UNIT II

BJT AMPLIFIERS

2.1. Small signal hybrid π equivalent circuit of the bipolar transistor:

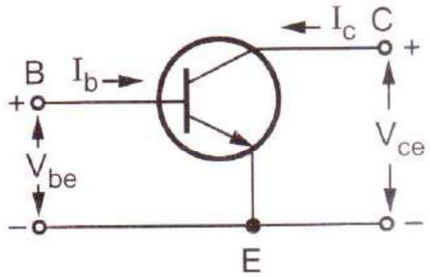


Fig 2.1. npn transistor

$$v_{be} = r_\pi i_b$$

[∵Small signal input current is related to small signal input voltage]

$$i_b = \frac{v_{be}}{r_\pi}$$

$$i_b = \left(\frac{I_{BQ}}{V_T}\right) v_{be}$$

$$r_\pi = \frac{v_{be}}{i_b} = \frac{V_T}{I_{BQ}} = \frac{\beta V_T}{I_{CQ}}$$

The resistance r_π is called the diffusion resistance or base emitter input resistance.

Output side,

$$i_c = \frac{\partial i_c}{\partial v_{BE}} \Big|_{Q.pt} \times v_{be}$$

$$\text{Where,} \; i_c = I_s \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$\frac{\partial i_c}{\partial v_{BE}} = \left(\frac{1}{V_T}\right) I_s \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$g_m = \frac{I_{CQ}}{V_T}$$

This parameter is called a transconductance.

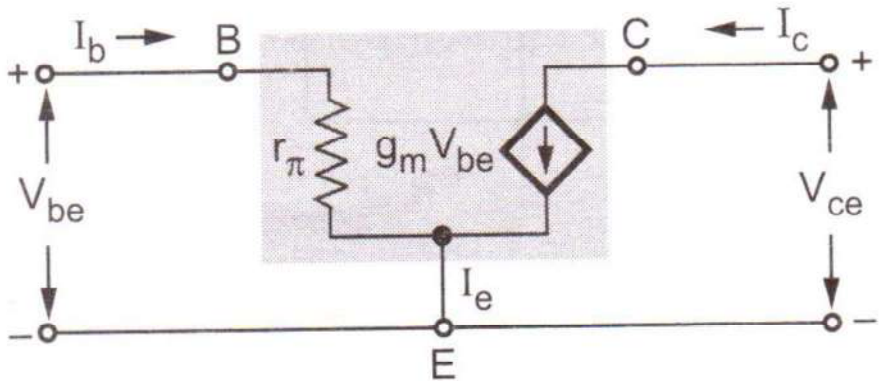


Fig 2.2. Simplified small signal hybrid π equivalent circuit for npn transistor

2.1.1. Common emitter current gain:

$$\text{Current gain} = g_m r_\pi$$

$$= \left(\frac{I_{CQ}}{V_T}\right)\left(\frac{\beta V_T}{I_{CQ}}\right) = \beta$$

2.1.2. Common emitter amplifier:

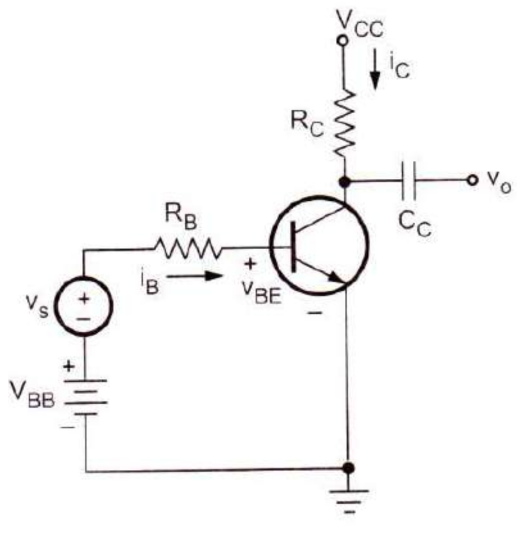


Fig 2.3. Common emitter amplifier circuit

For a.c. equivalent circuit, remove all the capacitors & d.c. supply voltage.

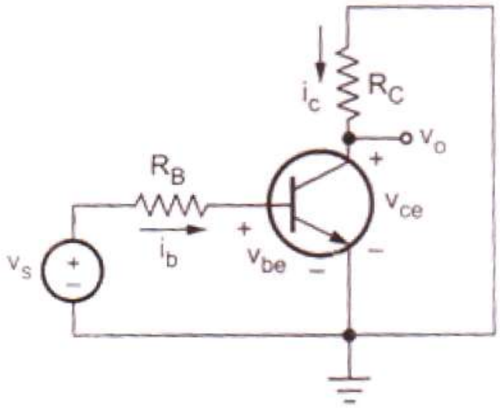


Fig 2.4. a.c equivalent circuit for Common emitter amplifier

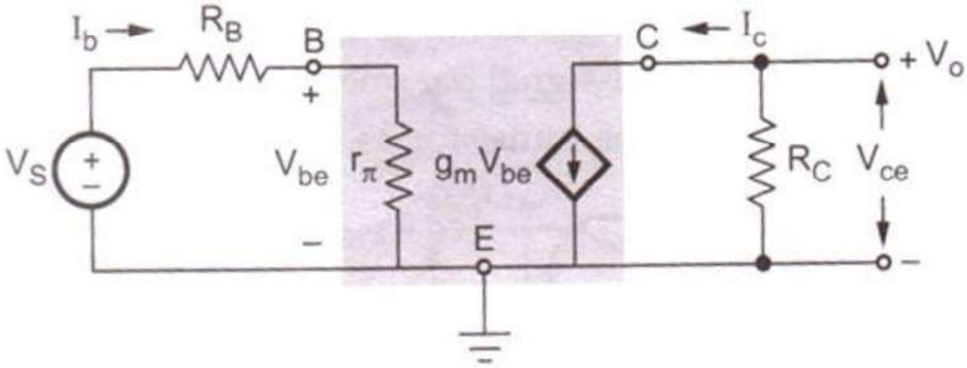


Fig 2.5. Small signal equivalent circuit of common emitter amplifier

2.1.3. Voltage gain:

It is defined as the ratio of output signal voltage to input signal voltage. It is given by

$$A_v = \frac{V_o}{V_s}$$

$$V_o = V_{ce} = -(g_m V_{be})R_c$$

$$V_{be} = \frac{r_\pi}{r_\pi + R_B} V_s \quad [\because \text{Voltage divider theorem}]$$

$$V_s = \frac{V_{be}(r_\pi + R_B)}{r_\pi}$$

$$A_v = \frac{-g_m V_{be} R_c}{V_{be}\left(\frac{r_\pi + R_B}{r_\pi}\right)}$$

$$= -g_m R_c \left(\frac{r_\pi}{r_\pi + R_B}\right)$$

2.1.4. Hybrid π equivalent circuit including early effect:

According to early effect, the collector current does vary with collector-emitter voltage.

$$r_o = \frac{\partial V_{CE}}{\partial i_c} \simeq \frac{V_A}{I_{CQ}}$$

Where, V_A − early voltage

r_o −small signal transistor output resistance

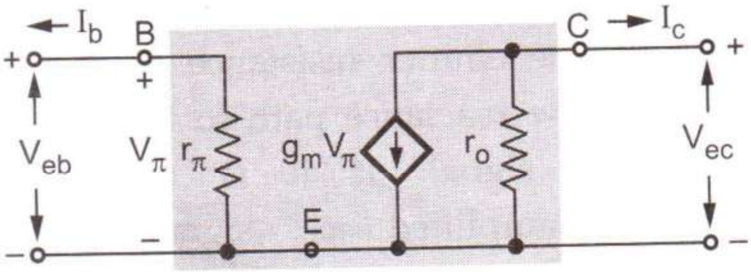


Fig 2.6. Hybrid π equivalent circuit

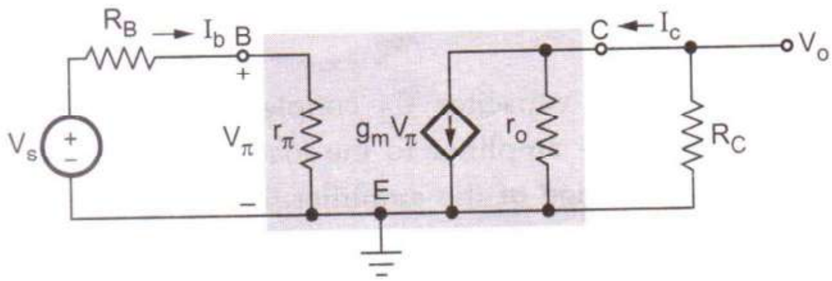


Fig 2.7. Small signal equivalent circuit of common emitter amplifier

$$V_o = -g_m V_\pi (r_o || R_c)$$

$$V_\pi = \left(\frac{r_\pi}{r_\pi + R_B}\right) V_s$$

$$V_s = V_\pi\left(\frac{r_\pi + R_B}{r_\pi}\right)$$

$$A_v = \frac{V_o}{V_s} = \frac{-g_m V_\pi (r_o || R_c)}{V_\pi}\left(\frac{r_\pi}{r_\pi + R_B}\right)$$

$$= -g_m (r_o || R_c)\left(\frac{r_\pi}{r_\pi + R_B}\right)$$

$$A_v = \frac{-\beta(r_o || R_c)}{r_\pi + R_B} \quad \because g_m r_\pi = \beta$$

2.2. Small signal analysis of CE amplifier

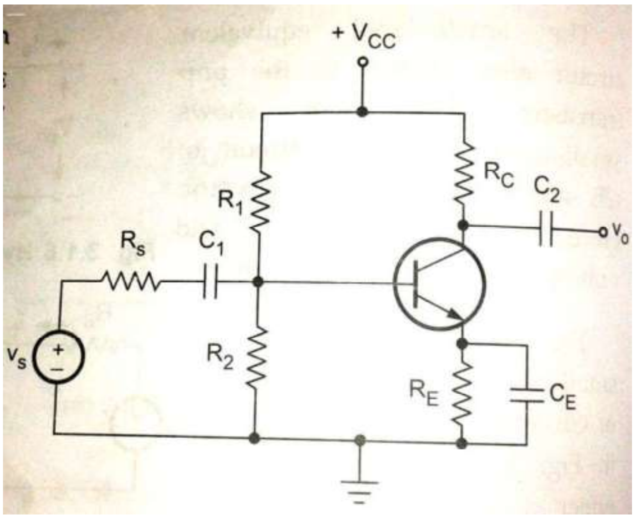


Fig 2.8. Common emitter amplifier

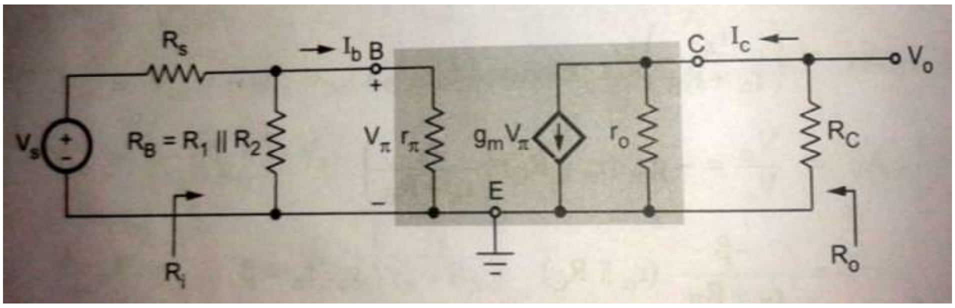


Fig 2.9. Common emitter amplifier

i) Input resistance (R_i):

$$R_i = R_1 || R_2 || r_\pi$$

ii) Voltage gain (A_v):

$$V_o = -g_m V_\pi (r_o || R_c)$$

$$V_\pi = \left(\frac{r_\pi || R_1 || R_2}{R_s + R_1 || R_2 || r_\pi}\right) V_s$$

$$A_v = \frac{V_o}{V_s} = \frac{-g_m V_\pi (r_o || R_c)}{V_\pi} \times \left(\frac{R_s + R_1 || R_2 || r_\pi}{r_\pi || R_1 || R_2}\right)$$

$$A_v = -g_m (r_o || R_c) X \left(\frac{r_\pi || R_1 || R_2}{R_s + R_1 || R_2 || r_\pi}\right)$$

$$A_v = -g_m (r_o || R_c) \left(\frac{R_i}{R_i + R_s}\right)$$

iii) Output resistance:

$$R_o = r_o || R_c$$

2.2.1. CE amplifier with unbypassed R_E:

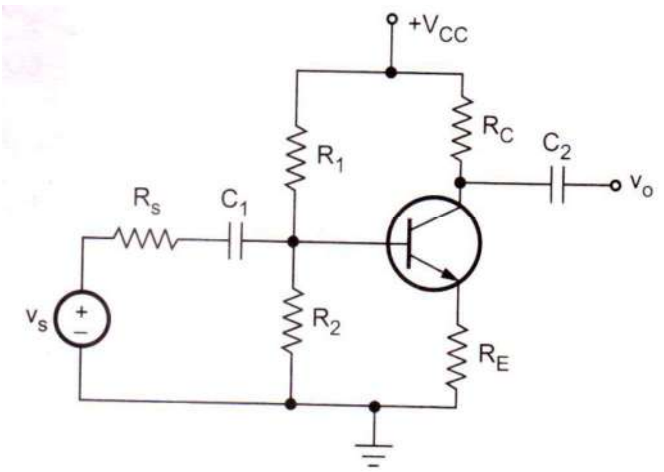


Fig 2.10. Common emitter amplifier with unbypassed R_E circuit

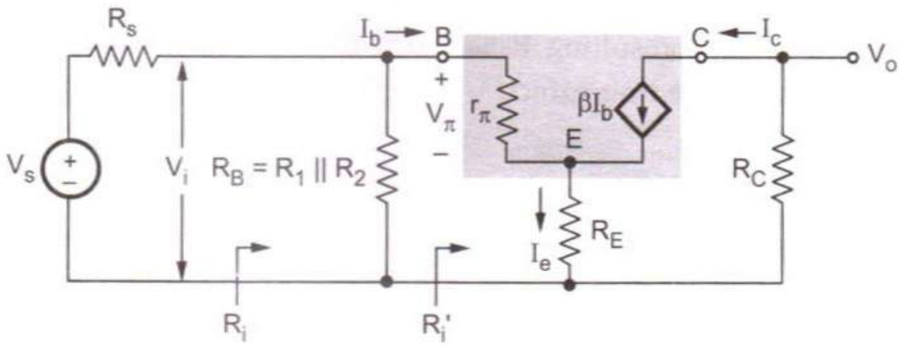


Fig 2.11. Small signal equivalent circuit for CE amplifier with unbypassed R_E circuit

i) Input resistance:

$$V_i = I_b r_\pi + (1+\beta) I_b R_E$$

$$= I_b [r_\pi + (1+\beta) R_E]$$

$$R_i^{'} = \frac{V_i}{I_b} = \frac{I_b [r_\pi + (1+\beta) R_E]}{I_b}$$

$$R_i^{'} = r_\pi + (1+\beta) R_E$$

$$R_i = R_1 \,||\, R_2 \,||\, R_i^{'} = R_B \,||\, R_i^{'}$$

ii) Voltage gain:

$$V_o = -\beta I_b R_c$$

$$A_v = \frac{V_o}{V_s} = \frac{V_o}{V_i} \times \frac{V_i}{V_s}$$

$$V_i = I_b R_i^{'}$$

$$V_i = \left(\frac{R_i}{R_i + R_s}\right) \quad [\because \text{voltage divider theorem}]$$

$$\frac{V_i}{V_s} = \frac{R_i}{R_i + R_s}$$

$$\frac{V_o}{V_i} = \frac{-\beta I_b R_c}{I_b [r_\pi + (1+\beta) R_E]}$$

$$A_v = \frac{-\beta R_c}{[r_\pi + (1+\beta)R_E]} X \left(\frac{R_i}{R_i + R_s}\right)$$

If $R_i \gg R_s$ & if $(1+\beta)R_E \gg r_\pi$,

$$A_v = \frac{-\beta R_c}{(1+\beta)R_E} X1$$

$$A_v \simeq \frac{-R_c}{R_E}$$

Advantages of unbypasssed R_E:

1. The voltage gain is less depended on the current gain β than the CE amplifier with bypassed R_E.
2. It also reduces the loading effect.

2.2.2. CE with partially bypassed R_E:

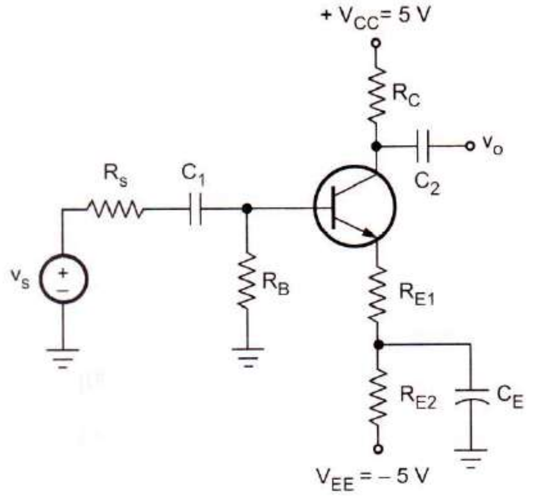


Fig 2.12. Common emitter amplifier with partially bypassed R_E circuit

2.3. Common collector amplifier (or) Emitter follower:

i) Input resistance:

$$R_i = R_B || R_i'$$

$$R_i' = \frac{V_i}{I_b}$$

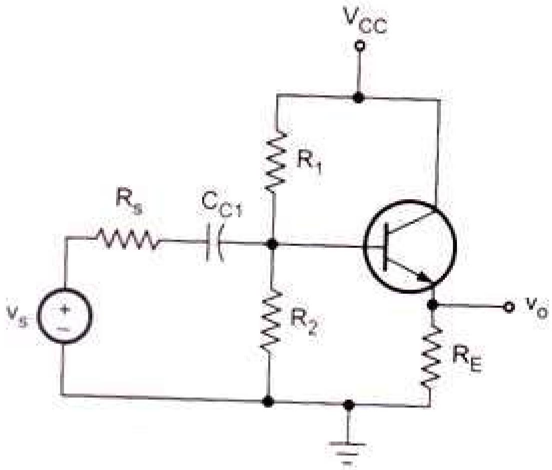


Fig 2.13. Common collector amplifier

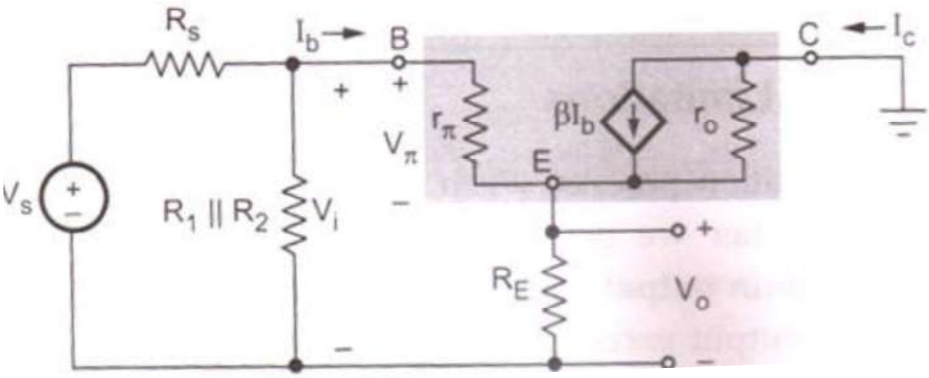


Fig 2.14. Small signal equivalent circuit of common collector amplifier

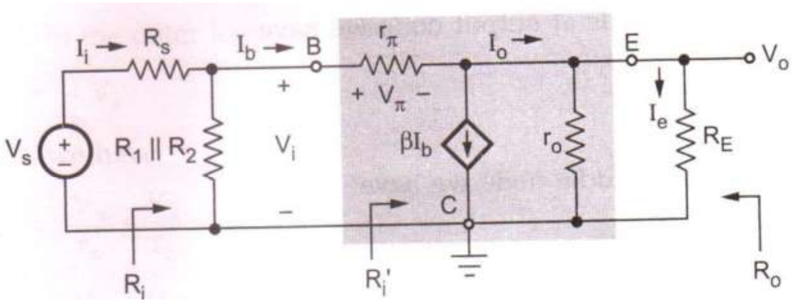


Fig 2.15. Small signal equivalent circuit of common collector amplifier with all signals grounds connected together

$$V_i = V_\pi + V_o$$

$$I_e = I_b + I_c$$

$$I_o = I_b + \beta I_b$$

$$= (1+\beta)I_b$$

$$V_o = (1+\beta)I_b\,(r_o || R_B)$$

$$V_1 = r_\pi I_b + (1+\beta)I_b(r_o || R_B)$$

$$= I_b[r_\pi + (1+\beta)(r_o || R_B)]$$

$$R_i' = r_\pi + (1+\beta)(r_o || R_B)$$

ii) Voltage gain:

$$A_v = \frac{V_o}{V_s} = \frac{V_o}{V_i} \times \frac{V_i}{V_s}$$

$$V_i = \left(\frac{R_i}{R_i + R_s}\right) V_s$$

$$\frac{V_i}{V_s} = \frac{R_i}{R_i + R_s}$$

$$A_v = \frac{(1+\beta)I_b(r_o || R_B)}{I_b[r_\pi + (1+\beta)(r_o || R_B)]} X \frac{R_i}{R_i + R_s}$$

$$A_v = \frac{(1+\beta)(r_o || R_B)}{r_\pi + (1+\beta)(r_o || R_B)}$$

iii) Current gain:

$$A_i = \frac{I_e}{I_1} = \frac{I_e}{I_1} \times \frac{I_o}{I_b} \times \frac{I_b}{I_i}$$

