3. Multistage Transistor Amplifiers

3.1 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 *multistage amplifier*. It may be emphasized 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 topic, we shall focus our attention on the various multistage transistor amplifiers and their practical applications.

3.2 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 (in series) 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 a coupling device (e.g. a capacitor, a transformer etc.) is;

(i) To transfer a.c. output of one stage to the input of the next stage.
(ii) To isolate the d.c. conditions of one stage from the next stage.

Fig. 3.1 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	*RC* coupled amplifier
Transformer coupling	Transformer coupled amplifier
Direct coupling	Direct coupled amplifier

Fig. 3.1

(i) In *RC* coupling, a capacitor is used as the coupling device. The capacitor connects the 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, a 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.

3.3 Role of Capacitors in Transistor Amplifiers

Regardless of the manner in which a capacitor is connected in a transistor amplifier, its behavior towards d.c. and a.c. is as follows. A capacitor blocks d.c. i.e. a capacitor behaves as an "open ($X_C = 1/2\pi fC$. For d.c., $f = 0$ so that $X_C \to \infty$. Therefore, a capacitor behaves as an open to d.c.)" to d.c. Therefore, for d.c. analysis, we can remove the capacitors from the transistor amplifier circuit. A capacitor offers reactance ($= 1/2\pi fC$) to a.c. depending upon the values of f and C. In practical transistor circuits, the size of capacitors is so selected that they offer negligible (ideally zero) reactance to the range of frequencies handled by the circuits. Therefore, for a.c. analysis, we can replace the capacitors by a short i.e. by a wire. The capacitors serve the following two roles in transistor amplifiers;

a) As coupling capacitors
b) As bypass capacitors

3.3.1 As Coupling Capacitors

In most applications, you will not see a single transistor amplifier. Rather we use a multistage amplifier i.e. a number of transistor amplifiers are connected in series or cascaded. The capacitors are commonly used to connect one amplifier stage to another. When a capacitor is used for this purpose, it is called a *coupling capacitor*. Fig. 3.2 shows the coupling capacitors (C_{C1}, C_{C2}, C_{C3} and C_{C4}) in a multistage amplifier. A coupling capacitor performs the following two functions;

(i) It blocks d.c. i.e. it provides d.c. isolation between the two stages of a multistage amplifier.
(ii) It passes the a.c. signal from one stage to the next with little or no distortion.

