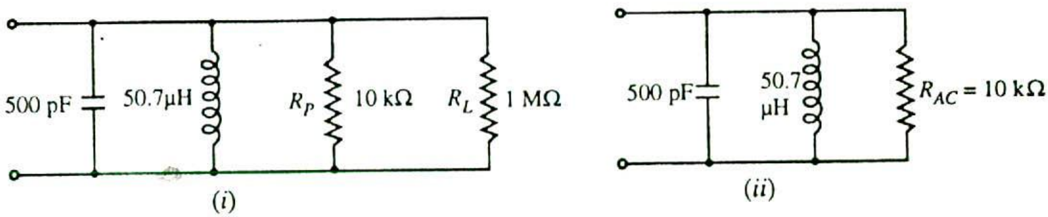


Fig. 17.19

The equivalent circuit is shown in Fig. 17.19 (*i*). This further reduces to the circuit shown in Fig. 17.19 (*ii*).

$$\therefore \qquad R_{AC} = R_P \,||\, R_L = 10\ \text{k}\Omega \,||\, 1\ \text{M}\Omega \simeq \mathbf{10\ k\Omega}$$

17.17 Maximum A.C. Output Power

Fig. 17.20 (*i*) shows tuned class *C* amplifier. When no signal is applied, the collector-emitter voltage is *V_{CC} *i.e.*

$$v_{CE} = V_{CC}$$

When signal is applied, it causes the total collector-emitter voltage to swing above and below this voltage. The collector-emitter voltage can have a maximum value of $2V_{CC}$ and minimum value 0 (ideally) as shown in Fig. 17.20 (*ii*).

Referring to Fig. 17.20 (*ii*), output voltage has a peak value of V_{CC}. Therefore, the maximum a.c. output power is :

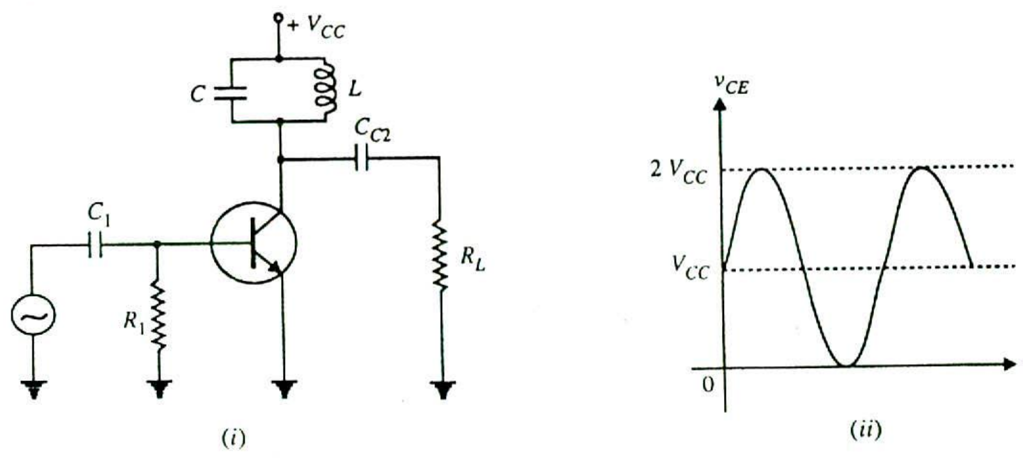


Fig. 17.20

$$P_{o(max)} = \frac{V_{r.m.s.}^2}{R_{AC}} = \frac{(V_{CC}/\sqrt{2})^2}{R_{AC}} = \frac{V_{CC}^2}{2\,R_{AC}}$$

where R_{AC} = a.c. load

Maximum efficiency. The d.c. input power (P_{dc}) from the supply is :

* Because the drop in *L* due to d.c. component is negligible.

$$P_{dc} = P_{o(max)} + P_D$$

where P_D = power dissipation of the transistor

$$\therefore \quad \text{Max. collector } \eta = \frac{P_{o(max)}}{P_{o(max)} + P_D}$$

As discussed earlier, P_D in class *C* operation is very small because the transistor remains biased off during most of the input signal cycle. Consequently, P_D may be neglected as compared to $P_{o(max)}$.

$$\therefore \quad \text{Maximum } \eta \simeq \frac{P_{o(max)}}{P_{o(max)}} \simeq 100\ \%$$

It is worthwhile to give a passing reference about the maximum efficiencies of class *A*, class *B* and class *C* amplifiers. *A* class *A* amplifier (transformer-coupled) has a maximum efficiency of 50%, class *B* of 78.5% and class *C* nearly 100%. It is emphasised here that class *C* operation is suitable only for *resonant *RF* applications.

Example 17.7. *Calculate (i) a.c. load (ii) maximum load power in the circuit shown in Fig. 17.21.*

Solution.

(*i*) A.C. load, R_{AC} = Reflected load resistance seen by the collector

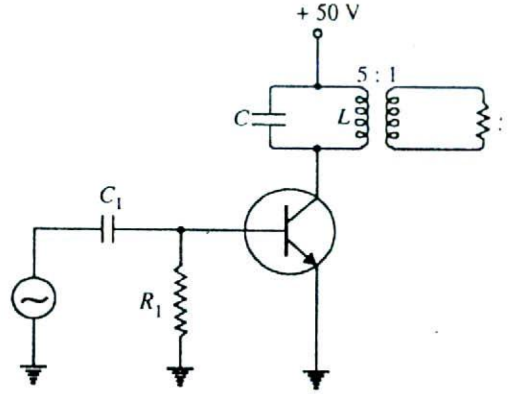


Fig. 17.21

$$= (N_p/N_s)^2 \times 50 = (5/1)^2 \times 50 = \mathbf{1250\ \Omega}$$

(*ii*) Max. load power, $P_{o(max)} = \dfrac{V_{CC}^2}{R_{AC}} = \dfrac{(50)^2}{1250} = \mathbf{2\ W}$

Multiple-Choice Questions

1. A tuned amplifier uses .... load.
   (*i*) resistive (*ii*) capacitive
   (*iii*) LC tank (*iv*) inductive

2. A tuned amplifier is generally operated in .... operation.
   (*i*) class A (*ii*) class C
   (*iii*) class B (*iv*) none of the above

3. A tuned amplifier is used in .... applications.
   (*i*) radio frequency

---

* Because power losses are very small (less than 1 %) in high - *Q* resonant circuits. An extremely narrow pulse will compensate the losses.

(*ii*) low frequency
(*iii*) audio frequency
(*iv*) none of the above

4. Frequencies above .... kHz are called radio frequencies.
(*i*) 2 (*ii*) 10
(*iii*) 50 (*iv*) 200

5. At series or parallel resonance, the circuit power factor is ....
(*i*) 0 (*ii*) 0.5
(*iii*) 1 (*iv*) 0.8

6. The voltage gain of a tuned amplifier is .... at resonant frequency.
(*i*) minimum (*ii*) maximum
(*iii*) half-way between maximum and minimum
(*iv*) zero

7. At parallel resonance, the line current is ....
(*i*) minimum (*ii*) maximum
(*iii*) quite large (*iv*) none of the above

8. At series resonance, the circuit offers .... impedance.
(*i*) zero (*ii*) maximum
(*iii*) minimum (*iv*) none of the above

9. A resonant circuit contains .... elements.
(*i*) *R* and *L* only (*ii*) *R* and *C* only
(*iii*) only *R* (*iv*) *L* and *C*

10. At series or parallel resonance, the circuit behaves as a .... load.
(*i*) capacitive (*ii*) resistive
(*iii*) inductive (*iv*) none of the above

11. At series resonance, voltage across *L* is .... voltage across *C*.
(*i*) equal to but opposite in phase to
(*ii*) equal to but in phase with
(*iii*) greater than but in phase with
(*iv*) less than but in phase with

12. When either *L* or *C* is increased, the resonant frequency of *LC* circuit ....
(*i*) remains the same
(*ii*) increases (*iii*) decreases
(*iv*) insufficient data

13. At parallel resonance, the net reactive component of circuit current is ....
(*i*) capacitive (*ii*) zero
(*iii*) inductive (*iv*) none of the above

14. At parallel resonance, the circuit impedance is ....
(*i*) $\frac{C}{LR}$ (*ii*) $\frac{R}{LC}$
(*iii*) $\frac{CR}{L}$ (*iv*) $\frac{L}{CR}$

15. In a parallel *LC* circuit, if the input signal frequency is increased above resonant frequency, then ....
(*i*) X_L increases and X_C decreases
(*ii*) X_L decreases and X_C increases
(*iii*) both X_L and X_C increase
(*iv*) both X_L and X_C decrease

16. The *Q* of an *LC* circuit is given by ....
(*i*) $2\pi f_r \times R$ (*ii*) $\frac{R}{2\pi f_r L}$
(*iii*) $\frac{2\pi f_r L}{R}$ (*iv*) $\frac{R^2}{2\pi f_r L}$

17. If *Q* of an *LC* circuit increases, then bandwidth ....
(*i*) increases (*ii*) decreases
(*iii*) remains the same
(*iv*) insufficient data

18. At series resonance, the net reactive component of circuit current is ....
(*i*) zero (*ii*) inductive
(*iii*) capacitive (*iv*) none of the above

19. The dimensions of *L/CR* are that of ....
(*i*) farad (*ii*) henry
(*iii*) ohm (*iv*) none of the above

20. If *L/C* ratio of a parallel *LC* circuit is increased, the *Q* of the circuit ....
(*i*) is decreased (*ii*) is increased
(*iii*) remains the same
(*iv*) none of the above

21. At series resonance, the phase angle between applied voltage and circuit current is ....
(*i*) 90° (*ii*) 180°

(*iii*) 0° (*iv*) none of the above

22. At parallel resonance, the ratio *L/C* is ....

(*i*) very large (*ii*) zero

(*iii*) small (*iv*) none of the above

23. If the resistance of a tuned circuit is increased, the *Q* of the circuit ....

(*i*) is increased (*ii*) is decreased

(*iii*) remains the same

(*iv*) none of the above

24. The *Q* of a tuned circuit refers to the property of ....

(*i*) sensitivity (*ii*) fidelity

(*iii*) selectivity (*iv*) none of the above

25. At parallel resonance, the phase angle between the applied voltage and circuit current is ....

(*i*) 90° (*ii*) 180°

(*iii*) 0° (*iv*) none of the above

26. In a parallel *LC* circuit, if the signal frequency is decreased below the resonant frequency, then ....

(*i*) X_L decreases and X_C increases

(*ii*) X_L increases and X_C decreases

(*iii*) line current becomes minimum

(*iv*) none of the above

27. In series resonance, there is ....

(*i*) voltage amplification

(*ii*) current amplification

(*iii*) both voltage and current amplification

(*iv*) none of the above

28. The *Q* of a tuned amplifier is generally ....

(*i*) less than 5 (*ii*) less than 10

(*iii*) more than 10 (*iv*) none of the above

29. The *Q* of a tuned amplifier is 50. If the resonant frequency for the amplifier is 1000 kHz, then bandwidth is ....

(*i*) 10 kHz (*ii*) 40 kHz

(*iii*) 30 kHz (*iv*) 20 kHz

30. In the above question, what are the values of cut-off frequencies ?

(*i*) 140 kHz, 60 kHz

(*ii*) 1020 kHz, 980 kHz

(*iii*) 1030 kHz, 970 kHz

(*iv*) none of the above

31. For frequencies above the resonant frequency, a parallel *LC* circuit behaves as a .... load.

(*i*) capacitive

(*ii*) resistive

(*iii*) inductive

(*iv*) none of the above

32. In parallel resonance, there is ....

(*i*) both voltage and current amplification

(*ii*) voltage amplification

(*iii*) current amplification

(*iv*) none of the above

33. For frequencies below resonant frequency, a series *LC* circuit behaves as a .... load.

(*i*) resistive (*ii*) capacitive

(*iii*) inductive (*iv*) none of the above

34. If a high degree of selectivity is desired, then double-tuned circuit should have .... coupling.

(*i*) loose (*ii*) tight

(*iii*) critical (*iv*) none of the above

35. In the double tuned circuit, if the mutual inductance between the two tuned circuits is decreased, the level of resonance curve ....

