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 $mA \times 5K\Omega$ = 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 10μA *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.

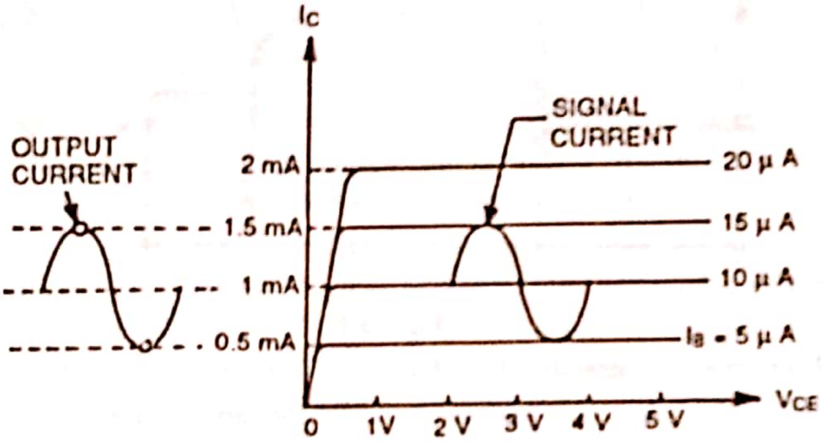


Fig. 12.2

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 1mA. 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 15μA and the corresponding collector current is 1.5 mA. In the second half-cycle peak, the base current is reduced to 5μA and the corresponding collector current is 0.5 mA. For other values of the signal, the collector current is in between these values *i.e.* 1.5 mA and 0.5 mA.

It is clear from Fig. 12.2 that 10μA base current variations result in 1mA (1,000 μA) collector current variations *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 :

(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 by-pass the a.c. signal. The designer intentionally selects capacitors that are large enough to appear as *short*

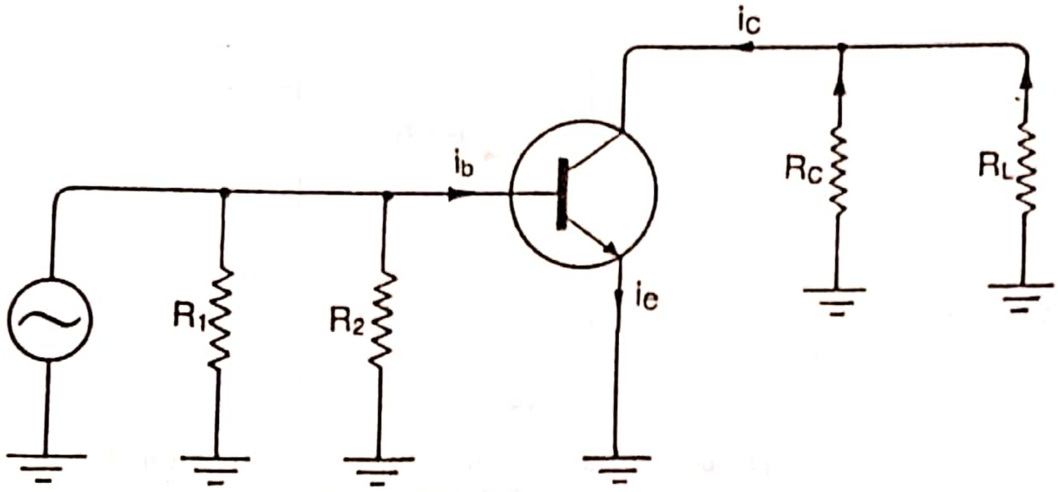


Fig. 12.9

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 shown in Fig. 12.9. We can easily calculate the a.c. currents and voltages from this circuit.