By current divider rule,

$$\frac{I_e}{I_o} = \frac{r_o}{r_o + R_E}$$

$$I_o = I_e = I_b + \beta I_b = I_b(1+\beta)$$

$$\frac{I_o}{I_b} = (1 + \beta)$$

Using current divider rule,

$$I_b = \frac{R_B}{R_B + R_i'} \times I_i$$

$$\frac{I_b}{I_i} = \frac{R_1 || R_2}{(R_1 || R_2) + R_i'}$$

$$A_i = \frac{I_e}{I_1} = \frac{I_e}{I_1} X \frac{I_o}{I_b} X \frac{I_b}{I_i}$$

$$= \left(\frac{r_o}{r_o + R_E}\right)(1 + \beta)\frac{R_1 || R_2}{(R_1 || R_2) + R_i'}$$

If $R_B \gg R_i'$ & $r_o \gg R_E$

$$A_i \simeq 1 + \beta$$

iv) Output resistance:

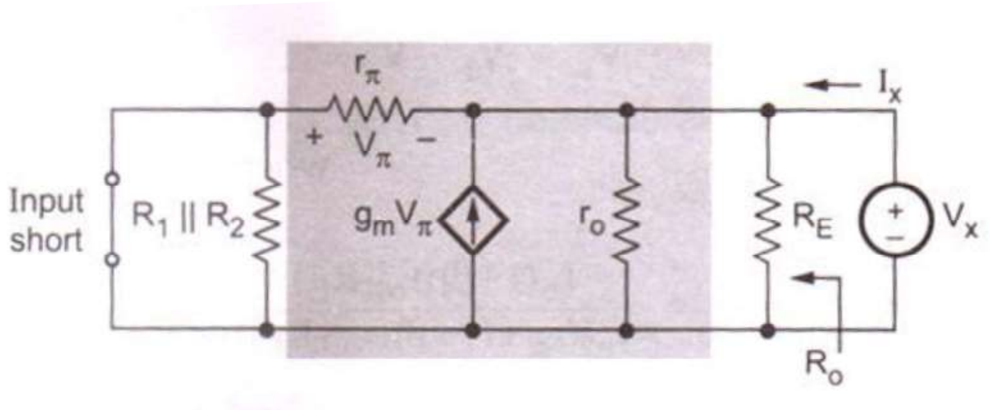


Fig 2.16. Small signal equivalent circuit to determine R_o

$$R_o = \frac{V_x}{I_x}$$

Apply KVL to the outer loop we have,

$$V_\pi + V_x = 0$$

$$V_\pi = -V_x$$

Apply KVL,

$$I_x + g_m V_\pi = \frac{V_x}{V_\pi} + \frac{V_x}{r_o} + \frac{V_x}{R_E}$$

$$\text{Sub } V_\pi = -V_x$$

$$I_x - g_m V_x = \frac{V_x}{r_\pi} + \frac{V_x}{r_o} + \frac{V_x}{R_E}$$

$$I_x = g_m V_x + \frac{V_x}{r_\pi} + \frac{V_x}{r_o} + \frac{V_x}{R_E}$$

$$I_x = V_x\left[g_m + \frac{1}{r_\pi} + \frac{1}{r_o} + \frac{1}{R_E}\right]$$

$$\frac{I_x}{V_x} = \frac{1}{R_o} = g_m + \frac{1}{r_\pi} + \frac{1}{r_o} + \frac{1}{R_E}$$

$$\frac{1}{R_o} = \left(g_m + \frac{1}{r_\pi}\right) + \frac{1}{r_o} + \frac{1}{R_E}$$

$$= \left(\frac{\beta + 1}{r_\pi}\right) + \frac{1}{r_o} + \frac{1}{R_E}$$

$$R_o = \frac{r_\pi}{\beta + 1} || r_o || R_E$$

2.4. Common base amplifier:

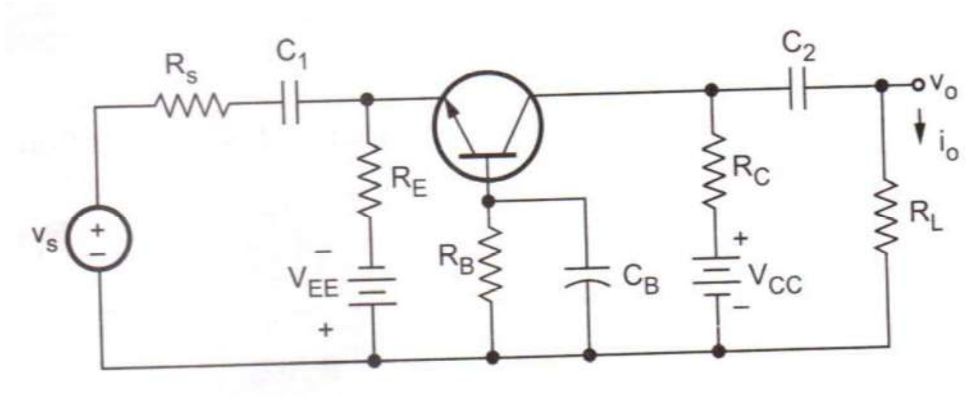


Fig 2.17. Common base amplifier circuit

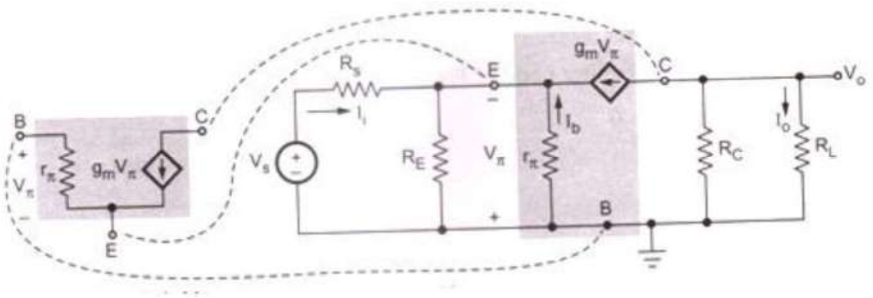


Fig 2.18. Simplified hybrid π model of npn transistor **Fig 2.19. Small signal equivalent circuit Common base amplifier**

i) Voltage gain (A_v):

$$A_v = \frac{V_o}{V_s}$$

$$V_o = -g_m V_\pi (R_c || R_L)$$

Apply KCL to the emitter side,

$$\frac{V_s}{R_s} + \frac{V_\pi}{R_s} + \frac{V_\pi}{R_E} + \frac{V_\pi}{r_\pi} + g_m V_\pi = 0$$

$$V_\pi \left[\frac{1}{R_s} + \frac{1}{R_E} + \frac{1}{r_\pi} + g_m\right] = -\frac{V_s}{R_s}$$

$$V_\pi \left[\frac{1}{R_s} + \frac{1}{R_E} + \frac{1+\beta}{r_\pi}\right] = -\frac{V_s}{R_s} \quad \because \beta = g_m r_\pi$$

$$V_\pi = -\frac{V_s}{R_s}\left[R_s || R_E || \left(\frac{r_\pi}{1+\beta}\right)\right]$$

Sub V_π in V_o,

$$V_o = -g_m \left[-\frac{V_s}{R_s}\left[R_s || R_E || \left(\frac{r_\pi}{1+\beta}\right)\right]\right](R_c || R_L)$$

$$A_v = \frac{V_o}{V_s} = \frac{g_{m(R_c || R_L)}}{R_s}\left[R_s || R_E || \left(\frac{r_\pi}{1+\beta}\right)\right]$$

As $R_s \to 0$,

$$A_v = \frac{V_o}{V_s} = g_m (R_c || R_L)$$

ii) Current gain:

Apply KCL to emitter node,

$$I_i + \frac{V_\pi}{R_E} + \frac{V_\pi}{r_\pi} + g_m V_\pi = 0$$

$$V_\pi\left[\frac{1}{R_E} + \frac{1}{r_\pi} + g_m\right] = -I_i$$

$$V_\pi\left[\frac{1}{R_E} + \frac{1+\beta}{r_\pi}\right] = -I_i$$

$$V_\pi = -I_i\left[R_E||\left(\frac{r_\pi}{1+\beta}\right)\right]$$

Using current divider rule output I_o,

$$I_o = -g_m V_\pi\left(\frac{R_c}{R_c + R_L}\right)$$

Sub V_π in I_o,

$$I_o = -g_m\left[-I_i\left[R_E||\left(\frac{r_\pi}{1+\beta}\right)\right]\right]\left(\frac{R_c}{R_c + R_L}\right)$$

$$A_i = \frac{I_o}{I_i} = \frac{g_m R_c}{R_c + R_L}\left[R_E||\left(\frac{r_\pi}{1+\beta}\right)\right]$$

If $R_E \to \infty, R_L \to 0$,

$$A_i = g_m\frac{r_\pi}{1+\beta} = \frac{\beta}{1+\beta} = \propto$$

where, $\propto$ −CB current gain

i) Input resistance (R_i):

$$R_i = R_E||R_i'$$

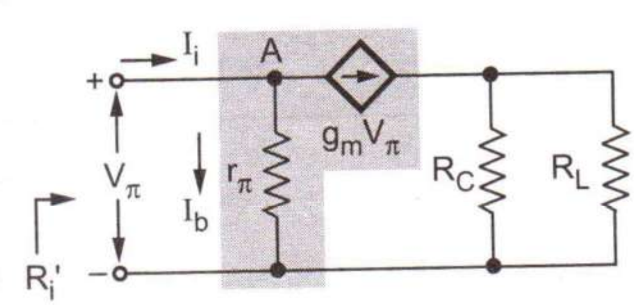


Fig 2.20. Small signal equivalent circuit to determine R_i

$$I_i = I_b + g_m V_\pi$$

$$= \frac{V_\pi}{r_\pi} + g_m V_\pi = V_\pi \left[\frac{1}{r_\pi} + g_m\right]$$

$$I_i = V_\pi \left(\frac{1+\beta}{r_\pi}\right)$$

$$R_i' = \frac{V_\pi}{I_i} = \frac{r_\pi}{1+\beta} = r_e$$

ii) Output resistance (R_o):

$$R_o = R_c$$

2.5. AC load line :

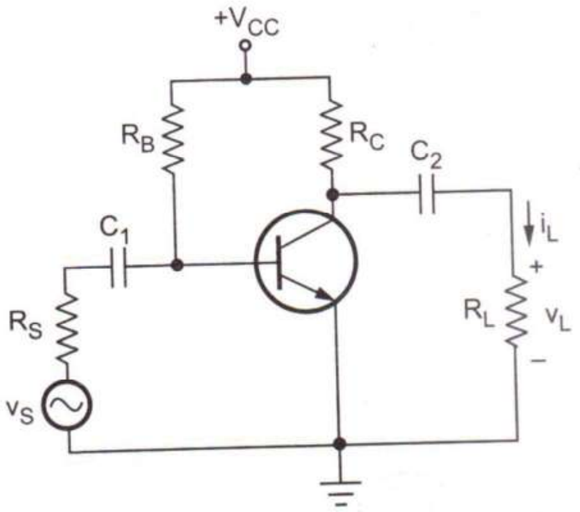


Fig 2.21. Common emitter amplifier circuit

For AC analysis,

1. Coupling & bypass capacitors act as a short circuit
2. Shorting V_{CC} & ground lines

$$V_{ce} = I_C R_{ac}$$

$$I_C = i_C - I_{CQ} \qquad V_{ce} = V_{CEQ} - v_{CE}$$

V_{ce} : ac collector to emitter voltage

I_C: ac collector current

$$V_{CEQ} - v_{CE} = [i_C - I_{CQ}]R_{ac}$$

where, i_C = Total instantaneous collector current

v_{CE} = Total instantaneous collector to emitter voltage

Rearranging the equation,

$$[i_C - I_{CQ}]R_{ac} = V_{CEQ} - v_{CE}$$

$$R_{ac}\, i_C - I_{CQ}\, R_{ac} = V_{CEQ} - v_{CE}$$

$$R_{ac}\, i_C = V_{CEQ} - v_{CE} - I_{CQ}\, R_{ac}$$

$$i_C = \frac{V_{CEQ}}{R_{ac}} - \frac{v_{CE}}{R_{ac}} + I_{CQ}$$

i)X axis: $i_C = 0$

$$0 = V_{CEQ} - V_{CE} + I_{CQ}\, R_{ac}$$

$$V_{CEmax} = V_{CEQ} + I_{CQ}\, R_{ac}$$

ii)Y axis: $v_{CE} = 0$

$$i_C = \frac{V_{CEQ}}{R_{ac}} + I_{CQ}$$

$$I_{cmax} = \frac{V_{CEQ}}{R_{ac}} + I_{CQ}$$

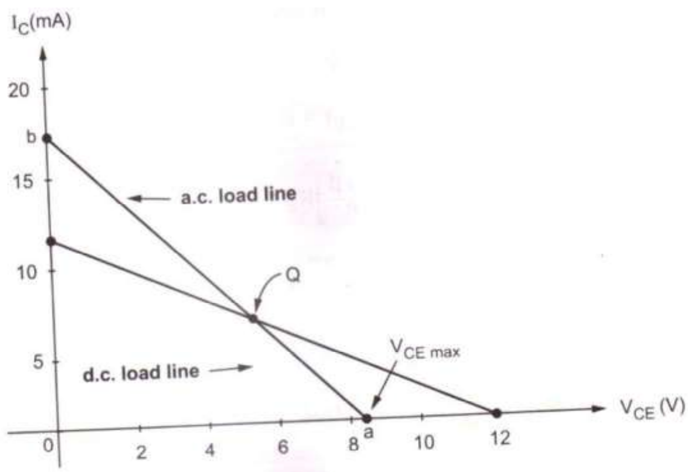


Fig 2.22. d.c. & a.c. load lines

2.6. Voltage swing limitations:

In the linear amplification process, when symmetrical sinusoidal signals are applied to the input of an amplifier we get amplified sinusoidal signals at the output. It is possible to obtain maximum output symmetrical swing that amplifier can provide using an ac load line. If the output exceeds this limit, a portion of the output signal will be clipped resulting signal distortion.

2.7. Differential amplifier:

The differential amplifier amplifies the difference between two voltage signals. Hence it is also called difference amplifier.

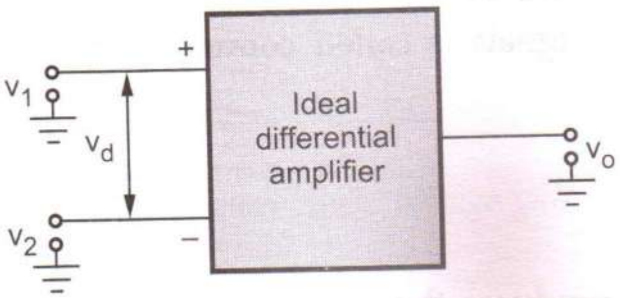


Fig 2.23. Ideal differential amplifier

$$V_d = V_1 - V_2$$

$$V_d \propto (V_1 - V_2)$$

i) Differential gain A_d:

$$V_o = A_d(V_1 - V_2)$$

where, A_d −constant of proportionality of Differential gain

$$V_o = A_d V_d$$

$$A_d = \frac{V_o}{V_d}$$

$$A_d = 20\log A_d \text{ in dB}$$

ii) Common mode gain A_{cm}:

Two inputs are equals,

$$V_{cm} = \frac{V_1 + V_2}{2}$$

$$V_o = A_{cm} V_{cm}$$

iii) CMRR (Common Mode Rejection Ratio):

It is defined as the ratio of the differential voltage gain A_d to common mode voltage gain A_{cm}.

$$CMRR = \left|\frac{A_d}{A_{cm}}\right| = \rho$$

2.8. BJT differential amplifier:

The transistorised differential amplifier basically uses the emitter biased circuits which are identical in characteristics. The two transistors Q_1 and Q_2 have exactly matched characteristics. The two collector resistances R_{C1} and R_{C2} are equal, emitters of Q_1 and Q_2 are connected together and biased by a constant current source I_Q.

The magnitudes of the $+V_{CC}$ and $-V_{EE}$ are also same. The differential amplifier can be obtained by using such two emitter biased circuits. The base B_1 of Q_1 is connected to the input 1 which is v_{b1} , while the base B_2 of Q_2 is connected to the input 2 which is v_{b2}. The supply voltages are measured with respect to ground.

The balanced output is taken between the collector C_1 of Q_1 and the collector C_2 of Q_2. Such an amplifier is called emitter coupled differential amplifier. The two collector resistances are same hence can be denoted as R_C.