(*i*) remains the same

(*ii*) is lowered

(*iii*) is raised (*iv*) none of the above

36. For frequencies above the resonant frequency, a series *LC* circuit behaves as a .... load.

(*i*) resistive (*ii*) inductive

(*iii*) capacitive (*iv*) none of the above

37. Double tuned circuits are used in .... stages of a radio receiver

(*i*) IF (*ii*) audio

(*iii*) output (*iv*) none of the above

38. A class C amplifier always drives .... load

(*i*) a pure resistive (*ii*) a pure inductive

(*iii*) a pure capacitive

(*iv*) a resonant tank

39. Tuned class C amplifiers are used for RF signals of ....

(*i*) low power

(*ii*) high power

(*iii*) very low power

(*iv*) none of the above

40. For frequencies below the resonant frequency, a parallel LC circuit behaves as a .... load.

(*i*) inductive (*ii*) resistive

(*iii*) capacitive (*iv*) none of the above

Answers to Multiple-Choice Questions

1. (*iii*)	**2.** (*ii*)	**3.** (*i*)	**4.** (*iv*)	**5.** (*iii*)
6. (*ii*)	**7.** (*i*)	**8.** (*iii*)	**9.** (*iv*)	**10.** (*ii*)
11. (*i*)	**12.** (*iii*)	**13.** (*ii*)	**14.** (*vi*)	**15.** (*i*)
16. (*iii*)	**17.** (*ii*)	**18.** (*i*)	**19.** (*iii*)	**20.** (*ii*)
21. (*iii*)	**22.** (*i*)	**23.** (*ii*)	**24.** (*iii*)	**25.** (*iii*)
26. (*i*)	**27.** (*i*)	**28.** (*iii*)	**29.** (*iv*)	**30.** (*ii*)
31. (*i*)	**32.** (*iii*)	**33.** (*ii*)	**34.** (*i*)	**35.** (*iii*)
36. (*ii*)	**37.** (*i*)	**38.** (*iv*)	**39.** (*iv*)	**40.** (*i*)

Chapter Review Topics

1. What are tuned amplifiers and where are they used ?
2. Discuss parallel tuned circuit with special reference to resonant frequency, circuit impedance and frequency response.
3. What do you understand by quality factor Q of parallel tuned circuit ?
4. Discuss the advantages of tuned amplifiers.
5. Discuss the circuit operation of a single tuned amplifier.
6. Write short notes on the following :
   (*i*) Double tuned amplifier (*ii*) Bandwidth of tuned amplifier

Problems

1. A parallel circuit has a capacitor of 100 pF in one branch and an inductance of 100 μH plus a resistance of 10 Ω in the second branch. The line voltage is 100V. Find (*i*) resonant frequency (*ii*) circuit impedance at resonance and (*iii*) line current at resonance. [(*i*) **1590 kHz** (*ii*) **100 kΩ** (*iii*) **100 mA**]
2. A tuned amplifier is designed to have a resonant frequency of 1000 kHz and a bandwidth of 40 kHz. What is the Q of this amplifier ? **[25]**
3. The Q of a tuned amplifier is 25. If the resonant frequency of the circuit is 1400 kHz, what is its bandwidth? **[56 kHz]**
4. A tuned amplifier has parallel LC circuit. One branch of this parallel circuit has a capacitor of 100 pF and the other branch has an inductance of 1mH plus a resistance of 25 Ω. Determine (*i*) the resonant frequency and (*ii*) Q of the tank circuit. [(*i*) **503.3 kHz** (*ii*) **126.5**]
5. It is desired to obtain a bandwidth of 12 kHz at an operating frequency of 800 kHz, using a double-tuned circuit. What value of co-efficient of coupling should be used ? **[0.015]**

Discussion Questions

1. Why are tuned circuits not used for low frequency applications ?
2. Why is tuned amplifier operated in class C operation ?
3. How does coupling affect the gain of tuned amplifiers ?
4. What is the effect of Q on the resonance curve ?
5. What are the practical applications of tuned amplifiers ?

18

Modulation And Demodulation

Introduction

In radio transmission, it is necessary to send audio signal (*e.g.* music, speech etc.) from a broadcasting station over great distances to a receiver. This communication of audio signal does not employ any wire and is sometimes called *wireless*. The audio signal cannot be sent directly over the air for appreciable distance. Even if the audio signal is converted into electrical signal, the latter cannot be sent very far without employing large amount of power. The energy of a wave is directly proportional to its frequency. At audio frequencies (20 Hz to 20 kHz), the signal power is quite small and radiation is not practicable.

The radiation of electrical energy is practicable only at high frequencies *e.g.* above 20 kHz. The high frequency signals can be sent thousands of miles even with comparatively small power. Therefore, if audio signal is to be transmitted properly, some means must be devised which will permit transmission to occur at high frequencies while it simultaneously allows the carrying of audio signal. This is achieved by superimposing electrical audio signal on high frequency carrier. The resultant waves are known *as modulated waves* or *radio waves* and the process is called *modulation*. At the radio receiver, the audio signal is extracted from the modulated wave by the process called *demodulation*. The signal is then amplified and reproduced into sound by the loudspeaker. In this chapter, we shall focus our attention on the various aspects of modulation and demodulation.

18.1 Radio Broadcasting, Transmission and Reception

Radio communication means the radiation of radio waves by the transmitting station, the propagation of these waves through space and their reception by the radio receiver. Fig. 18.1 shows the general principles of radio broadcasting, transmission and reception. As a matter of convenience, the entire arrangement can be divided into three parts *viz. transmitter, transmission of radio waves* and *radio receiver.*

1. Transmitter. Transmitter is an extremely important equipment and is housed in the broadcasting station. Its purpose is to produce radio waves for transmission into space. The important components of a transmitter are microphone, audio amplifiers, oscillator and modulator (See Fig. 18.1).

(*i*) *Microphone.* A microphone is a device which converts sound waves into electrical waves. When the speaker speaks or a musical instrument is played, the varying air pressure on the microphone generates an audio electrical signal which corresponds in frequency to the original signal. The output of microphone is fed to a multistage audio amplifier for raising the strength of weak signal.

(*ii*) *Audio amplifier.* The audio signal from the microphone is quite weak and requires amplification. This job is accomplished by cascaded audio amplifiers. The amplified output from the last audio amplifier is fed to the modulator for rendering the process of modulation.

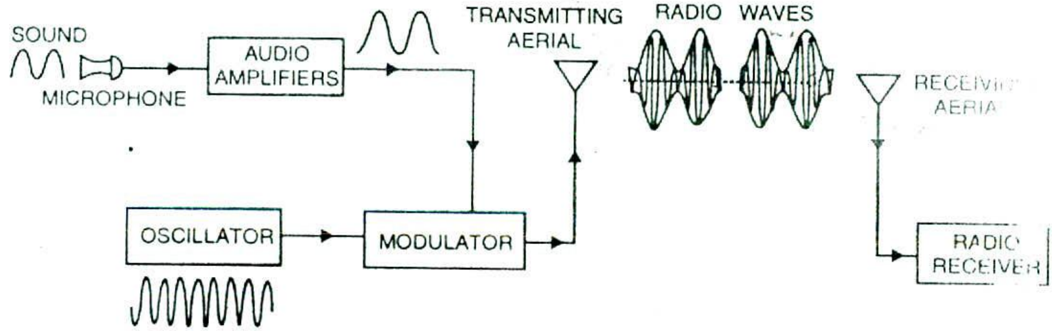


Fig. 18.1

(*iii*) *Oscillator.* The function of oscillator is to produce a high frequency signal, called a *carrier wave*. Usually, a crystal oscillator is used for the purpose. The power level of the carrier wave is raised to a sufficient level by radio frequency amplifier stages (not shown in Fig. 18.1). Most of the broadcasting stations have carrier wave power of several kilowatts. Such high power is necessary for transmitting the signal to the required distances.

(*iv*) *Modulator.* The amplified audio signal and carrier wave are fed to the modulator. Here, the audio signal is superimposed on the carrier wave in a suitable manner. The resultant waves are called *modulated waves or radio waves* and the process is called *modulation*. The process of modulation permits the transmission of audio signal at the carrier frequency. As the carrier frequency is very high, therefore, the audio signal can be transmitted to large distances. The radio waves from the transmitter are fed to the transmitting antenna or aerial from where these are radiated into space.

2. Transmission of radio waves. The transmitting antenna radiates the radio waves in space in all directions. These radio waves travel with the velocity of light *i.e.* 3×10^8 m/sec. The radio waves are electromagnetic waves and possess the same general properties. These are similar to light and heat waves except that they have longer wavelengths. It may be emphasised here that radio waves are sent without employing any wire. It can be easily shown that at high frequency, electrical energy can be radiated into space.

3. Radio receiver. On reaching the receiving antenna, the radio waves induce tiny e.m.f. in it. This small voltage is fed to the radio receiver. Here, the radio waves are first amplified and then signal is extracted from them by the process of *demodulation*. The signal is amplified by audio amplifiers and then fed to the speaker for reproduction into sound waves.

18.2 Modulation

As discussed earlier, a high frequency carrier wave is used to carry the audio signal. The question arises how the audio signal should be "added" to the carrier wave. The solution lies in changing some characteristic of carrier wave in accordance with the signal. Under such conditions, the audio signal will be contained in the resultant wave. This process is called modulation and may be defined as under :

The process of changing some characteristic (e.g. amplitude, frequency or phase) of a carrier wave in accordance with the intensity of the signal is known as **modulation**.

Modulation means to "change". In modulation, some characteristic of carrier wave is changed in accordance with the intensity (*i.e.* amplitude) of the signal. The resultant wave is called modulated wave or radio wave and contains the audio signal. Therefore, modulation permits the transmission to occur at high frequency while it simultaneously allows the carrying of the audio signal.

Need for modulation. Modulation is extremely necessary in communication system due to the following reasons :

(*i*) *Practical antenna length.* Theory shows that in order to transmit a wave effectively, the length of the transmitting antenna should be approximately equal to the wavelength of the wave.

$$\text{Now, wavelength} = \frac{\text{velocity}}{\text{frequency}} = \frac{3 \times 10^8}{\text{frequency (Hz)}} \text{ metres}$$

As the audio frequencies range from 20 Hz to 20 kHz, therefore, if they are transmitted directly into space, the length of the transmitting antenna required would be extremely large. For instance, to radiate a frequency of 20 kHz directly into space, we would need an antenna length of $3 \times 10^8/20 \times 10^3 = 15{,}000$ metres. This is too long antenna to be constructed practically. For this reason, it is impracticable to radiate audio signal directly into space. On the other hand, if a carrier wave say of 1000 kHz is used to carry the signal, we need an antenna length of 300 metres only and this size can be easily constructed.