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. Because a voltage source looks like a short, it will bypass all other resistances except R_C

* 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.

and R_E which will appear in series. Consequently, transistor amplifier will see a d.c load of R_C + R_E *i.e.*

$$\text{d.c. load} = R_C + R_E$$

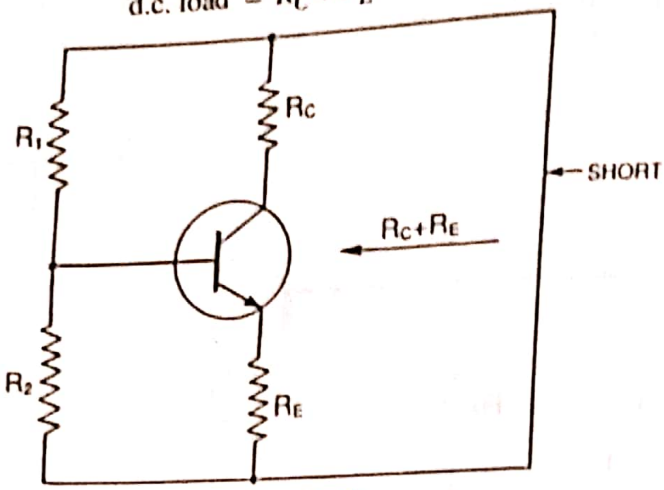


Fig. 12.10

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.*

$$\text{a.c. load,} \qquad R_{AC} = R_C \parallel R_L = \frac{R_C R_L}{R_C + R_L}$$

(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.* $I_C = 0$.

$\therefore$ Maximum $V_{CE} = V_{CC}$

The maximum collector current will flow when $V_{CE} = 0$.

$$\therefore \quad \text{Maximum} \quad I_C = \frac{V_{CC}}{R_C + R_E}$$

(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

$\therefore$ 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

$$= V_{CE} / R_{AC}$$

$\therefore$ Total maximum collector current

$$= I_C + V_{CE} / R_{AC}$$

* For faithful amplification

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.

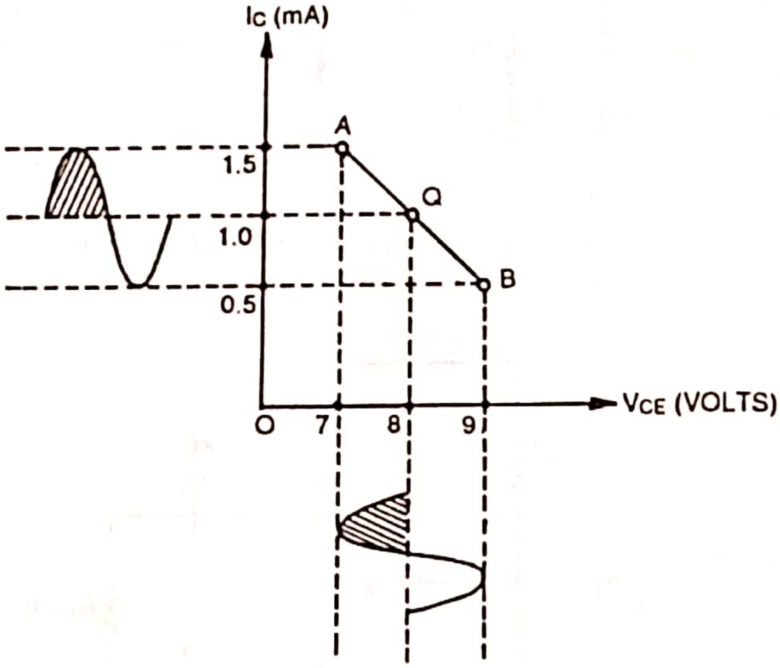


Fig. 12.17

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 ;

$$\text{a.c. load } R_{AC} = R_C \parallel R_L = \frac{R_C \times R_L}{R_C + R_L}$$

Output voltage, $V_{out} = i_c R_{AC}$

Input voltage, $V_{in} = i_b R_{in}$

∴ 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;

$$A_P = \frac{i_c^2 R_{AC}}{i_b^2 R_{in}} = \beta^2 \times \frac{R_{AC}}{R_{in}}$$

