36.3 HYBRID EQUIVALENT CIRCUIT OF COMMON EMITTER AMPLIFIER

Fig. 36.7 shows the common-emitter *NPN* transistor amplifier circuit. R_g is the output resistance of input signal and R_L is the load resistance.

The general *h*-parameter expressions become,

$$V_i = V_{be} = h_{ie} I_b + h_{re} V_o \quad ...(1)$$

$$I_c = h_{fe} I_b + h_{0e} V_0 \quad ...(2)$$

where $V_0 = V_{ce}$.

From Eq. (1), we get

$$I_b = \frac{V_i - h_{re} V_o}{h_{ie}} \quad ...(3)$$

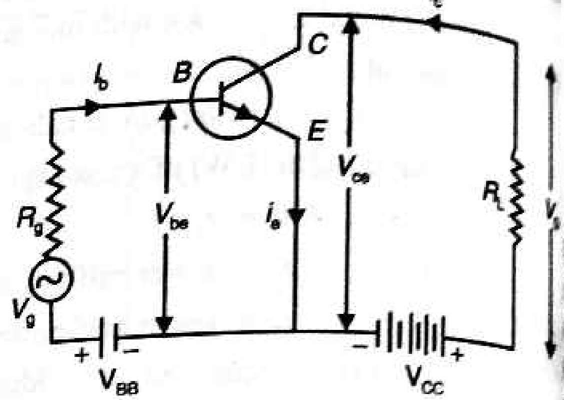

Fig. 36.7

The d.c. voltage of the collector with respect to the emitter is given by

$$V_{ce} = V_{cc} - I_c R_L$$

$$\therefore \quad dV_{ce} = -R_L \, dI_c \qquad (\because V_{cc} \text{ is constant})$$

or

$$V_{ce} = -R_L \, i_c$$

In terms of usual notations, we can write

$$V_{ce} = -R_L I_c$$

or

$$V_0 = -R_L I_c$$

Substituting the value of V_0 in Eq. (2), we have

$$I_c = h_{fe} I_b - h_{0e} R_L I_c$$

or

$$h_{fe} I_b = h_{0e} R_L I_c + I_c$$

$$= \frac{I_c R_L}{1/h_{0e}} + \frac{I_C R_L}{R_L} \quad ...(4)$$

Equation (3) indicates that the base-emitter circuit is equivalent to a.c. voltage source of $h_{re} V_0$ which opposes the a.c. input voltage V_i and is connected in series with the input resistance h_{ie}.

Equation (4) indicates that the collector-emitter circuit is equivalent to current source which supplies a current $h_{fe} I_b$ and in parallel of which are connected the output resistance $1/h_{0e}$ and load resistance R_L.

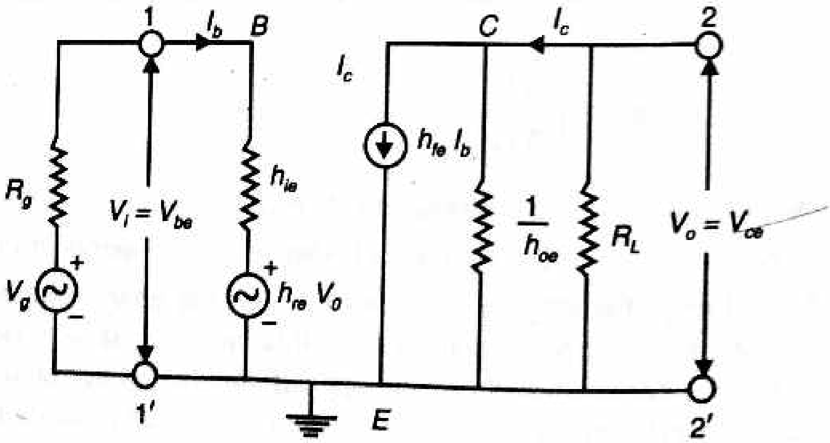

Fig. 36.8

Accordingly, the equivalent circuit is drawn in Fig. 36.8. Here the a.c. voltage source $h_{re} V_0$ which acts in opposition to the input signal V_i, represents the 'feedback' of the output voltage to the input circuit. The current source of magnitude $h_{fe} I_b$ may be looked as if the input current I_b is amplified and appears as $h_{fe} I_b$ in the output circuit. Thus $h_{fe} = \beta$, the current amplification factor.

36.3.1. Analysis of a Transistor CE Amplifier using h-parameters

Figure 36.8 shows the h-parameters equivalent circuit of a common emitter transistor amplifier.

