5.1 POWER AMPLIFIERS

An amplifying system usually has several cascaded stages. The input and intermediate stages are small signal amplifiers. Their function is only to amplify the input signal to a suitable value. The last stage usually drives a transducer such as a loud speaker, CRT, Servomotor etc. Hence this last stage amplifier must be capable of handling and deliver appreciable power to the load. These large signal amplifiers are called as power amplifiers.

Power amplifiers are classified according to the class operation, which is decided by the location of the quiescent point on the device characteristics. The different classes of operation are:

(i) Class A

(ii) Class B

(iii) Class AB

((iv) Class C

CLASS A OPERATION:

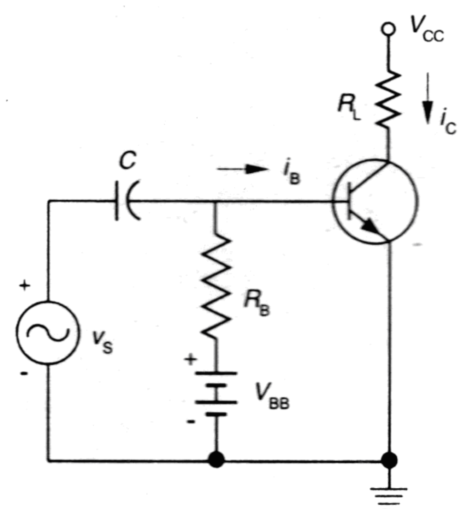

Fig.1 Series-fed transistor amplifier

A simple transistor amplifier that supplies power to a pure resistive load R_L is shown above. Let i_C represent the total instantaneous collector current, i_c designate the instantaneous variation from the quiescent value of I_C. Similarly, i_B ,i_b and I_B represent corresponding base currents. The total instantaneous collector to emitter voltage is given by v_c and instantaneous variation from the quiescent value V_C is represented by v_c.

Let us assume that the static output characteristics are equidistant for equal increments of input base current i_b as shown in fig. below.

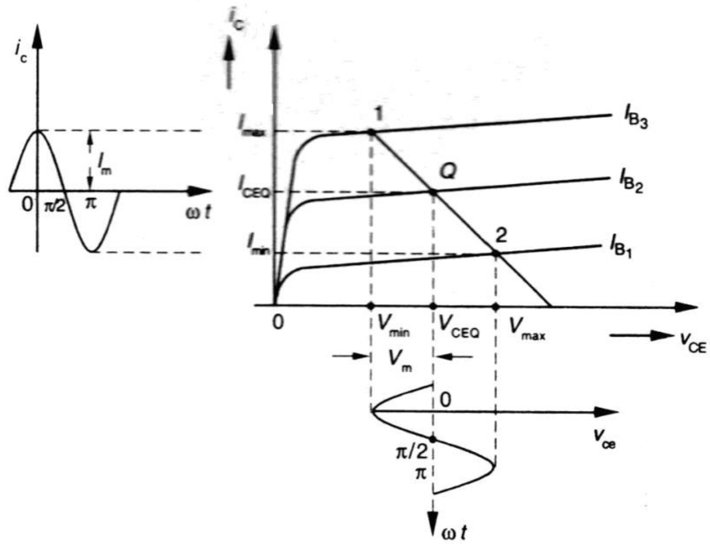

Fig. 2 The output characteristics and the current and voltage waveforms

If the input signal i_b is a sinusoid , the output current and voltage are also sinusoidal.Under these conditions, the non-linear distortion is neglible and the power output may be found graphically as follows.

$P = V_c I_c = I_c^2 R_L$ ------------------------------ (1)

Where V_c & I_c are the rms values of the output voltage and current respectively.The numerical values of V_c and I_c can be determined graphically in terms of the maximum and minimum voltage and current swings.It is seen that

$$I_c = \frac{I_m}{\sqrt{2}} = \frac{I_{\max} - I_{\min}}{2\sqrt{2}} \text{ ---------------------------- (2)}$$

and

$$V_c = \frac{V_m}{\sqrt{2}} = \frac{V_{\max} - V_{\min}}{2\sqrt{2}} \text{ ------------------------- (3)}$$

Power, $P_{ac} = \frac{V_m I_m}{2} = \frac{I_m^2 R_L}{2} = \frac{V_m^2}{2R_L}$ ----------------- (4)

This can also be written as,

$$P_{ac} = \frac{(V_{max} - V_{min})(I_{max} - I_{min})}{8} \quad \text{--------------(5)}$$

DC power $P_{dc} = V_{CC} \ I_{CQ}$

$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{(V_{max} - V_{min})(I_{max} - I_{min})}{8 V_{CC} I_{CQ}}$$

MAXIMUM EFFICIENCY:

For a maximum swing, refer the figure below.