(*ii*) *Operating range.* The energy of a wave depends upon its frequency. The greater the frequency of the wave, the greater the energy possessed by it. As the audio signal frequencies are small, therefore, these cannot be transmitted over large distances if radiated directly into space. The only practical solution is to modulate a high frequency carrier wave with audio signal and permit the transmission to occur at this high frequency (*i.e.* carrier frequency).

(*iii*) *Wireless communication.* One desirable feature of radio transmission is that it should be carried without wires *i.e.* radiated into space. At audio frequencies, radiation is not practicable because the efficiency of radiation is poor. However, efficient radiation of electrical energy is possible at high frequencies (> 20 kHz). For this reason, modulation is always done in communication systems.

18.3 Types of Modulation

As you will recall, modulation is the process of changing amplitude or frequency or phase of a carrier wave in accordance with the intensity of the signal. Accordingly, there are three basic types of modulation, namely ;

(*i*) amplitude modulation (*ii*) frequency modulation (*iii*) phase modulation

In India, amplitude modulation is used in radio broadcasting. However, in television transmission, frequency modulation is used for sound signal and amplitude modulation for picture signal. Therefore, our attention in this chapter shall be confined to the first two most important types of modulation.

18.4 Amplitude Modulation

When the amplitude of high frequency carrier wave is changed in accordance with the intensity of the signal, it is called **amplitude modulation**.

In amplitude modulation, only the amplitude of the carrier wave is changed in accordance with the intensity of the signal. However, the frequency of the modulated wave remains the same *i.e.* carrier frequency. Fig. 18.2 shows the principle of amplitude modulation. Fig. 18.2 (*i*) shows the audio electrical signal whereas Fig. 18.2 (*ii*) shows a carrier wave of constant amplitude. Fig. 18.2 (*iii*) shows the amplitude modulated (AM) wave. Note that the amplitudes of both positive and negative half-cycles of carrier wave are changed in accordance with the signal. For instance, when the signal is increasing in the positive sense, the amplitude of carrier wave also increases. On the other hand, during negative half-cycle of the signal, the amplitude of carrier wave decreases. Amplitude modulation is done by an electronic circuit called *modulator*.

The following points are worth noting in amplitude modulation :

(*i*) The amplitude of the carrier wave changes according to the intensity of the signal.

(*ii*) The amplitude variations of the carrier wave is at the signal frequency f_s.

(*iii*) The frequency of the amplitude modulated wave remains the same *i.e.* carrier frequency f_c.

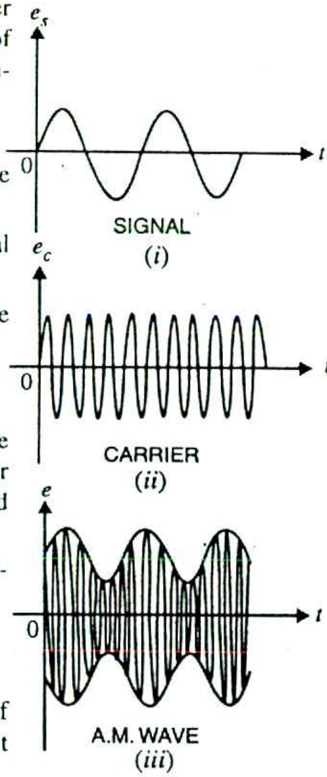


Fig. 18.2

18.5 Modulation Factor

An important consideration in amplitude modulation is to describe the depth of modulation *i.e.* the extent to which the amplitude of carrier wave is changed by the signal. This is described by a factor called modulation factor which may be defined as under :

The ratio of change of amplitude of carrier wave to the amplitude of normal carrier wave is called the **modulation factor** *m i.e.*

$$\text{Modulation factor, } m = \frac{\text{Amplitude change of carrier wave}}{\text{Normal carrier wave (unmodulated)}}$$

The value of modulation factor depends upon the amplitudes of carrier and signal. Fig. 18.3 shows amplitude modulation for different values of modulation factor *m*.

(*i*) When signal amplitude is zero, the carrier wave is not modulated as shown in Fig. 18.3 (*i*). The amplitude of carrier wave remains unchanged.

$$\text{Amplitude change of carrier} = 0$$
$$\text{Amplitude of normal carrier} = A$$
$$\therefore \quad \text{Modulation factor, } m = 0/A = 0 \text{ or } 0\%$$

(*ii*) When signal amplitude is equal to the carrier amplitude as shown in Fig. 18.3 (*ii*), the amplitude of carrier varies between 2A and zero.

$$\text{Amplitude change of carrier} = 2A - A = A$$
$$\therefore \quad \text{Modulation factor, } m = \frac{\text{Amplitude change of carrier}}{\text{Amplitude of normal carrier}} = A/A = 1 \text{ or } 100\%$$

In this case, the carrier is said to be 100% modulated.

(*iii*) When the signal amplitude is one-half the carrier amplitude as shown in Fig. 18.3 (*iii*), the amplitude of carrier wave varies between 1.5 A and 0.5 A.

$$\text{Amplitude change of carrier} = 1.5A - A = 0.5A$$
$$\therefore \quad \text{Modulation factor, } m = 0.5A/A = 0.5 \text{ or } 50\%$$

In this case, the carrier is said to be 50% modulated.

(*iv*) When the signal amplitude is 1.5 times the carrier amplitude as shown in Fig. 18.3 (*iv*), the maximum value of carrier wave becomes 2.5 *A*.

$$\text{Amplitude change of carrier wave} = 2.5A - A = 1.5A$$
$$\therefore \quad \text{Modulation factor, } m = \frac{1.5A}{A} = 1.5 \text{ or } 150\%$$

In this case, the carrier is said to be 150% modulated *i.e.* over-modulated.

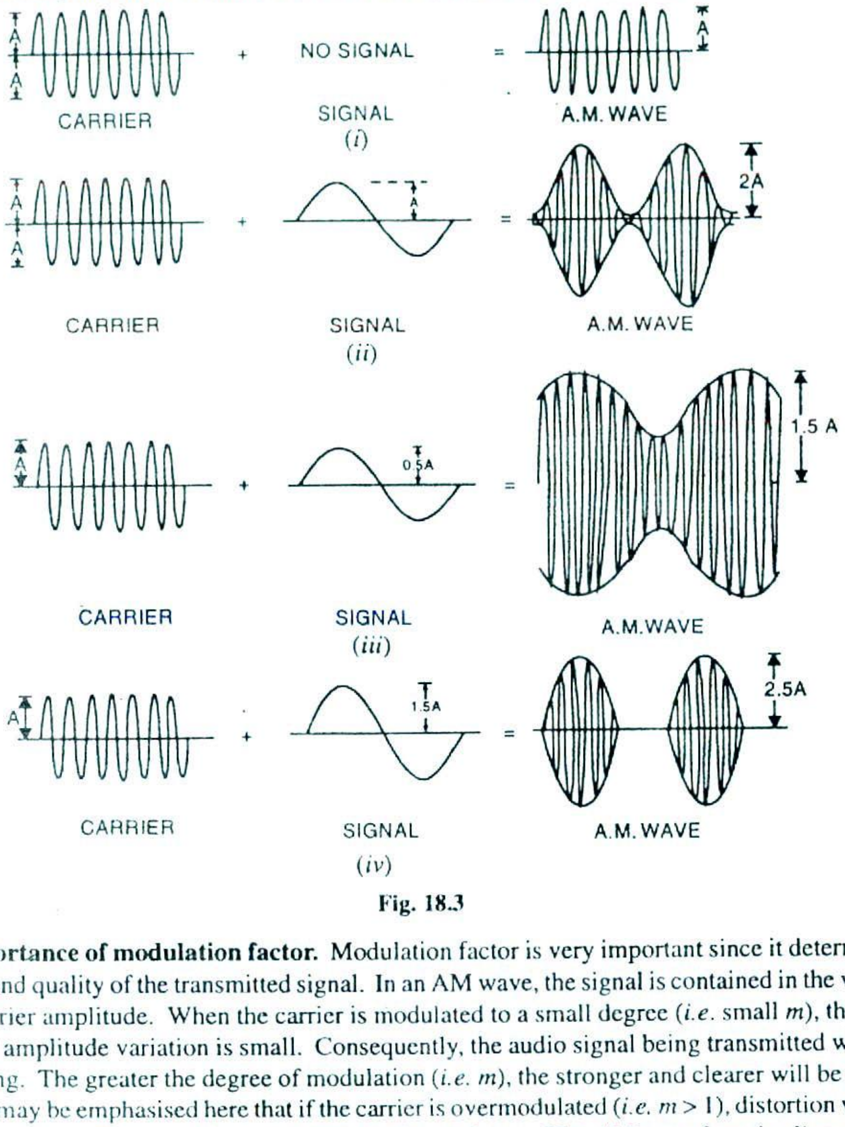


Fig. 18.3

Importance of modulation factor. Modulation factor is very important since it determines the strength and quality of the transmitted signal. In an AM wave, the signal is contained in the variations of the carrier amplitude. When the carrier is modulated to a small degree (*i.e.* small m), the amount of carrier amplitude variation is small. Consequently, the audio signal being transmitted will not be very strong. The greater the degree of modulation (*i.e.* m), the stronger and clearer will be the audio signal. It may be emphasised here that if the carrier is overmodulated (*i.e.* $m > 1$), distortion will occur during reception. This condition is shown in Fig. 18.3 (*iv*). The AM waveform is clipped and the envelope is discontinuous. Therefore, degree of modulation should never exceed 100%.

Example 18.1. *If the maximum and minimum voltage of an AM wave are V_{max} and V_{min} respectively, then show that modulation factor m is given by ;*

$$m = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}$$

Solution. Fig. 18.4 shows the waveform of amplitude modulated wave. Let the amplitude of the normal carrier wave be E_C. Then, it is clear from Fig. 18.4 that :

$$E_C = \frac{V_{max} + V_{min}}{2}$$

If E_S is the signal amplitude, then it is clear from Fig. 18.4 that :

$$E_S = \frac{V_{max} - V_{min}}{2}$$

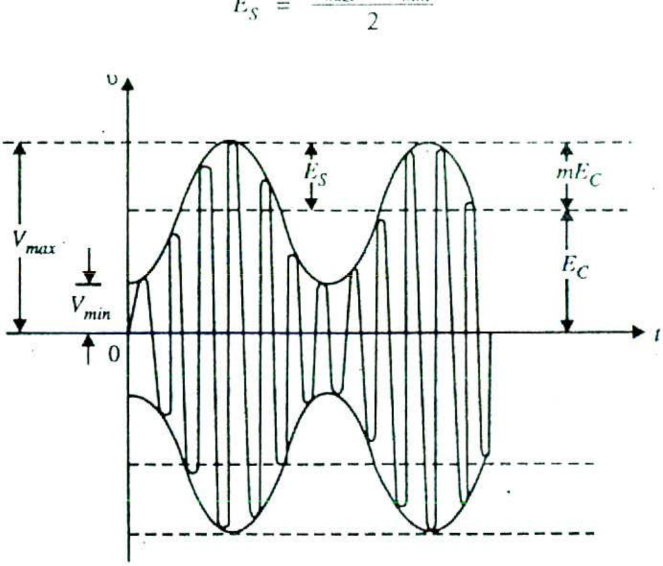


Fig. 18.4

But $$E_S = m\,E_C$$

or $$\frac{V_{max} - V_{min}}{2} = m\,\frac{V_{max} + V_{min}}{2} \quad \text{or} \quad m = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}$$

Example 18.2. *The maximum peak-to-peak voltage of an AM wave is 16 mV and the minimum peak-to-peak voltage is 4 mV. Calculate the modulation factor.*

Solution. Fig. 18.5 shows the conditions of the problem.