Here,

$$h_{ie} = \text{input impedance,}$$
$$h_{0e} = \text{output admittance,}$$
$$h_{fe} = \text{forward current gain,}$$
$$h_{re} = \text{reverse voltage transfer ratio of the transistor.}$$

The signal source V_g is across the input port along with its source impedance R_g. The load resistance R_L appears across the output port. V_i and V_0 are the input and output signals respectively. The input and output currents are taken to be positive, while flowing inward. This circuit is an *a.c.* equivalent circuit and *d.c.* values do not appear in the circuit. I_b and I_c are the input and output currents, with the presence of the source and load.

We will now derive expressions for current gain, voltage gain, input impedance, output impedance and power gain.

(*i*) **Current Gain.** Let Z be the equivalent impedance of $1/h_{0e}$ and R_L in parallel. Then,

$$\frac{1}{Z} = 1/\frac{1}{h_{0e}} + \frac{1}{R_L} = h_{0e} + \frac{1}{R_L}$$

or

$$Z = \frac{R_L}{1 + h_{0e} R_L}$$

Voltage across R_L = voltage across Z

or

$$I_c R_L = h_{fe} I_b (Z) = h_{fe} I_b \left(\frac{R_L}{1 + h_{0e} R_L}\right)$$

or

$$\frac{I_c}{I_b} = \frac{h_{fe}}{1 + h_{0e} R_L}$$

$$\text{Current Gain } A_{ie} = \frac{\text{Output Current}}{\text{Input Current}}$$

$$\therefore \quad A_{ie} = \frac{I_c}{I_b} = \frac{h_{fe}}{1 + h_{0e} R_L}. \quad \text{...(1)}$$

(*ii*) **Input impedance.** The input impedance Z_{ie} of the transistor is the impedance at the input terminals 1 and 1′.

$$\text{Input impedance } Z_{ie} = \frac{\text{Input Voltage}}{\text{Input Current}} = \frac{V_i}{I_b}$$

But

$$V_i = h_{ie} I_b + h_{re} V_0$$
$$= h_{ie} I_b + h_{re}(-I_c R_L) \qquad (\because V_0 = -I_c R_L)$$

$$Z_{ie} = \frac{V_i}{I_b} = h_{ie} - h_{re} R_L \left(\frac{I_c}{I_b}\right)$$

$$\therefore \quad Z_{ie} = h_{ie} - h_{re} R_L A_{ie} = h_{ie} - \frac{h_{re} \cdot h_{fe} \cdot R_L}{(1 + h_{0e} \cdot R_L)} \quad \text{...(2)}$$

***(iii)* Voltage gain.**

$$\text{Voltage gain } A_{ve} = \frac{\text{Output Voltage}(V_0)}{\text{Input Voltage}(V_i)}$$

But

$$V_0 = -I_c R_L$$

$$A_{ve} = -\frac{I_c R_L}{V_i} = -\left(\frac{I_c}{I_b}\right)\left(\frac{I_b}{V_i}\right) R_L$$

$$= -A_{ie}\left(\frac{1}{Z_{ie}}\right) R_L = -\frac{A_{ie} R_L}{Z_i} \quad ...(3)$$

Substituting the value of $Z_i = Z_{ie} = h_{ie} - h_{re} R_L A_{ie}$ from Eq. (2),

$$A_{ve} = -\frac{A_{ie} R_L}{h_{ie} - h_{re} R_L A_{ie}} = \frac{R_L}{\dfrac{h_{ie}}{A_{ie}} - h_{re} R_L}$$

Substituting

$$A_{ie} = \frac{h_{fe}}{1 + h_{0e} R_L} \text{ from Eq. (1), we get}$$

$$A_{ve} = -\frac{R_L}{\dfrac{h_{ie}(1 + h_{0e} R_L)}{h_{fe}} - h_{re} R_L}$$

$$= -\frac{h_{fe} R_L}{h_{ie}(1 + h_{0e} R_L) - h_{fe} h_{re} R_L}$$

$$= -\frac{h_{fe} R_L}{h_{ie} + (h_{ie} h_{0e} - h_{fe} h_{re}) R_L}$$

$$= -\frac{h_{fe} R_L}{h_{ie} + R_L \Delta h} \quad ...(4)$$

where $\Delta h = h_{ie} h_{0e} - h_{fe} h_{re}$.

The negative sign shows that the input and the output are 180° out of phase.

***(iv)* Output impedance.** The output impedance Z_0 of an amplifier is defined as the ratio of the output voltage to the output current with the input signal generator V_g reduced to zero and replaced by its internal resistance R_g and an a.c. voltage source V_0 (rms) applied to the output terminals as shown in Fig. 36.9. Thus

$$Z_{0e} = \frac{V_0}{I_c}$$

where I_c is the current sent by the applied source.