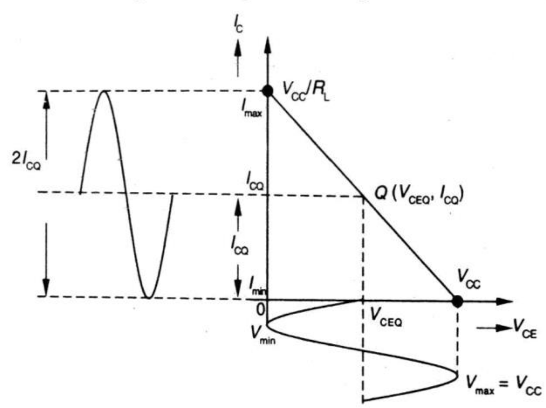

Fig. 3 **Maximum voltage and current swings**

$$V_{max} = V_{CC} \ \& V_{min} = 0$$

$$I_{max} = 2I_{CQ} \ \& \ I_{min} = 0$$

$$\eta_{max} = \frac{V_{CC} \, 2I_{CQ}}{8 V_{CC} I_{CQ}} = 25\%$$

SECOND HARMONIC DISTORTION:

In the previous section, the active device (BJT) is treated as a perfectly linear device. But in general, the dynamic transfer characteristics are not a straight line. This non-linearity arises because of the static output characteristics are not equidistant straight lines for constant increments of input excitation. If the dynamic curve is non-linear over the operating range, the waveform of the output differs from that of the input signal. Distortion of this type is called non-linear or amplitude distortion.

To investigate the magnitude of this distortion, we assume that the dynamic curve with respect to the quiescent point 'Q' can be represented by a parabola rather than a straight line as shown below.

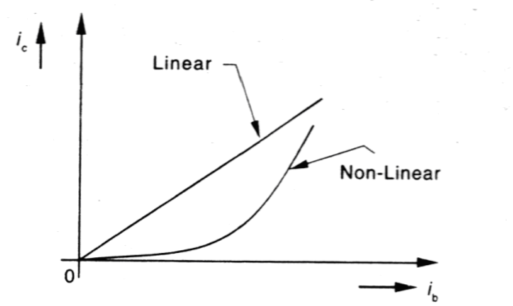

Fig. 4 Nonlinear dynamic characteristics

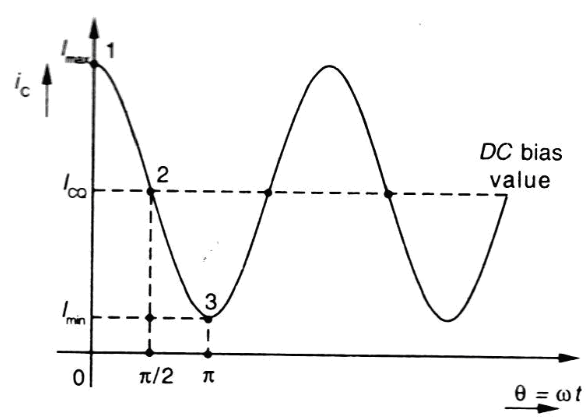

Fig. 1 Output current waveform

Thus instead of relating the alternating output current i_c with the input excitation i_b by the equation $i_c = Gi_b$ resulting from a linear circuit. We assume that the relationship between i_c and i_b is given more accurately by the expression

$$i_c = G_1 i_b + G_2 i_b^2 \quad \text{--}(1)$$

where the G' s are constants.

Actually these two terms are the beginning of a power series expansion of i_c as a function of i_b.

If the input waveform is sinusoidal and of the form

$$i_b = I_{bm} \text{Cos}\, \omega t \text{ ---}(2)$$

Substituting equation (3), into equation (2)'

$$i_c = G_1 I_{bm} \text{Cos}\, \omega t + G_2 I_{bm}^2 \text{Cos}^2\, \omega t$$

Since $Cos^2 \omega t = \frac{1}{2} + \frac{1}{2} Cos 2\omega t$, the expression for the instantaneous total current reduces the form,

$$i_C = I_C + i_c = I_C + B_0 + B_1 \text{Cos}\, \omega t + B_2 \text{Cos}\, 2\omega t \quad \text{------------------------}(3)$$

Where B's are constants which may be evaluated in terms of the G's.