The circuit operation in the two modes namely,

1. Differential mode operation
2. Common mode operation

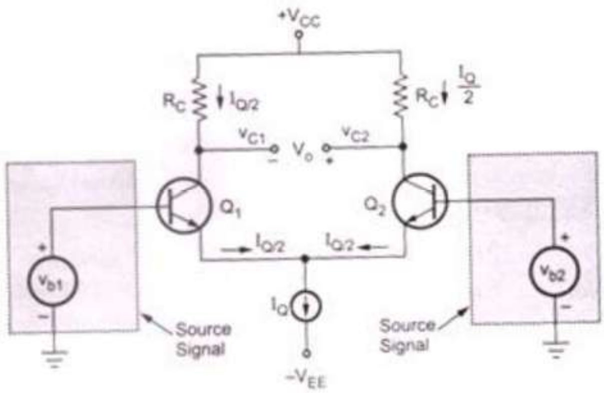


Fig 2.24. Dual input, balanced output differential amplifier

2.8.1. Differential mode operation:

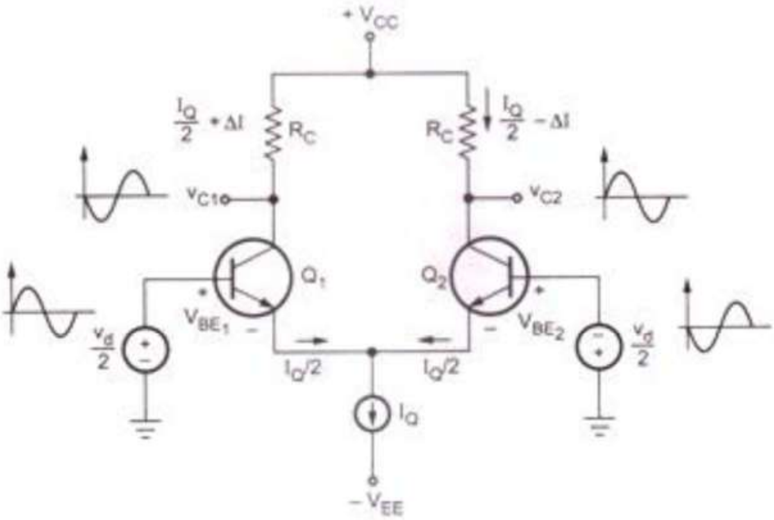


Fig 2.25. Differential mode operation

The two input signals which are same in magnitude but 180° out of phase.

$$V_{b1} = \frac{V_1}{2}, \qquad V_{b2} = \frac{-V_d}{2}$$

$$V_{cc} - \left(\frac{I_Q}{2} + \Delta I\right) R_c - V_{c1} = 0$$

$$V_{c1} = V_{cc} - \left(\frac{I_Q}{2} + \Delta I\right) R_c$$

$$V_{c2} = V_{cc} - \left(\frac{I_Q}{2} - \Delta I\right) R_c$$

$$V_o = V_{c2} - V_{c1}$$

$$= V_{cc} - \frac{I_Q}{2} R_c + \Delta I R_c - V_{cc} + \frac{I_Q}{2} R_c + \Delta I R_c$$

$$V_o = 2\Delta I R_c$$

2.8.2. Common mode operation:

$$V_{cc} - \frac{I_Q}{2} R_c - V_{c1} = 0$$

$$V_{c1} = V_{cc} - \frac{I_Q}{2} R_c$$

$$V_{c2} = V_{cc} - \frac{I_Q}{2} R_c$$

$$V_{c1} = V_{c2} = V_{cc} - \frac{I_Q}{2} R_c$$

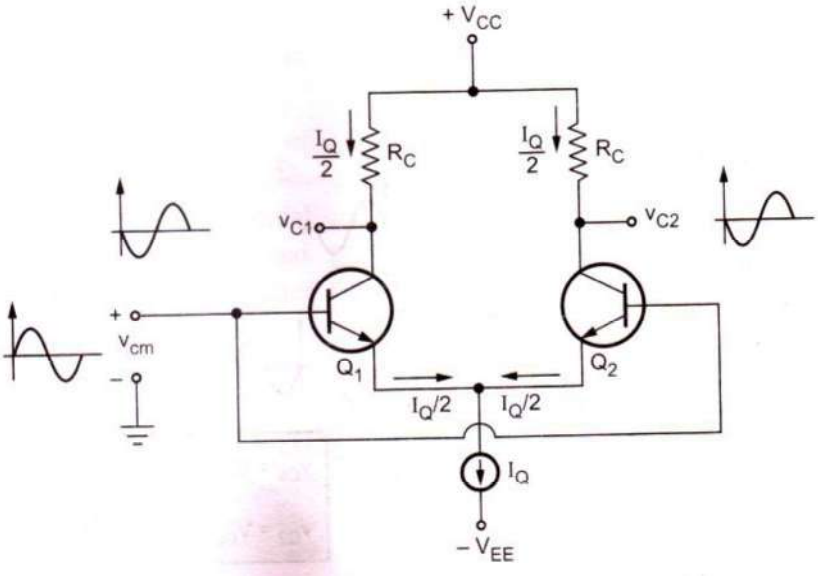


Fig 2.26. Common mode operation

2.8.3. Configuration of differential amplifier:

1. Dual input, balanced output differential amplifier
2. Dual input, unbalanced output differential amplifier
3. Single input, balanced output differential amplifier
4. Single input, unbalanced output differential amplifier

The differential amplifier uses two transistors in common emitter configuration. If output is taken between the two collectors it is called balanced output or double ended output. While if the output is taken between one collector with respect to ground it is called unbalanced output (or) single ended output.

If the signal is given to both the input terminals it is called dual input, while if the signal is given to only one input terminal and other terminal is grounded it is called single input or single ended input.

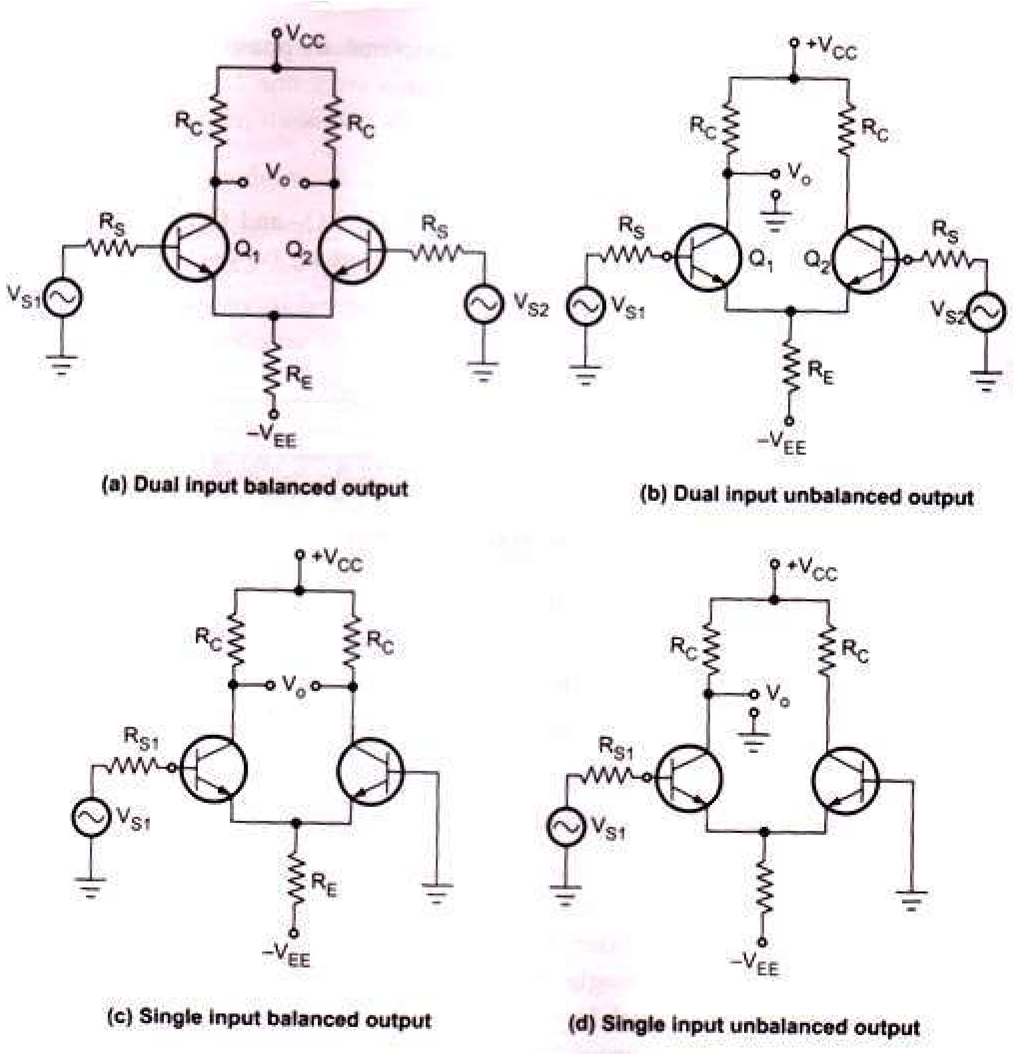


Fig 2.27. Configuration of differential amplifier

2.8.4. DC transfer characteristics:

To maintain the transfer characteristics, the following assumptions are made.

1. The current source circuit used with current I_Q has infinite output resistance.
2. The source resistances R_s in the base of transistors Q_1 & Q_2 are neglected.
3. The output resistance of each transistor is ∞.

Consider the dual input, balanced output differential amplifier circuit,

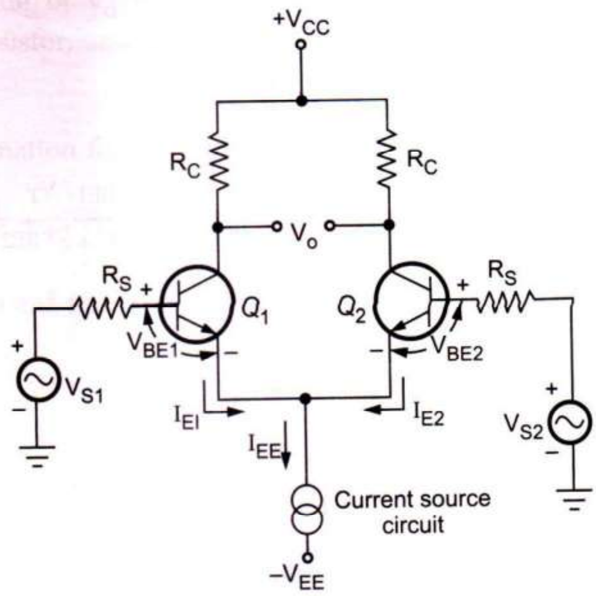


Fig 2.28. Differential amplifier circuit

For transistor, we can write,

$$i_c = I_s e^{V_{be}/V_T}$$

Where, I_s – reverse saturation current

V_{be} – base emitter voltage

V_T - voltage equivalent of temperature

For two transistors,

$$i_{c1} = I_s e^{V_{BE1}/V_T}$$

$$i_{c2} = I_s e^{V_{BE2}/V_T}$$

$$I_{s1} = I_{s2} = I_s$$

$$I_Q = i_{c1} + i_{c2}$$

$$I_Q = I_s\left[e^{V_{BE1}/V_T} + e^{V_{BE2}/V_T}\right]$$

Taking the ratio

$$\frac{i_{c1}}{I_Q} = \frac{I_s e^{V_{BE1}/V_T}}{I_s\left[e^{V_{BE1}/V_T} + e^{V_{BE2}/V_T}\right]}$$

$$= \frac{e^{V_{BE1}/V_T}}{e^{V_{BE1}/V_T} + e^{V_{BE2}/V_T}}$$

$$\frac{i_{c1}}{I_Q} = \frac{1}{1 + e^{V_{BE2}-V_{BE1}/V_T}}$$

Similarly,

$$\frac{i_{c2}}{I_Q} = \frac{1}{1 + e^{-(V_{BE2}-V_{BE1})/V_T}}$$

$$V_d = V_{BE1} - V_{BE2}$$

Sub V_d in $\frac{i_{c1}}{I_Q}$ & $\frac{i_{c2}}{I_Q}$,

$$i_{c1} = \frac{I_Q}{1 + e^{-V_d/V_T}},$$

$$i_{c2} = \frac{I_Q}{1 + e^{V_d/V_T}}$$

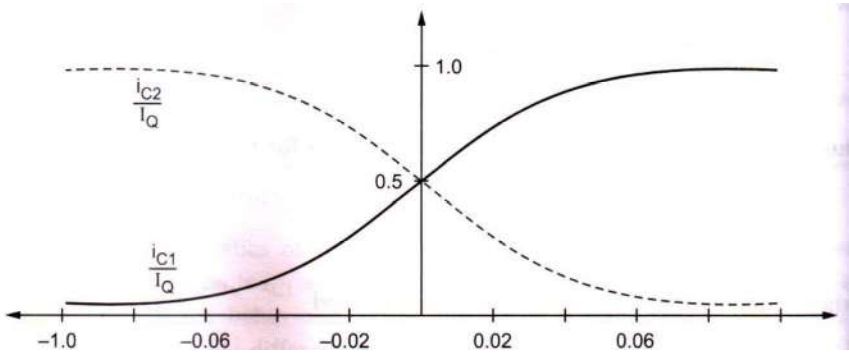


Fig 2.29. Normalized d.c. transfer characteristics of BJT differential amplifier

2.8.5. Small signal analysis of differential amplifier:

Assume that early voltage $V_A \rightarrow \infty$

Applying KCL to the V_e node,

$$\frac{V_{\pi1}}{r_\pi} + g_m V_{\pi1} + g_m V_{\pi2} + \frac{V_{\pi2}}{r_\pi} - \frac{V_e}{R_o} = 0 \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\frac{V_{\pi1} + g_m r_\pi V_{\pi1}}{r_\pi} + \frac{g_m r_\pi V_{\pi2} + V_{\pi2}}{r_\pi} = \frac{V_e}{R_o}$$

$$V_{\pi 1}\left(\frac{1+\beta}{r_\pi}\right)+V_{\pi 2}\left(\frac{1+\beta}{r_\pi}\right)=\frac{V_e}{R_o} \dots\dots\dots\dots\dots\dots (2)$$

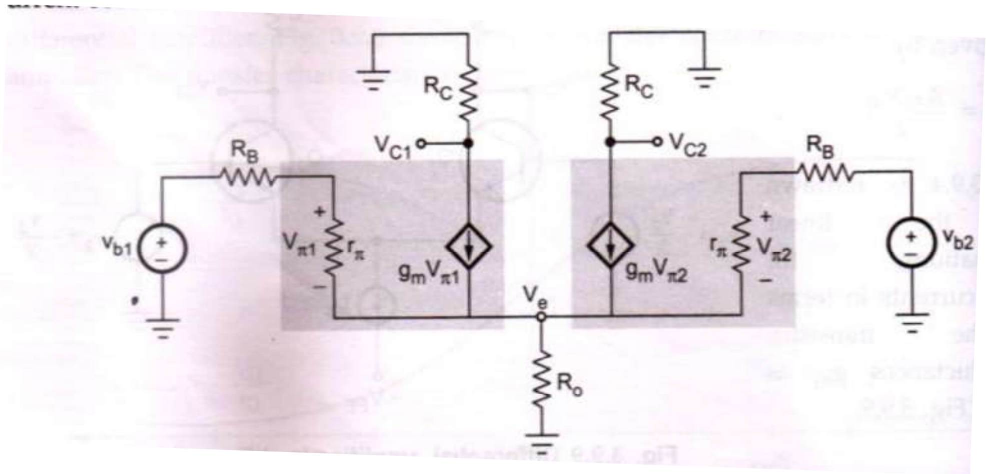


Fig 2.30. Small signal equivalent circuit of differential amplifier

From figure,

$$\frac{V_{\pi 1}}{r_\pi}=\frac{V_{b1}-V_e}{r_\pi+R_B}, \qquad \frac{V_{\pi 2}}{r_\pi}=\frac{V_{b2}-V_e}{r_\pi+R_B}$$

$$V_{\pi 1}=\frac{r_\pi(V_{b1}-V_e)}{r_\pi+R_B}, \qquad V_{\pi 2}=\frac{r_\pi(V_{b2}-V_e)}{r_\pi+R_B} \dots\dots\dots\dots\dots\dots (3)$$

Sub (3) in (2)

$$\frac{r_\pi(V_{b1}-V_e)}{r_\pi+R_B}\left(\frac{1+\beta}{r_\pi}\right)+\frac{r_\pi(V_{b2}-V_e)}{r_\pi+R_B}\left(\frac{1+\beta}{r_\pi}\right)=\frac{V_e}{R_o}$$

$$(1+\beta)\left[\frac{V_{b1}-V_e+V_{b2}-V_e}{r_\pi+R_B}\right]=\frac{V_e}{R_o}$$

Solving for V_e,

$$\frac{V_e}{R_o}+\frac{2V_e(1+\beta)}{r_\pi+R_B}=(1+\beta)\left[\frac{V_{b1}+V_{b2}}{r_\pi+R_B}\right]$$

$$V_e\left[\frac{(r_\pi+R_B+2R_o(1+\beta))}{R_o(r_\pi+R_B)}\right]=(1+\beta)\left[\frac{V_{b1}+V_{b2}}{r_\pi+R_B}\right]$$

$$V_e = \frac{(V_{b1} + V_{b2})(1+\beta)R_o}{r_\pi + R_B 2R_o(1+\beta)}$$

$$= \frac{(V_{b1} + V_{b2})(1+\beta)R_o}{R_o(1+\beta)\left[\frac{r_\pi + R_B}{R_o(1+\beta)} + 2\right]}$$

$$V_e = \frac{V_{b1} + V_{b2}}{2 + \frac{r_\pi + R_B}{R_o(1+\beta)}} \dots\dots\dots\dots\dots\dots\dots (4)$$

One sided output at the collector of Q_2 is given by,

$$V_o = V_{c2} = -(g_m V_{\pi 2})R_2$$

$$= -g_m r_\pi \left(\frac{V_{\pi 2}}{r_\pi}\right) R_c$$

From (3),

$$\frac{V_{\pi 2}}{r_\pi} = \frac{V_{b2} - V_e}{r_\pi + R_B}$$

$$V_o = -\beta R_c \left(\frac{V_{b2} - V_e}{r_\pi + R_B}\right) \dots\dots\dots\dots\dots\dots\dots (5)$$

Sub (4) in (5),

$$V_o = -\beta R_c \left[\frac{V_{b2} - \left[\frac{V_{b1} + V_{b2}}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}\right]}{r_\pi + R_B}\right]$$

$$V_o = \frac{-\beta R_c}{r_\pi + R_B}\left[\frac{-V_{b1} - V_{b2}\left(2 + \frac{r_\pi + R_B}{(1+\beta)R_o}\right)}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}\right]$$

$$= \frac{-\beta R_c}{r_\pi + R_B}\left[\frac{V_{b2}\left(-1 + 2 + \frac{r_\pi + R_B}{(1+\beta)R_o}\right) - V_{b1}}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}\right]$$

$$V_o = \frac{-\beta R_c}{r_\pi + R_B}\left[\frac{V_{b2}\left(1 + \frac{r_\pi + R_B}{(1+\beta)R_o}\right) - V_{b1}}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}\right] \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

For ideal current source $R_o \to \infty$

$$V_o = \frac{-\beta R_c}{r_\pi + R_B}\left(\frac{V_{b2} - V_{b1}}{2}\right) \because V_d = V_{b1} - V_{b2}$$

The differential mode gain,

$$A_d = \frac{V_o}{V_d} = \frac{\beta R_c}{2(r_\pi + R_B)} \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

If $R_B \to 0$

$$A_d = \frac{\beta R_c}{2r_\pi} = \frac{g_m R_c}{2} \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$V_{b1} = V_{cm} + \frac{V_d}{2}, \qquad V_{b2} = V_{cm} - \frac{V_d}{2} \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Sub (9) in (6),

$$V_o = \frac{-\beta R_c}{r_\pi + R_B}\left(\frac{\left(V_{cm} - \frac{V_d}{2}\right)\left(1 + \frac{r_\pi + R_B}{(1+\beta)R_o}\right) - \left(V_{cm} + \frac{V_d}{2}\right)}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}\right)$$

$$= \frac{-\beta R_c}{r_\pi + R_B}\left(\frac{V_{cm} - \frac{V_d}{2} + V_{cm}\left(\frac{r_\pi + R_B}{(1+\beta)R_o}\right) - \frac{V_d}{2}\left(\frac{r_\pi + R_B}{(1+\beta)R_o}\right) - V_{cm} - \frac{V_d}{2}}{\frac{2(1+\beta)R_o + (r_\pi + R_B)}{(1+\beta)R_o}}\right)$$

$$= \frac{-\beta R_c}{r_\pi + R_B}\left(\frac{-V_d + \left(V_{cm} - \frac{V_d}{2}\right)\left(\frac{r_\pi + R_B}{(1+\beta)R_o}\right)}{\frac{2(1+\beta)R_o + (r_\pi + R_B)}{(1+\beta)R_o}}\right)$$

$$= \frac{-\beta R_c}{r_\pi + R_B}\left(\frac{\frac{-V_d(1+\beta)R_o - \frac{V_d}{2}(r_\pi + R_B) + V_{cm}}{(1+\beta)R_o}}{\frac{2(1+\beta)R_o + (r_\pi + R_B)}{(1+\beta)R_o}}\right)$$

$$= \frac{-\beta R_c}{r_\pi + R_B}\left(\frac{-\frac{V_d}{2}[2(1+\beta)R_o + (r_\pi + R_B)]}{2(1+\beta)R_o + (r_\pi + R_B)}\right)$$

$$= \frac{\beta R_c V_d}{2(r_\pi + R_B)} - \frac{\beta R_c V_{cm}(r_\pi + R_B)}{(r_\pi + R_B)(r_\pi + R_B)\left[1 + \frac{2(1+\beta)R_o}{(r_\pi + R_B)}\right]}$$

$$V_o = \frac{\beta R_c V_d}{2(r_\pi + R_B)} - \frac{g_m R_c V_{cm}(r_\pi + R_B)}{1 + \frac{2(1+\beta)R_o}{(r_\pi + R_B)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

In general form, the output equation is given by,

$$V_o = A_d V_d + A_{cm} V_{cm} \ldots\ldots\ldots\ldots\ldots (11)$$

Comparing (10) & (11),

$$A_d = \frac{\beta R_c}{2(r_\pi + R_B)}, \quad A_{cm} = \frac{g_m R_c (r_\pi + R_B)}{1 + \frac{2(1+\beta)R_o}{(r_\pi + R_B)}}$$

Considering source resistors, $R_B = 0$,

$$A_d = \frac{\beta R_c}{2r_\pi} = \frac{g_m R_c}{2} = \frac{I_{CQ} R_c}{2V_T} \because g_m = \frac{\beta}{r_\pi}, g_m = \frac{I_{CQ}}{V_T}$$

$$A_d = \frac{I_Q R_c}{4V_T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$A_{cm} = \frac{-g_m R_c}{\frac{1 + 2(1+\beta)R_o}{r_\pi}} = \frac{\frac{-I_{CQ} R_c}{V_T}}{\frac{1 + 2(1+\beta)R_o}{r_\pi}}$$

$$= \frac{\frac{-I_{CQ} R_c}{V_T}}{1 + \frac{2(1+\beta)R_o I_{CQ} g_m}{V_T \beta}}$$

$$A_{cm} = \frac{-\frac{I_Q R_c}{2V_T}}{\frac{1 + (1+\beta)R_o I_Q}{V_T \beta}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

2.8.6. CMRR:

$$CMRR = \left|\frac{A_d}{A_{cm}}\right| = \frac{\frac{I_Q R_c}{4V_T}}{\frac{I_Q R_c}{2V_T}} \times \frac{1 + (1+\beta)R_o I_Q}{V_T \beta}$$

$$CMRR = \frac{1}{2}\left[1 + \frac{(1+\beta)R_o I_Q}{V_T \beta}\right] \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

2.9. Darlington amplifier:

The input impedance can be increased using two techniques:

1. Using direct coupling
2. Using Bootstrap technique

2.9.1. Darlington amplifier (or) direct coupling:

Cascaded connection of two emitter follower is called the Darlington connection. It improves the current gain.