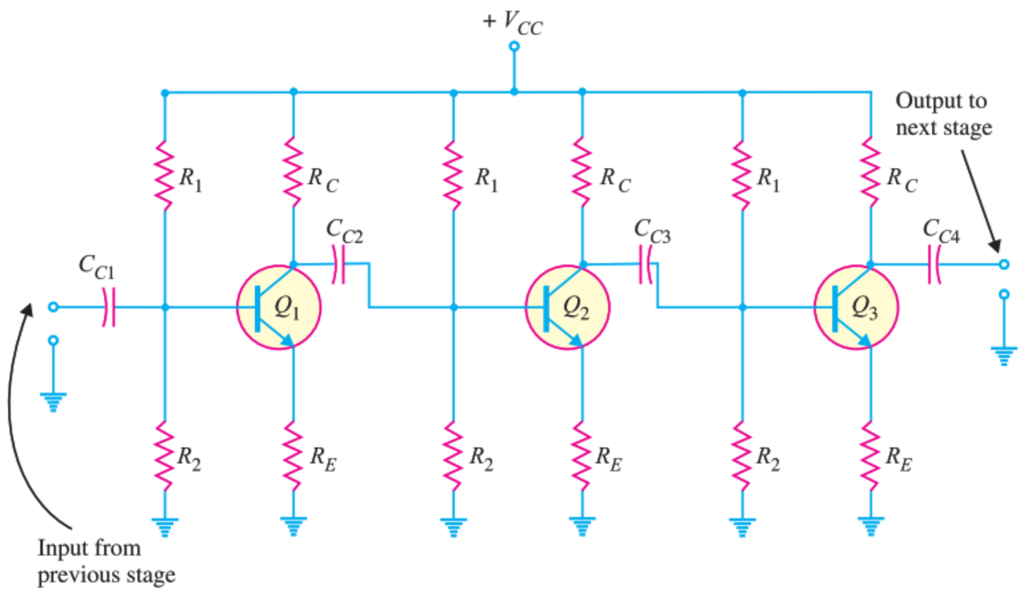

Fig. 3.2

3.3.2 As Bypass Capacitors

Like a coupling capacitor, a bypass capacitor also blocks d.c. and behaves as a short or wire (due to proper selection of capacitor size) to an a.c. signal. But it is used for a different purpose. A bypass capacitor is connected in parallel with a circuit component (e.g. resistor) to bypass the a.c. signal and hence the name. Fig. 3.3 shows a bypass capacitor C_E connected across the emitter resistance R_E. Since C_E behaves as a short to the a.c. signal, the whole of a.c. signal (ie) passes through it. Note that C_E keeps the emitter at a.c. ground. Thus for a.c. purposes, R_E does not exist. C_E also plays an important role in determining the voltage gain of the amplifier circuit. If C_E is removed, the voltage gain of the amplifier is greatly reduced. Note that C_{in} is the coupling capacitor in this circuit.

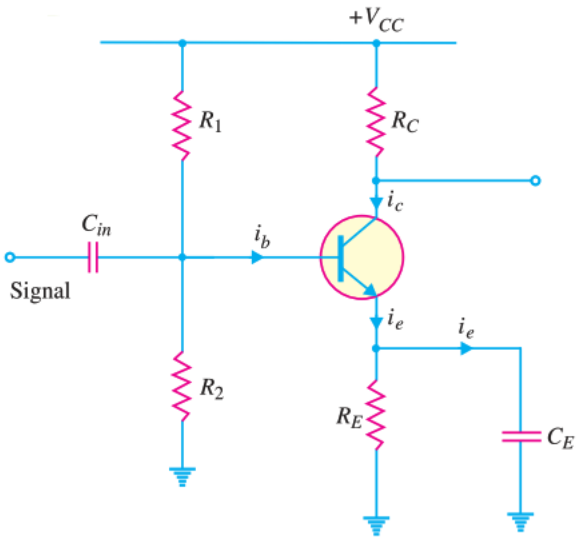

Fig. 3.3

3.4 Important Terms

In the study of multistage amplifiers, we shall frequently come across the terms *gain*, *frequency response*, *decibel gain* and *bandwidth*. These terms stand discussed below:

3.4.1 Gain

This is the ratio of the output electrical quantity (current, voltage or power) to the corresponding input quantity of the amplifier.

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.

3.4.2 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 affects the output voltage. The curve between voltage gain and signal frequency of an amplifier is known as *frequency response*. Fig. 3.4 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.

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.

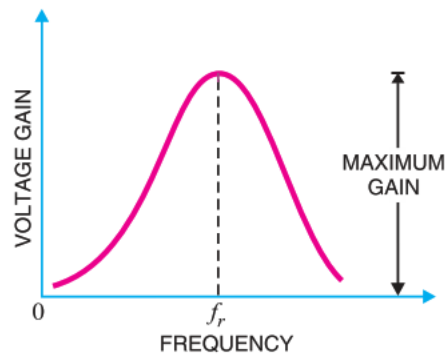

Fig. 3.4

3.4.3 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.

$$\text{Power gain} = \log_{10}\frac{P_{out}}{P_{in}} \ \ bel$$

$$1\ bel = 10\ db$$

Therefore;

$$\text{Power gain} = 10\log_{10}\frac{P_{out}}{P_{in}}\ db$$

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;

$$\text{Voltage gain in } db = 10\log_{10}\frac{V_{out}^2/R}{V_{in}^2/R} = 20\log_{10}\frac{V_{out}}{V_{in}}$$

$$\text{Current gain in } db = 10\log_{10}\frac{I_{out}^2 R}{I_{in}^2 R} = 20\log_{10}\frac{I_{out}}{I_{in}}$$

Advantages: The following are the advantages of expressing the gain in *db*:

(i) 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.

(ii) 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. 3.5;

$$\text{Gain as number} = \frac{V_2}{V_1}\times\frac{V_3}{V_2}$$

$$\text{Gain in } db = 20\log_{10}\left(\frac{V_2}{V_1}\times\frac{V_3}{V_2}\right)$$

$$= 20\log_{10}\frac{V_2}{V_1} + 20\log_{10}\frac{V_3}{V_2}$$
$$= \text{1st stage gain in } db + \text{2nd stage gain in } db$$

However, absolute gain is obtained by multiplying the gains of individual stages. Obviously, it is easier to add than to multiply.