The physical meaning of this equation is evident. It shows that the application of a sinusoidal signal on a parabolic dynamic characteristic results in an output current which contains, in addition to a term of the same frequency as the input, a second harmonic term and also a constant current. This constant term B_0 adds to the original dc value I_C to yield a total dc component of current $I_C + B_0$.Thus the parabolic non-linear distortion introduces into the output a component whose frequency is twice that of the sinusoidal input excitation.

The amplitudes B_0, B_1 & B_2 for a given load resistor are readily determined from either the static or the dynamic characteristics. From fig. 7.2 above, we observe that

When $\omega t = 0$, $i_c = I_{max}$

$\omega t = \pi/2$, $i_c = I_C$ --(4)

$\omega t = \pi$, $i_c = I_{min}$

By substituting thase values in equation (4)'

$$I_{max} = I_C + B_0 + B_1 + B_2$$

$$I_C = I_C + B_0 - B_2 \quad \text{---}(5)$$

$$I_{min} = I_C + B_0 - B_1 + B_2$$

This set of three equations determines the three unknowns B_0, B_1 & B_2.

It follows from the second group that

$$B_0 = B_2 \text{ ---(6)}$$

By subtracting the third equation from the first,

$$B_1 = \frac{I_{max} - I_{min}}{2} \text{ --- ---(7)}$$

Then from the first or last of equation (6),

$$B_2 = B_0 = \frac{I_{max} + I_{min} - 2Ic}{4} \text{ -- (8)}$$

The second harmonic distortion D_2 is defined as,

$$D_2 = \frac{|B_2|}{|B_1|} \text{ --- (9)}$$

If the dynamic characteristics is given by the parabolic form & if the input contains two frequencies ω_1 & ω_2, then the output will consist of a dc term & sinusoidal components of frequencies ω_1, ω_2, $2\omega_1$,$2\omega_2$, $\omega_1+\omega_2$ and $\omega_1-\omega_2$.The sum & difference frequencies are called intermodulation or combination frequencies.

HIGHER ORDER HARMONIC GENERATION

The analysis of the previous section assumed a parabolic dynamic characteristic. But this approximation is usually valid for amplifier where the swing is small. For a power amplifier with

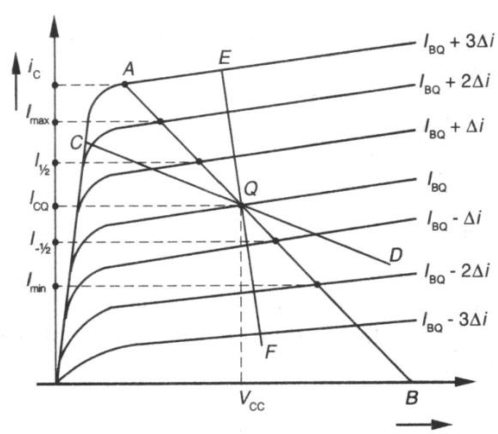

Fig. 2 Graphical evaluation of harmonic distortion

a large input swing, it is necessary to express the dynamic transfer curve with respect to the Q point by a power series of the form,

$$i_c = G_1 i_b + G_2 i^2{}_b + G_3 i^3{}_b + \text{---------------------------------} \quad (1)$$

If the input wave is a simple cosine function of time, then

$$i_b = I_{bm} Cos\omega t \quad \text{---} \quad (2)$$

Then, $i_c = B_0 + B_1 Cos\omega t + B_2 Cos2\omega t + B_3 Cos3\omega t + --- \quad (3)$

Where B_0, B_2, B_3 – are the coefficients in the Fourier series for the current.
i.e. the total output current is given by

$$i_C = I_{CQ} + i_c = I_{CQ} + B_0 + B_1 Cos\omega t + B_2 Cos2\omega t + ------ (4)$$

Where ($\left(I_{CQ} + B_0\right)$ is the dc component. Since i_C is an even function of time, the Fourier series in equation (4) representing a periodic function possessing the symmetry, contains only Cosine terms.