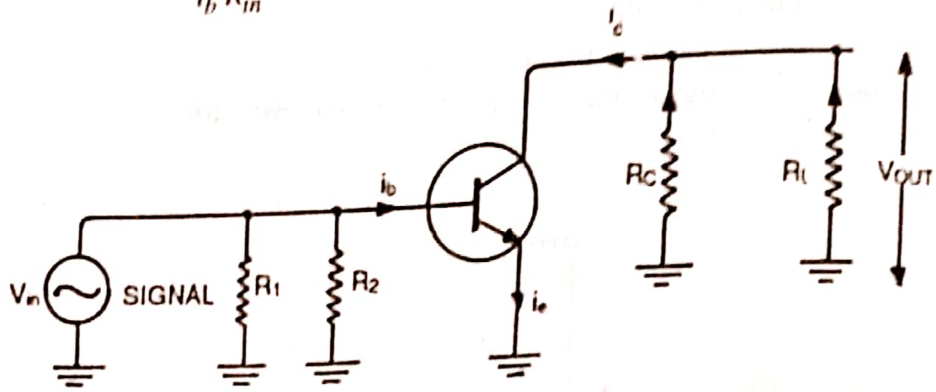


Fig. 12.18

Example 12.6. *In the circuit shown in Fig. 12.19, find the voltage gain. Given that* β = *60 and input resistance* R_{in} = *1KΩ.*

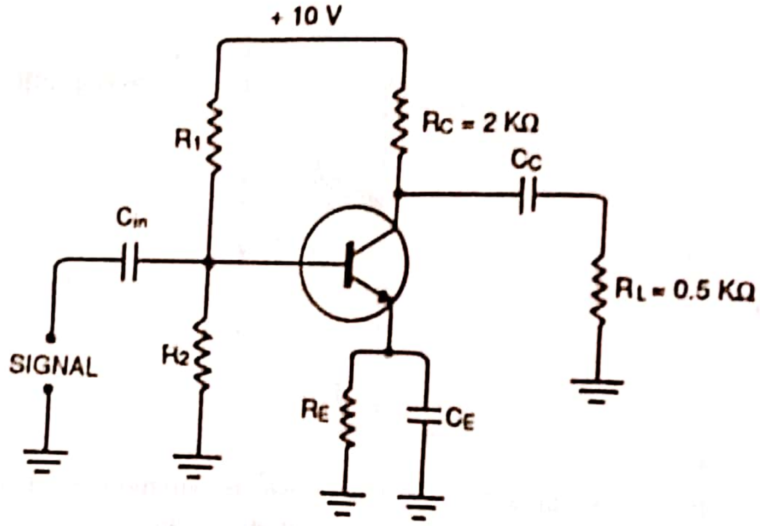


Fig. 12.19

Solution

So far as voltage gain of the circuit is concerned, we need only R_{AC}, β and R_{in}.

Effective load, $R_{AC} = R_C \parallel R_L$

$$= \frac{R_C \times R_L}{R_C + R_L} = \frac{2 \times 0.5}{2 + 0.5} = 0.4 \text{ K}\Omega$$

$$\text{Voltage gain} = \beta \times \frac{R_{AC}}{R_{in}} = \frac{60 \times 0.4 \text{ K}\Omega}{1 \text{ K}\Omega} = \mathbf{24}$$

Example 12.7. *In the circuit shown in Fig. 12.19 if* $R_C = 10K\Omega$, $R_L = 10K\Omega$, $R_{in} = 2.5K\Omega$, $\beta = 100$, *find the output voltage for an input voltage of 1mV r.m.s.*

Solution

$$\text{Effective load, } R_{AC} = \frac{R_C \times R_L}{R_C + R_L} = \frac{10 \times 10}{10 + 10} = 5K\Omega$$

$$\text{Voltage gain} = \beta \times \frac{R_{AC}}{R_{in}} = 100 \times \frac{5\ \text{K}\Omega}{2.5\ \text{K}\Omega} = 200$$

or

$$\frac{V_{out}}{V_{in}} = 200$$

$$\therefore \quad V_{out} = 200 \times V_{in} = 200 \times 1\ mV = \mathbf{200\ mV}$$

Example 12.8. *In a transistor amplifier, when the signal changes by 0.02V, the base current changes by 10μA and collector current by 1mA. If collector load R_C = 5KΩ and R_L = 10KΩ, find: (i) current gain (ii) input impedance (iii) a.c. load (iv) voltage gain (v) power gain.*

Solution

$\Delta I_B = 10\mu A$, $\Delta I_C = 1 mA$, $\Delta V_{BE} = 0.02V$, $R_C = 5K\Omega$, $R_L = 10K\Omega$