Maximum voltage of AM wave is

$$V_{max} = \frac{16}{2} = 8 \text{ mV}$$

Minimum voltage of AM wave is

$$V_{min} = \frac{4}{2} = 2 \text{ mV}$$

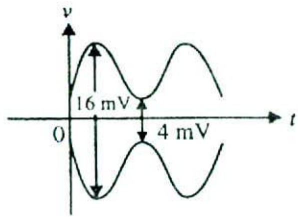


Fig. 18.5

∴ Modulation factor, $$m = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}$$

$$= \frac{8-2}{8+2} = \frac{6}{10} = \mathbf{0.6}$$

Example 18.3. *A carrier of 100V and 1200 kHz is modulated by a 50 V, 1000 Hz sine wave signal. Find the modulation factor.*

Solution.

Modulation factor, $$m = \frac{E_S}{E_C} = \frac{50 \text{ V}}{100 \text{ V}} = \mathbf{0.5}$$

18.6 Analysis of Amplitude Modulated Wave

A carrier wave may be represented by ;

$$e_c = E_C \cos \omega_c t$$

where
e_c = instantaneous voltage of carrier
E_C = amplitude of carrier
$\omega_c = 2 \pi f_c$
= angular velocity at carrier frequency f_c

In amplitude modulation, the amplitude E_C of the carrier wave is varied in accordance with the intensity of the signal as shown in Fig. 18.6. Suppose the modulation factor is m. It means that signal produces a maximum change of $m E_C$ in the carrier amplitude. Obviously, the amplitude of signal is $m E_C$. Therefore, the signal can be represented by ;

$$e_s = m E_C \cos \omega_s t$$

where
e_s = instantaneous voltage of signal
$m E_C$ = amplitude of signal
$\omega_s = 2 \pi f_s$ = angular velocity at signal frequency f_s

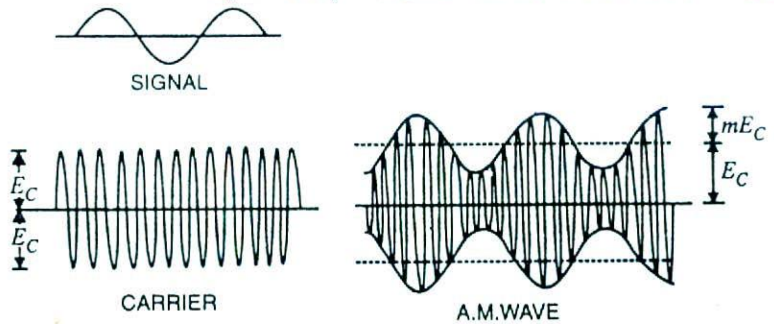


Fig. 18.6

The amplitude of the carrier wave varies at signal frequency f_s. Therefore, the amplitude of AM wave is given by ;

$$\text{Amplitude of AM wave} = E_C + m E_C \cos \omega_s t = E_C (1 + m \cos \omega_s t)$$

The instantaneous voltage of AM wave is :

$$e = \text{Amplitude} \times \cos \omega_c t$$
$$= E_C (1 + m \cos \omega_s t) \cos \omega_c t$$
$$= E_C \cos \omega_c t + m E_C \cos \omega_s t \cos \omega_c t$$
$$= E_C \cos \omega_c t + \frac{mE_C}{2} (2 \cos \omega_s t \cos \omega_c t)$$
$$= E_C \cos \omega_c t + \frac{mE_C}{2} [\cos (\omega_c + \omega_s) t + \cos (\omega_c - \omega_s) t]^*$$
$$= E_C \cos \omega_c t + \frac{mE_C}{2} \cos (\omega_c + \omega_s) t + \frac{mE_C}{2} \cos (\omega_c - \omega_s) t$$

The following points may be noted from the above equation of amplitude modulated wave:

---

* From trigonometry, we have the expansion formula :

$$2 \cos A \cos B = \cos (A + B) + \cos (A - B)$$

(*i*) The AM wave is equivalent to the summation of three sinusoidal waves; one having amplitude E_C and frequency *f_c, the second having amplitude $mE_C/2$ and frequency $(f_c + f_s)$ and the third having amplitude $mE_C/2$ and frequency $f_c - f_s$.

(*ii*) The AM wave contains three frequencies *viz* f_c, $f_c + f_s$ and $f_c - f_s$. The first frequency is the carrier frequency. Thus, the process of modulation does not change the original carrier frequency but produces two new frequencies $(f_c + f_s)$ and $(f_c - f_s)$ which are called sideband frequencies.

(*iii*) The sum of carrier frequency and signal frequency *i.e.* $(f_c + f_s)$ is called *upper sideband frequency*. The *lower sideband frequency* is $f_c - f_s$ *i.e.* the difference between carrier and signal frequencies.

18.7 Sideband Frequencies in AM Wave

In an amplitude modulated wave, the sideband frequencies are of our interest. It is because the signal frequency f_s is contained in the sideband frequencies. Fig. 18.7 shows the frequency spectrum of an amplitude modulated wave. The frequency components in the AM wave are shown by vertical lines. The height of each vertical line is equal to the amplitude of the components present. It may be added here that in practical radio transmission, carrier frequency f_c is many times greater than signal frequency f_s. Hence, the sideband frequencies are generally close to the carrier frequency. It may be seen that a carrier modulated by a single frequency is equivalent to three simultaneous signals; the carrier itself and two other steady frequencies *i.e.* $f_c + f_s$ and $f_c - f_s$.

Let us illustrate sideband frequencies with an example. Suppose the carrier frequency is 400 kHz and the signal frequency is 1 kHz. The AM wave will contain three frequencies *viz* 400 kHz, 401 kHz and 399 kHz. It is clear that upper sideband frequency (401 kHz) and lower sideband frequency (399 kHz) are very close to the carrier frequency (400 kHz).

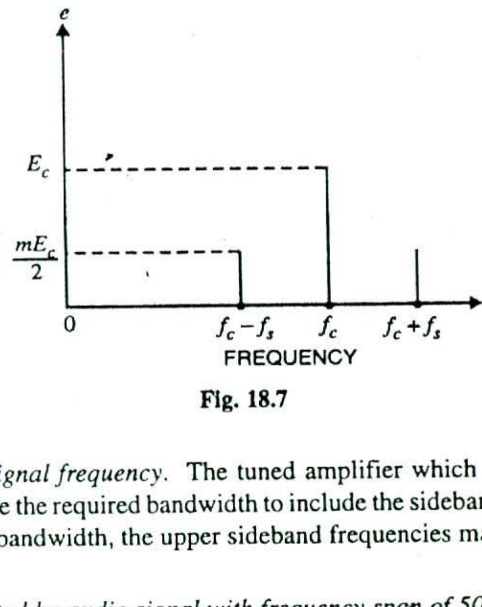


Fig. 18.7

Bandwidth. In an AM wave, the bandwidth is from $(f_c - f_s)$ to $(f_c + f_s)$ *i.e.*, $2f_s$. Thus in the above example, bandwidth is from 399 to 401 kHz or 2 kHz which is twice the signal frequency. Therefore, we arrive at a very important conclusion that *in amplitude modulation, bandwidth is twice the signal frequency*. The tuned amplifier which is called upon to amplify the modulated wave must have the required bandwidth to include the sideband frequencies. If the tuned amplifier has insufficient bandwidth, the upper sideband frequencies may not be reproduced by the radio receiver.

Example 18.4. *A 2500 kHz carrier is modulated by audio signal with frequency span of 50 – 15000 Hz. What are the frequencies of lower and upper sidebands ? What bandwidth of RF amplifier is required to handle the output ?*

Solution. The modulating signal (*e.g.* music) has a range of 0.05 to 15 kHz. The sideband frequencies produced range from $f_c \pm 0.05$ kHz to $f_c \pm 15$ kHz. Therefore, upper sideband ranges from 2500.05 to 2515 kHz and lower sideband ranges from 2499.95 to 2485 kHz.

The sideband frequencies produced can be approximately expressed as 2500 ± 15 kHz. There-

---

* $f_c = \frac{\omega_c}{2\pi}$, $f_c + f_s = \frac{\omega_c + \omega_s}{2\pi}$, $f_c - f_s = \frac{\omega_c - \omega_s}{2\pi}$

fore bandwidth requirement = 2515 – 2485 = 30 kHz. Note that bandwidth of *RF* amplifier required is twice the frequency of highest modulating signal frequency.

18.8 Transistor AM *Modulator

Fig. 18.8 shows the circuit of a simple AM modulator. It is essentially a *CE* amplifier having a voltage gain of A. The carrier signal is the input to the amplifier. The modulating signal is applied in the emitter resistance circuit.

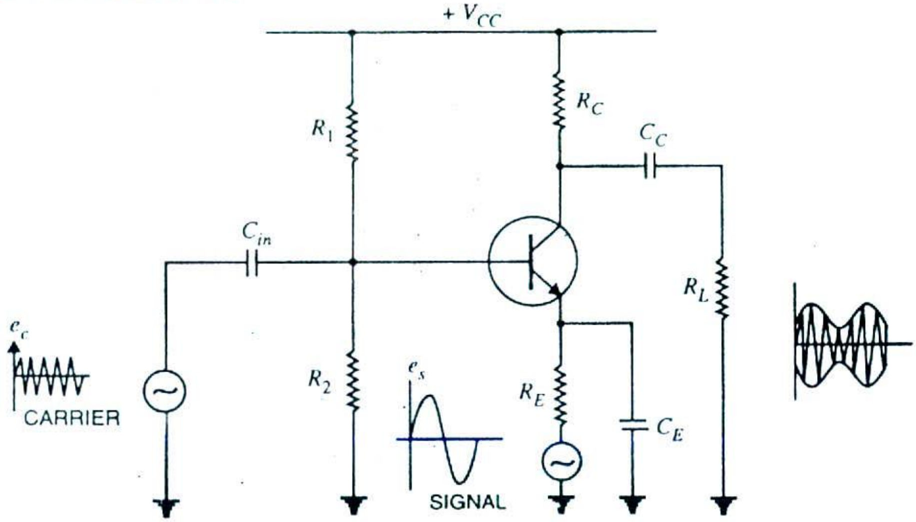


Fig. 18.8

Working. The carrier e_c is applied at the input of the amplifier and the modulating signal e_s is applied in the emitter resistance circuit. The amplifier circuit amplifies the carrier by a factor "*A*" so that the output is Ae_c. Since the modulating signal is a part of the biasing circuit, it produces low-frequency variations in the emitter circuit. This in turn causes **variations in "*A*". The result is that amplitude of the carrier varies in accordance with the strength of the signal. Consequently, amplitude modulated output is obtained across R_L. It may be noted that carrier should not influence the voltage gain A; only the modulating signal should do this. To achieve this objective, carrier should have a small magnitude and signal should have a large magnitude.