Suppose we assume as an approximation that harmonics higher than the fourth are negligible in the above Fourier series, then we have five unknown terms $B_{0,} B_1, B_2, B_{3,}$ & B_4.To evaluate those we need output currents at five different value of $I_{B.}$

Let us assume that $i_C = 2\Delta i Cos\omega t$ ---------------------------- (5)

Hence, $I_B = I_{BQ} + 2\Delta i Cos\omega t$ ---------------------------------- - (6)

At $\omega t = 0,\quad I_B = I_{BQ} + 2\Delta i,\quad i_C = I_{max}$ ------------------- (7)

At $\omega t = \frac{\pi}{3},\ I_B = I_{BQ} + \Delta i,\quad i_C = I_{\frac{1}{2}}$ ------------------- ---(8)

At $\omega t = \frac{\pi}{2},\ I_B = I_{BQ},\quad i_C = I_{CQ}$ -------------------- (9)

At $\omega t = \frac{2\pi}{3},\ I_B = I_{BQ} - \Delta i,\quad i_C = I_{-\frac{1}{2}}$ ---------------------(10)

At $\omega t = \pi,\ I_B = I_{BQ} - 2\Delta i,\quad i_C = I_{min}$ ----------------------(11)

By combining equations (4) & (7) to (11), we get five equations & solving them, we get the following relations,

$$B_0 = \frac{1}{6}\left[I_{max} + 2I_{\frac{1}{2}} + 2I_{-\frac{1}{2}} + I_{min}\right] - I_{CQ} \quad \text{-------------------------} \quad (12)$$

$$B_1 = \frac{1}{3}\left[I_{\max} + I_{\frac{1}{2}} - I_{-\frac{1}{2}} - I_{\min}\right] \text{ ----------------------------------- (13)}$$

$$B_2 = \frac{1}{4}\left[I_{\max} - 2I_{CQ} + I_{\min}\right] \text{ --------------------------------------- (14)}$$

$$B_3 = \frac{1}{6}\left[I_{\max} - 2I_{\frac{1}{2}} + 2I_{-\frac{1}{2}} - I_{\min}\right] \text{ ------------------------------ (15)}$$

$$B_4 = \frac{1}{12}\left[I_{\max} - 4I_{\frac{1}{2}} + 6I_{CQ} - 4I_{-\frac{1}{2}} + I_{\min}\right] \text{ -------------------- (16)}$$

The harmonic distortion is defined as,

$$D_2 = \frac{|B_2|}{|B_1|},\ D_3 = \frac{|B_3|}{|B_1|},\ D_4 = \frac{|B_4|}{|B_1|} \text{ -----------------------------(17)}$$

Where D_n represents the distortion of the n^{th} harmonic. Since this method uses five points on the output waveform to obtain the amplitudes of harmonics, the method is known as the five point method of determining the higher order harmonic distortion.

POWER OUTPUT DUE TO DISTORTION

If the distortion is not negligible, the power delivered to the load at the fundamental frequency is given by

$$P_1 = \frac{B_1^{\,2} R_L}{2} \text{ --------------------------------- (1)}$$

The ac power output is,

$$P_{ac} = \left(B_1^{\,2} + B_2^{\,2} + B_3^{\,2} + ---\right)\frac{R_L}{2} \text{ -------- (2)}$$

$$= \left(1 + D_2^{\,2} + D_3^{\,2} + ----\right)P_1 \text{ --------- (3)}$$

Where D_2, D_3 etc are the second, third harmonic distortions.

Hence, $P_{ac} = \left(1 + D^2\right)P_1$ -------------------------------- (4)

Where D is the total distortion factor & is given by

$$D = \sqrt{D_2^{\,2} + D_3^{\,2} + D_4^{\,2} + -----} \text{ --------- (5)}$$

For e.g. if $D = 10\%$ of the fundamental, then

$$P_{ac} = \frac{1 + (0.1)^2}{P_1}$$

$\therefore P_{ac} = 1.01P_1$ --------------------------------------- (6)

When the total distortion is 10%, the power output is only 1%.higher than the fundamental power. Thus, only a small error is made in using only the fundamental term P_1 for calculating the output power.

THE TRANSFORMER COUPLED AUDIO POWER AMPLIER

The main reason for the poor efficiency of a direct-coupled classA amplifier is the large amount of dc power that the resistive load in collector dissipates. This problem can be solved by using a transformer for coupling the load.