(*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.*

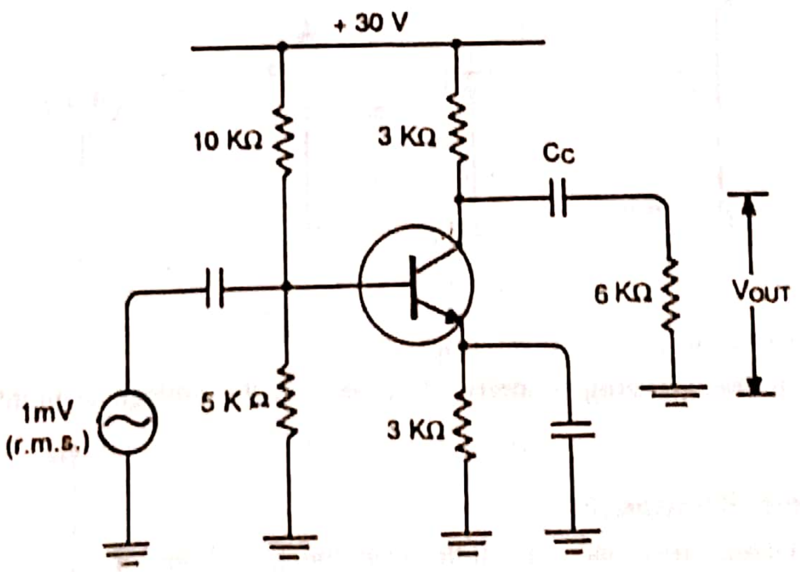


Fig. 12.20

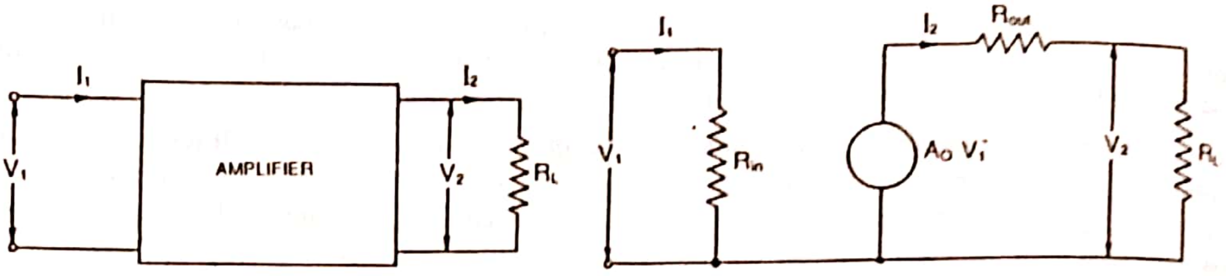
I_2 = output current

V_2 = output voltage across load R_L

R_{out} = output resistance of the amplifier

R_L = load resistance

A_V = voltage gain when load R_L is connected



(*i*) (*ii*)

Fig. 12.28

Note that capability of the amplifier to produce voltage gain is represented by the voltage generator A_oV_1. The voltage gain of the loaded amplifier is A_v. Clearly, A_v will be less than A_o 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.