Since the current through the output resistance $1/h_{0e}$ is $I_c - h_{fe} I_b$, the output voltage V_0 is given by

$$V_0 = (I_c - h_{fe} I_b)\frac{1}{h_{0e}}$$

or

$$h_{0e} V_0 = I_c - h_{fe} I_b \quad ...(5)$$

But the base current I_b is given by

$$I_b = -\frac{h_{re} V_0}{h_{ie} + R_g}$$

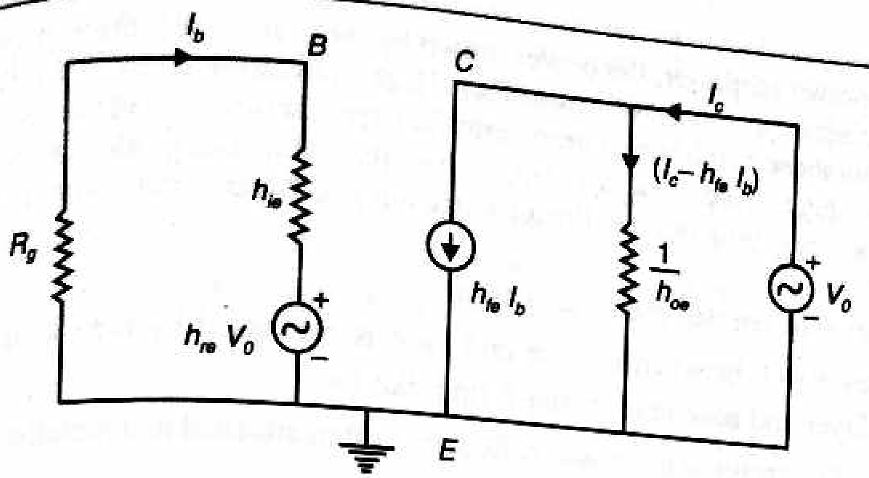

Fig. 36.9

Substituting the value of I_b in Eq. (5), we get

$$h_{0e} V_0 = I_c + \frac{h_{fe} h_{re}}{h_{ie} + R_g} V_0$$

or

$$V_0 \left(h_{0e} - \frac{h_{fe} h_{re}}{h_{ie} + R_g} \right) = I_c$$

or

$$Z_{0e} = \frac{V_0}{I_c} = \frac{1}{h_{0e} - \dfrac{h_{fe} h_{re}}{h_{ie} + R_g}}$$

∴

$$Z_{0e} = \frac{h_{ie} + R_g}{h_{0e}(h_{ie} + R_g) - h_{fe} h_{re}} \quad ...(6)$$

(*v*) **Power gain.** Power gain of the amplifier is the product of current gain and voltage gain. Thus power gain

$$A_{pe} = |A_{ve}| \times |A_{ie}|$$

Substituting the values of A_{ve} and A_{ie} from Eqs. (4) and (1), we get

$$A_{pe} = \left(\frac{h_{fe} R_L}{h_{ie} + R_L \Delta h} \right) \left(\frac{h_{fe}}{1 + h_{0e} R_L} \right)$$

$$= \frac{h_{fe}^2 R_L}{(1 + h_{0e} R_L)(h_{ie} + R_L \Delta h)} \quad ...(7)$$

where

$$\Delta h = h_{ie} h_{0e} - h_{fe} h_{re}.$$

In actual practice, h_{0e}, h_{re} are very small quantities. $h_{0e} < 1$ and $R_L \Delta h < h_{ie}$.

∴

$$A_{pe} = \frac{h_{fe}^2 R_L}{h_{ie}}.$$

POWER AMPLIFIERS

POWER AMPLIFIER

A transistor amplifier which raises the power level of the signals is known as power amplifier. Here a concentrated effort is made to obtain maximum output power. A power amplifier actually takes power from the *d.c.* supply and delivers it as useful signal power to the load. The ratio of signal power delivered as output to the *d.c.* power input is known as the efficiency of the power amplifier.

In the case of power amplifier, the power drawn by the load impedance is high. This is because of high collector current in this power amplifier. High collector current is the result of low load resistances driven by these amplifiers. These amplifiers (power) are used in the last stage of cascaded amplifier. The last stage drives low resistances like that of a loudspeaker. Power amplifiers use *power transistor* as amplifying device. Power transistor is different from ordinary bipolar transistor in following aspects :

(*i*) Doping level of emitter and base is high.

(*ii*) Ohmic resistance between emitter and base is decreased by increasing the contact area between the base layer and base lead giving it ring like form.

(*iii*) The area of collector is more and collector is often attached to a metallic heat sink in order to dissipate the generated heat.

Power amplifiers are used mainly in four modes — *class A*, *class B*, *class AB* and *class C*.

Class A Power Amplifier. It operates in the linear region at all times (Fig. 36.10).