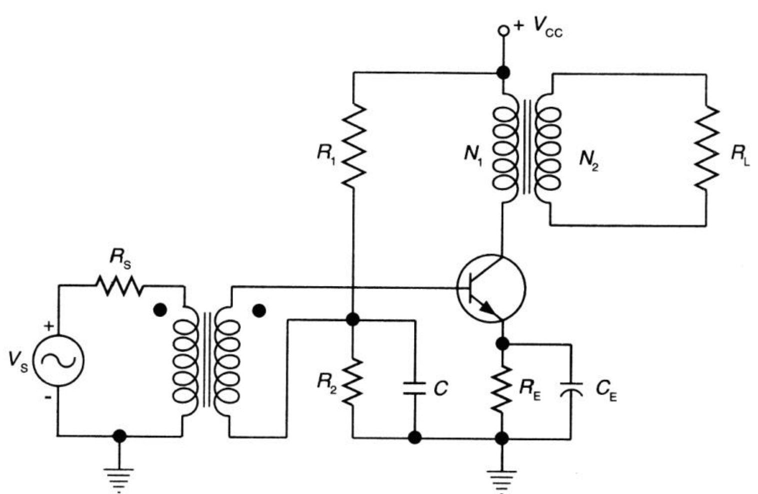

Fig. 3 Transformer-coupled transistor amplifier

TRANDFORMER IMPEDANCE MATCHING

Assume that the transformer is ideal and there are no losses in the transformer. The resistance seen looking into the primary of the transformer is related to the resistance connected across the secondary .The impedance matching properties follow the basic transformer relation.

$V_1 = \frac{N_1}{N_2} V_2$ and $I_1 = \frac{N_2}{N_1} I_2$ ---------------------------------- (1)

Where

$V_1 =$ Primary voltage, $V_2 =$ Secondary voltage.

$I_1 =$ Primary current, $V_2 =$ Secondary current.

$N_1 =$ No. of turns in the primary.

$N_2 =$ No. of turns in the secondary.

From Eq. (1)

$$\frac{V_1}{I_1} = \frac{\left(\frac{N_1}{N_2}\right)V_2}{\left(\frac{N_2}{N_1}\right)I_2} = \left(\frac{N_1}{N_2}\right)^2 \frac{V_2}{I_2}$$

$$\frac{V_1}{I_1} = \left(\frac{1}{n^2}\right)\frac{V_2}{I_2} \quad \text{-- (2)}$$

As both $\frac{V_1}{I_1}$ & $\frac{V_2}{I_2}$ are resistive terms, we can write

$$R'_L = \frac{1}{n^2} R_L = \left(\frac{N_1}{N_2}\right)^2 R_L \quad \text{--------------------- (3)}$$

In an ideal transformer, there is no primary drop.Thus the supply voltage V_{CC} appears as the collector-emitter voltage of the transistor.

i.e. $V_{CC} = V_{CE}$ ------------------------------------ (4)

When the values of the resistance R_B(= R_1I I R_2) and V_{CC} are known, the base current at the operating point may be calculated by the equation.

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} \approx \frac{V_{CC}}{R_B} \quad \text{---------------------- (5)}$$

OPERATING POINT:

Operating point is obtained graphically at the point of intersection of the dc load line and the transistor base current curve.