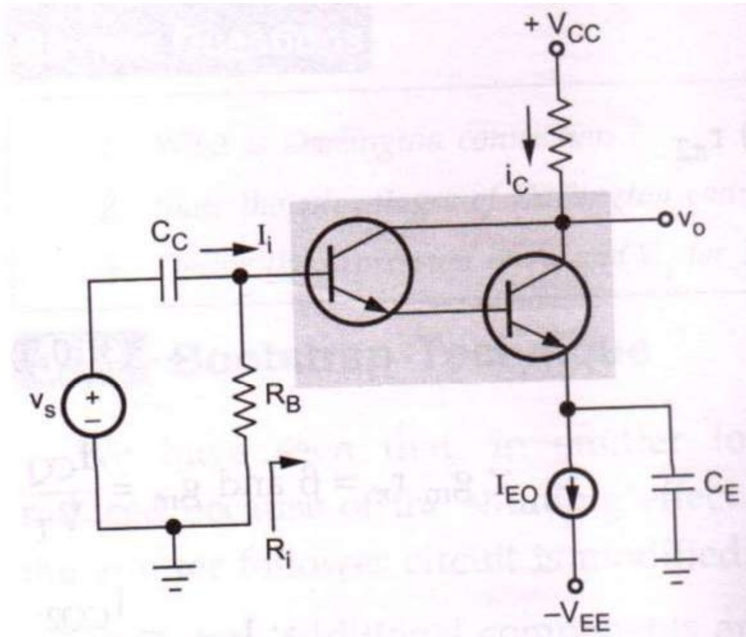


Fig 2.31. Darlington pair amplifier

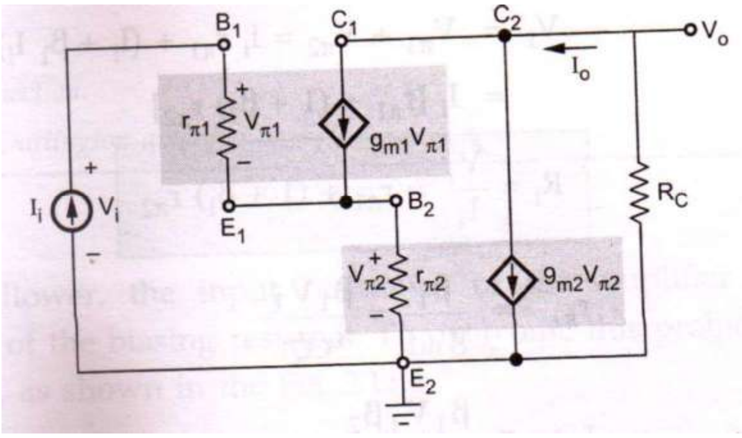


Fig 2.32. Small signal equivalent circuit

2.9.2. Small signal current gain:

$$V_{\pi 1} = I_i r_{\pi 1} \dots\dots\dots\dots\dots\dots (1)$$

Multiply by g_{m1},

$$g_{m1}V_{\pi 1} = g_{m1}I_i r_{\pi 1} = \beta_1 I_i \dots\dots\dots\dots\dots\dots (2)$$

$$V_{\pi 2} = (I_i + g_{m1}V_{\pi 1})r_{\pi 2} \dots\dots\dots\dots\dots\dots\dots (3)$$

Sub (1) in (3),

$$V_{\pi 2} = (I_i + \beta_1 I_i)r_{\pi 2} \dots\dots\dots\dots\dots\dots (4)$$

$$I_o = g_{m1}V_{\pi 1} + g_{m V_{\pi 2}}$$

$$= \beta_1 I_i + g_{m2}(I_i + \beta_1 I_i)$$

$$I_o = \beta_1 I_i + \beta_2(1 + \beta_1)I_i$$

$$A_i = \frac{I_o}{I_i} = \beta_1 + \beta_2(1 + \beta_1)$$

$$= \beta_1 + \beta_2 + \beta_1\beta_2 \approx \beta_1\beta_2 \dots\dots\dots\dots\dots\dots (5)$$

2.9.3. Input resistance:

$$R_i = \frac{V_i}{I_i} \dots\dots\dots\dots\dots\dots\dots\dots (6)$$

$$V_i = V_{\pi 1} + V_{\pi 2}$$

$$= I_i r_{\pi 1} + (I_i + \beta_1 I_i) r_{\pi 2}$$

$$= I_i [r_{\pi 1} + (1 + \beta_1) r_{\pi 2}]$$

$$R_i = \frac{V_i}{I_i} = r_{\pi 1} + (1 + \beta_1) r_{\pi 2} \ldots\ldots\ldots\ldots\ldots (7)$$

$$r_{\pi 1} = \frac{\beta_1}{g_{m1}} = \frac{\beta_1 V_T}{I_{CQ1}}$$

$$r_{\pi 1} = \frac{\beta_1 V_T \beta_2}{I_{CQ2}}$$

$$I_{CQ1} \approx \frac{I_{CQ2}}{\beta_2}$$

$$V_{\pi 1} = \beta_1 \left(\frac{\beta_2 V_T}{I_{CQ2}}\right) = \beta_1 r_{\pi 2}$$

$$R_i = r_{\pi 1} + (1 + \beta_1) r_{\pi 2}$$

$$= \beta_1 r_{\pi 2} + (1 + \beta_1) r_{\pi 2}$$

$$\approx 2\beta_1 r_{\pi 2} \ldots\ldots\ldots\ldots\ldots (8)$$

Equation (8) shows that the input resistance of a Darlington pair is large, because of the β multiplication.

2.10. Bootsrap technique:

In emitter follower, the input resistance of the amplifier is reduced because of the shunting effect of the biasing resistors. To overcome this problem the emitter follower circuit is modified.

1. Two additional components are used, resistance R_s and capacitance C.
2. The capacitor is connected between the emitter & the junction of R_1, R_2 &R_3.

For d.c. signal, capacitor C acts as a open circuit & therefore resistance R_1, R_2 and R_3 providess necessary biasing to keep transistor in the active region.

For a.c. signal, the capacitor acts as a short circuit. Its value is chosen such that it provides very low reactance nearly short circuit at lowest operating frequency. Hence, for a.c., the bottom of R_3 is effectively connected to the output (the emitter), whereas the top of R_3 is at the input (the base). In other words, R_3 is connected between input node & output node.

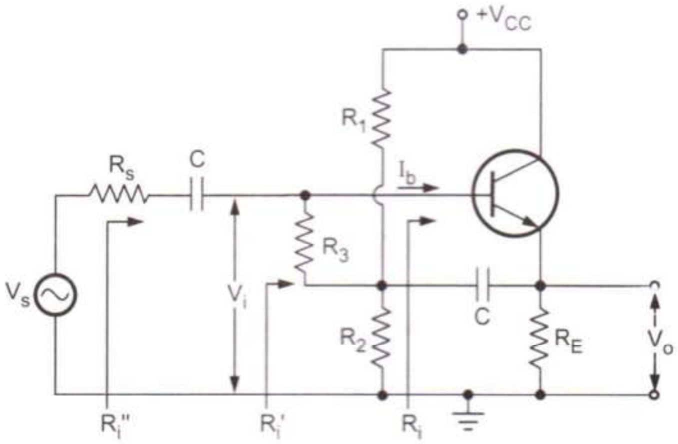


Fig 2.33. Bootsrap emitter follower.

For such connection effective input resistance is given by the Miler's theorem. The theorem says that the impedance between the two nodes can be resolved into two components, one from each node to ground. The two components are:

$$\frac{z}{1-k} \;\&\; \frac{z.k}{k-1}$$

In our case R_3 is the impedance between output voltage and input voltage and K is the voltage gain,

$$A_v = \frac{V_o}{V_i}$$

There are,

$$R_{M1} = \frac{R_3}{1 - A_v}$$

$$R_{M2} = \frac{R_3 A_v}{A_v - 1}$$

Since, for an emitter follower, A_v approaches unity, then R_{M2} becomes extremely large.

$$R_i' = R_M || R_i$$

When $A_v \rightarrow 1$ is called bootsrapping. The effective load on the emitter follower can be given as,

$$\therefore R_{L\,eff} = R_E || R_1 || R_2 || R_{M2}$$

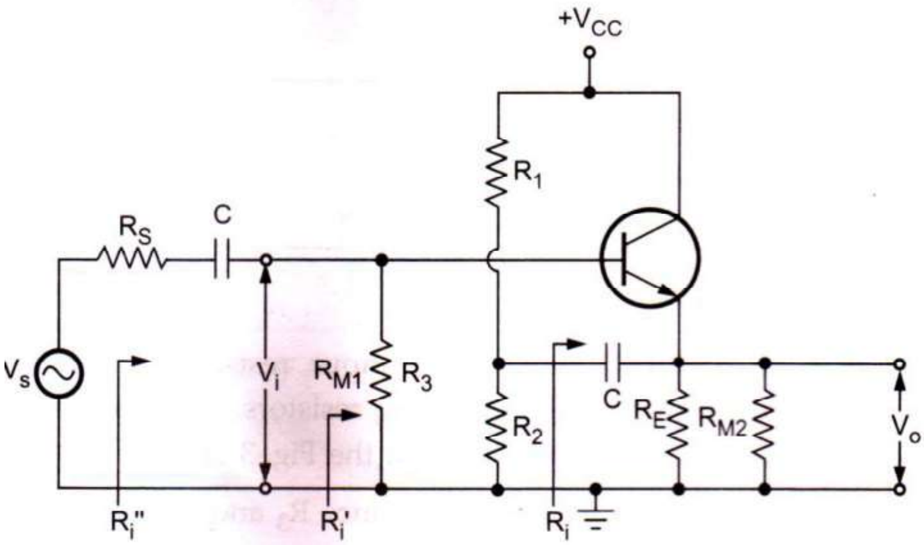


Fig 2.34. Bootsrap circuit using Miller's theorem

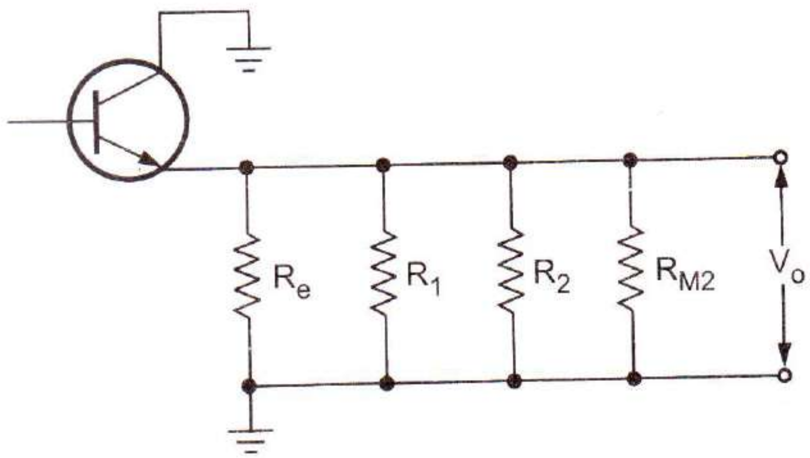


Fig 2.35. Effective load resistance $R_{L\,eff}$

The resistance R_{M2} is very large and hence it is often neglected.

$$\therefore R_{L\,eff} = R_E || R_1 || R_2$$

2.11. Multistage amplifiers:

Cascading number of amplifier stages known as multistage amplifier.

2.11.1. Cascaded amplifier:

The output of the first stage is connected to the input of the second stage.

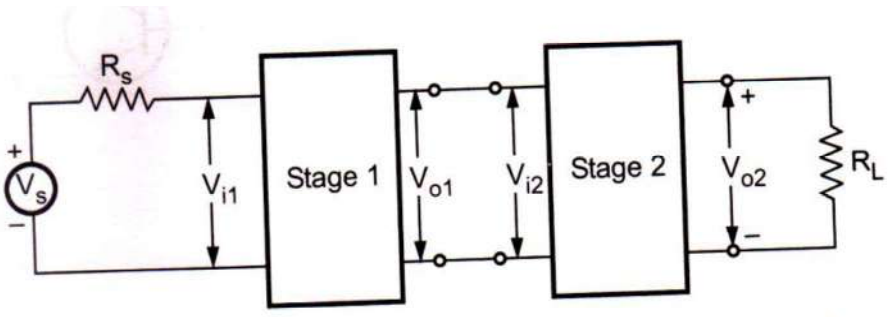


Fig 2.36. Block diagram of two stage cascade amplifier

Overall voltage gain,

$$A_v = \frac{V_{o2}}{V_{i1}} = \frac{V_{o2}}{V_{i2}} \times \frac{V_{i2}}{V_{i1}}$$

$$V_{o1} = V_{o2}$$

$$A_v = \frac{V_{o2}}{V_{i2}} X \frac{V_{o1}}{V_{i2}} = A_{v1} A_{v2}$$

The voltage gain of multistage amplifier is the product of voltage gain of the individual stages.

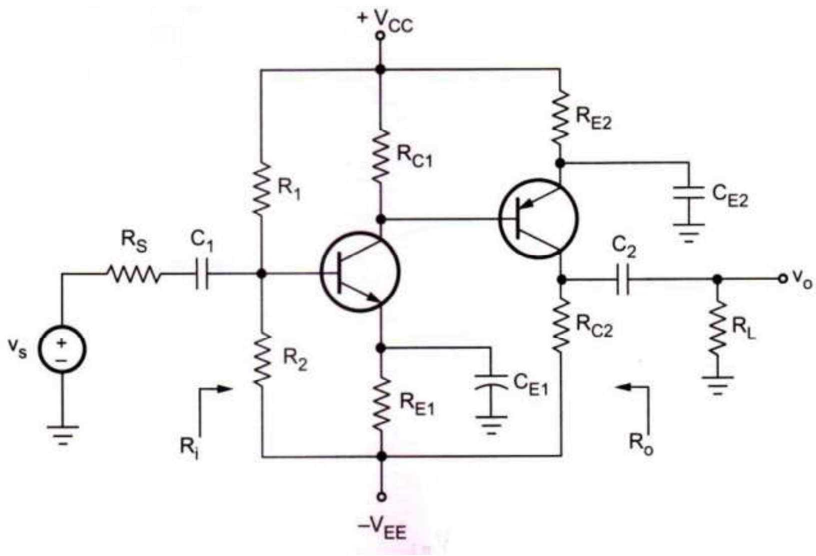


Fig 2.37. Two stage CE amplifier

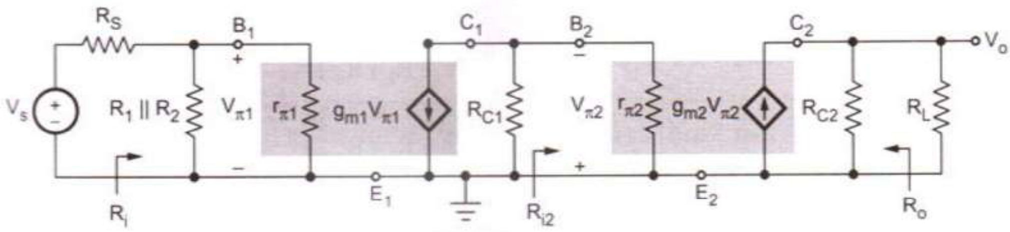


Fig 2.38. Small signal equivalent circuit

Stage 2:

$$\text{Input resistance, } R_{i2} = r_{\pi 2}$$

$$\text{Voltage gain} = \frac{V_o}{V_{\pi 2}}$$

$$V_o = g_{m2}V_{\pi 2}(R_{c2}||R_L)$$

$$\frac{V_o}{V_{\pi 2}} = g_{m2}(R_{c2}||R_L)$$

$$\text{Input resistance, } R_{i1} = R_i = R_B||r_{\pi 1}$$

$$\text{Voltage gain, } A_v = \frac{V_{\pi 2}}{V_{\pi 1}}$$

$$V_{\pi 2} = g_{m1}V_{\pi 1}(R_{i1})$$

$$= g_{m1}V_{\pi 1}(R_{c1}||R_{i2})$$

$$= g_{m1}V_{\pi 1}(R_{c1}||r_{\pi 2})$$

$$\frac{V_{\pi 2}}{V_{\pi 1}} = g_{m1}(R_{c1}||r_{\pi 2})$$

Applying voltage divider rule,

$$V_{\pi 1} = \frac{R_1}{R_1 + R_s} V_s$$

i) Overall voltage gain:

$$A_v = \frac{V_o}{V_s} = \frac{V_o}{V_{\pi 2}} X \frac{V_{\pi 2}}{V_{\pi 1}} X \frac{V_{\pi 1}}{V_s}$$

$$= g_{m2}(R_{c2}||R_L)g_{m1}(R_{c1}||r_{\pi 2})\left(\frac{R_1}{R_1 + R_s}\right)$$

$$A_v = g_{m1} g_{m2} (R_{c2} || R_L)(R_{c1} || r_{\pi 2}) \left(\frac{R_1}{R_1 + R_s} \right)$$

ii) Output resistance:

$$R_o = R_{c2}$$

2.11.2. Cascode amplifier

The cascade amplifier consists of a common emitter amplifier stage in series with a CB amplifier stage.