Example 18.5. *An AM wave is represented by the expression :*

$$v = 5\,(1 + 0.6 \cos 6280\, t) \sin 211 \times 10^4\, t \text{ volts}$$

(*i*) *What are the minimum and maximum amplitudes of the AM wave ?*

(*ii*) *What frequency components are contained in the modulated wave and what is the amplitude of each component?*

Solution.

The AM wave equation is given by ; $v = 5\,(1 + 0.6 \cos 6280\, t) \sin 211 \times 10^4\, t$ volts ...(*i*)

Compare it with standard AM wave eq., $v = E_C\,(1 + m \cos \omega_s\, t) \sin \omega_c\, t$ ...(*ii*)

From eqs. (*i*) and (*ii*), we get, E_C = carrier amplitude = 5 V

* A circuit which does amplitude modulation is called AM modulator.

** The principle of this circuit is to change the gain A (and hence the amplitude of carrier) by the modulating signal.

m = modulation factor = 0.6

f_s = signal frequency = $\omega_s/2\pi$ = $6280/2\pi$ = 1 kHz

f_c = carrier frequency = $\omega_c/2\pi = 211 \times 10^4/2\pi = 336$ kHz

(*i*) Minimum amplitude of AM wave $= E_C - mE_C = 5 - 0.6 \times 5 = \mathbf{2\ V}$

Maximum amplitude of AM wave $= E_C + mE_C = 5 + 0.6 \times 5 = \mathbf{8\ V}$

(*ii*) The AM wave will contain three frequencies *viz*

	$f_c - f_s$,	f_c,	$f_c + f_s$
or	336 – 1 ,	336 ,	336 + 1
or	**335 kHz,**	**336 kHz,**	**337 kHz**

The amplitudes of the three components of AM wave are :

	$\dfrac{mE_C}{2}$,	E_C,	$\dfrac{mE_C}{2}$
or	$\dfrac{0.6 \times 5}{2}$,	5,	$\dfrac{0.6 \times 5}{2}$
or	**1.5 V,**	**5 V,**	**1.5 V**

Example 18.6. *A sinusoidal carrier voltage of frequency 1 MHz and amplitude 100 volts is amplitude modulated by sinusoidal voltage of frequency 5 kHz producing 50% modulation. Calculate the frequency and amplitude of lower and upper sideband terms.*

Solution.

Frequency of carrier, f_c = 1 MHz = 1000 kHz

Frequency of signal, f_s = 5 kHz

Modulation factor, m = 50% = 0.5

Amplitude of carrier, E_C = 100 V

The lower and upper sideband frequencies are :

$f_c - f_s$ and $f_c + f_s$

or (1000 – 5) kHz and (1000 + 5) kHz

or **995 kHz** and **1005 kHz**

Amplitude of each sideband term

$$= \frac{mE_C}{2} = \frac{0.5 \times 100}{2} = \mathbf{25\ V}$$

18.9 Power in AM Wave

The power dissipated in any circuit is a function of the square of voltage across the circuit and the effective resistance of the circuit. Equation of AM wave reveals that it has three components of amplitude E_C, $m\,E_C/2$ and $m\,E_C/2$. Clearly, power output must be distributed among these components.

$$\text{Carrier power, } P_C = \frac{{}^*\left(E_C/\sqrt{2}\right)^2}{R} = \frac{E_C^2}{2R} \qquad ...(i)$$

$$\text{Total power of sidebands, } P_S = \frac{\left(m\,E_C/2\sqrt{2}\right)^2}{R} + \frac{\left(m\,E_C/2\sqrt{2}\right)^2}{R}$$

$$= \frac{m^2\,E_C^2}{8R} + \frac{m^2\,E_C^2}{8R} = \frac{m^2\,E_C^2}{4R} \qquad ...(ii)$$

* r.m.s. values are considered.

$$\text{Total power of AM wave, } P_T = P_C + P_S$$

$$= \frac{E_C^2}{2R} + \frac{m^2 E_C^2}{4R} = \frac{E_C^2}{2R}\left[1 + \frac{m^2}{2}\right]$$

or

$$P_T = \frac{E_C^2}{2R}\frac{\left[2 + m^2\right]}{2} \qquad ...(iii)$$

Fraction of total power carried by sidebands is

$$\frac{P_S}{P_T} = \frac{\text{Exp. }(ii)}{\text{Exp. }(iii)} = \frac{m^2}{2 + m^2} \qquad ....(iv)$$

As the signal is contained in the sideband frequencies, therefore, useful power is in the sidebands. Inspection of exp. (*iv*) reveals that sideband power depends upon the modulation factor m. The greater the value of m, the greater is the useful power carried by the sidebands. This emphasises the importance of modulation factor.

(*i*) When $m = 0$, power carried by sidebands $= 0^2/2 + 0^2 = 0$

(*ii*) When $m = 0.5$, power carried by sidebands

$$= \frac{(0.5)^2}{2 + (0.5)^2} = 11.1\ \% \text{ of total power of AM wave}$$

(*iii*) When $m = 1$, power carried by sidebands

$$= \frac{(1)^2}{2 + (1)^2} = 33.3\% \text{ of total power of AM wave}$$

As an example, suppose the total power of an AM wave is 600 watts and modulation is 100%. Then sideband power is 600/3 = 200 watts and carrier power will be 600 – 200 = 400 watts.

The sideband power represents the signal content and the carrier power is that power which is required as the means of transmission.

Note. $$P_C = \frac{E_C^2}{2R} \quad \text{and} \quad P_S = \frac{m^2 E_C^2}{4R}$$

$$\therefore \quad \frac{P_S}{P_C} = \frac{1}{2}m^2$$

or

$$P_S = \frac{1}{2}m^2 P_C \qquad ...(v)$$

Expression (v) gives the relation between total sideband power (P_S) and carrier power (P_C).

18.10 Limitations of Amplitude Modulation

Although theoretically highly effective, amplitude modulation suffers from the following drawbacks:

(*i*) *Noisy reception.* In an AM wave, the signal is in the amplitude variations of the carrier. Practically all the natural and man made noises consist of electrical amplitude disturbances. As a radio receiver cannot distinguish between amplitude variations that represent noise and those that contain the desired signal, therefore, reception is generally noisy.

(*ii*) *Low efficiency.* In amplitude modulation, useful power is in the sidebands as they contain the signal. As discussed before, an AM wave has low sideband power. For example, if modulation is 100%, the sideband power is only one-third of the total power of AM wave. Hence the efficiency of this type of modulation is low.

(*iii*) *Small operating range.* Due to low efficiency of amplitude modulation, transmitters employing this method have a small operating range *i.e.* messages cannot be transmitted over larger distances.

(*iv*) *Lack of audio quality.* This is a distinct disadvantage of amplitude modulation. In order to attain high-fidelity reception, all audio frequencies up to 15 kHz must be reproduced. This necessitates bandwidth of 30 kHz since both sidebands must be reproduced. But AM broadcasting stations are assigned bandwidth of only 10 kHz to minimise the interference from adjacent broadcasting stations. This means that the highest modulating frequency can be 5 kHz which is hardly sufficient to reproduce the music properly.

Example 18.7. *A carrier wave of 500 watts is subjected to 100% amplitude modulation. Determine :*

(*i*) *power in sidebands* (*ii*) *power of modulated wave*

Solution.

(*i*) Sideband power, $P_S = \frac{1}{2} m^2 P_C = \frac{1}{2} \times 500 = \mathbf{250\ W}$

Thus there are 125 W in upper sideband and 125 W in lower sideband.

(*ii*) Power of AM wave, $P_T = P_C + P_S = 500 + 250 = \mathbf{750\ W}$

Example 18.8. *A 50 kW carrier is to be modulated to a level of (i) 80% (ii) 10%. What is the total sideband power in each case ?*

Solution. (*i*) $P_S = \frac{1}{2} m^2 P_C = \frac{1}{2} (0.8)^2 \times 50 = \mathbf{16\ kW}$

(*ii*) $P_S = \frac{1}{2} m^2 P_C = \frac{1}{2} (0.1)^2 \times 50 = \mathbf{0.25\ kW}$

Note the effect of modulation factor on the magnitude of sideband power. In the first case (m = 80%), we generated and transmitted 50 kW carrier in order to send 16 kW of intelligence. In the second case (m = 10%), the same carrier level — 50 kW — is used to send merely 250 W of intelligence. Clearly, the efficiency of operation decreases rapidly as modulation factor decreases. For this reason, in amplitude modulation, the value of m is kept as close to unity as possible.

Example 18.9. *A 40kW carrier is to be modulated to a level of 100%.*

(*i*) *What is the carrier power after modulation ?*

(*ii*) *How much audio power is required if the efficiency of the modulated RF amplifier is 72% ?*

Solution. Fig. 18.9 shows the block diagram indicating the power relations.

(*i*) Since the carrier itself is unaffected by the modulating signal, there is no change in the carrier power level.

$\therefore$ $P_C = \mathbf{40\ kW}$

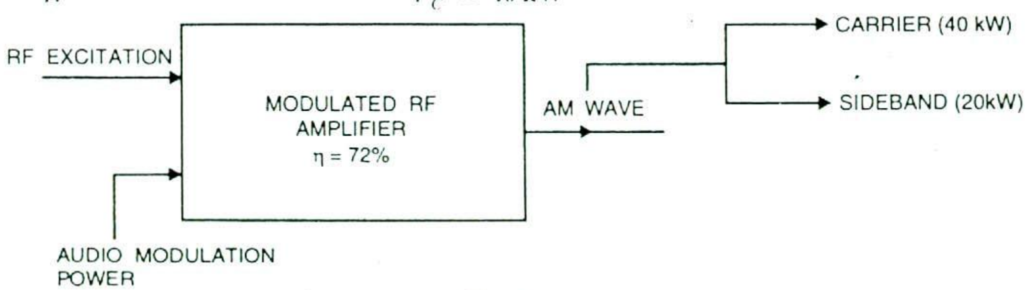


Fig. 18.9

(ii)
$$P_S = \frac{1}{2}m^2P_C = \frac{1}{2}(1)^2 \times 40 = 20 \text{ kW}$$

$$\therefore \quad P_{audio} = \frac{P_S}{0.72} = \frac{20}{0.72} = \mathbf{27.8\ kW}$$

Example 18.10. *An audio signal of 1 kHz is used to modulate a carrier of 500 kHz. Determine (i) sideband frequencies (ii) bandwidth required*

Solution. Carrier frequency, f_c = 500 kHz

Signal frequency, f_s = 1 kHz

(i) As discussed in Art. 18.6, the *AM* wave has sideband frequencies of $(f_c + f_s)$ and $(f_c - f_s)$.