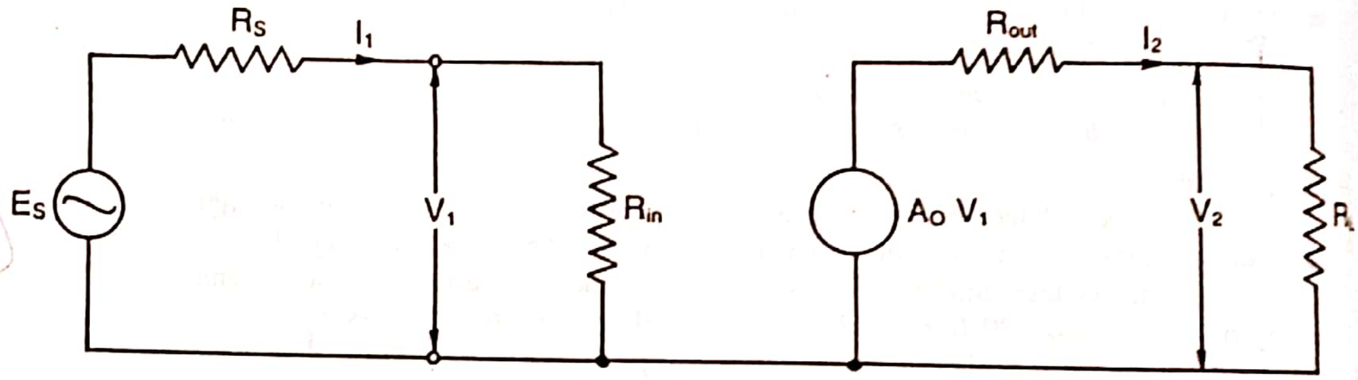


Fig. 12.29

Referring to Fig. 12.29, we have,

$$I_1 = \frac{E_s}{R_s + R_{in}}$$

$$\therefore \quad V_1 = I_1 R_{in} = \frac{E_s R_{in}}{R_s + R_{in}}$$

$$I_2 = \frac{A_o V_1}{R_{out} + R_L} \quad \text{...(i)}$$

$$= \frac{A_0 I_1 R_{in}}{R_{out} + R_L} \quad ...(ii)$$

$$\therefore \quad V_2 = I_2 R_L = \frac{A_o V_1 R_L}{R_{out} + R_L} \quad ...(iii)$$

$$\text{Voltage gain, } A_v = \frac{V_2}{V_1} = \frac{A_o R_L}{R_{out} + R_L}$$

$$\text{Current gain, } A_i = \frac{I_2}{I_1} = \frac{A_o R_{in}}{R_{out} + R_L}$$

$$\text{Power gain, } A_p = \frac{I_2^2 R_L}{I_1^2 R_{in}} = \frac{(I_2 R_L) I_2}{(I_1 R_{in}) I_1}$$

$$= \frac{V_2 I_2}{V_1 I_1} = \left(\frac{V_2}{V_1}\right) \times \left(\frac{I_2}{I_1}\right)$$

$$= A_v \times A_i$$

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 2KΩ 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.*

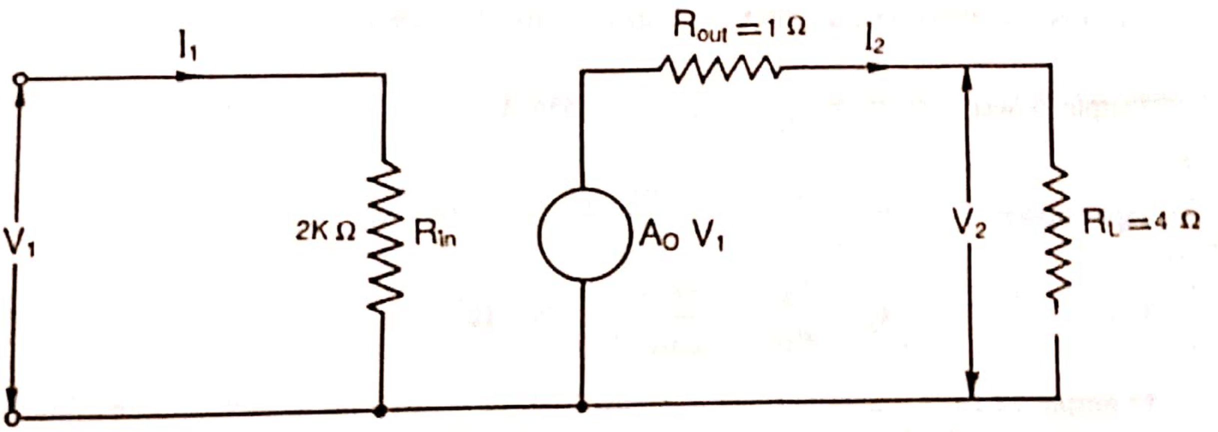


Fig. 12.30

Solution

Fig. 12.30 shows the equivalent circuit of the amplifier. Here $A_o = 1000$.