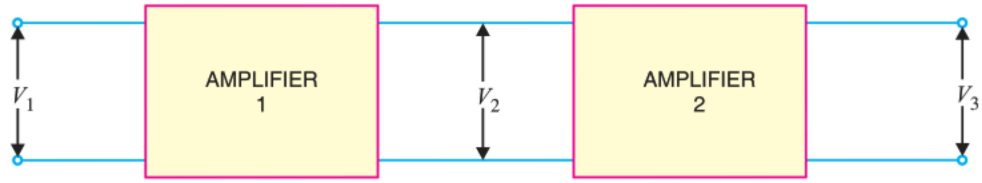

Fig. 3.5

3.4.4 Bandwidth

The range of frequency over which the voltage 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. 3.6, 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 distortion-less amplification, it is important that signal frequency range must be within the bandwidth of the amplifier.

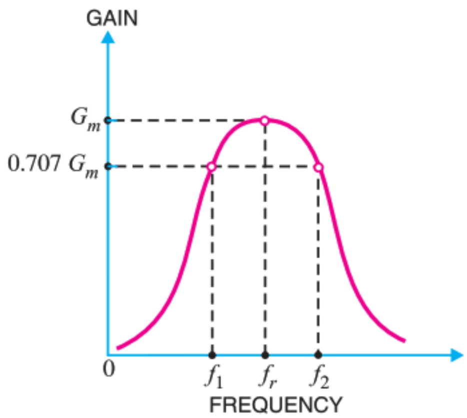

Fig. 3.6

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.

Therefore, fall in voltage gain from maximum gain;

$$= 20\log_{10} 100 - 20\log_{10} 70.7$$
$$= 20\log_{10}\frac{100}{70.7}\ db$$
$$= 20\log_{10} 1.4142\ db = 3db$$

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 (0.5) of its maximum value.

Example 3.1

Find the gain in *db* in the following cases:

(i) Voltage gain of 30

(ii) Power gain of 100

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 3.2

A multistage amplifier employs five stages each of which has a power gain of 30.

(i) 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

$$\text{Absolute gain of each stage} = 30$$
$$\text{No of stages} = 5$$

(i) ..

$$\text{Power gain of one stage in } db = 10\log_{10} 30 = 14.77$$
$$\text{Therefore, total power gain in } db = 5 \times 14.77 = \mathbf{73.85\ db}$$

(ii) …

$$\text{Resultant gain with feedback} = 73.85 - 10 = \mathbf{63.85\ db}$$

Example 3.3

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

$$\begin{aligned}\text{Total voltage gain} &= 20\log_{10} 100 + 20\log_{10} 200 + 20\log_{10} 400 \\ &= 40 + 46 + 52 \\ &= \mathbf{138\ db}\end{aligned}$$

Example 3.4

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: Output power is 1.5 W and input power is 10 mW;

$$\Longrightarrow \text{Power gain in } db = 10\log_{10}\frac{1.5\text{ W}}{10\text{ mW}} = 21.76$$

db power gain at 20 Hz: Output power is 0.3 W and input power is 10 mW;

$$\Longrightarrow \text{Power gain in } db = 10\log_{10}\frac{0.3\text{ W}}{10\text{ mW}} = 14.77$$

$$\text{Therefore, fall in gain from 2 kHz to 20 Hz} = 21.76 - 14.77 = \mathbf{6.99\ db}$$

Exercise

1. A certain amplifier has voltage gain of 15 *db*. If the input signal voltage is 0.8V, what is the output voltage?
2. An amplifier feeding a resistive load of 1 kΩ has a voltage gain of 40 *db*. If the input signal is 10 mV, find;
   (i) Output voltage
   (ii) Load power.
3. An amplifier rated at 40 W output is connected to a 10 Ω speaker.
   (i) Calculate the input power required for full power output if the power gain is *25 db*.
   (ii) Calculate the input voltage for rated output if the amplifier voltage gain is 40 *db*.
4. 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

3.5 Properties of *db* Gain

The power gain expressed as a number is called ordinary power gain. Similarly, the voltage gain expressed as a number is called ordinary voltage gain.