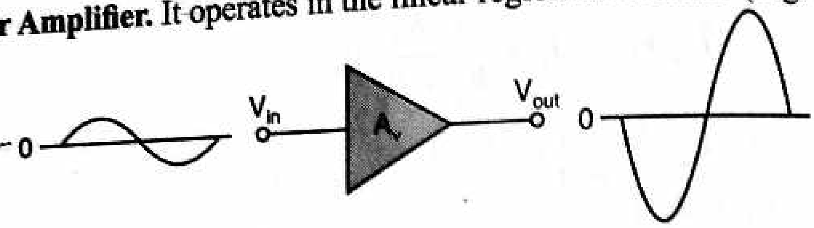

Fig. 36.10

- Output is shown 180° out of phase with the input (inverted).
- Class A power amplifiers are large-signal amplifiers with the objective of providing power (rather than voltage) to a load.
- In a power amplifier, it is necessary to consider the problem of heat dissipation in components.

Power Gain. The *power gain* of an amplifier is the ratio of the power delivered to the load to the input power.

$$A_p = \frac{P_L}{P_{in}}$$

Here, A_p = power gain

P_L = signal power delivered to the load

P_{in} = signal power delivered to the amplifier.

Efficiency. The efficiency of any amplifier is the ratio of the signal power supplied to a load to the power from the dc supply.

36.4.1. Class A Power Amplifier

Figure 36.11 shows a typical *class A transistor power amplifier* operating in the common emitter mode. Here resistors R_1 and R_2 form voltage divider circuit to provide forward biasing of the emitter-base junction. R_E is the emitter resistor for bias stabilisation and C_E is the emitter bypass capacitor which prevents the a.c. voltages from appearing across R_E. The capacitor C_B is called '*Blocking capacitor*'. It is used to block d.c. component of the input signal so that only a.c. signal reaches the base. The amplifier is directly coupled to the load resistance R_L.

Operation of the Amplifier

The collector characteristics of the transistor used in Fig. 36.11 is shown in Fig. 36.12. The load line corresponding to R_L is drawn on the characteristics. The operating point Q is selected in almost the middle of a.c. load line.

When no signal is applied, the Q-point is operating point. When an a.c. signal is applied, the operating point shifts. It keeps on oscillating along the load line with Q as the mean position. The maximum signal condition occurs when the operation swings between saturation and cut-off.

Efficiency: The curves, in Fig. 36.12, show the voltage and current values at saturation and cut-off. In saturation stage, collector current is maximum and collector voltage is minimum. In cut-off stage, voltage is maximum and current is minimum. We denote voltage and current at saturation by $V_{C\,min}$ and $I_{C\,max}$ while these quantities at cut-off are denoted by $V_{C\,max}$ and $I_{C\,min}$ and at Q-point are V_{CQ} and I_{CQ}.

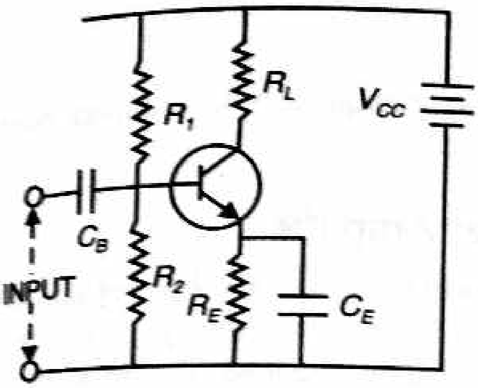

Fig. 36.11

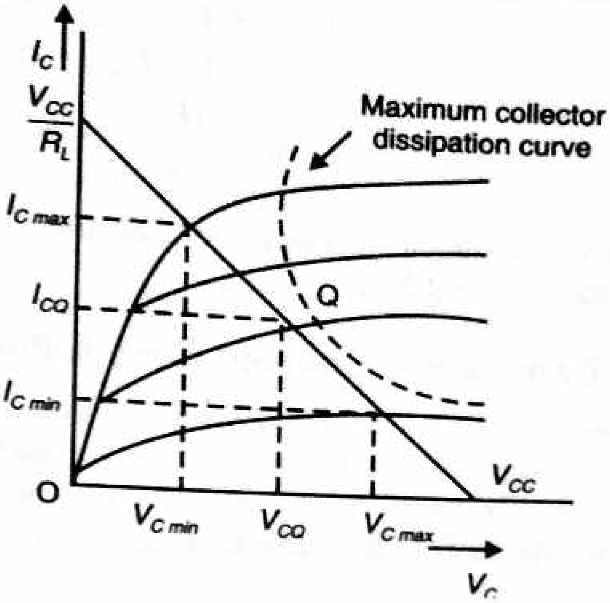

Fig. 36.12

Efficiency η is given by

$$\eta = \frac{\text{output a.c. power}}{\text{input d.c. power}} \qquad ...(1)$$