∴ Sideband frequencies = (500 + 1) kHz and (500 − 1) kHz

= **501 kHz** and **499 kHz**

(ii) Bandwidth required = 499 kHz to 501 kHz = **2 kHz**

Example 18.11. *The load current in the transmitting antenna of an unmodulated AM transmitter is 8A. What will be the antenna current when modulation is 40% ?*

Solution.
$$P_S = \frac{1}{2}m^2P_C$$

$$P_T = P_C + P_S = P_C\left(1 + \frac{m^2}{2}\right)$$

$$\therefore \quad \frac{P_T}{P_C} = 1 + \frac{m^2}{2}$$

or
$$\left(\frac{I_T}{I_C}\right)^2 = 1 + \frac{m^2}{2}$$

Given that I_C = 8A; m = 0.4

$$\therefore \quad \left(\frac{I_T}{8}\right)^2 = 1 + \frac{(0.4)^2}{2}$$

or
$$(I_T/8)^2 = 1.08$$

or
$$I_T = 8\sqrt{1.08} = \mathbf{8.31\ A}$$

Example 18.12. *The antenna current of an AM transmitter is 8A when only carrier is sent but it increases to 8.93A when the carrier is sinusoidally modulated. Find the % age modulation.*

Solution. As shown in example 18.11,

$$\left(\frac{I_T}{I_C}\right)^2 = 1 + \frac{m^2}{2}$$

Given that, I_C = 8.93 A; I_C = 8 A ; m = ?

$$\therefore \quad \left(\frac{8.93}{8}\right)^2 = 1 + \frac{m^2}{2}$$

or
$$1.246 = 1 + m^2/2$$

or
$$m^2/2 = 0.246$$

or
$$m = \sqrt{2 \times 0.246} = 0.701 = \mathbf{70.1\%}$$

Example 18.13. *The r.m.s. value of carrier voltage is 100 V. After amplitude modulation by a sinusoidal a.f. voltage, the r.m.s. value becomes 110 V. Calculate the modulation index.*

Solution.
$$\frac{P_T}{P_C} = 1 + \frac{m^2}{2}$$

or
$$\left(\frac{V_T}{V_C}\right)^2 = 1 + \frac{m^2}{2}$$

Given that $V_T = 110\text{ V}$; $V_C = 100\text{ V}$; $m = ?$

∴
$$\left(\frac{110}{100}\right)^2 = 1 + \frac{m^2}{2}$$

or
$$1.21 = 1 + \frac{m^2}{2}$$

or
$$m^2/2 = 0.21$$

or
$$m = \sqrt{0.21 \times 2} = \mathbf{0.648}$$

Example 18.14. *An AM wave consists of the following components :*

Carrier component = 5 V peak value
Lower sideband component = 2.5 V peak value
Upper sideband component = 2.5 V peak value

If the AM wave drives a 2 kΩ resistor, find the power delivered to the resistor by (i) carrier (ii) lower sideband component and (iii) upper sideband component. What is the total power delivered?

Solution. Fig. 18.10 (*i*) shows the spectrum of AM wave whereas Fig. 18.10 (*ii*) shows the equivalent circuit.

$$\text{Power} = \frac{(\text{r.m.s. voltage})^2}{R} = \frac{(0.707 \times \text{peak value})^2}{R}$$

(*i*) Power delivered by the carrier, $P_C = \frac{(0.707 \times 5)^2}{2000} = \mathbf{6.25\ mW}$

(*ii*) Power delivered by lower sideband component is

$$P_{lower} = \frac{(0.707 \times 2.5)^2}{2000} = \mathbf{1.562\ mW}$$

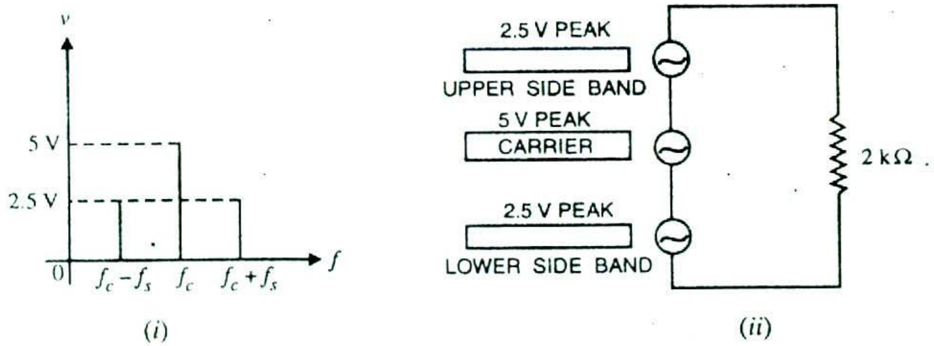


Fig. 18.10

(*iii*) Power delivered by upper sideband component is

$$P_{upper} = \frac{(0.707 \times 2.5)^2}{2000} = \mathbf{1.562\ mW}$$

Total power delivered by the AM wave $= 6.25 + 1.562 + 1.562 = \mathbf{9.374\ mW}$

18.11 Frequency Modulation

When the frequency of carrier wave is changed in accordance with the intensity of the signal, it is called **frequency modulation.**

In frequency modulation, only the frequency of the carrier wave is changed in accordance with the signal. However, the amplitude of the modulated wave remains the same *i.e.* carrier wave amplitude. The frequency variations of carrier wave depend upon the instantaneous amplitude of the signal as shown in Fig. 18.11 (*iii*). When the signal voltage is zero as at A, C, E and G, the carrier frequency is unchanged. When the signal approaches its positive peaks as at B and F, the carrier frequency is increased to maximum as shown by the closely spaced cycles. However, during the negative peaks of signal as at D, the carrier frequency is reduced to minimum as shown by the widely spaced cycles.

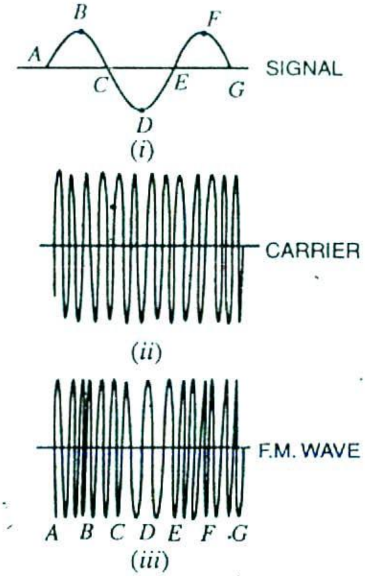


Fig. 18.11

Advantages :

(*i*) It gives noiseless reception. As discussed before, noise is a form of amplitude variations and a FM receiver will reject such signals.

(*ii*) The operating range is quite large.

(*iii*) It gives high-fidelity reception.

(*iv*) The efficiency of transmission is very high.

18.12 Demodulation

The process of recovering the audio signal from the modulated wave is known as **demodulation** *or* **detection.**

At the broadcasting station, modulation is done to transmit the audio signal over larger distances to a receiver. When the modulated wave is picked up by the radio receiver, it is necessary to recover the audio signal from it. This process is accomplished in the radio receiver and is called demodulation.

Necessity of demodulation. It was noted previously that amplitude modulated wave consists of carrier and sideband frequencies. The audio signal is contained in the sideband frequencies which are radio frequencies. If the modulated wave after amplification is directly fed to the speaker as shown in Fig. 18.12, no sound will be heard. It is because diaphragm of the speaker is not at all able to respond to such high frequencies. Before the diaphragm is able to move in one direction, the rapid reversal of current tends to move it in the opposite direction i.e. diaphragm will not move at all. Consequently, no sound will be heard.

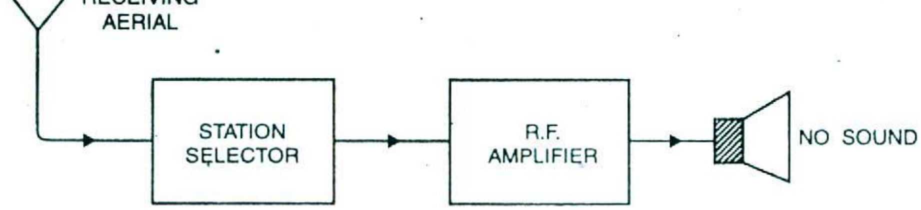


Fig. 18.12

From the above discussion, it follows that audio signal must be separated from the carrier at a suitable stage in the receiver. The recovered audio signal is then amplified and fed to the speaker for conversion into sound.

18.13 Essentials in Demodulation

In order that a modulated wave is audible, it is necessary to change the nature of modulated wave. This is accomplished by a circuit called *detector*. A detector circuit performs the following two functions :

(*i*) *It rectifies the modulated wave i.e.* negative half of the modulated wave is eliminated. As shown in Fig. 18.13 (*i*), a modulated wave has positive and negative halves exactly equal. Therefore, average current is zero and speaker cannot respond. If the negative half of this modulated wave is eliminated as shown in Fig. 18.13 (*ii*), the average value of this wave will not be zero since the resultant pulses are now all in one direction. The average value is shown by the dotted line in Fig. 18.13 (*ii*). Therefore, the diaphragm will have definite displacement corresponding to the average value of the wave. It may be seen that shape of the average wave is similar to that of the modulation envelope. As the signal is of the same shape as the envelope, therefore, average wave shape is of the same form as the signal.

(*ii*) *It separates the audio signal from the carrier.* The rectified modulated wave contains the audio signal and the carrier. It is desired to recover the audio signal. This is achieved by a filter circuit which removes the carrier frequency and allows the audio signal to reach the load *i.e.*speaker.

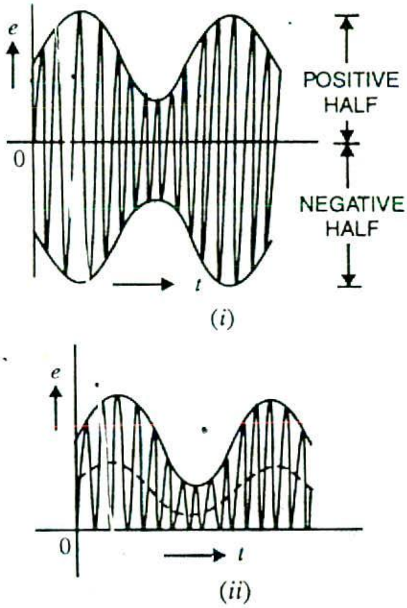


Fig. 18.13

18.14 A.M. Diode Detector

Fig. 18.14 shows a simple detector circuit employing vacuum diode and filter circuit. The modulated wave of desired frequency is selected by the parallel tuned circuit L_1C_1 and is applied to the vacuum diode. During the positive half-cycles of modulated wave, the diode conducts while during negative half-cycles, it does not. The result of this rectifying action is that output of the diode consists of positive half-cycles of modulated wave as shown.

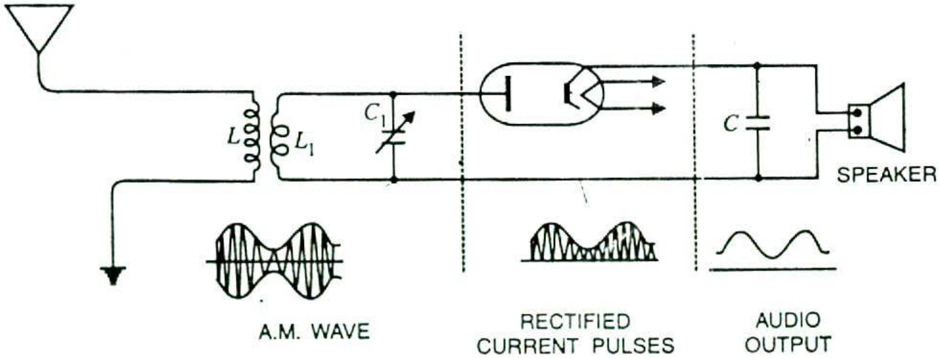


Fig. 18.14

The rectified modulated wave contains radio frequency and the signal and cannot be fed to the speaker for sound reproduction. If done so, no sound will be heard due to the inertia of speaker diaphragm. The *r.f.* component is filtered by the capacitor *C* shunted across the speaker. The value of this capacitor is sufficiently large to present low reactance to the r.f. component while presenting a relatively high reactance to the audio signal. The result is that the r.f. component is bypassed by the capacitor *C* and the signal is passed on to the speaker for sound reproduction.