3.5.1 Properties of *db* Power Gain

(i) Each time the ordinary power gain increases (decreases) by a factor of 10, the *db* power gain increases (decreases) by 10 *db*.
For example, suppose the ordinary power gain increases from 100 to 1000 (i.e. by a factor of 10).

$$\text{Increse in power gain} = 10\log_{10} 1000 - 10\log_{10} 100 = 30 - 20 = 10\ db$$

(ii) Each time the ordinary power gain increases (decreases) by a factor of 2, the *db* power gain increases (decreases) by 3 *db*.
For example, suppose the power gain increases from 100 to 200 (i.e. by a factor of 2).

$$\text{Increse in power gain} = 10\log_{10} 200 - 10\log_{10} 100 = 23 - 20 = 3\ db$$

3.5.2 Properties of *db* Voltage Gain

Each time the ordinary voltage gain increases (decreases) by a factor of 10, the *db* voltage gain increases (decreases) by 10 *db*.

(i) For example, suppose the ordinary voltage gain increases from 100 to 1000 (i.e. by a factor of 10).

$$\text{Increse in voltage gain} = 20\log_{10} 1000 - 20\log_{10} 100 = 60 - 40 = 20\ db$$

(ii) Each time the ordinary voltage gain increases (decreases) by a factor of 2, the *db* voltage gain increases (decreases) by 3 *db*.
For example, suppose the voltage gain increases from 100 to 200 (i.e. by a factor of 2).

$$\text{Increse in voltage gain} = 20\log_{10} 200 - 20\log_{10} 100 = 46 - 40 = 6\ db$$

3.6 *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. 3.7 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 C_E 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 the operating point.

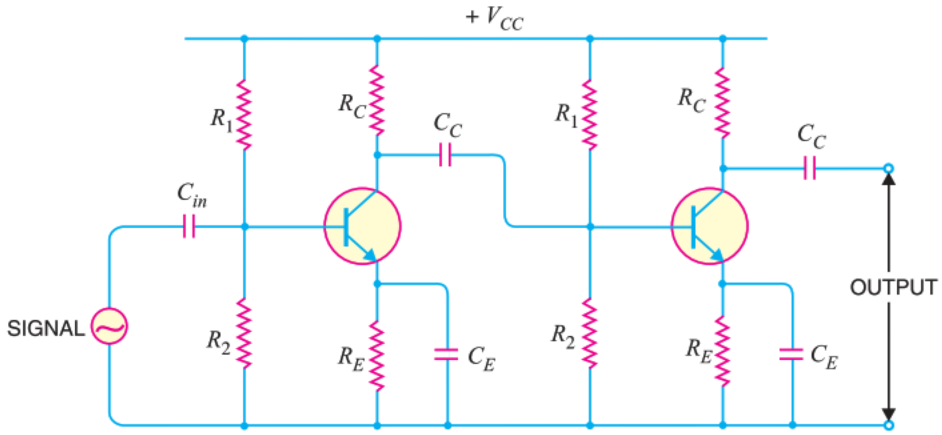

Fig. 3.7

3.6.1 Operation

When an a.c. signal is applied to the base of the first transistor, it appears in amplified form across its collector load R_C. The amplified signal developed across R_C is given to base of next stage through the 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 is considerably increased.

It may be mentioned here that total gain is less than the product of the gains of individual stages. This 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.

3.6.2 Frequency Response

Fig. 3.8 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.

(ii) 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, the 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.

(iii) 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.

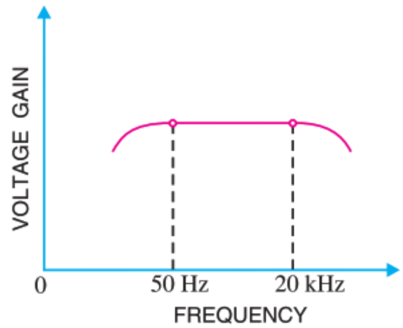

Fig. 3.8

3.6.3 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.

3.6.4 Disadvantages

(i) *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.

3.6.5 Applications

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. However, because of poor impedance matching, *RC* coupling is rarely used in the final stages.

Note: When there is an even number of cascaded stages (2, 4, 6 etc), the output signal is not inverted from the input. When the number of stages is odd (1, 3, 5 etc.), the output signal is inverted from the input.

Example 3.5

A single stage amplifier has a voltage gain of 60. The collector load $R_C = 500\ \Omega$ and the input impedance is 1 kΩ. Calculate the overall gain when two such stages are cascaded through *RC* coupling. Comment on the result.