$$\frac{I_2}{I_1} = \frac{A_o R_{in}}{R_{out} + R_L} \quad \text{[See Art. 12.15]}$$

$$= \frac{1000 \times 2000}{1 + 4} = 4 \times 10^5$$

$$\therefore \quad I_1 = \frac{I_2}{4 \times 10^5} = \frac{0.5}{4 \times 10^5} = 1.25 \times 10^{-6} \text{ A}$$

26

HYBRID PARAMETERS

Introduction

In order to predict the behaviour of a small - signal transistor amplifier, it is important to know its operating characteristics *e.g.*, input impedance, output impedance, voltage gain *etc.* In the text so far, these characteristics were determined by using *β and circuit resistance values. This method of analysis has two principal advantages. Firstly, the values of circuit components are readily available and secondly the procedure followed is easily understood. However, the major drawback of this method is that accurate results cannot be obtained. It is because the input and output circuits of a transistor amplifier are not completely independent. For example, output current is affected by the value of load resistance rather than being constant at the value βI_b. Similarly, output voltage has an effect on the input circuit so that changes in the output cause changes in the input.

One of the methods that takes into account all the effects in a transistor amplifier is the hybrid parameter approach. In this method, four parameters (one measured in ohm, one in mho, two dimensionless) of a transistor are measured experimentally. These are called hybrid or *h* parameters of the transistor. Once these parameters for a transistor are known, formulas can be developed for input impedance, voltage gain *etc.* in terms of *h* parameters. There are two main reasons for using *h* parameter method in describing the characteristics of a transistor. Firstly, it yields exact results because the inter-effects of input and output circuits are taken into account. Secondly, these parameters can be measured very easily. To begin with, we shall apply *h* parameter approach to general circuits and then extend it to transistor amplifiers.

26.1 Hybrid Parameters

*Every **linear circuit having input and output terminals can be analysed by four parameters (one measured in ohm, one in mho and two dimensionless) called* **hybrid** *or h* **Parameters.**

Hybrid means "mixed". Since these parameters have mixed dimensions, they are called

* Since transistor is generally connected in *CE* arrangement, current amplification factor β is mentioned here.

** A linear circuit is one in which resistances, inductances and capacitances remain fixed when voltage across them changes.

hybrid parameters. Consider a linear circuit shown in Fig. 26.1. This circuit has input voltage and current labeled v_1 and i_1. This circuit also has output voltage and current labelled v_2 and i_2. Note that both input and output currents (i_1 and i_2) are assumed to flow *into* the box ; input and output voltages (v_1 and v_2) are assumed *positive* from the upper to the lower terminals. These are standard conventions and do not necessarily correspond to the actual directions and polarities. When we analyse circuits in which the voltages are of opposite polarity or where the currents flow out of the box, we simply treat these voltages and currents as negative quantities.

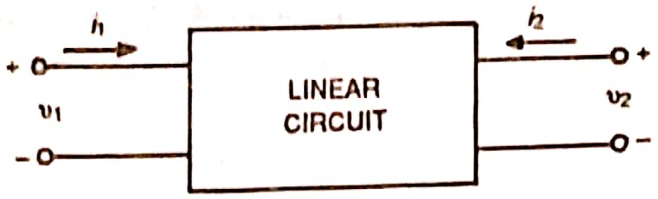


Fig. 26.1

It can be proved by advanced circuit theory that voltages and currents in Fig. 26.1 can be related by the following sets of equations :

$$v_1 = h_{11}\, i_1 + h_{12}\, v_2 \quad \text{. . . (i)}$$

$$i_2 = h_{21}\, i_1 + h_{22}\, v_2 \quad \text{. . . (ii)}$$

In these equations, the *hs* are fixed constants for a given circuit and are called *h* parameters. Once these parameters are known, we can use equations *(i)* and *(ii)* to find the voltages and currents in the circuit. If we look at eq.*(i)*, it is clear that *h_{11} has the dimension of ohm and h_{12} is dimensionless. Similarly, from eq. *(ii)*, h_{21} is dimensionless and h_{22} has the dimension of mho. The following points may be noted about *h* parameters :

(i) Every linear circuit has four *h* parameters ; one having dimension of ohm, one having dimension of mho and two dimensionless.