Note. If vacuum diode is replaced by a crystal diode, the circuit becomes crystal diode detector.

18.15 A. M. Radio Receivers

A radio receiver is a device which reproduces the modulated or radio waves into sound waves. In India, only amplitude modulation is used for radio transmission and reception. Therefore, such radio receivers are called A.M. radio receivers. In order to reproduce the A.M. wave into sound waves, every radio receiver must perform the following functions :

(*i*) The receiving aerial must intercept a portion of the passing radio waves.

(*ii*) The radio receiver must select the desired radio wave from a number of radio waves intercepted by the receiving aerial. For this purpose, tuned parallel *LC* circuits must be used. These circuits will select only that radio frequency which is in resonant with them.

(*iii*) The selected radio wave must be amplified by the tuned frequency amplifiers.

(*iv*) The audio signal must be recovered from the amplified radio wave.

(*v*) The audio signal must be amplified by suitable number of audio-amplifiers.

(*vi*) The amplified audio signal should be fed to the speaker for sound reproduction.

18.16 Types of A. M. Radio Receivers

A.M. radio receivers can be broadly classified into two types *viz.*, *straight radio receiver* and *superhetrodyne radio receiver*. The former was used in the early days of radio communication. However at present, all radio receivers are of superhetrodyne type.

1. Straight radio receiver. Fig. 18.15 shows the block diagram of a straight radio receiver. The aerial is receiving radio waves from different broadcasting stations. The desired radio wave is selected by the R.F. amplifier which employs a tuned parallel circuit. The selected radio wave is amplified by the tuned r.f. amplifiers. The amplified radio wave is fed to the detector circuit. This circuit extracts the audio signal from the radio wave. The output of the detector is the audio signal which is amplified by one or more stages of audio-amplification. The amplified audio signal is fed to the speaker for sound reproduction.

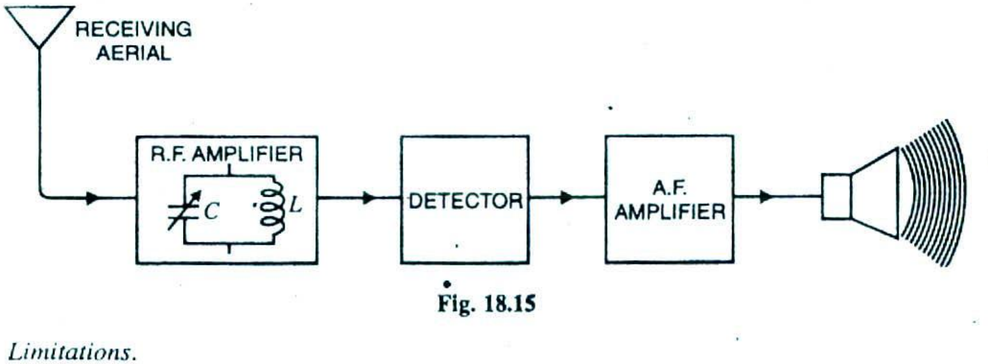


Fig. 18.15

Limitations.

(*i*) In straight radio receivers, tuned circuits are used. As it is necessary to change the value of variable capacitors (gang capacitors) for tuning to the desired station, therefore, there is a considerable variation of Q between the closed and open positions of the variable capacitors. This changes the sensitivity and selectivity of the radio receivers.

(*ii*) There is too much interference of adjacent stations.

2. Superhetrodyne receiver. The shortcomings of straight radio receiver were overcome by the invention of superhetrodyne receiver by Major Edwin H. Armstrong during the First World War. At present, all modern receivers utilise the superhetrodyne circuit. In this type of radio receiver, the selected radio frequency is converted to a fixed lower value, called *intermediate frequency (IF)*. This is achieved by a special electronic circuit called *mixer circuit*. There is a local oscillator in the radio receiver itself. This oscillator produces high frequency waves. The selected radio frequency is mixed with the high frequency wave by the mixer circuit. In this process, beats are produced and the *mixer produces a frequency equal to the difference between local oscillator and radio wave frequency*. As explained later, the circuit is so designed that oscillator always produces a frequency 455 kHz above the selected radio frequency. Therefore, the mixer will always produce an intermediate frequency of 455 kHz regardless of the station to which the receiver is tuned. For instance, if 600KHz station is tuned, then local oscillator will produce a frequency of 1055 kHz. Consequently, the output from the mixer will have a frequency of 455 kHz.

The production of fixed intermediate frequency (455 kHz) is the salient feature of superhetrodyne circuit. At this fixed intermediate frequency, the amplifier circuits operate with maximum stability, selectivity and sensitivity. As the conversion of incoming radio frequency to the intermediate frequency is achieved by *heterodyning* or beating the local oscillator against radio frequency, therefore, this circuit is called *superhetrodyne circuit.

18.17 Stages of Superhetrodyne Radio Receiver

Fig. 18.16 shows the block diagram of a superhetrodyne receiver. It may be seen that R.F. amplifier stage, mixer stage and oscillator stage use tuned parallel circuits with variable capacitors. These capacitors are ganged together as shown by the dotted interconnecting lines. The rotation of the common shaft simultaneously changes the capacitance of these tuned circuits.

(*i*) **R.F. amplifier stage.** The R.F. amplifier stage uses a tuned parallel circuit L_1C_1 with a variable capacitor C_1. The radio waves from various broadcasting stations are intercepted by the receiving aerial and are coupled to this stage. This stage selects the desired radio wave and raises the strength of the wave to the desired level.

(*ii*) **Mixer stage.** The amplified output of R.F. amplifier is fed to the mixer stage where it is combined with the output of a local oscillator. The two frequencies beat together and produce an intermediate frequency (*IF*). The intermediate frequency is the difference between oscillator frequency and radio frequency *i.e.*

$$I.F. = \text{Oscillator frequency} - \text{Radio frequency}$$

The *IF* is always 455 kHz regardless of the frequency to which the receiver is tuned. The reason why the mixer will always produce 455 kHz frequency above the radio frequency is that oscillator always produces a frequency 455 kHz **above the selected radio frequency. This is achieved by

* In a super-hetrodyne receiver, the hetrodyne principle is used to produce an intermediate frequency which is higher than that can be heard *i.e.*, supersonic. Superhetrodyne is short for supersonic hetrodyne.

** The reason that the oscillator is designed to produce a frequency 455 kHz above and not below the selected frequency is as follows. A radio receiver is required to tune over 550 to 1600 kHz frequency. To provide IF of 455 kHz, the oscillator frequency must vary from 1005 to 2055 kHz. If the oscillator is designed to produce a frequency 455 kHz below the selected frequency (of course IF will be still 455 kHz), then the frequency range of the oscillator will have to be 95 to 1145 kHz. This frequency ratio is too high to be covered in a single band.

making C_3 smaller than C_1 and C_2. By making C_3 smaller, oscillator will tune to a higher frequency. In practice, capacitance of C_3 is designed to tune the oscillator to a frequency higher than radio wave frequency by 455 kHz. This frequency difference (*i.e.* 455 kHz) will always be maintained because when C_1 and C_2 are varied, C_3 will also vary proportionally. It may be noted that in mixer stage, the carrier frequency is reduced. The *IF* still contains the audio signal.

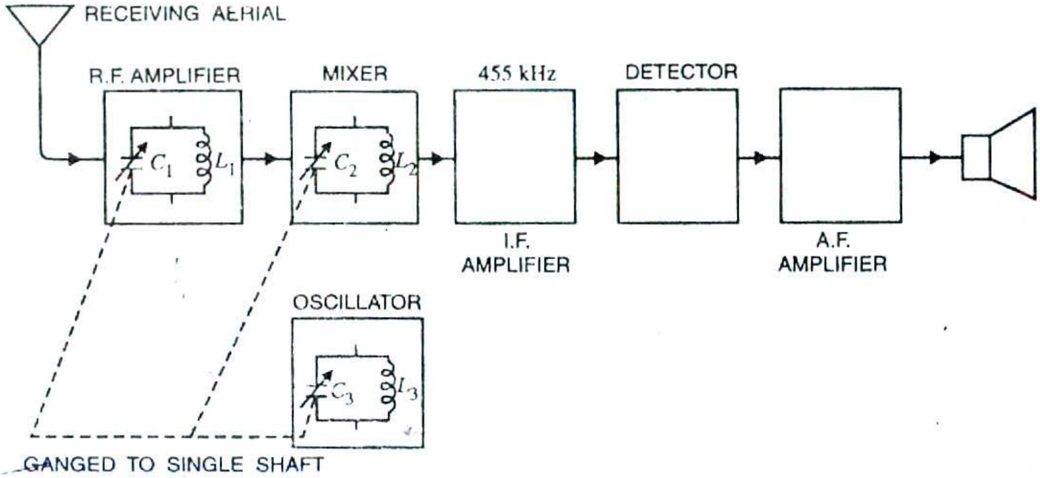


Fig. 18.16

(*iii*) **I.F. amplifier stage.** The output of mixer is always 455 kHz and is fed to fixed tuned I.F. amplifiers. These amplifiers are tuned to one frequency (*i.e.* 455 kHz) and render nice amplification.

(*iv*) **Detector stage.** The output from the last IF amplifier stage is coupled to the input of the detector stage. Here, the audio signal is extracted from the IF output. Usually, diode detector circuit is used because of its low distortion and excellent audio fidelity.

(*v*) **A.F. amplifier stage.** The audio signal output of detector stage is fed to a multistage audio amplifier. Here, the signal is amplified until it is sufficiently strong to drive the speaker. The speaker converts the audio signal into sound waves corresponding to the original sound at the broadcasting station.

18.18 Advantages of Superhetrodyne Circuit

The basic principle involved in superhetrodyne circuit is to obtain a fixed intermediate frequency with the help of a mixer circuit and local oscillator. The superhetrodyne principle has the following advantages :

(*i*) *High r.f. amplification.* The superhetrodyne principle makes it possible to produce an intermediate frequency (*i.e.* 455 kHz) which is much less than the radio frequency. R.F. amplification at low frequencies is more stable since feedback through stray and interelectrode capacitance is reduced.

(*ii*) *Improved selectivity.* Losses in the tuned circuits are lower at intermediate frequency. Therefore, the quality factor Q of the tuned circuits is increased. This makes the amplifier circuits to operate with maximum selectivity.

(*iii*) *Lower cost.* In a superhetrodyne circuit, a fixed intermediate frequency is obtained regardless of the radio wave selected. This permits the use of fixed R.F. amplifiers. The superhetrodyne receiver is thus cheaper than other radio receivers.