Solution

The gain of the second stage remains 60 because it has no loading effect of any stage. However, the gain of the first stage is less than 60 due to the loading effect of the input impedance of the second stage.

Therefore; gain of the second stage $= 60$

Effective load of the first stage;

$$R_C \ = R_C \| R_{in} = \frac{500 \times 1000}{500 + 1000} = 333\ \Omega$$

$$\text{Gain of first stage} = 60 \times \frac{333}{500} = 39.96$$

$$\text{Total gain} = 60 \times 39.96 = \mathbf{2397}$$

Comment: 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 3.6

Fig. 3.9 shows a two-stage *RC* coupled amplifier. If the input resistance R_{in} of each stage is 1 kΩ, find;

(i) Voltage gain of first stage

(ii) Voltage gain of second stage

(iii) Total voltage gain

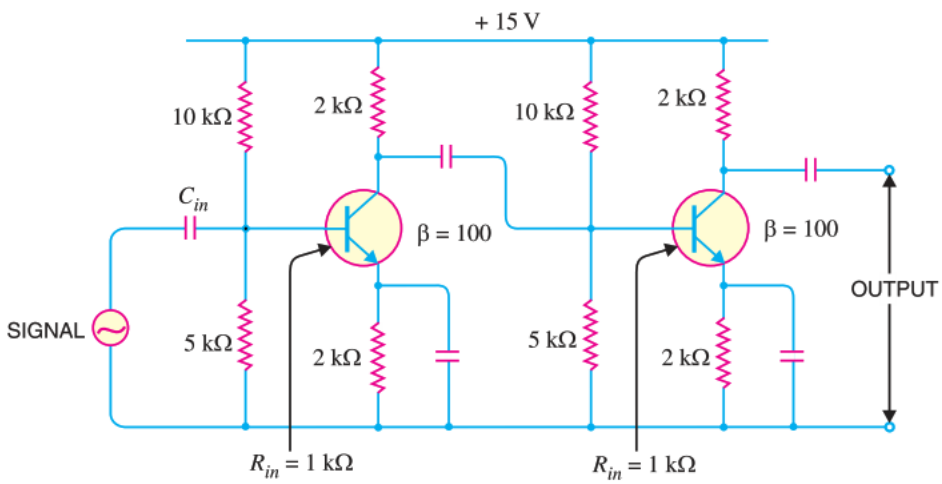

Fig. 3.9

Solution

$$R_{in} = 1\ \text{k}\Omega; \quad \beta = 100; \quad R_C = 2\ \text{k}\Omega$$

(i) Voltage gain of the first stage

The first stage has a loading of the input resistance of the second stage

$$\therefore \text{Effective load of the first stage, } R_{AC} = R_C \| R_{in} = \frac{2 \times 1}{2 + 1} = 0.67\ \text{k}\Omega$$

$$\Rightarrow \text{Voltage gain of the first stage} = \beta \times \frac{R_{AC}}{R_{in}} = 100 \times \frac{0.67}{1} = \mathbf{67}$$

(ii) Voltage gain of the second stage

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.

$$\Rightarrow \text{Voltage gain of the second stage} = \beta \times \frac{R_C}{R_{in}} = 100 \times \frac{2}{1} = \mathbf{200}$$

(iii) Total voltage gain

$$= 66 \times 200 = \mathbf{13200}$$

Exercise

A single stage amplifier has collector load $R_C = 10\ \text{k}\Omega$; input resistance $R_C = 1\ \text{k}\Omega$ and $\beta = 100$. If load $R_L = 1\ \text{k}\Omega$, find the voltage gain. Comment on the result.

3.7 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 (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)) 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 the impedance-changing properties of a transformer, the low resistance of a stage (or load) can be reflected as a high load resistance to the previous stage (the resistance on the secondary side of a transformer reflected on the primary depends upon the turn ratio of the transformer).

Transformer coupling is generally employed when the load is small. It is mostly used for power amplification. Fig. 3.10 shows two stages of a 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.