Input d.c. power is given by

$$P_{in} = V_{cc} I_{CQ} \qquad ...(2)$$

Output a.c. power is given by

$$P_{out} = V_{Crms} I_{Crms} \qquad ...(3)$$

Here V_{Crms} and I_{Crms} are the r.m.s. values of voltage and current. The signal makes excursions between V_{Cmax} and V_{Cmin} (or I_{Cmax} and I_{Cmin}). So, peak values V_{Cm} and I_{Cm} of voltage and current are given by

$$V_{Cm} = \frac{V_{Cmax} - V_{Cmin}}{2}$$

$$I_{Cm} = \frac{I_{Cmax} - I_{Cmin}}{2}$$

Therefore, the a.c. output power

$$P_{out} = V_{Crms} I_{Crms}$$

$$= \frac{V_{Cm}}{\sqrt{2}} \times \frac{I_{Cm}}{\sqrt{2}}$$

$$= \left(\frac{V_{Cmax} - V_{Cmin}}{2\sqrt{2}}\right) \times \left(\frac{I_{Cmax} - I_{Cmin}}{2\sqrt{2}}\right)$$

$$= \frac{(V_{Cmax} - V_{Cmin})(I_{Cmax} - I_{Cmin})}{8}$$

Therefore, the efficiency of power conversion

$$\eta = \frac{P_{a.c.}}{P_{d.c.}} = \frac{(V_{Cmax} - V_{Cmin})(I_{Cmax} - I_{Cmin})}{8V_{CC}\, I_{CQ}}$$

For ideal collector characteristic curves

$$V_{Cmin} = 0, \quad V_{Cmax} = V_{CC}$$

$$I_{Cmin} = 0, \quad I_{Cmax} = 2I_{CQ}$$

$$\therefore \quad \eta = \frac{(V_{CC})(2I_{CQ})}{8V_{CC}\, I_{CQ}} = 0.25.$$

Thus the maximum efficiency obtainable from a class A amplifier when coupled directly to the load resistance is only 25%.

36.4.2. Transformer Coupled Class A Power Amplifier

Figure 36.13 shows the circuit diagram of a transformer coupled class A power amplifier. R_1 and R_2 form a potential divider arrangement to give base bias. V_{CC} provides reverse bias to the collector-base junction. The transformer is used to couple the transistor to the load. The transformer matches the output impedance of the transistor to the load resistance so that power transfer is maximum.

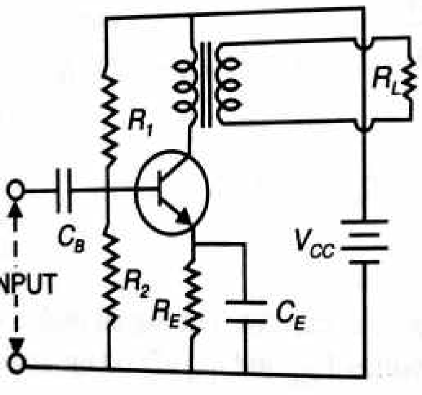

Fig. 36.13

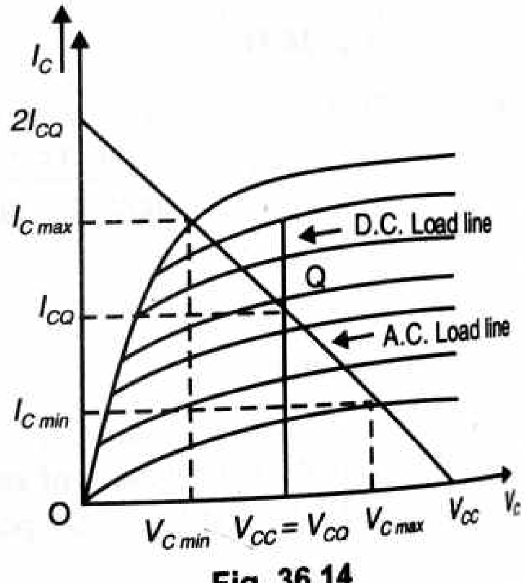

Fig. 36.14

In the circuit shown, load resistance R_L is connected across the secondary coil of the transformer. Its value as seen from the primary coil terminal is given by

$$R_L = n^2 R_L.$$

Here, n is the turns ratio of the transformer given by

$$n = \frac{N_p}{N_s}.$$

Here N_p and N_s are the number of turns in primary and secondary coils, respectively, in primary circuits. Secondary coil also has d.c. resistance, say R_s. The total resistance as seen at the primary coil terminals is given by

$$R_L' = n^2 (R_s + R_L)$$

Efficiency,

$$\eta = \frac{\text{output a.c. power}}{\text{input d.c. power}}.$$

d.c. input power is given by

$$P_{in} = V_{CC} I_{CQ} \quad ...(2)$$

where I_{CQ} is the collector current at the operating point.