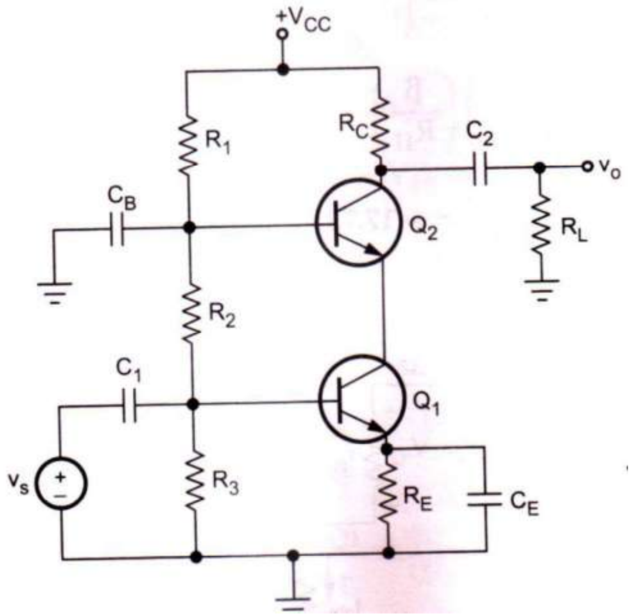


Fig 2.39. CE-CB Cascode amplifier

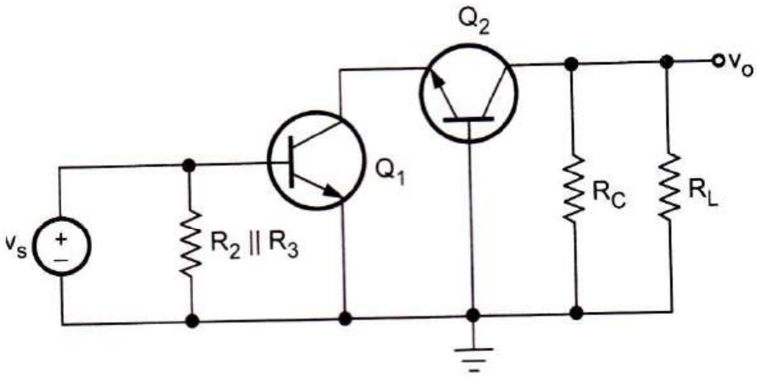


Fig 2.40. a.c. equivalent circuit

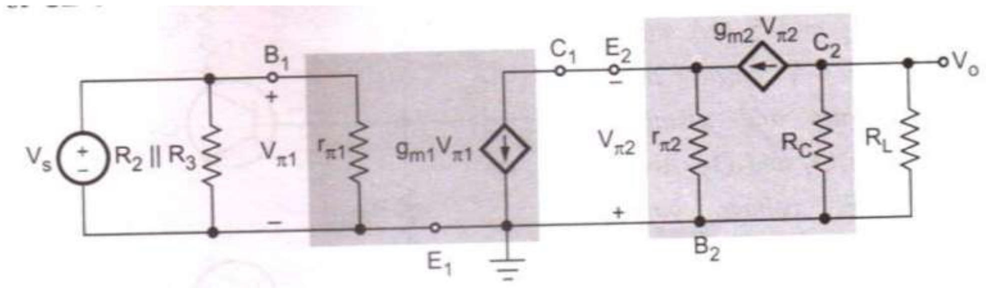


Fig 2.41. Small signal equivalent circuit of CE-CB Cascode amplifier

$$V_s = V_{\pi 1}$$

KCL to the E_2,

$$g_{m1}V_{\pi 1} = \frac{V_{\pi 2}}{r_{\pi 2}} + g_{m2}V_{\pi 2}$$

$$g_{m1}V_s = \frac{V_{\pi 2}}{r_{\pi 2}} + g_{m2}V_{\pi 2}$$

$$g_{m1}V_s = \frac{V_{\pi 2} + \beta_2 V_{\pi 2}}{r_{\pi 2}}$$

$$g_{m1}V_s = \frac{V_{\pi 2}(1+\beta_2)}{r_{\pi 2}}$$

$$V_{\pi 2} = \frac{r_{\pi 2}}{1+\beta_2}(g_{m1}V_s)$$

$$V_o = (-g_{m2}V_{\pi 2})(R_c|\,|\,R_L)$$

Sub $V_{\pi 2}$ in this equation,

$$V_o = -g_{m2}(g_{m1}V_s)\left(\frac{r_{\pi 2}}{1+\beta_2}\right)(R_c|\,|\,R_L)$$

$$A_v = -g_{m1}\left(\frac{g_{m1}r_{\pi 2}}{1+\beta_2}\right)(R_c|\,|\,R_L)$$

$$A_v \cong -g_m(R_c|\,|\,R_L)$$

2.12. Large signal amplifiers:

2. 12.1. Class A amplifiers:

The power amplifier is said to be a class A amplifier if the Q point and the input signal are selected such that the output signal is obtained for a full input cycle.

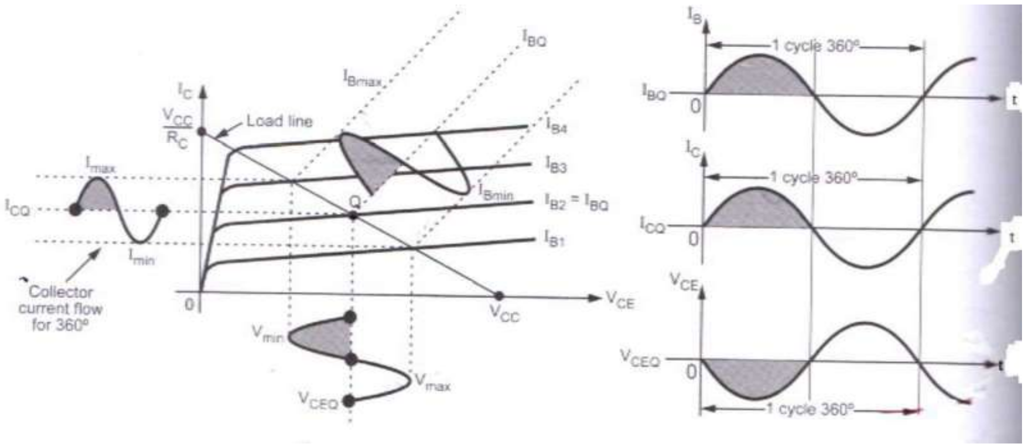


Fig 2.42. Waveforms representing class A operation

For this class, position of the Q point is approximately a the midpoint of the d.c load line. Here signal is faithfully reproduced, at the output, without any distortion. This is an important feature of a class A operation. The efficiency of a class A operation is very small.

2.12.2. Class B amplifiers:

The power amplifier is said to be a class B amplifier if the Q point and the input signal are selected such that the output signal is obtained only for one half cycle for a full input cycle. For this operation, the Q point is shifted on X-axis i.e) transistor is biased to cut-off.

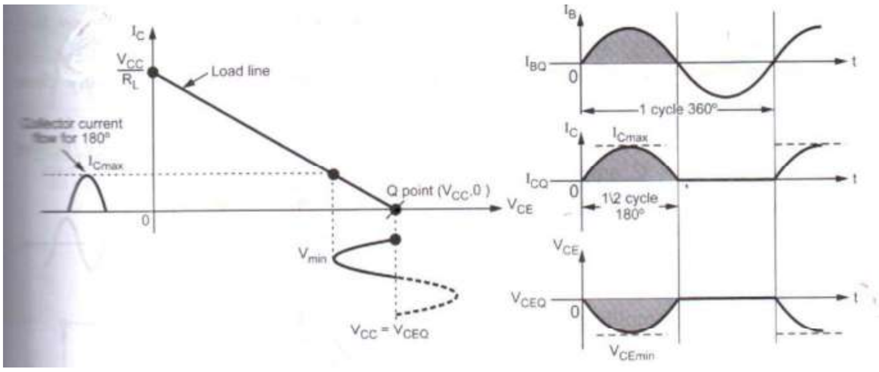


Fig 2.43. Waveforms representing class B operation

As only a half cycle is obtained a the input, for full input cycle, the output signal is distorted in this mode of operation. The efficiency of class class B operation is much higher than the class A operation.

2.12.3. Class C amplifiers:

The power amplifier is said to be a class C amplifier if the Q point and the input signal are selected such that the output signal is obtained for less than a half cycle, for a full input cycle. For this operation, the Q point is to be shifted below X-axis. But the efficiency of this class of operation is much higher and can reach very close to 100%.

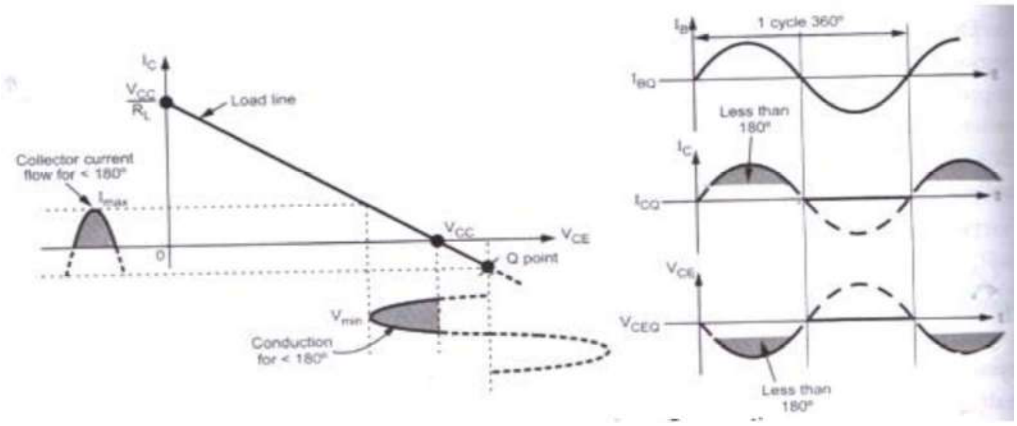


Fig 2.44. Waveforms representing class C operation

2.13. Analysis of class A amplifiers:

The class A amplifiers are further classified as directly coupled and transformer coupled amplifiers. In directly coupled type, the load is directly connected in the collector circuit. While in the transformer coupled type, the load is coupled to the collector using the transformer called an output transformer. Let us study in detail the various aspects of the two types of Class A amplifiers.

2.13.1. Series fed, directly coupled Class A amplifier:

The difference between small signal version of this circuit is that the signals handled by this large signal circuit are of the order of few volts. Similarly the transistor used, is a power transistor. The value of R_B is selected in such a way that the Q point lies at the centre of the d.c load line.

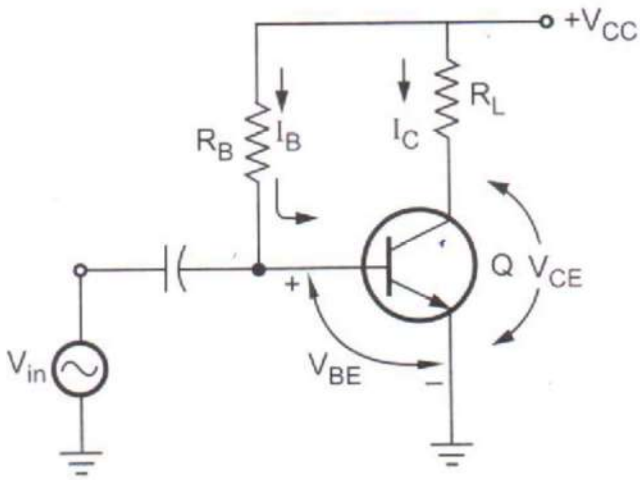


Fig 2.45. Large signal class A amplifier

The circuit represents the directly coupled Class A amplifier as the load resistance is directly connected in the collector circuit. Most of the times the load is a loudspeaker, the impedance of which varies from 3 to 4 ohms to 16 ohms. The beta of the transistor used is less than 100.

Key point: This is called direcly coupled as the load R_L is directly connected in the collector circuit of power transistor. The overall circuit handles large power, in the range of few to tens of watts without providing much voltage gain.

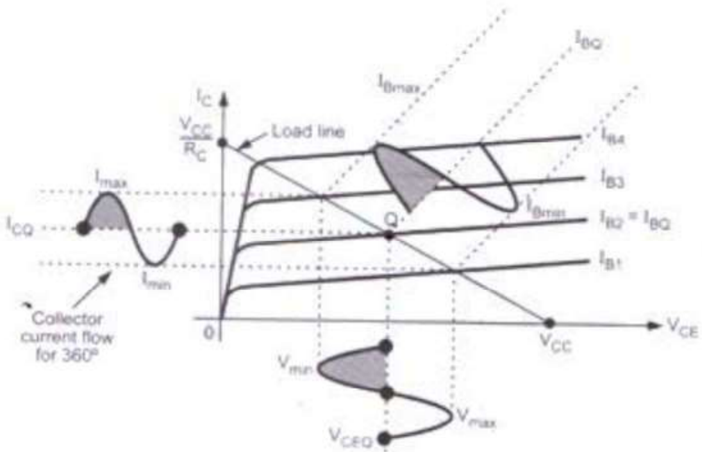


Fig 2.46. Classical representation of class A amplifier

Applying Kirchoff's voltage law to the circuit,

$$V_{cc} = I_c R_L + V_{CE}$$

$$I_c R_L = -V_{CE} + V_{cc}$$

$$I_c = \left[-\frac{1}{R_L}\right] V_{CE} + \frac{V_{cc}}{R_L}$$

The slope of the load line is $-\frac{1}{R_L}$ while the Y-intercept is $\frac{V_{cc}}{R_L}$. The change is because the collector resistance R_C is named as load resistance R_L in this circuit. The Q point is adjusted approximately at the centre of the load line.

i) D.C Operation:

The collector supply voltage V_{CC} and load resistance R_B decides the d.c base-bias current I_{BQ}. The expression is obtained applying KVL to the B-E loop with VBE=0.7 V.

$$I_{BQ} = \frac{V_{cc} - 0.7}{R_B}$$

The corresponding collector current is then,

$$I_{CQ} = \beta I_{BQ}$$

From the equation (1) the corresponding collector to emitter voltage is,

$$V_{CEQ} = V_{CC} - I_{CQ} R_L$$

Hence the Q point can be defined as Q (V_{CEQ}, I_{CQ}).

ii) D.C power input:

The d.c power input is provided by the supply. With no a.c input signal, the d.c current drawn is the collector bias current I_{CQ}. Hence d.c power input is,

$$P_{DC} = V_{CC} I_{CQ}$$

It is important to note that even if a.c input signal is applied, the average current drawn from the d.c supply remains same. Hence equation (5) represents d.c power input to the class A series fed amplifier.

iii) A.C operation:

When an input a.c signal is applied, the base current varies sinusoidally. Assuming that the nonlinear distortion is absent, the nature of the collector current and collector to emitter voltage also vary sinusoidally.

The output current i.e. collector current varies around its quiescent value while the output voltage i.e. collector to emitter voltage varies around its quiescent value. The varying output voltage and output current deliver an a.c power to the load.

iv) A.C Power Output:

V_{min} = minimum instantaneous value of the collector (output) voltage

V_{max} =maximum instantaneous value of the collector (output) voltage

V_{pp} = peak to peak value of a.c output voltage across the load

$$V_{pp} = V_{max} - V_{min}$$

Now V_m = Amplitude (peak) of a.c output voltage

$$V_m = \frac{V_{pp}}{2} = \frac{V_{max} - V_{min}}{2}$$

Similarly we can write for the output current as,

I_{min} = minimum instantaneous value of the collector (output) current

I_{max} = maximum instantaneous value of the collector (output) current

I_{pp} = peak to peak value of a.c output (load) current

$$I_{pp} = I_{max} - I_{min}$$

Now I_m = amplitude (peak) of a.c output (load) current

$$I_m = \frac{I_{pp}}{2} = \frac{I_{max} - I_{min}}{2}$$

Hence the r.m.s values of alternating output voltage and current can be obtained as,

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

Hence we can write,

$$V_{rms} = I_{rms} R_L$$

$$\text{i.e. } V_m = I_m R_L$$

The a.c power delivered by the amplifier to the load can be expressed by using r.m.s values, maximum i.e. peak values and peak to peak values of output values of output voltage and current.

a) Using r.m.s values,

$$P_{ac} = V_{rms} I_{rms}$$

$$P_{ac} = I_{rms}^2 R_L$$

$$P_{ac} = \frac{V_{rms}^2}{R_L}$$

b) Using peak values,

$$P_{ac} = V_{rms} I_{rms} = \frac{V_m}{\sqrt{2}} X \frac{I_m}{\sqrt{2}}$$

$$\therefore \quad P_{ac} = \frac{V_m I_m}{2}$$

$$\text{or} \quad P_{ac} = \frac{I_m^2 R_L}{2}$$

$$\text{or} \quad P_{ac} = \frac{V_m^2}{2R_L}$$

c) Using peak to peak values,

$$P_{ac} = \frac{V_m I_m}{2} = \frac{\left(\frac{V_{pp}}{2}\right)\left(\frac{I_{pp}}{2}\right)}{2}$$

$$P_{ac} = \frac{V_{pp} I_{pp}}{8}$$

$$\text{or} \quad P_{ac} = \frac{I_{pp}^2 R_L}{8}$$

$$\text{or} \quad P_{ac} = \frac{V_{pp}^2}{8R_L}$$

But as $V_{pp} = V_{max} - V_{min}$ and $I_{pp} = I_{max} - I_{min}$.

The a.c power can be expressed as ,

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

v) Efficiency:

The efficiency of an amplifier represents the amount of a.c power delivered or transferred to the load, from the d.c source i.e. accepting the d.c power input.

The generalized expression for an efficiency of an amplifier is,

$$\%\eta = \frac{P_{ac}}{P_{dc}} X100$$

$$\%\eta = \frac{(V_{max} - V_{min})(I_{max} - I_{min})}{8V_{CC} I_{CQ}} X100$$

The efficiency is also called conversion efficiency of an amplifier.

vi) Maximum efficiency:

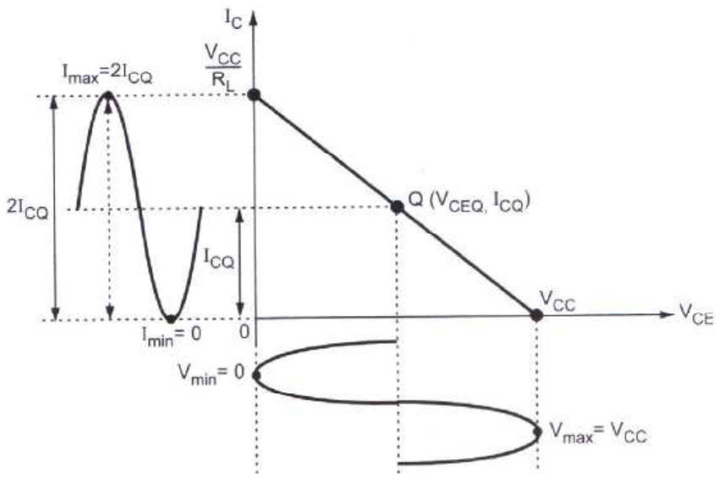


Fig 2.47. Maximum voltage & current swings

For maximum efficiency calculation, assume maximum swings of both the output voltage and the output current.

$$V_{max} = V_{cc} \text{ and } V_{min} = 0$$

$$I_{max} = 2I_{CQ} \text{ and } I_{min} = 0$$

$$\% \eta_{max} = \frac{(V_{CC} - 0)(2I_{CQ} - 0)}{8V_{CC} I_{CQ}} X100 = \frac{2V_{CC} I_{CQ}}{8V_{CC} I_{CQ}} X100 = = 25\%$$

Key point: Thus the maximum efficiency possible in case of directly coupled series fed class A amplifier is just 25%. This maximum efficiency is an ideal value. For a practical circuit, it is much less than 25% , of the order of 10 to 15%. Very low efficiency is the biggest disadvantage of class A amplifier.

vii) Power dissipation:

Power dissipation in large signal amplifier is so large. The amount of power that must be dissipated by the transistor is the difference between the d.c power input P_{dc} and the a.c power delivered to the load P_{ac}.

$$\text{Power dissipation, } P_d = P_{DC} - P_{ac}$$

The maximum power dissipation occurs when there is zero a.c input signal. When a.c input is zero, the a.c power output is also zero. But transistor operates at quiescent condition, drawing d.c input power from the supply equal to $V_{CC}I_{CQ}$. this entire power gets dissipated in the form of heat. The d.c power input without a.c input signal is the maximum power dissipation.

$$(P_d)max = V_{CC} I_{CQ}$$

Key point: Thus value of maximum power dissipation decides the maximum power dissipation rating of the transistor to be selected for the amplifier.

viii) Advantages and disadvantages:

The advantages of directly coupled class A amplifier can be stated as,

1. The circuit is simple to design and to implement.
2. The load is connected directly in the collector circuit. Hence the output transformer is not necessary. This makes the circuit cheaper.
3. Less number of components required as load is directly coupled.

The disadvantages are,

1. The load resistance is directly connected in collector and carries the quiescent collector current. This causes considerable wastage of power.
2. Power dissipation is more. Hence power dissipation arrangements like heat sink are essential.
3. The output impedance is high hence circuit cannot be used for low impedance loads, such as loudspeakers.
4. The efficiency is very poor, due to large power dissipation.

2.13.2. Transformer coupled class A amplifier:

For maximum power transfer to the load, the impedance matching is necessary. For loads like loudspeaker, having low impedance values, impedance matching is difficult using directly coupled amplifier circuit. This is because loudspeaker resistance is in the range of 3 to 4 ohms to 16 ohms while the output impedance of series fed directly coupled class A amplifier is very much high. This problem can be eliminated by using a transformer to deliver power to the load.