(ii) The *h* parameters of a given circuit are constant. If we change the circuit, *h* parameters would also change.

(iii) Suppose that in a particular linear circuit, voltages and currents are related as under:

$$v_1 = 10 i_1 + 6 v_2$$

$$i_2 = 4 i_1 + 3 v_2$$

Here we can say that the circuit has *h* parameters given by $h_{11} = 10\Omega$; $h_{12} = 6$; $h_{21} = 4$ and $h_{22} = 3\mho$

26.2 Determination of h Parameters

The major reason for the use of *h* parameters is the relative ease with which they can be measured. The h parameters of a circuit shown in Fig. 26.1 can be found out as under :

(i) If we short-circuit the output terminals (See Fig. 26.2), we can say that output voltage $v_2 = 0$. Putting $v_2 = 0$ in equations *(i)* and *(ii)*, we get,

$$v_1 = h_{11} i_1 + h_{12} \times 0$$

* The two parts on the R.H.S. of eq. (i) must have the unit of voltage. Since current (amperes) must be multiplied by resistance (ohms) to get voltage (volts), h_{11} should have the dimension of resistance *i.e.* ohms.

$$i_2 = h_{21} i_1 + h_{22} \times 0$$

$$\therefore \quad h_{11} = \frac{v_1}{i_1} \quad \text{for } v_2 = 0 \text{ i.e. output shorted}$$

and $$h_{21} = \frac{i_2}{i_1} \quad \text{for } v_2 = 0 \text{ i.e. output shorted}$$

Let us now turn to the physical meaning of h_{11} and h_{21}. Since h_{11} is a ratio of voltage and current (*i.e.* v_1/i_1), it is an impedance and is called *"*input impedance with output shorted*". Similarly, h_{21} is the ratio of output and input current (*i.e.*, i_2/i_1), it will be dimensionless and is called "*current gain with output shorted*".

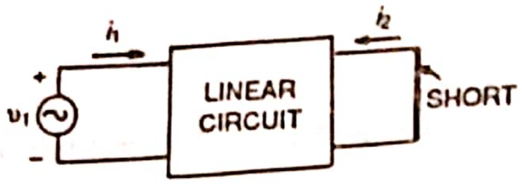


Fig. 26.2

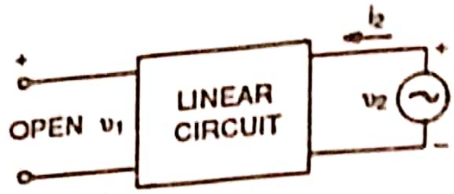


Fig. 26.3

(*ii*) The other two *h* parameters (*viz* h_{12} and h_{22}) can be found by making $i_1 = 0$. This can be done by the arrangement shown in Fig. 26.3. Here, we drive the output terminals with voltage v_2, keeping the input terminals open. With this set up, $i_1 = 0$ and the equations become:

$$v_1 = h_{11} \times 0 + h_{12} v_2$$

$$i_2 = h_{21} \times 0 + h_{22} v_2$$

$$\therefore \quad h_{12} = \frac{v_1}{v_2} \quad \text{for } i_1 = 0 \text{ i.e. input open}$$

and $$h_{22} = \frac{i_2}{v_2} \quad \text{for } i_1 = 0 \text{ i.e. input open}$$

Since h_{12} is a ratio of input and output voltages (*i.e.* v_1/v_2), it is dimensionless and is called "*voltage feedback ratio with input terminals open*". Similarly, h_{22} is a ratio of output current and output voltage (*i.e.* i_2/v_2), it will be admittance and is called *output admittance with input terminals open*.