Output a.c. power is given by

$$P_{out} = V_{Crms} I_{Crms}$$

$$= \frac{V_{Cm}}{\sqrt{2}} \cdot \frac{I_{Cm}}{\sqrt{2}}$$

$$= \frac{(V_{Cmax} - V_{Cmin})(I_{Cmax} - I_{Cmin})}{8} \quad ...(3)$$

From Fig. 36.14, it can be seen that

$$V_{Cmax} = 2V_{CC}, \quad V_{Cmin} = 0$$

$$I_{Cmax} = 2I_{CQ}, \quad I_{Cmin} = 0.$$

$$P_{out} = \frac{4V_{CC} I_{CQ}}{8} = \frac{V_{CC} I_{CQ}}{2}.$$

∴ The efficiency of power amplifier is

$$\eta = \frac{P_{a.c.}}{P_{d.c.}} = \frac{\frac{V_{CC} I_{CQ}}{2}}{V_{CC} I_{CQ}}$$

∴ $\eta = 0.5$

∴ The efficiency of transformer coupled class A amplifier is 50% in ideal case.

COMPARISON OF AMPLIFIER CONFIGURATIONS

The choice of configuration and the type of transistor used depends on the desired input and output impedances, current and voltage gains and the frequency response. The following table gives a comparison of small signal amplifiers in the three possible configurations.

Parameter	*Common base*	*Common emitter*	*Common collector*
Voltage gain	High	Very-high	nearly 1
Current gain	nearly 1	high	highest
Input impedance	lowest	moderate	highest
Output impedance	highest	moderate	lowest
Phase reversal	no	yes	no

Class B Amplifier. Class B amplifier is biased at cutoff so that it operates in the linear region for 180° of the input cycle and is in cutoff for 180°.

Fig. 36.15 shows class B amplifier operation (noninverting).

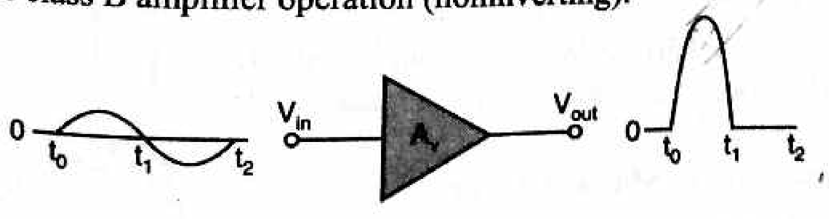

Fig. 36.15

The output waveform is shown relative to the input in terms of time (t).

The circuit only conducts for the positive half of the cycle.

To amplify the entire cycle, it is necessary to add a second class B amplifier that operates on the negative half of the cycle. The combination of two class B amplifiers working together is called **push-pull** operation.

We shall discuss a class B push-pull amplifier. It uses two *complementary symmetry* BJTs to reproduce the entire waveform.

36.5 CLASS B PUSH-PULL AMPLIFIER

Fig. 36.16 shows the circuit arrangement of a class *B* push-pull amplifier.

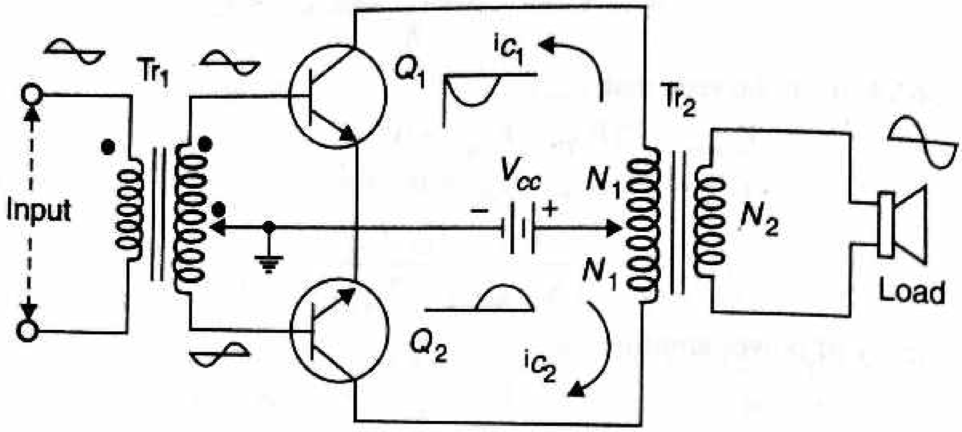

Fig. 36.16

It consists of two identical NPN transistors Q_1 and Q_2 placed in parallel (back to back) and operated as class *B* amplifiers. The input transformer Tr_1 has a centre tapped secondary winding which provides opposite polarity signals to the two transistors. So the input signal drives the two transistors on alternate half cycles. The collector terminals of the transistors are connected across the primary of the output transformer Tr_2. The *dc* supply voltage V_{cc} is applied at the centre tap of this primary. The load resistance (loudspeaker) is connected across the secondary of the output transformer. When no signal is applied, both the transistors are cut-off.