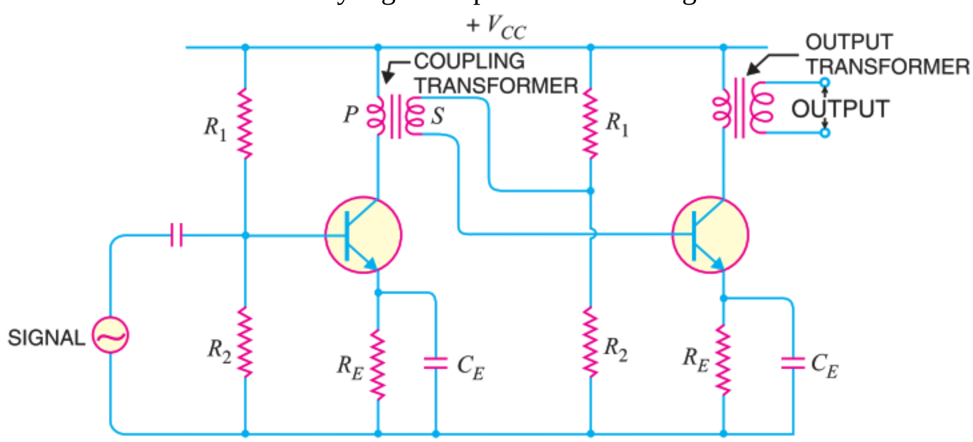

Fig. 3.10

3.7.1 Operation

When an a.c. signal is applied to the base of the 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. 3.10. The second stage renders amplification in an exactly similar manner.

3.7.2 Frequency Response

The frequency response of a transformer coupled amplifier is shown in Fig. 3.11. 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 signal 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.

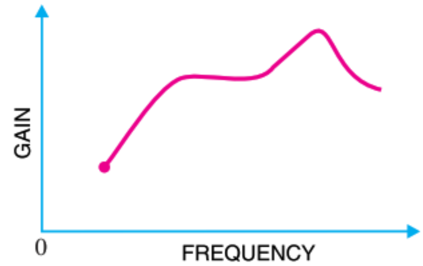

Fig. 3.11

3.7.3 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.

3.7.4 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 (due to the hundreds of turns of primary and secondary. These turns will multiply an induced e.m.f. from nearby power wiring).

3.7.5 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 equal to the output impedance of transistor.

Fig. 3.12 illustrates the impedance matching by a stepdown transformer. The output device (e.g. speaker) connected to the secondary has a small resistance R_L. The load R_L' appearing on the primary side of the transformer 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 resistance 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 favorable value at the collector of transistor by using appropriate turn ratio.

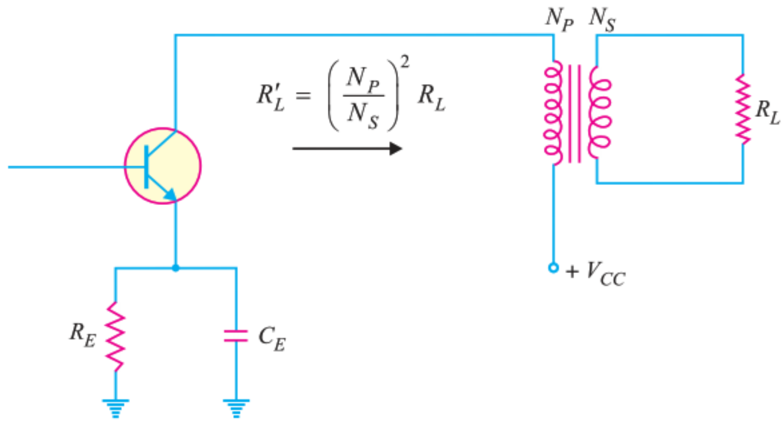

Fig. 3.12

Example 3.7

A transformer coupling is used in the final stage of a multistage amplifier. If the output impedance of transistor is 1 kΩ and the speaker has a resistance of 10 Ω, 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.;

$$\text{Primary impedance}, R_L' = 1\ \text{k}\Omega = 1000\ \Omega$$

$$\text{Load impedance}, R_L = 10\ \Omega$$

$$\text{Let the turn ratio of the transformer be } n = \frac{N_p}{N_S}$$

$$\text{But primary impedance}, R_L' = \left(\frac{N_P}{N_S}\right)^2 R_L$$

$$\therefore n^2 = \left(\frac{N_P}{N_S}\right)^2 = \frac{R_L'}{R_L}$$

$$\Rightarrow n = \frac{N_P}{N_S} = \sqrt{\frac{R_L'}{R_L}} = \sqrt{\frac{1000}{10}} = \mathbf{10}$$

A step-down transformer with turn ratio 10:1 is required.