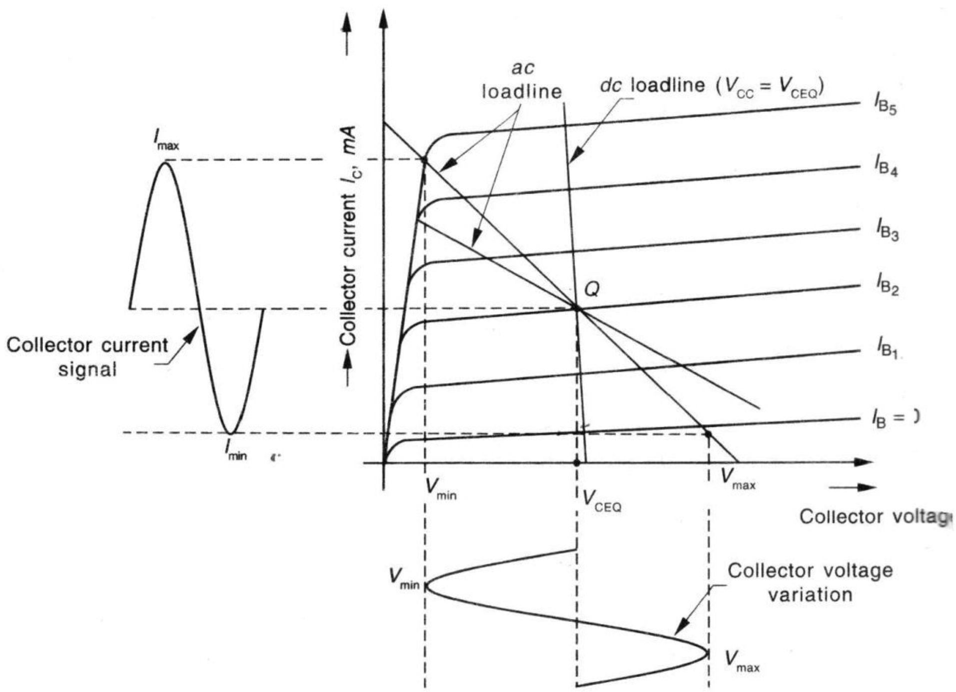

Fig. 4 Collector characteristics of a power transistor showing the *dc* and the

After the operating point is determined; the next step is to construct the ac load line passing through this point.

AC LOAD LINE:

In order to draw the ac load line, first calculate the load resistance looking into the primary side of the transformer. The effective load resistance is calculated using Eq.(3) from the values of the secondary load resistance and transformer ratio. Having obtained the value of R'_L, the ac loads line must be drawn so that it passes through the operating point Q and has a slope equal to $-\frac{1}{R'_L}$. The dc and the ac load lines along the operating point Q are shown. In the above figure, two ac load lines are drawn through Q for different values of R'_L.

For R'_L very small, the voltage swing and hence the output power 'P', approaches zero.For R'_L very large, the current swing is small and again 'P' approaches zero.The variation of power & distortion wrto load resistance is shown in the plot below.

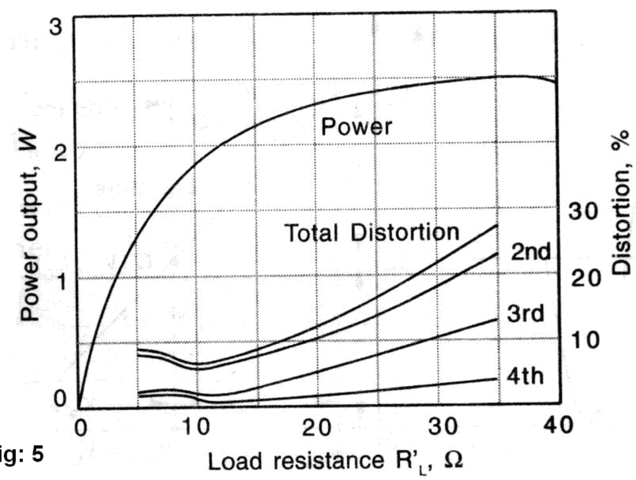

Fig: 5

Output power and distortion as a function of load resistance

EFFICIENCY:

Assume that the amplifier as supplying power to a pure resistance load. Then the average power input from the dc supply ic $V_{CC}I_C$. The power absorbed by the output circuit is, $I_C{}^2R_1 + I_CV_{ce}$, where I_C &V_{ce} are the rms output current & voltage respectively & R_1 is the static load resistance. If P_D is the average power dissipated by the active device, then by the principle of conservation.of energy,

$$V_{CC}I_C = I_C{}^2R_1 + I_CV_{ce} + P_D \text{ ------------ (1)}$$

Since $V_{CC} = V_{CEQ}I_C - V_{ce}I_c$, P_D may be written in the form,

$$P_D = V_{CEQ}I_C - V_{ce}I_c \text{---------------------- (2)}$$

If the load is not pure resistance, then $V_{ce}I_e$ must be replaced by $V_{ce}I_c$ must be replaced by $V_{ce}I_cCos\phi$, where $Cos\phi$ is the power factor of the load.