Working :

(*i*) When the input signal is applied, the phase splitter transformer Tr_1 produces two signals which are 180° out of phase with each other. The transistors Q_1 and Q_2 are driven by these two signals.

(*ii*) During positive half cycle of the signal, transistor Q_1 conducts because its base is driven positive. Now collector current i_{c_1} flows as shown in Fig. 36.16. Transistor Q_2 does not conduct because its base has negative voltage. Thus i_{c_2} is zero. In this way one positive half cycle of ouput signal appears across the primary of Tr_2.

(*iii*) During the negative half cycle of the input signal, Q_2 is forward biased and allows a current i_{c_2} to flow. Transistor Q_1 becomes nonconducting.

Thus only one transistor conducts at a time.

The output transformer serves to join the two currents producing an almost undistorted output waveform as shown in Fig. 36.17.

(*i*) Fig. 36.17 (a) shows the input signal v_i.

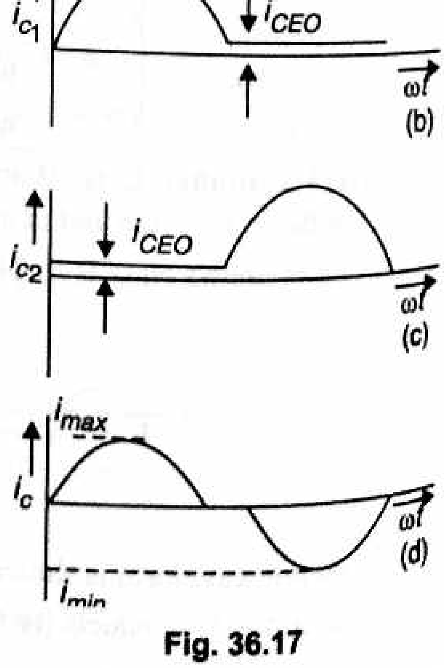

Fig. 36.17

(ii) The collector currents in Q_1 and Q_2 transistors are represented by Figs. (b) and (c).

(iii) The current responsible for output voltage across the load is represented by Fig. (d).

Cross-Over Distortion :

When the *d.c.* base voltage is zero, both transistors are off. In order that a transistor begins to conduct, the input signal voltage must have exceeded V_{BE} (Fig. 36.18). The transistor remains cut off until the base voltage exceeds 0.3 V for Ge and 0.7 V for Si.

Because of this there will be a time interval between the positive and negative alternations of the input, when neither transistor is conducting. The output does not follow the input around the zero input voltage condition. Thus the output collector current is not a uniformly enlarged sine wave at low values of current. The resulting distortion in the output waveform is called crossover distortion.

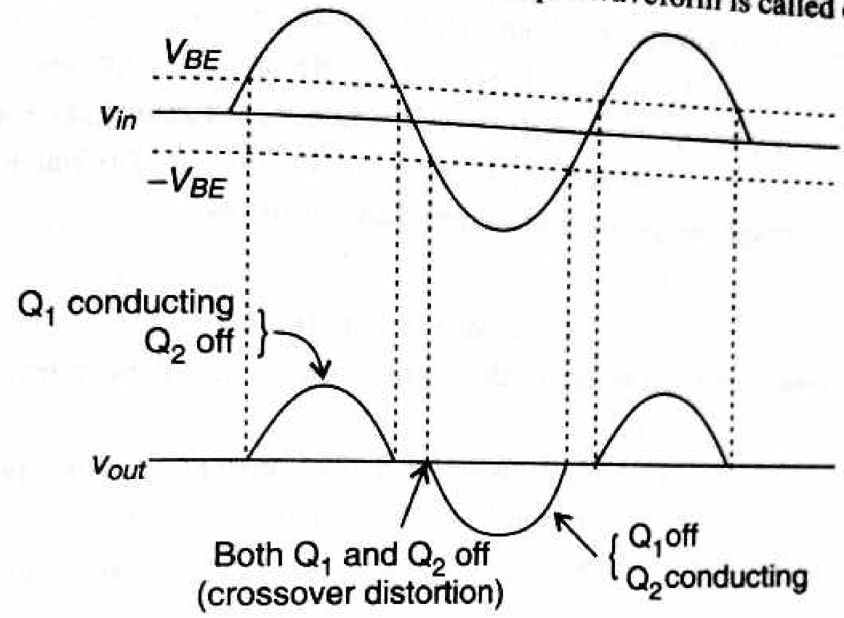

Fig. 36.18

Power Efficiency of Class B Push-Pull Amplifier

The current in each transistor is the average value of half sine loop.

For half sine loop, I_{dc} is given by

$$I_{dc} = \frac{(I_c)_{\max}}{\pi}$$

$$\therefore \quad (P_{in})_{dc} = 2 \times \left[\frac{(I_c)_{\max}}{\pi} \times V_{CC}\right] \qquad ...(1)$$

Here factor 2 is introduced as there are two transistors in push-pull amplifier.