Key point: The transformer is called an output transformer and the amplifier is called transformer coupled class A amplifier.

i) Circuit diagram of transformer coupled amplifier:

The basic circuit of a transformer coupled amplifier is shown in the fig. The loudspeaker connected to the secondary acts as a load having impedance of R_L ohms. The transformer used is a step down transformer with the turns ratio as,

$$n = \frac{N_2}{N_1}$$

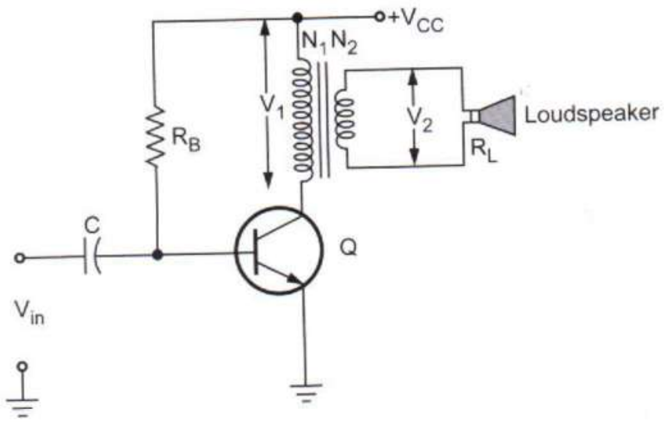


Fig 2.48. Transformer coupled class A amplifier

ii) D.C Operation:

It is assumed that the winding resistances are zero ohms. Hence for d.c purposes, the resistance is 0 Ω. There is no d.c voltage drop across the primary winding of the transformer. The slope of the d.c load line is reciprocal of the d.c resistance in the collector circuit, which is zero in this case, hence slope of the d.c load line is ideally infinite. This tells that the d.c load line in the ideal condition is a vertically straight line.

Applying Kirchoff's voltage law to the collector circuit we get,

$$V_{CC} - V_{CE} = 0$$

i.e. $V_{CC} = V_{CE}$ drop across winding is zero.

This is the d.c bias voltage V_{CEQ} for the transistor.

So $V_{CEQ} = V_{CC}$

Hence the d.c load line is a vertical straight line passing through a voltage point on the X-axis which is $V_{CEQ} = V_{CC}$. The intersection of d.c load line and the base current set by the circuit is the quiescent operating point of the circuit. The corresponding collector current is I_{CQ}.

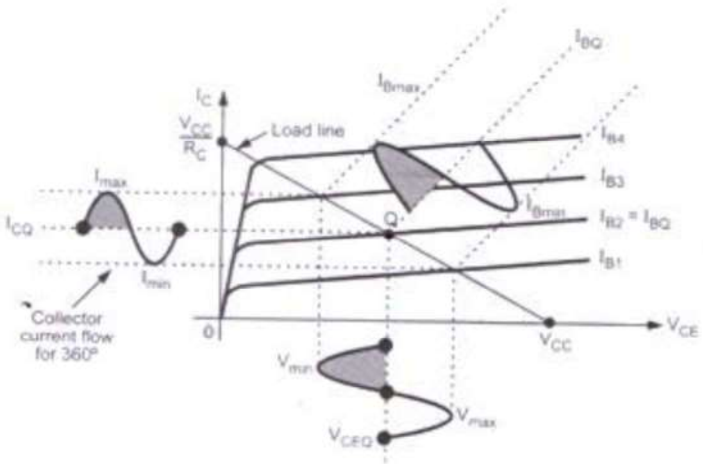


Fig 2.49. Load lines for transformer coupled class A amplifier

iii) D.C power input:

The d.c power input is provided by the supply voltage with no signal input, the d.c current drawn is the collector bias current I_{CQ}. Hence the d.c power input is given by,

$$P_{DC} = V_{CC}\, I_{CQ}$$

iv) A.C Operation:

For the a.c analysis, it is necessary to draw an a.c load line on the output characteristics. For the a.c purposes, the load on the secondary is the load impedance R_L ohms. And the reflected load on the primary i.e. R_L can be calculated using the equation,

$$R_L' = \frac{R_L}{n^2} = \left(\frac{N_1}{N_2}\right)^2 R_L$$

. The load line drawn with the slope of $\left(-\frac{1}{R_L}\right)$ and passing through the operating point i.e. quiescent point Q is called a.c load line. The output current i.e. collector current varies around its quiescent value I_{CQ} , when a.c input signal is applied to the amplifier. The corresponding output voltage also varies sinusoidally around its quiescent value V_{CEQ} which is V_{CC} in this case.

v) A.C Output power:

The a.c power developed is on the primary side of the transformer. While calculating this power, the primary values of voltage and current and reflected load R_L must be considered. The a.c power delivered to the load is on the secondary side of the transformer. While calculating load voltage, load current, load power the secondary voltage, current and the load R_L must be considered.

Let , $V_{1\,m}$ = Magnitude ofr peak value of primary voltage

$V_{1\,rms}$ = R.M.S value of primary voltage

$I_{1\,m}$ = Peak value of primary current

$I_{1\,rms}$ = R.M.S value of primary current

Hence the a.c power developed on the primary is given by,

$$P_{ac} = V_{1\,rms} I_{1\,rms}$$

$$P_{ac} = I_{1\,rms}^2 R_L'$$

$$P_{ac} = \frac{V_{1\,rms}^2}{R_L'}$$

$$P_{ac} = \frac{V_{1\,m}}{\sqrt{2}} \cdot \frac{I_{1\,m}}{\sqrt{2}}$$

$$= \frac{V_{1\,m} I_{1\,m}}{2}$$

$$P_{ac} = \frac{I_{1\,m}^2 R_L'}{2}$$

$$P_{ac} = \frac{V_{1\,m}^2}{2R_L'}$$

Similarly the a.c power delivered to the load on secondary, also can be calculated, using secondary quantities.

Let , V_{2m} =Magnitude or peak value of secondary or load voltage

V_{2rms} = R.M.S value of secondary or load voltage

I_{2m} = Magnitude or Peak value of secondary or load current

I_{2rms} = R.M.S value of secondary or load current

$$P_{ac} = V_{2\,rms} I_{2\,rms}$$

$$P_{ac} = I^2_{2rms} R_L$$

$$P_{ac} = \frac{V^2_{2\,rms}}{R_L}$$

$$= \frac{V_{2\,m} I_{2\,m}}{2}$$

$$P_{ac} = \frac{I^2_{2\,m} R_L}{2}$$

$$P_{ac} = \frac{V^2_{2\,m}}{2R_L}$$

The generalized expression for a.c power output represented by the equation,

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

Key point: The a.c power calculated is the power developed across the primary winding of the output transformer. Assuming ideal transformer, the power delivered to the load on secondary is same as that developed across the primary. If the transformer efficiency is known, the power delivered to the load must be calculated from the power developed on the primary, considering the efficiency of the transformer.

vi) Efficiency:

The general expression for the efficiency remains same as that given by equations,

$$\%\eta = \frac{P_{ac}}{P_{dc}} X100$$

$$= \frac{(V_{max} - V_{min})(I_{max} - I_{min})}{8V_{CC} I_{CQ}} X100$$

vi) Maximum efficiency:

Assume maximum swings of both the output voltage and current, to calculate maximum efficiency, as shown in fig.

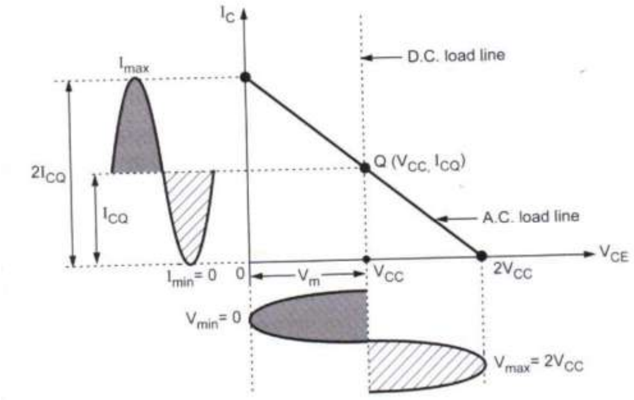


Fig 2.50. Maximum voltage & current swings

Assuming that the Q point is exactly centre of the load line, for maximum swing we can write,

$$V_{max} = 2V_{cc} \text{ and } V_{min} = 0$$

$$I_{max} = 2I_{CQ} \text{ and } I_{min} = 0$$

$$\% \, \eta_{max} = \frac{(2V_{CC} - 0)(2I_{CQ} - 0)}{8V_{CC} I_{CQ}} X100$$

$$= \frac{4V_{CC} I_{CQ}}{8V_{CC} I_{CQ}} X100 = 50\%$$

Key point: hence maximum possible theoretical efficiency in case of transformer coupled class A amplifier is 50%.

vii) Power dissipation:

The power dissipation by the transistor is the difference between the a.c power output and the d.c power input. The power dissipated by the transformer is very small due to negligible (d.c) winding resistances and can be neglected.

$$\therefore P_d = P_{DC} - P_{ac}$$

When the input signal is larger, more power is delivered to the load and less is the power dissipation. But when there is no input signal, the entire d.c input power gets dissipated in the form of heat, which is the maximum power dissipation.

$$\therefore \quad (P_d)max = V_{CC}\, I_{CQ}$$

Thus the class A amplifier dissipates less power when delivers maximum power to the load. While it dissipates maximum power while delivering zero power to the load i.e. when load is removed and there is no a.c input signal. The maximum power dissipation decides the maximum power dissipation rating for the power transistor to be selected for an amplifier.

viii) Advantages and disadvantages:

The advantages of transformer coupled class A amplifier circuit are,

1. The efficiency of the operation is higher than directly coupled amplifier.
2. The d.c bias current that flows through th load in case of directly coupled amplifier is stopped in case of transformer coupled.
3. The impedance matching required for maximum power transfer is possible.

The disadvantages are,

1. Due to the transformer, the circuit becomes bulkier, heavier and costlier compared to directly coupled circuit.
2. The circuit is complicated to design and implement compared to directly coupled circuit.
3. The frequency response of the circuit is poor.

2.14. Analysis of class B amplifiers:

For class B operation, the quiescent operating point is located on the X-axis itself. Due to this collector current flows only for a half cycle for a full cycle of the input signal. Hence the output signal is distorted. To get a full cycle across the load, a pair of transistors is used in class B operation. The two transistors conduct in alternate half cycles of the input signal and a full wave across the load is obtained. The two transistors are identical in characteristics and called matched transistors.

Depending on the type of the two transistors whether p-n-p or n-p-n, the two circuit configurations of class B amplifier are possible. These are,

1. When both the transistors are of same type i.e. either p-n-p or n-p-n then the circuit is called push pull class B A.F power amplifier circuit.

2. When the two transistors form a complementary pair i.e. one n-p-n and other p-n-p then the circuit is called complementary symmetry class B A.F. power amplifier circuit. Let us analyze these two circuits of class B amplifiers in detail.

2.14.1. Push pull class B amplifier:

The Push pull circuit requires two transformers, one as input transformer called driver transformer and the other to connect to load called output transformer. The input signal is applied to primary of the driver transformer. Bothe the transformers are centre tapped transformers. The Push pull class B amplifier circuit is shown in fig.

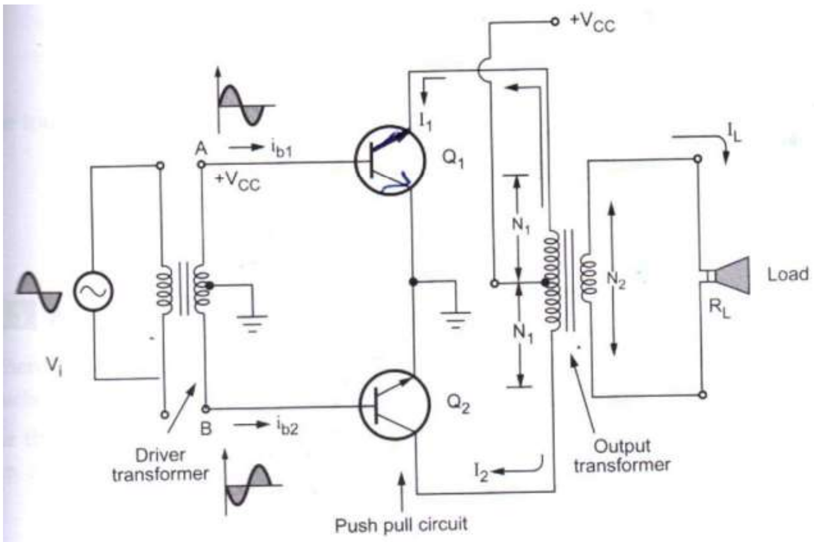


Fig 2.51. Push pull class B amplifier

In the circuit both Q_1 and Q_2 transistors are of n-p-n type. The circuit can use both Q_1 and Q_2 of p-n-p type. In such a case, the only change is that the supply voltage must be $-V_{CC}$, the basic circuit remains the same. Generally the circuit using n-p-n transistors is used. Both the transistors are in common emitter configuration.

The driver transformer drives the circuit. The input signal is applied to the primary of the driver transformer. The centre tap on the secondary of the driver transformer is grounded. The centre tap on the primary of the output transformer is connected to the supply voltage $+V_{CC.}$

With respect to the centre tap, for a positive half cycle of input signal, the point A shown on the secondary of the driver transformer will be positive. While the point B will be negative. Thus the voltages in the two halves of the secondary of the driver transformer will be equal but with positive polarity. Hence the input signals applied to the base of the transistors Q_1 and Q_2 will be 180 out of phase.

The transformer Q_1 conducts foe a positive cycle for the positive half cycle of the input producing positive half cycle across the load. While the transistor Q_2 conducts for a negative half cycle of the input producing negative half cycle of the output producing negative half cycle across the load. Thus across the load, we get a full cycle for a full input half cycle. The basic push pull operation is shown in fig.

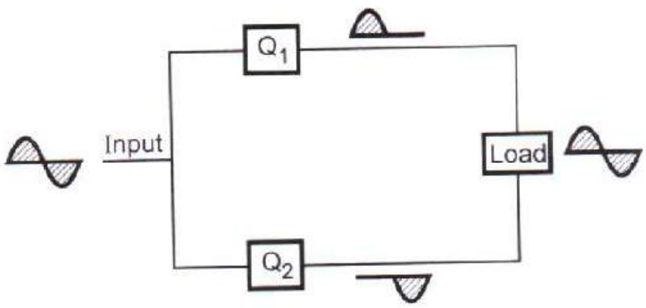


Fig 2.52. Basic push pull operation

When positive A is positive, the transistor Q_1 gets driven into an active region while the transistor Q_2 is in cut-off region. While when point A is negative, the point B is positive, hence the transistor Q_2 gets driven into an active region while the transistor Q_1 is in cut-off region.

i) D.C Operation:

The d.c biasing point i.e. Q point is adjusted on the X-axis such that $V_{CEQ} = V_{CC}$ and I_{CEQ} is zero. Hence the co-ordinates of the Q point are $(V_{CC}, 0)$. There is no d.c base bias voltage.

ii) D.C Power Input:

Each transistor output is in the form of half rectified waveform. Hence if I_m is the peak value of the output current of each transistor, the d.c or average value is $\frac{I_m}{\pi}$, due to half rectified form. The two currents, drawn by the two transistors, form the d.c supply are in the same direction. Hence the total d.c or average current drawn from the supply is the algebraic sum of the individual average current drawn by each transistor.

$$I_{dc} = \frac{I_m}{\pi} + \frac{I_m}{\pi} = \frac{2I_m}{\pi}$$

The total d.c power input is given by,

$$P_{DC} = V_{CC} I_m$$

$$P_{DC} = \frac{2}{\pi} V_{CC} I_m$$

iii) A.C Operation:

When the a.c signal is applied to the driver transformer, for positive half cycle Q_1 conducts. For the negative half cycle Q_2 conducts. It can be seen that Q_1 conducts, lower half of the primary of the output transformer does not carry any current. Hence only N_1 number of turns carry the current. While when Q_2 conducts, upper half of the primary does not carry any current. Hence again only N_1number of turns carry the current. Hence the reflected load on the primary can be written as,

$$R_L^{'} = \frac{R_L}{n^2}$$

$$n = \frac{N_2}{N_1}$$

The slope of the a.cc load line is $-1/R_L^{'}$ while the d.c load line is the vertical line passing through the operating point Q on the X-axis. The slope of the a.c load line (magnitude of slope) can be represented interms of V_m and I_m as,

$$\frac{1}{R_L^{'}} = \frac{I_m}{V_m}$$

$$\because R_L^{'} = \frac{V_m}{I_m}$$

Where, I_m =peak value of the collector current

iv) A.C power output:

As I_m and V_m are the peak values of the output current and the output voltage respectively, then,

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$\text{And } I_{rms} = \frac{I_m}{\sqrt{2}}$$

Hence the a.c power output is expressed as,

$$P_{ac} = V_{rms}\, I_{rms} = I_{rms}{}^2 R_L{}' = \frac{V_{rms}{}^2}{R_L^{'}}$$

While using peak values it can be expressed as,

$$P_{ac} = \frac{V_m I_m}{2} = \frac{I_m^2}{2} R_L' = \frac{V_m^2}{2R_L'}$$

v) Efficiency:

The efficiency of the class B amplifier can be calculated using the basic equation.

$$\%\eta = \frac{P_{ac}}{P_{DC}} X100 = \frac{\left(\frac{V_m I_m}{2}\right)}{\frac{2}{\pi} V_{CC} I_m} X100$$

$$\% = \frac{\pi}{4} \frac{V_m}{V_{CC}} X100$$

vi) Maximum efficiency:

The maximum value of V_m possible is equal to V_{CC} as shown in the fig.

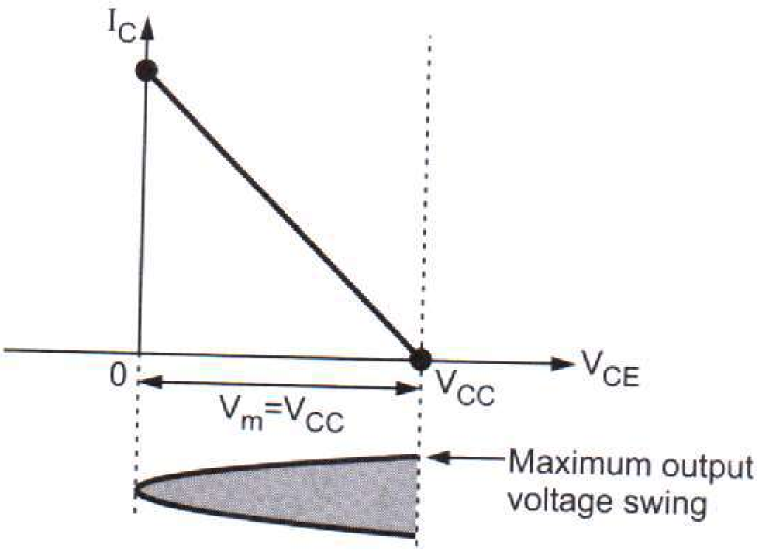


Fig 2.53. Maximum voltage & current swings

$$V_m = V_{CC} \text{ for maximum } \eta$$

$$\therefore \ \% \boldsymbol{\eta}_{max} = \frac{\pi}{4} \frac{V_{CC}}{V_{CC}} X100$$

$$= 78.5\%$$

Key point: Thus the maximum possible theoretical efficiency in case of push pull class B amplifier is 78.5% which is much higher than the transformer coupled class A transformer. For practical circuits it is upto 65 to 70%. Practically the collector-emitter voltage of transistor is neglected as small. But if $V_{CE(\min)}$ is given then maximum collector voltage V_m reduces $V_{CE(\min)}$ and becomes $V_m = V_{CC} - V_{CE(\min)}$ under maximum efficiency condition.

vii) Power dissipation:

The power dissipation by both the transistors is the difference between a.c power output and d.c power input.

$$\therefore P_d = P_{DC} - P_{ac} = \frac{2}{\pi} V_{CC} I_m - \frac{V_m I_m}{2}$$

$$\therefore \quad P_d = \frac{2}{\pi} V_{CC} \frac{V_m{}^2}{2R_L{}'}$$

Let us find out the condition for maximum power dissipation. In case of class A amplifier, it is maximum when no input signal is there. But in class B operation, when the input signal is zero, $\boldsymbol{V_m}$=0 hence the power dissipation is zero and not the maximum.

viii) Maximum power dissipation:

The condition for maximum power dissipation can be obtained by differentiating the equation () with respect to V_m and equating it to zero.

$$\frac{dP_d}{dV_m} = \frac{2}{\pi}\frac{V_{CC}}{R_L{}'} = 0$$

$$\therefore \frac{2}{\pi}\frac{V_{CC}}{R_L{}'} = \frac{V_m}{R_L{}'}$$

$$V_m = \frac{2}{\pi} V_{CC} \quad \text{for maximum power dissipation}$$

This is the condition for maximum power dissipation. Hence the maximum power dissipation is,

$$(P_d)_{max} = \frac{2}{\pi} V_{CC} X \frac{2}{\pi}\frac{V_{CC}}{R_L{}'} - \frac{4}{\pi^2}\frac{V_{CC}^2}{R_L{}'}$$

$$= \frac{4}{\pi^2}\frac{V_{CC}^2}{R_L{}'} - \frac{2}{\pi^2}\frac{V_{CC}^2}{R_L{}'}$$

$$(P_d)_{max} = \frac{2}{\pi^2}\frac{V_{CC}^2}{R_L{}'}$$

Key point: For maximum efficiency $V_m = V_{CC}$ hence power dissipation is not maximum when the efficiency is maximum. And when power dissipation is maximum efficiency is not maximum. So maximum efficiency and maximum power dissipation do not occur simultaneously in in case of class B amplifiers.