Multiple-Choice Questions

1. Modulation is done in ....
   (*i*) transmitter
   (*ii*) radio receiver
   (*iii*) between transmitter and radio receiver
   (*iv*) none of the above
2. In a transmitter, ... oscillator is used.
   (*i*) Hartley (*ii*) RC phase-shift
   (*iii*) Wien-bridge (*iv*) crystal
3. In India, ... modulation is used for radio transmission.
   (*i*) frequency (*ii*) amplitude
   (*iii*) phase (*iv*) none of the above
4. In an AM wave, useful power is carried by ....
   (*i*) carrier
   (*ii*) sidebands
   (*iii*) both sidebands and carrier
   (*iv*) none of the above
5. In amplitude modulation, bandwidth is .... the audio signal frequency.
   (*i*) thrice (*ii*) four times
   (*iii*) twice (*iv*) none of the above
6. In amplitude modulation, the .... of carrier is varied according to the strength of the signal.
   (*i*) amplitude (*ii*) frequency
   (*iii*) phase (*iv*) none of the above
7. Overmodulation (amplitude) occurs when signal amplitude is .... carrier amplitude.
   (*i*) equal to (*ii*) greater than
   (*iii*) less than (*iv*) none of the above
8. In an AM wave, the majority of the power is in ....
   (*i*) lower sideband
   (*ii*) upper sideband
   (*iii*) carrier
   (*iv*) none of the above
9. At 100 % modulation, the power in each sideband is .... of that of carrier.
   (*i*) 50 % (*ii*) 40 %
   (*iii*) 60 % (*iv*) 25 %
10. Overmodulation results in ....
    (*i*) weakening of the signal
    (*ii*) excessive carrier power
    (*iii*) distortion
    (*iv*) none of the above
11. If modulation is 100 %, then signal amplitude is .... carrier amplitude.
    (*i*) equal to (*ii*) greater than
    (*iii*) less than (*iv*) none of the above
12. As the modulation level is increased, the carrier power ....
    (*i*) is increased (*ii*) remains the same
    (*iii*) is decreased (*iv*) none of the above
13. Demodulation is done in ....
    (*i*) receiving antenna
    (*ii*) transmitter
    (*iii*) radio receiver
    (*iv*) transmitting antenna
14. A high *Q* tuned circuit will permit an amplifier to have high ....
    (*i*) fidelity (*ii*) frequency range
    (*iii*) sensitivity (*iv*) selectivity
15. In radio transmission, the medium of transmission is ....
    (*i*) space (*ii*) an antenna
    (*iii*) cable (*iv*) none of the above
16. If level of modulation is increased .... power is increased.
    (*i*) carrier
    (*ii*) sideband
    (*iii*) carrier as well as sideband
    (*iv*) none of the above
17. In TV transmission, picture signal is .... modulated.
    (*i*) frequency (*ii*) phase
    (*iii*) amplitude (*iv*) none of the above
18. In a radio receiver, noise is generally developed at ....
    (*i*) IF stage (*ii*) receiving antenna
    (*iii*) audio stage (*iv*) RF stage

19. Man made noises are .... variations.
   (i) amplitude
   (ii) frequency
   (iii) phase
   (iv) both phase and frequency
20. The signal voltage induced in the aerial of a radio receiver is of the order of ....
   (i) mV (ii) μV
   (iii) V (iv) none of the above
21. Superhetrodyne principle refers to ....
   (i) using a large number of amplifier stages
   (ii) using a push-pull circuit
   (iii) obtaining lower fixed intermediate frequency
   (iv) none of the above
22. If a radio receiver amplifies all the signal frequencies equally well, it is said to have high ....
   (i) sensitivity (ii) selectivity
   (iii) distortion (iv) fidelity
23. Most of the amplification in a superhetrodyne receiver occurs at .... stage.
   (i) IF (ii) RF amplifier
   (iii) audio amplifier (iv) detector
24. The letters AVC stand for ....
   (i) audio voltage control
   (ii) abrupt voltage control
   (iii) automatic volume control
   (iv) automatic voltage control
25. The superhetrodyne principle provides selectivity at .... stage.
   (i) RF (ii) IF
   (iii) audio (iv) before RF
26. In superhetrodyne receiver, the input at the mixer stage is ....
   (i) IF and RF
   (ii) RF and AF
   (iii) IF and AF
   (iv) RF and local oscillator signal
27. The major advantage of FM over AM is ....
   (i) reception is less noisy
   (ii) higher carrier frequency
   (iii) smaller bandwidth
   (iv) small frequency deviation
28. When the modulating signal controls the frequency of the carrier, we get, ...
   (i) phase modulation
   (ii) amplitude modulation
   (iii) frequency modulation
   (iv) may be any one of the above
29. Modulation refers to a low-frequency signal controlling the ....
   (i) amplitude of the carrier
   (ii) frequency of the carrier
   (iii) phase of the carrier
   (iv) may be any of the above
30. The IF is 455 kHz. If the radio receiver is tuned to 855 kHz, the local oscillator frequency is ....
   (i) 455 kHz (ii) 1310 kHz
   (iii) 1500 kHz (iv) 1520 kHz
31. If A_{min} = 40 and A_{max} = 60, what is the percentage modulation ?
   (i) 20 % (ii) 40 %
   (iii) 50 % (iv) 10 %
32. The function of ferrite antenna is to ....
   (i) reduce stray capacitance
   (ii) stabilise d.c. bias
   (iii) increase the Q of tuned circuit
   (iv) reduce noise
33. In a radio receiver, we generally use .... oscillator as a local oscillator.
   (i) crystal (ii) Wien-bridge
   (iii) phase-shift (iv) Hartley
34. A 100 V carrier is made to vary between 160 V and 40 V by the signal. What is the modulation factor ?
   (i) 0.3 (ii) 0.6
   (iii) 0.5 (iv) none of the above
35. A 50 kW carrier is to be amplitude modulated to a level of 85 %. What is the carrier power after modulation ?
   (i) 50 kW (ii) 42.5 kW
   (iii) 58.8 kW (iv) 25 kW

36. In the above question, what is the power in sidebands ?

(*i*) 7.8 kW (*ii*) 11.6 kW
(*iii*) 18.06 kW (*iv*) 15.9 kW

37. In a superhetrodyne receiver, the difference frequency is chosen as the IF rather than the sum frequency because ....

(*i*) the difference frequency is closer to oscillator frequency
(*ii*) lower frequencies are easier to amplify
(*iii*) only the difference frequency can be modulated
(*iv*) none of the above.

38. The diode detector in an AM radio receiver is usually found ....

(*i*) before the first RF stage
(*ii*) after the first RF stage
(*iii*) after several stages of amplification
(*iv*) none of the above

39. In a TRF radio receiver, the RF and detection stages are tuned to ....

(*i*) radio frequency
(*ii*) IF
(*iii*) audio frequency
(*iv*) none of the above

40. In TV transmission, sound signal is .... modulated

(*i*) amplitude (*ii*) frequency
(*iii*) phase (*iv*) none of the above

Answers to Multiple-Choice Questions

1. (*i*)	**2.** (*iv*)	**3.** (*ii*)	**4.** (*ii*)	**5.** (*iii*)
6. (*i*)	**7.** (*ii*)	**8.** (*iii*)	**9.** (*iv*)	**10.** (*iii*)
11. (*i*)	**12.** (*ii*)	**13.** (*iii*)	**14.** (*iv*)	**15.** (*i*)
16. (*ii*)	**17.** (*iii*)	**18.** (*iv*)	**19.** (*i*)	**20.** (*ii*)
21. (*iii*)	**22.** (*vi*)	**23.** (*i*)	**24.** (*iii*)	**25.** (*ii*)
26. (*iv*)	**27.** (*i*)	**28.** (*iii*)	**29.** (*iv*)	**30.** (*ii*)
31. (*i*)	**32.** (*iii*)	**33.** (*iv*)	**34.** (*ii*)	**35.** (*i*)
36. (*iii*)	**37.** (*ii*)	**38.** (*iii*)	**39.** (*i*)	**40.** (*ii*)

Chapter Review Topics

1. Explain the general principles of radio broadcasting, transmission and reception.
2. What is modulation ? Why is modulation necessary in communication system ?
3. Explain amplitude modulation. Derive the voltage equation of an AM wave.
4. What do you understand by modulation factor ? What is its significance ?
5. Draw the waveform of AM wave for the following values of modulation factor :

   (*i*) 0 (*ii*) 0.5 (*iii*) 1 (*iv*) 1.5
6. What do you understand by sideband frequencies in an AM wave ?
7. Derive an expression for the fraction of total power carried by the sidebands in amplitude modulation.
8. What are the limitations of amplitude modulation ?
9. What do you understand by frequency modulation ? Explain its advantages over amplitude modulation.
10. What is demodulation ? What are essentials in demodulation ?
11. Draw the diode detector circuit and explain its action.
12. What is superhetrodyne principle ? Explain the function of each stage of superhetrodyne receiver with the help of a block diagram.

Problems

1. The maximum peak-to-peak voltage of an AM wave is 16 mV while the minimum peak-to-peak voltage is 8 mV. Find the percentage modulation. **[60%]**
2. A carrier of peak voltage 0.05 V and frequency 200 kHz is amplitude modulated by a signal of peak voltage 10 V and frequency 1 kHz. Find (*i*) frequencies in the output spectrum and (*ii*) the peak values of output components if $m = 0.5$ and voltage gain $A = 100$. **[(*i*) 199 kHz, 200 kHz, 201 kHz (*ii*) 1.25 V, 5 V, 1.25 V]**
3. An AM transmitter supplies 10kW to the antenna when unmodulated. Determine the total power radiated by the transmitter when modulated to 30%. **[10.45 kW]**
4. A certain AM transmitter radiates 8kW with carrier unmodulated and 9kW when the carrier is modulated. Find the percentage modulation. **[50%]**
5. A transmitter radiates a total power of 10 kW. The carrier is modulated to a depth of 60% . Calculate (*i*) the power in the carrier and (*ii*) power in each sideband. **[(*i*) 8.47kW (*ii*) 0.765kW]**
6. A carrier of 100 V and 1500 kHz is moduiated by 60V, 1200 Hz sinusoidal signal. Calculate modulation factor and express this as percentage. **[0.6; 60%]**
7. A carrier with an amplitude of 140 V is modulated by a signal with an amplitude of 80V. What is the percentage modulation ? What is the amplitude of lower sideband frequency ? **[57% ; 40V]**
8. A 50 kW carrier is to be modulated to a level of 85%. What is the carrier power after modulation ? What is sideband power ? **[50 kW ; 18.06 kW]**
9. The r.m.s. antenna current of a radio transmitter is 10 A when unmodulated, rising to 12 A when the carrier is sinusoidally modulated. What is the modulation index ? **[0.94]**
10. The r.m.s. antenna current of an AM transmitter increases by 15% over the unmodulated value when sinusoidal modulation is applied. Determine the modulation index. **[0.8]**

Discussion Questions

1. Why cannot electrical energy be radiated at low frequencies (< 20 kHz) ?
2. Why is radio transmission carried at high frequencies ?
3. Why does amplitude modulation give noisy reception ?
4. Why do we always design the oscillator to produce a frequency of 455 kHz above and not below the incoming radio wave ?
5. What is the importance of modulation factor in communication system ?
6. Why is superhetrodyne principle employed in radio receivers ?
7. Why is AM and not FM employed for radio transmission in India ?
8. Why does frequency modulation give noiseless reception ?
9. Why have we selected *IF* as 455 kHz ?
10. What is the importance of sideband frequencies ?