R.M.S. value of collector current = $(I_c)_{\max} / \sqrt{2}$.

R.M.S. value of output voltage = $V_{CC} / \sqrt{2}$.

(Under ideal conditions of maximum power)

$$\therefore \quad (P_0)_{ac} = \frac{(I_c)_{\max}}{\sqrt{2}} \times \frac{V_{CC}}{\sqrt{2}} = \frac{(I_c)_{\max} \times V_{CC}}{2} \qquad ...(2)$$

Now overall maximum efficiency

$$\eta_{\text{overall}} = \frac{(P_0)_{\text{a.c.}}}{(P_{\text{in}})_{\text{d.c.}}}$$

$$= \frac{(I_c)_{\max} \times V_{CC}}{2} \times \frac{\pi}{2(I_c)_{\max} \times V_{CC}} = \frac{\pi}{4} = 0.785 = 78.5\%$$

Advantages. (*i*) The output has much less distortion due to cancellation of even harmonics.

(*ii*) The maximum efficiency of class *B* push pull amplifier is quite high (≈ 79%).

EXAMPLE 1. *Prove that a push-pull circuit balances all the even harmonics in the output and leaves the third harmonic term as the principal source of distortion.*

(Rohilkhand, 1999, Kumaun, 2000)

SOLUTION. A power amplifier has to handle large signal inputs. Hence there will be harmonic distortions (frequency components in the signal getting modified) due to non-linear characteristics of the transistors used in the amplifier.

Let the input signal be sinusoidal. The base currents in the two transistors will be opposite in phase. Hence the collector currents will also be opposite in phase.

The collector currents in transistors Q_1 and Q_2 are given by

$$i_{c_1} = A_0 + A_1 \sin \omega t + A_2 \sin 2\omega t + A_3 \sin 3\omega t + \ldots, \quad ...(1)$$

and

$$i_{c_2} = A_0 + A_1 \sin (\omega t + \pi) + A_2 \sin 2(\omega t + \pi) + A_3 \sin 3(\omega t + \pi)$$

or

$$i_{c_2} = A_0 - A_1 \sin \omega t + A_2 \sin 2\omega t - A_3 \sin 3\omega t + \ldots \quad ...(2)$$

The total current through the primary of output transformer is

$$i = i_{c_1} - i_{c_2}$$

$$\therefore \quad i = 2[A_1 \sin \omega t + A_3 \sin 3\omega t + \ldots] \quad ...(3)$$

The voltage induced in the secondary of the output transformer is proportional to *i*.

$$\therefore \quad v_0 \propto i$$

$$v_0 = ki \quad \text{where } k \text{ is the constant of proportionality.}$$

$$\therefore \quad v_0 = 2k[A_1 \sin \omega t + A_3 \sin 3\omega t + \ldots] \quad ...(4)$$

Thus, the output is free from even harmonics.

The principal source of distortion is the third harmonic 3ω.

MULTISTAGE AMPLIFIERS

Multistage Amplifiers. Single-stage amplifiers are connected in sequence with various coupling methods to form multistage amplifiers.

- The output of one amplifier drives the input of the next.

  The output of the first stage is used as the input to a second stage.

  The output of the second stage is used as the input to the third stage, and so on.

- The basic purpose of a multistage arrangement is to *increase* the overall *voltage gain*.

The *total voltage gain* of a multistage amplifier is the *product of the individual gains* (*sum of dB gains*).

36.6 MULTISTAGE VOLTAGE GAIN

Fig. 36.19 shows a multistage amplifier.

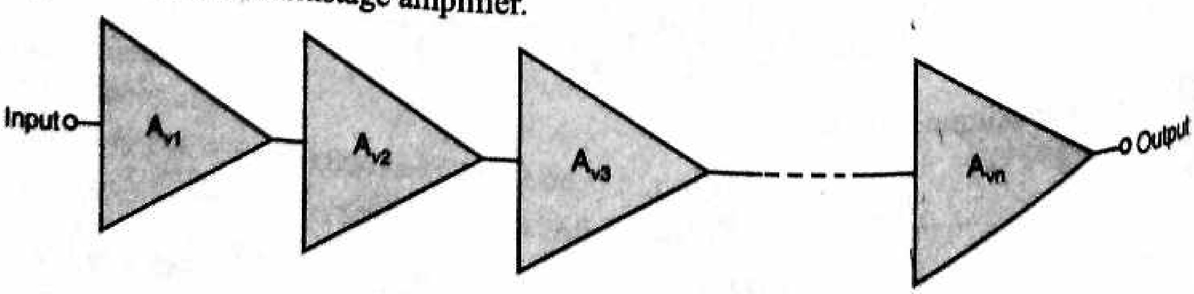

Fig. 36.19