Now,

$$P_{ac} = \frac{{V_m}^2}{2R_L},$$

And $V_m = V_{CC}$ is the maximum condition

Hence

$$(P_{ac})_{max} = \frac{V_{CC}^2}{2R_L},$$

$$(P_d)_{max} = \frac{2}{\pi^2}\frac{V_{CC}^2}{R_L}, = \frac{4}{\pi^2}\left(\frac{V_{CC}^2}{R_L},\right)$$

$$(P_d)_{max} = \frac{4}{\pi^2}(P_{ac})_{max}$$

This much power is dissipated by the both transistors hence the maximum power dissipation per transistor is ${(P_d)_{max}}/{2}$.

$$(P_d)_{max} \text{ per transistor} = \frac{2}{\pi^2}(P_{ac})_{max}$$

This is the maximum power dissipation rating of each transistor. For example, if 10 W maximum power is to be supplied to the load, then power dissipation rating of each transistor should be $\frac{2}{\pi^2}x10$ i.e. 2.02 W. The $\left(\frac{2}{\pi^2}\right)$ is approximately 0.2 which is $\left({1}/{5}\right)$. thus the maximum power dissipation is approximately $\left(\frac{1}{5}\right)^{th}$ of the maximum a.c output power.

2.14.2. Complementary symmetry class B amplifier:

As stated earlier, instead of using same type of transistors (n-p-n or p-n-p), one n-p-n and other p-n-p is used, the amplifier circuit is called as complementary symmetry class B amplifier. This circuit is transformer less circuit. But with common emitter configuration, it becomes difficult to match the output impedance for maximum power transfer without an output transformers. Hence the matched pair of complementary transistors are used in common collector (emitter follower) configuration, in this circuit.

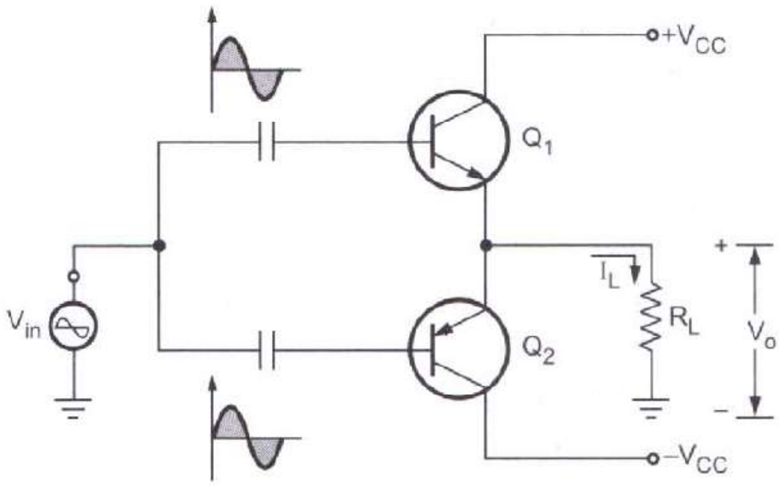


Fig 2.54. Complementary symmetry class B amplifier

Key point: this is because common collector configuration has lowest output impedance and hence the output impedance matching is possible.

In addition, voltage feedback can be used to reduce the output impedance for matching. The basic circuit of complementary symmetry class B amplifier is shown in fig.

The circuit is driven a dual supply of $\pm V_{CC}$. The transistor Q_1 is n-p-n while Q_2 is of p-n-p type. In the positive half cycle of the input signal, the transistor Q_1 gets driven into active region and starts conducting. The same signal gets applied to the base of Q_2 but as it is of complementary type, remains in off condition, during positive half cycle. This results into positive half cycle across the load R_L.

During the negative half cycle of the signal, the transistor Q_2 being p-n-p gets biased into condition. While the transistor Q_1 gets driven into cut-off region. Hence only Q_2 conducts during negative half cycle of the input, producing negative half cycle across the load R_L.

Thus for a complete cycle of input, a complete cycle of output signal is developed across the load R_L.

i) Mathematical analysis:

All the results derived for push pull transformer coupled class B amplifier are applicable to the complementary class B amplifier. The only change is that as the output transformer is not present, hence the expression, R_L value must be used as it is, instead of $R_L{}'$.

ii) Advantages and disadvantages:

The advantages are,

1. As the circuit is transformerless, its weight, size and cost are less.
2. Due to common collector configuration, impedance matching is possible.
3. The frequency response improves due to transformerless class B amplifier circuit.

The disadvantages are,

1. The circuit needs two separate voltage supplies.
2. The output is distorted to cross over distortion.

iii) Applications:

The various application areas of class B push pull power amplifiers are public address systems, audio frequency amplifiers, AM/PM radio amplifiers, portable tape player amplifiers small servo amplifiers, power convertors and output stages of devices like operational amplifiers.

Key point: while solving problems remember:

1. Given power is to be assumed maximum unless and otherwise specified. Hence use the expression,

$$(P_{ac})_{max} = \frac{V_{CC}^2}{2R_L} \quad \text{or} \quad (P_{ac})_{max} = \frac{V_{CC}^2}{2R_L{}'}$$

   Depending on type of circuit.
2. Most of the times, the circuit uses dual supply as $\pm V_{CC}$.
3. The circuit may operate with single positive supply $+V_{CC}$. this is single supply version and discussed later in detail. So if supply given in the problem is +10V, +20V i.e. $+V_{CC}$ it is single supply version and while solving such problems V_{CC} should be taken as half of the given positive single supply i.e. 5V, 10V respectively.
4. If in the problem V_m is given then remember that this circuit is common collector circuit which has unity gain. Thus $V_{out} = V_{in}$ and then voltage across R_L is same as V_{in}. The peak value of V_{in} is V_m and $V_m \neq V_{CC}$ in such a case.

2.15. Class C operation:

In class C amplifier, a resonating circuit is used as a load. Thus most of the class C amplifiers are used as tuned amplifiers.

i) Resonant frequency:

A parallel resonant circuit acts as a load impedance. The collector current flows for less than half a cycle hence it consists of a series of pulses with the harmonics of the input signal. A parallel tuned circuit acting as a load is tuned to the input frequency. Thus it filters the harmonic frequencies and produce a sine wave output voltage consisting of the fundamental component of the input signal.

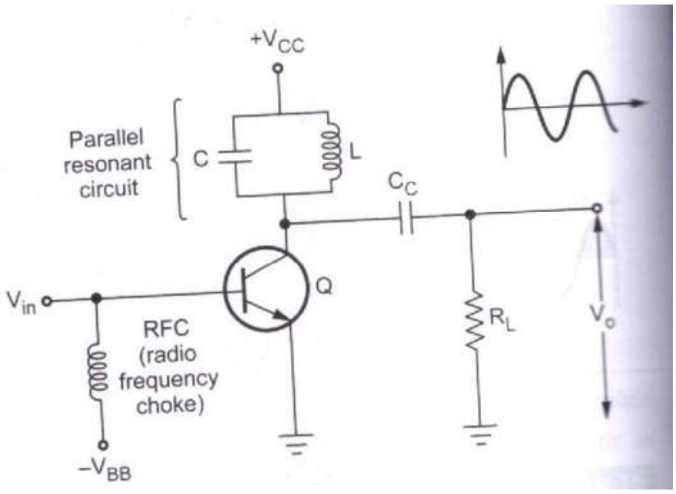


Fig 2.55. Class C tuned amplifier

The a.c input voltage drives the base and amplified output voltage is available at the collector. The amplified and inverted collector voltage is connected to load resistance R_L through coupling capacitor.

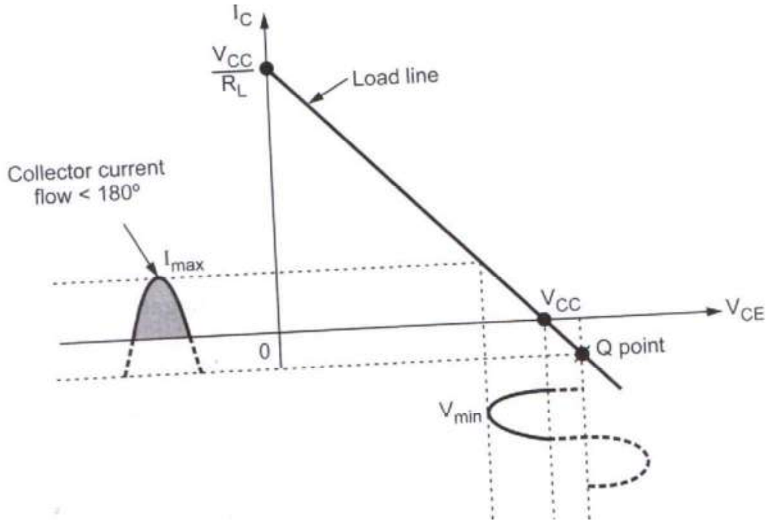


Fig 2.56. Waveform representing Class C operation

As class C amplifier is used with parallel tuned circuit, the output voltage is maximum at the resonant frequency. The resonant frequency is given by,

$$f_r = \frac{1}{2\pi\sqrt{LC}} Hz$$

The gain drops on either side of the resonant frequency. Thus the frequency response of class C amplifier is as shown in fig. As gain is maximum at resonant frequency, these amplifiers are used to amplify only narrow band of frequencies.

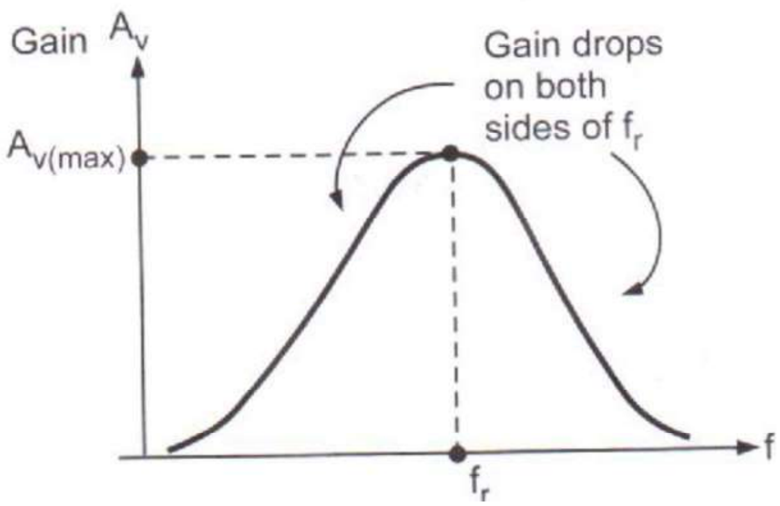


Fig 2.57. Frequency response

ii) Load lines:

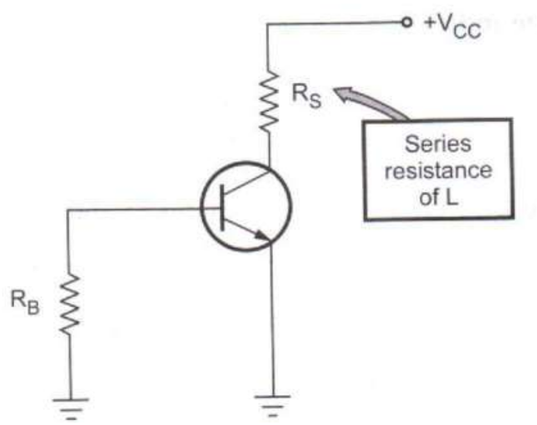


Fig 2.58. DC equivalent of class C amplifier

The fig shows the d.c equivalent circuit of the unbiased class C amplifier. The resistance R_S is the series resistance of an inductor L. The value of R_S is very very small. For d.c., the capacitor C acts as an open circuit and does not affect the d.c operation.

As R_S is very small, the slope of d.c load line is reciprocal of R_S and is very high tending to infinity. Hence d.c load line is almost vertical. The d.c load line is not important for class C amplifiers.

For a.c load line, Q point is designed to be at the lower end of the a.cload line. When a.c input signal is applied, instantaneously a.c operating point moves up the a.c load line towards the saturation point. The maximum value of the collector current i.e. when $V_{CE} = 0$ is given by $\frac{V_{CC}}{r_c}$. both d.c and a.c load lines are shown in the fig.

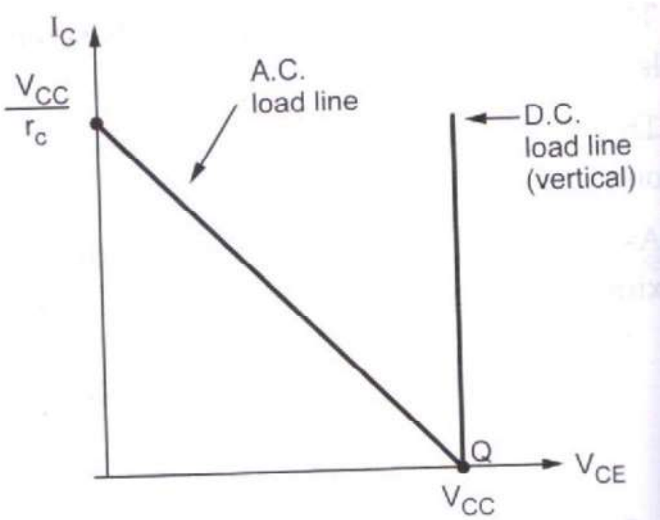


Fig 2.59. Frequency response

iii) A.C equivalent circuit:

The a.c equivalent circuit of class C amplifier is shown in the fig().

The inductor has a series resistanceR_S. The quality factor Q of the inductor is,

$$Q_L = \frac{X_L}{R_S} = \frac{\omega_r L}{R_S}$$

Where,

Q_L=quality factor of coil

X_L=inductive resistance of coil

R_S=series coil resistance

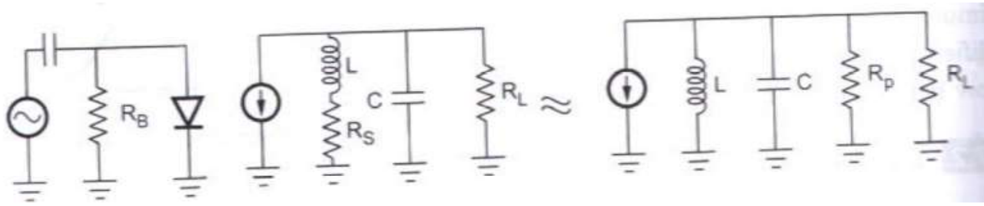


Fig 2.60. A.C equivalent circuit

The series resistance R_S can be replaced by a parallel resistance R_P. This is given by,

$$R_P = Q_L \omega_r L = Q_L X_L$$

At resonance X_L cancels X_C and hence only R_P remains in parallel with R_L . thus the a.c resistance seen by the collector at resonance is,

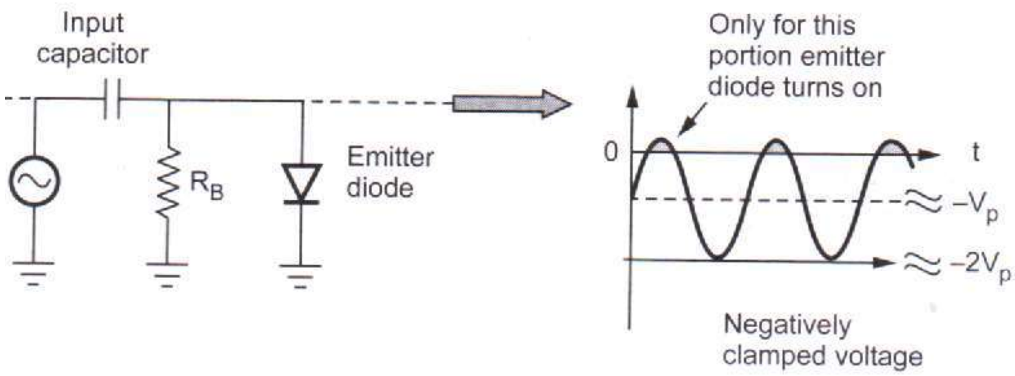
$$r_c = R_P || R_L$$

The Q factor of the overall circuit is,

$$Q = \frac{r_c}{\omega_r L} = \frac{r_c}{X_L}$$

iv) D.C clamping of input signal:

The a.c input dives the base-emitter junction i.e. the emitter diode. While the amplified current pulse drives the resonant circuit. The input capacitor with emitter diode forms a clamper circuit and hence signal available across the emitter diode is negatively clamped. This is shown in fig.



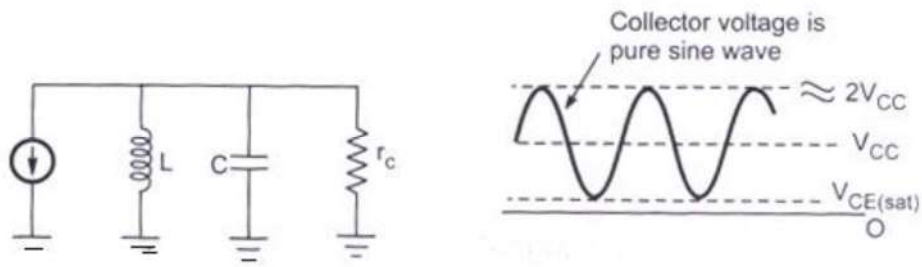
.**Fig 2.61. D.C clamping of input**

The input is almost clamped by $-V_P$. Only positive peaks of input can turn on the emitter diode. Hence the current flows in brief pulse.

v) Filtering the harmonics:

The current pulses consist of harmonics i.e. the components which are multiples of the fundamental input frequency f. Thus the pulses are equivalent to a group of sine waves having frequencies f, 2f, 3f ... nf. These components are called harmonics.

At fundamental frequency, the impedance of the tank circuit is high which produces a large voltage gain. For all other harmonics, due to low impedance of tank circuit, the voltage gain is very less. Hence all the harmonics are filtered and pure sine wave of fundamental frequency is available across the tank circuit as shown in the fig.



.**Fig 2.62. Collector voltage waveform**

vi) Bandwidth:

We know that, bandwidth of resonant circuit is defined as

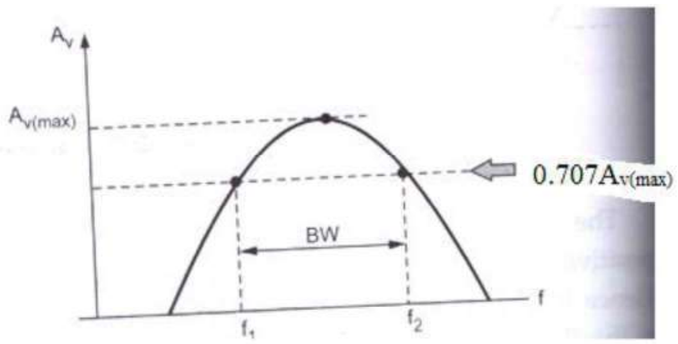
$$BW = f_1 - f_2$$

Where, f_1 =lower half power (3 dB) frequency

f_2 = upper half power (3 dB) frequency

The half power frequencies are identical to the frequencies at which the volyage gain equal 0.707 times the maximum gain.

The bandwidth is shown in the fig.