Exercise

1. Determine the necessary transformer turn ratio for transferring maximum power to a 16 Ω 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 10 V r.m.s.
2. The output resistance of the transistor shown in Fig. 3.13 is 3 kΩ. 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.

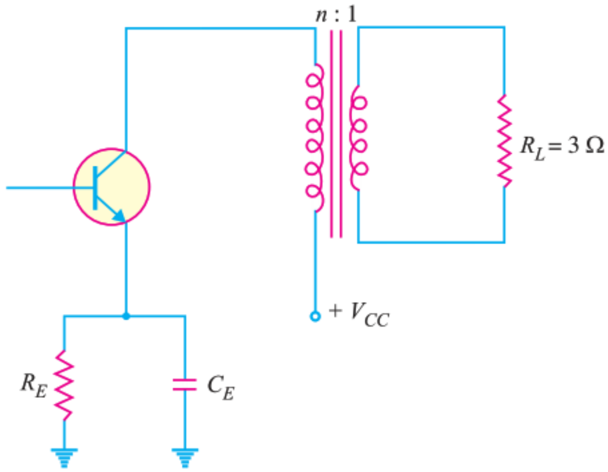

Fig. 3.13

3.8 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*.

3.8.1 Operation

Fig. 3.14 shows the circuit of a three-stage direct-coupled amplifier. It uses complementary transistors. 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.

A 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 the weak signal.

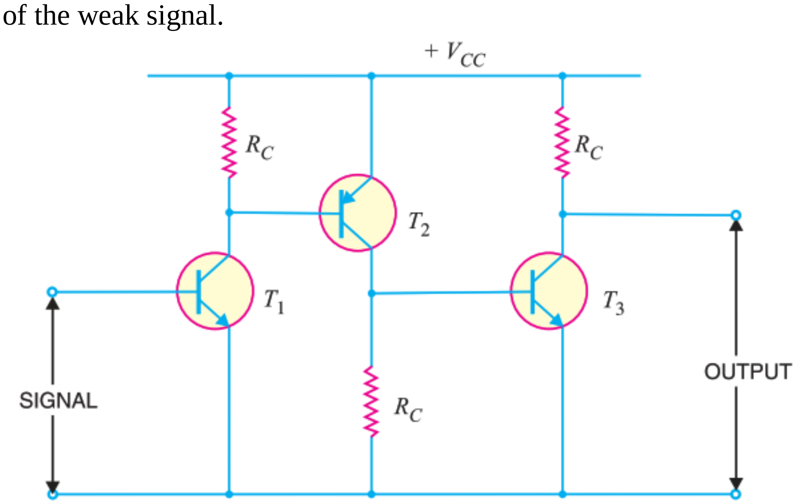

Fig. 3.14

3.8.2 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.

3.8.3 Disadvantages

(i) It cannot be used for amplifying high frequencies.
(ii) The operating point is shifted due to temperature variations.

Example 3.8

Fig. 3.15 shows a direct coupled two-stage amplifier. Determine;

(i) d.c. voltages for both stages
(ii) voltage gain of each stage
(iii) overall voltage gain.

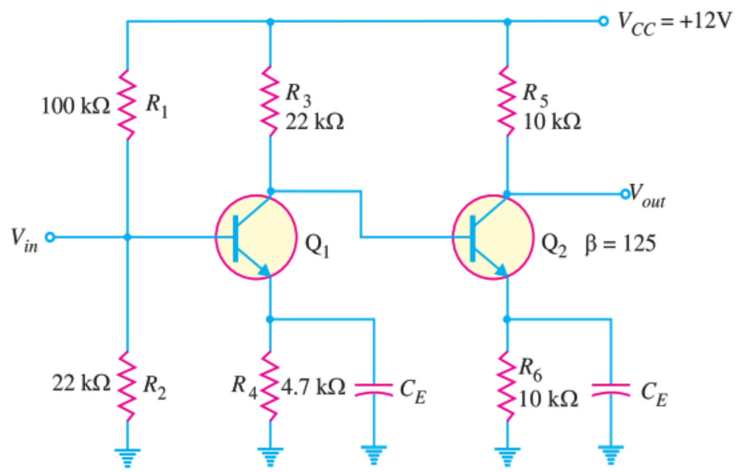

Fig. 3.15

Solution

(i) D.C. Voltages

First stage

$$\text{D.C. current thro' } R_1 \text{ and } R_2 = \frac{V_{CC}}{R_1 + R_2} = \frac{12\text{ V}}{(100\ + 22)\text{ k}\Omega} = 0.098\text{ mA}$$

$$\text{D.C. voltage across } R_2 = 0.098\text{ mA} \times 22\text{ k}\Omega = \mathbf{2.16\ V}$$