The above equation expresses the amount of power that must be dissipated by the active device. If the ac output power is zero i.e. If no applied signal exists, then

$$P_D = V_{CE}I_C \quad \text{-------------------------------- (3)}$$

$$\%Efficiency, \eta = \frac{ac\,output\,power}{dc\,power\,input} X100 \quad \text{--------------- (4)}$$

In general, $$\eta = \frac{\left(\frac{1}{2}\right) B_1^{\,2} R'_L}{V_{CC}\left(I_C + B_0\right)} X100\% \quad \text{--------------- (5)}$$

In the distortion components are neglected, then

$$\%\eta = \frac{\left(\frac{1}{2}\right) V_m I_m}{V_{CC} I_C} X100 = 50 \frac{V_m I_m}{V_{CC} I_C} \quad \text{-------------------- (6)}$$

MAXIMUM EFFICIENCY:

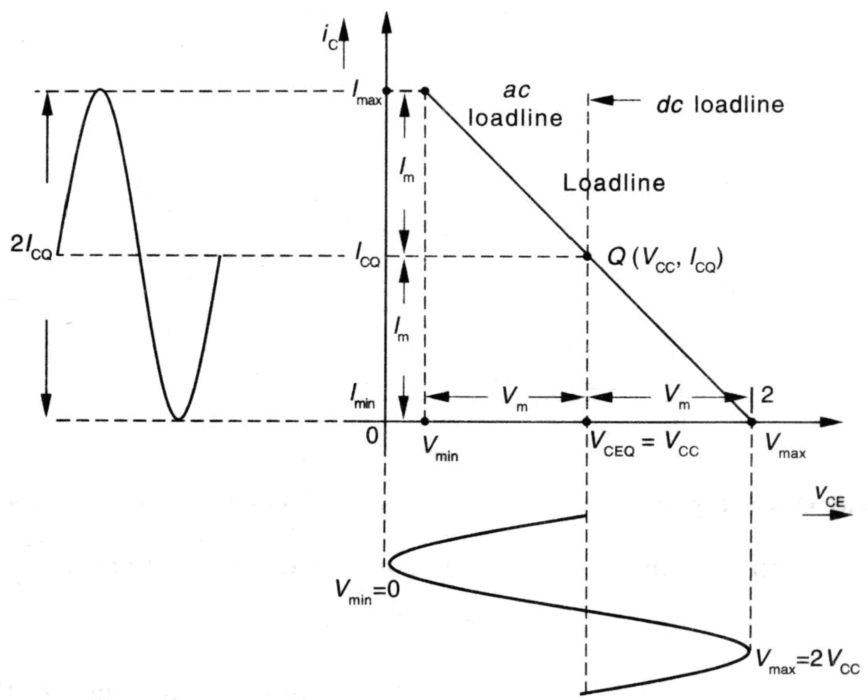

Fig. 6 Maximum voltage and current

An approximate expression for efficiency can be obtained by assuming ideal characteristic curves. Referring to above fig., maximum values of the sine wave output voltage is,

$$V_m = \frac{V_{max} - V_{min}}{2} \quad \text{-------------------------- (7)}$$

And $$I_m = I_{CQ} \quad \text{---------------------------------- (8)}$$

The rms value of collector voltage,

$$V_{rms} = \frac{V_m}{\sqrt{2}} = \frac{V_{\max} - V_{\min}}{2\sqrt{2}} \quad \text{-------------- (9)}$$

Similarly, $$I_{rms} = \frac{I_{\max} - I_{\min}}{2\sqrt{2}} \quad \text{--------------------- (10)}$$

The output power is,

$$P_{ac} = V_{rms}.I_{rms} = \frac{(V_{\max} - V_{\min})}{2\sqrt{2}} . \frac{(I_{\max} - I_{\min})}{2\sqrt{2}}$$

$$= \frac{(V_{\max} - V_{\min}).(I_{\max} - I_{\min})}{8} \text{----------------(11)}$$

The input power is,

$$P_{dc} = V_{CC}.I_{CQ}$$

$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{(V_{\max} - V_{\min})(I_{\max} - I_{\min})}{8V_{CC}I_{CQ}} \text{-------------(12)}$$

The efficiency of a transformer coupled class A amplifier can also be expressed as,

$$\eta = 50\left(\frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}\right)\% \quad \text{-------------------------- (13)}$$

The efficiency will be maximum when $V_{\min} = 0$, $I_{\min} = 0, V_{\max} = 2V_{cc}$ & $I_{\max} = 2I_{CQ}$, substituting these values in eq.(12), we get

$$\eta_{\max} = \frac{2V_{CC}.2I_{CQ}}{8V_{CC}.I_{CQ}} X100 = 50\% \quad \text{----------------- (14)}$$

In practice, the efficiency of class A power amplifier is less than 50% due to losses in the transformer winding.

DRAWBACKS:

(1) Total harmonic distortion is very high.

(2) The output transformer is subject to saturation problem due to the dc current in the primary.