Example. 26.1. *Find the h parameters of the circuit shown in Fig. 26.4 (i).*

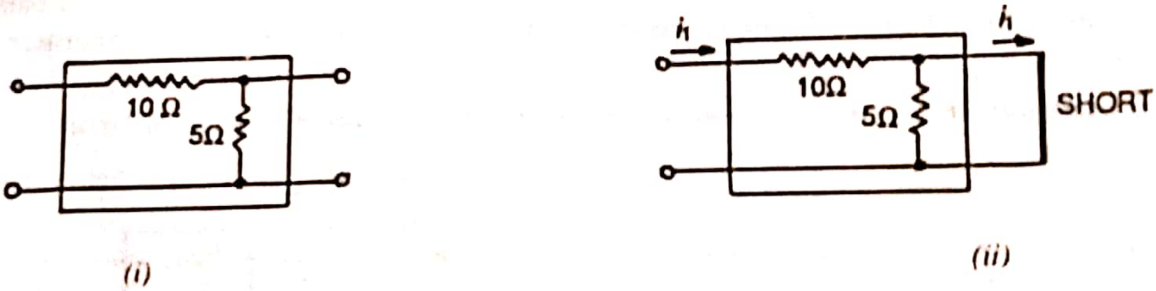


Fig. 26.4

* Note that v_1 is the input voltage and i_1 is the input current. Hence v_1/i_1 is given the name input impedance.

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 5μA and $\beta = 100$. This means that input current varies by 5μA both above and below a 10 μA dc level. At any instant, the output current will be 100 times the input current at that instant. Thus when the input current is 10μA, output current is $i_C = 100 \times 10\ \mu A = 1 mA$. However, when the input current is 15μA, 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.

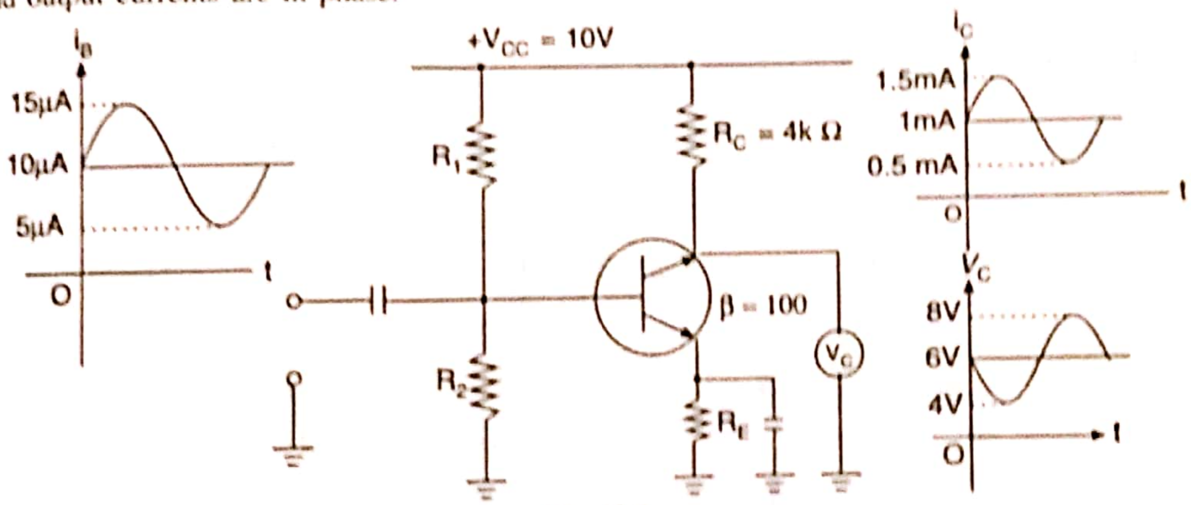


Fig. 12.6

The output voltage, $V_C = V_{CC} - i_C R_C$

(*i*) When signal current is zero (*i.e.*, in the absence of signal), $i_C = 1mA$.

$\therefore \quad V_C = V_{CC} - i_C R_C = 10V - 1mA \times 4k\Omega = 6V$

(*ii*) When signal reaches positive peak value, $i_C = 1.5\ mA$

$\therefore \quad V_C = V_{CC} - i_C R_C = 10V - 1.5mA \times 4k\Omega = 4V$

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 as shown in Fig. 12.6.

(*iii*) When signal reaches negative peak, $i_C = 0.5\ mA$

$\therefore \quad V_C = V_{CC} - i_C R_C = 10V - 0.5mA \times 4k\Omega = 8V$

Note that as i_C decreases from 1.5 mA to 0.5 mA, V_C increases from 4V to 8V. Clearly, output voltage is 180° out of phase from the input. The following points may be noted carefully about *CE* amplifier :