This is the d.c. voltage at the base of transistor Q_1.

$$\text{D.C. voltage at the emitter}, V_{E1} = 2.16\text{ V} - V_{BE} = 2.16\text{ V} - 0.7\text{ V} = \mathbf{1.46\ V}$$

$$\text{D.C. emitter current}, I_{E1} = \frac{V_{E1}}{R_4} = \frac{1.46\text{ V}}{4.7\text{ k}\Omega} = 0.31\text{ mA}$$

$$\text{D.C. collector current}, I_{c1} = 0.31\text{ mA} \qquad (\because I_{C1} \approx I_{E1})$$

$$\text{D.C. voltage at collector}, V_{c1} = V_{CC} - I_{C1}R_3 = 12 - (0.31\text{ mA} \times 22\text{ k}\Omega) = \mathbf{5.81\ V}$$

Second stage

$$\text{D.C. base voltage} = V_{c2} = \mathbf{5.81\ V}$$

$$\text{D.C. emitter voltage}, V_{E2} = 5.18\text{ V} - V_{BE} = 5.18\text{ V} - 0.7\text{ V} = \mathbf{4.48\ V}$$

$$\text{D.C. emitter current}, I_{E2} = \frac{V_{E2}}{R_6} = \frac{4.48\text{ V}}{10\text{ k}\Omega} = 0.448\text{ mA}$$

$$\text{D.C. collector current}, I_{c2} = 0.448\text{ mA} \qquad (\because I_{C2} \approx I_{E2})$$

$$\text{D.C. voltage at collector}, V_{c2} = V_{CC} - I_{C2}R_5 = 12 - (0.448\text{ mA} \times 10\text{ k}\Omega) = \mathbf{7.52\ V}$$

(ii) Voltage gain

To find voltage gain, we shall use the standard formula: total a.c. collector load divided by total a.c. emitter resistance.

First stage

$$r'_{e1} = \frac{25\text{ mV}}{I_{E1}} = \frac{25\text{ mV}}{0.31\text{ mA}} = 80.6\ \Omega$$

Input impedance Z_{in} of the second stage is given by;

$$Z_{in} = \beta r'_{e2}$$

$$\text{Here, } r'_{e2} = \frac{25\text{ mV}}{I_{E1}} = \frac{25\text{ mV}}{0.448\text{ mA}} = 55.8\ \Omega$$

$$\therefore Z_{in} = \beta r'_{e2} = 125 \times 55.8\ \Omega \approx 7000\ \Omega = 7\text{ k}\Omega$$

$$\text{Total collector load, } R_{AC} = R_3 \| Z_{in} = 22\text{ k}\Omega \| 7\text{ k}\Omega = 5.31\text{ k}\Omega$$

$$\therefore \text{Voltage gain of first stage, } A_{v1} = \frac{R_{AC}}{r'_{e1}} = \frac{5.31\text{ k}\Omega}{80.6\ \Omega} = \mathbf{66}$$

Second stage

There is no loading effect of any subsequent stage. Therefore, total a.c. collector load, $R_{AC} = R_5 = 7\text{ k}\Omega$.

$$\therefore \text{Voltage gain of second stage, } A_{v2} = \frac{R_5}{r'_{e2}} = \frac{10\text{ k}\Omega}{55.8\ \Omega} = \mathbf{179}$$

(iii) Overall voltage gain

$$A_v = A_{v1} \times A_{v2} = 66 \times 179 = \mathbf{11,814}$$

3.9 Comparison of Different Types of Coupling

S. No	Particular	*RC* 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

3.10 Difference between Transistors 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 respect:

(i) An electron tube is a voltage driven device while a transistor is a current operated device.

(ii) The input and output impedances of 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 a tube amplifier.

(v) The capacitances of the components of a transistor amplifier are usually larger than the corresponding components of the tube amplifier.