.**Fig 2.63. Bandwidth**

The bandwidth of class C tuned amplifier is given by,

$$BW = \frac{f_r}{Q}$$

Where Q= quality factor of circuit

Key point: Bandwidth is inversely proportional to Q. Higher the value of Q, smaller is the bandwidth of the circuit.

vii) Duty cycle:

The duty cycle is the ratio of ON period of the transistor to total period of the pulses. The width of current pulse represents on period of transistor.

Thus, W = width of pulse

T = period of pulses

Then the duty cycle D is given by,

$$D = \frac{W}{T}$$

Key point: the smaller the duty cycle, the narrower the pulses as compared to the period T. This is shown in fig

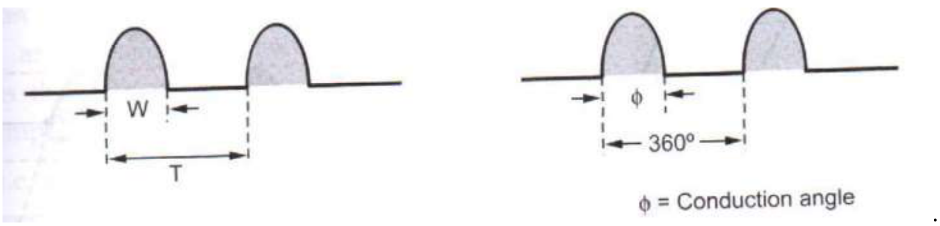


Fig 2.64. Representation of duty cycle

Interms of conduction angle Φ, the duty cycle is given by,

$$D = \frac{\Phi}{360^\circ}$$

viii) Output power:

If the r.m.s value of output voltage across load resistance is measured then the output power is given by,

$$P_{out} = \frac{V_{rms}^2}{R_L}$$

$$\text{But } V_{PP} = 2V_m = 2\sqrt{2}\,V_{rms}$$

$$P_{out} = \frac{\left(V_{PP}/2\sqrt{2}\right)^2}{R_L} = \frac{V_{PP}^2}{8R_L}$$

ix) Transistor dissipation:

The maximum power dissipation at $\Phi = 180°$ is given by,

$$P_D(\max) = \frac{V^2_{PP(\max)}}{40r_c}$$

Note that $V_{pp(\max)} = 2V_{CC}$

Key point: The transistor power rating must be greater than $P_D(\max)$ value of the circuit. Under normal working condition, as $\emptyset$ is much less than 180°, hence P_D is also much less than $P_D(\max)$.

x) D.C input power:

The d.c input power is given by,

$$P_D = V_{CC} I_{dc}$$

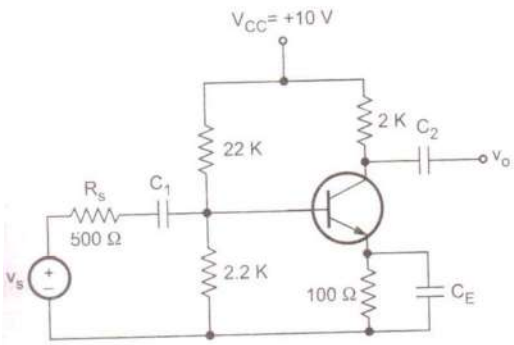
xi) Efficiency:

The efficiency is given by the ratio of a.c power output to the d.c power input.

$$\%\eta = \frac{P_{out}}{P_{DC}} X\ 100 = \frac{P_{out}}{V_{CC} I_{dc}} X100$$

SOLVED EXAMPLES:

1. For the CE amplifier circuit shown in fig determine R_i, A_v and R_o. The transistor parameters are: β=100, V_{BE}=0.7 and V_A=100.



Solution:

Step1: Calculate I_{CQ}

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

$$V_{TH} = \frac{2.2}{22 + 2.2} \times 10 = 0.909V$$

$$R_B = R_1 \| R_2 = 2K\Omega$$

$$I_B = \frac{V_{TH} - V_{BE}}{R_B + (1+\beta)R_E} = \frac{0.909 - 0.7}{2 + (1 + 100)0.1} = 17.27\mu A$$

$$I_{CQ} = I_C = 100 \times 17.27 = 1.727 \text{ mA}$$

Step 2: Determine small signal transistor parameters r_π, g_m and r_o

$$r_\pi = \frac{V_T \beta}{I_{CQ}} = \frac{(0.026)(100)}{1.727} = 1.5K\Omega$$

$$gm = \frac{I_{CQ}}{V_T} = \frac{1.727}{0.026} = 66.42mA/V$$

$$ro = \frac{V_A}{I_{CQ}} = \frac{100}{1.727} = 57.9 \text{ K}\Omega$$

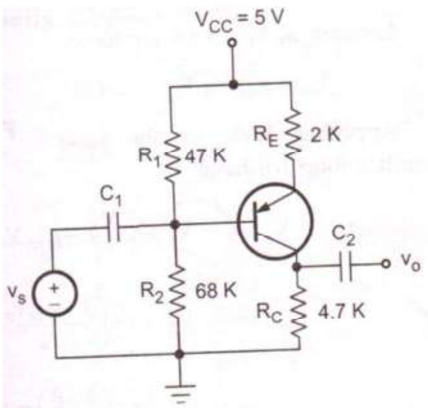
Step 3: Find R_i, A_V and R_O

$$R_i = R_1 \parallel R_2 \parallel r_\pi = 22\|2.2K\|1.5K = 857\Omega$$

$$A_V = -g_m(r_O\|R_C)\left(\frac{R_i}{R_i+R_S}\right) = -66.42(57.9\|2)\left(\frac{0.857}{0.857+0.5}\right) = -81$$

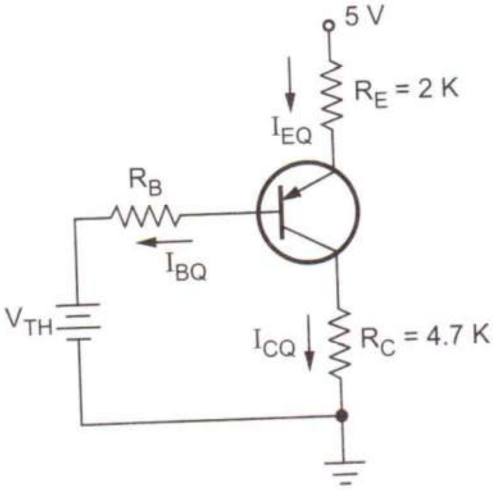
$$R_O = r_O\|R_C = 57.9\|2 = 1.933 \text{ k}\Omega$$

2. For the circuit shown in fig, determine I_{CQ}, R_i and A_v. Transistor parameters are, $\beta = 120$, V_{EB}=0.7V and $V_A=\infty$.



Solution:

Step 1: Calculate I_{CQ}



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

$$= \frac{68}{47 + 68} \times 5 = 2.96\text{V}$$

$$R_B = R_1 || R_2 = 47 || 68 = 27.8\text{K}\Omega$$

Applying KVL to the input circuit we get,

$$V_{CC} - (1 + \beta) I_{BQ} R_E - V_{EB} - I_B R_B - V_{TH} = 0$$

$$I_{BQ} = \frac{V_{CC} - V_{EB} - V_{TH}}{R_B + (1 + \beta) R_E} = \frac{5 - 0.7 - 2.96}{27.8 + (1 + 120)2} = 4.97\mu\text{A}$$

$$I_{CQ} = \beta I_{BQ} = 120 \times 4.97 = 0.6\text{ mA}$$

Step 2: Determine small signal parameters r_π, g_m and r_o

$$r_\pi = \frac{V_T \beta}{I_{CQ}} = \frac{(0.026)(120)}{0.6} = 5.2\text{K}\Omega$$

$$gm = \frac{I_{CQ}}{V_T} = \frac{0.6}{0.026} = 23\text{mA/V}$$

$$r_o = \frac{V_A}{I_{CQ}} = \infty$$

Step 3: Find R_i and A_V

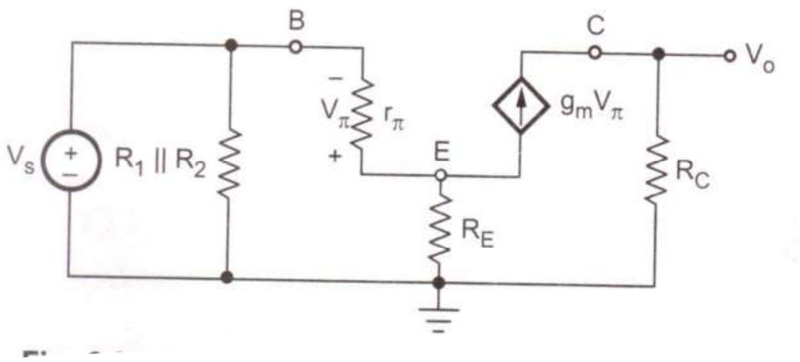


Fig shows the small signal equivalent circuit for given circuit.

Looking at fig we have,

$$V_0 = g_m V_\pi R_C \ldots\ldots\ldots\ldots\ldots (1)$$

Applying KVL to the base emitter loop we have,

$$V_S = -V_\pi - \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_E \ldots\ldots\ldots\ldots\ldots (2)$$

$$= -V_\pi \left[1 + \left(\frac{1 + g_m r_\pi}{r_\pi}\right) R_E\right] \ldots\ldots\ldots (3)$$

$$= -V_\pi \left[1 + \left(\frac{1+\beta}{r_\pi}\right) R_E\right] \quad \because \; g_m r_\pi = \beta \quad \ldots\ldots\ldots (4)$$

$$V_\pi = \frac{V_S}{1 + \left(\frac{1+\beta}{r_\pi}\right) R_E} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

Substituting value of V_π from equation (5) in (1) we have

$$V_0 = \frac{g_m R_C(-V_s)}{1 + (\frac{1+\beta}{r_\pi})R_E}$$

$$A_v = \frac{V_0}{V_s} = \frac{-g_m R_C}{1 + (\frac{1+\beta}{r_\pi})R_E} = \frac{-g_m r_\pi R_C}{r_\pi + (1+\beta)R_E}$$

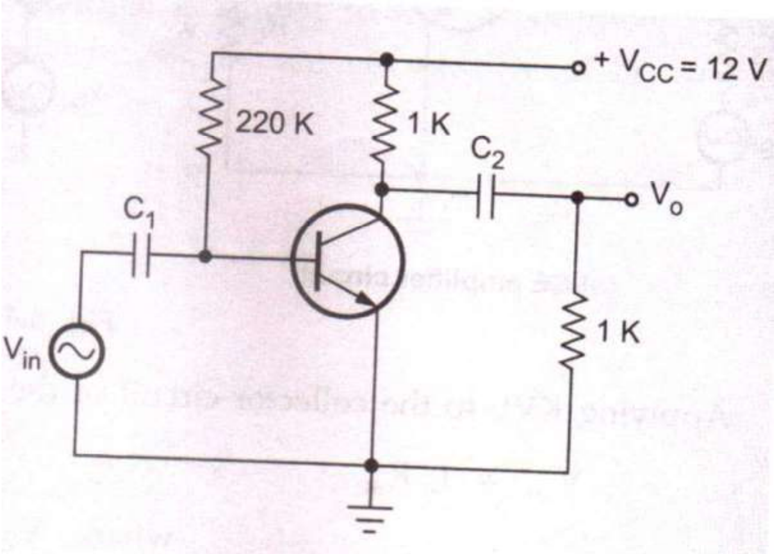
$$A_v = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E}$$

$$Av = \frac{-120 \times 4.7}{5.2 + (1 + 120) \times 2} = -2.28$$

$$R_i = R_1 \| R_2 \| R_i = R_1 \| R_2 \| [r_\pi + (1+\beta) R_E]$$

$$= 27.8 \| [5.2 + (1+120) \times 2] = 25 K\Omega$$

3. The circuit of BJT amplifier is shown in Fig, drawn a.c and d.c loadlines. Also find the Q-point. Assume V_{BE} =0.7 volts and $\beta = 100$.



Solution:

Step1: Obtain I_{CQ}, V_{CEQ}, point A and point B

Applying KVL to the base circuit we have,

$$V_{CC} - I_B R_B - V_{BE} = 0$$

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

$$= \frac{12 - 0.7}{220K} = 51.36 \mu A$$

$$I_{CQ} = \beta I_B = 100 \times 51.36\ \mu A = 5.136\ mA$$

Applying KVL to the collector circuit we have,

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

$$V_{CEQ} = V_{CC} - I_C R_C = 12 - 5.136 \times 10^{-3} \times 1000 = 6.864$$

Thus Q-point is I_{CQ} , V_{CEQ} =3.424 mA, 6.864 V

Axes Intersection Points:

Point A:

$$V_{CE} = V_{CC} = 12V \text{ at } I_C = 0$$

Point B:

$$I_C = \frac{V_{CC}}{R_{dc}} = \frac{V_{CC}}{R_C} = \frac{12}{1K} = 12mA$$

Step 2: Obtain R_{ac}, point a and point b

$$R_{ac} = R_C \| R_L = 1k \| 1k = 500\Omega$$

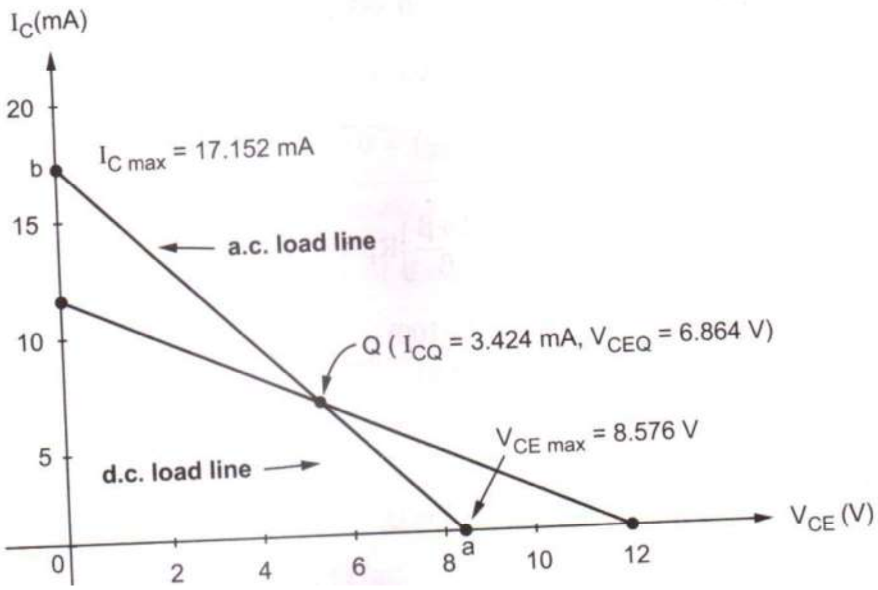
Point a:

$$V_{CE\ max} = V_{CEQ} + I_{CQ} R_{ac} = 6.864 + 3.424 \times 10^{-3} \times 500$$
$$= 8.576V$$

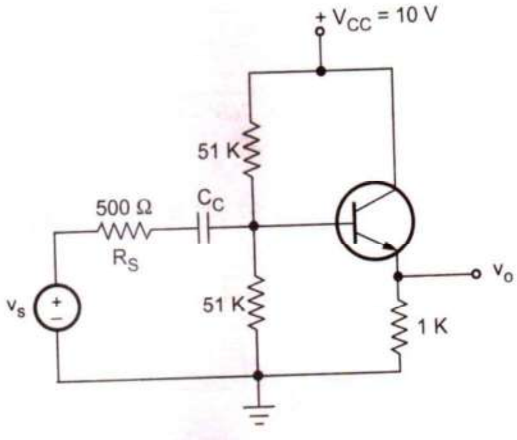
Point b:

$$I_{C\ max} = \frac{V_{CEQ}}{R_{ac}} + I_{CQ} = \frac{6.864}{500} + 3.424 \times 10^{-3} = 17.152\ mA$$

Step 3: Draw d.c. and a.c. load lines



4. Calculate R_i , R'_i , A_v , A_i and R_o for the circuit shown in Fig . Assume transistor parameters are β=100 , V_{BE}=0.7V, V_A=80V.



Solution:

Given: $R_1 = R_2 = 51K\Omega$, $V_{CC} = 10V$ and R_E=KΩ

Step 1: Find I_{CQ} and V_{CEQ}

$$V_{TH} = \frac{51K}{51K + 51K} V_{CC} = 5V$$

$$R_B = R_1 || R_2 = 25.5K\Omega$$

$$V_{TH} - I_B R_B - V_{BE} - (1 + \beta) I_B R_E = 0$$

$$I_B = I_{BQ} = \frac{V_{TH} - V_{BE}}{R_B + (1 + \beta) R_E} = \frac{5 - 0.7}{25.5 + (1 + 100) \times 1}$$

$$= 34\mu A$$

$$I_{CQ} = \beta I_{BQ} = 100 \times 34\mu A = 3.4mA$$

$$V_{CEQ} = V_{CC} - I_E R_E = V_{CC} - \left(\frac{1 + \beta}{\beta}\right) I_{CQ} R_E = 10 - \frac{(1 + 100)}{100} \times 3.4 \times 1$$

$$= 6.566\ V$$

Step 2 : Find r_π , g_m and r_o

$$r_\pi = \frac{V_T \beta}{I_{CQ}} = \frac{(0.026)(100)}{3.4} = 765\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{3.4}{0.026} = 130.77mA/V$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{80}{3.4} = 23.53K\Omega$$

Step 3: Find R_i , R'_i , A_v , A_i and R_o

$$R'_i = r_\pi + (1+\beta)(r_0 \| R_E) = 765 + (1+100)(23.53k\|1k)$$

$$= 97.647\ k\Omega$$

$$R_i = R_1 \| R_2 \| R_i = 25.5K \| 97.647K = 20.22K\Omega$$

$$A_v = \frac{(1+\beta)(r_o \parallel R_E)}{r_\pi + (1+\beta)(r_o \parallel R_E)} \times \left(\frac{R_i}{R_i + R_s}\right)$$

$$= \frac{(1+100)(23.53\|1)}{0.765 + (1+100)(23.53\|1)} \left(\frac{20.22}{20.22+0.5}\right) = 0.968$$

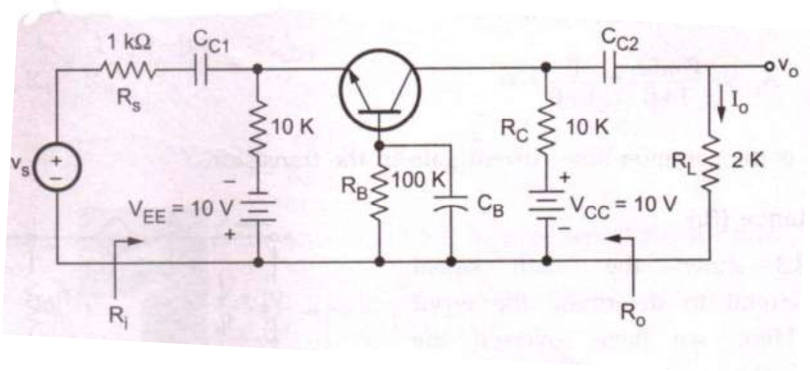
$$A_i = (1+\beta)\left(\frac{R_1\|R_2}{R_1\|R_2 + R_i}\right)\left(\frac{r_o}{r_o + R_E}\right)$$

$$= (1+100)\left(\frac{25.5}{25.5+97.647}\right)\left(\frac{23.53}{23.53+1}\right)$$

$$= 1.812$$

$$R_o = \frac{r_\pi}{1+\beta} \| R_E \| r_o = \frac{0.765}{1+100} \|1\|23.53 = 7.51\Omega$$

5. For a common base amplifier shown in Fig 3.8.5 .Calculate R_i , A_v , A_i and R_o. The transistor parameters are: β=100 , V_{BE}=0.7 and $V_A = \infty$.



Solution :

Step1: Find I_{CQ}

$$I_B = \frac{V_{EE} - V_{BE}}{R_B + (1+\beta)R_E} = \frac{10 - 0.7}{100 + (1+100)10} = 8.378\mu A$$

$$I_C = I_{CQ} = \beta I_B = 100 \times 8.378\mu A$$

Step2: Determine small-signal transistor parameters r_π , g_m and r_o

$$r_\pi = \frac{V_T\beta}{I_{CQ}} = \frac{(0.026)(100)}{0.8378} = 3.1K\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.8378}{0.026} = 32.223mA/V$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{\infty}{I_{CQ}} = \infty$$

Step3: Find R_i , A_v , A_i and R_o

$$R_i = \frac{r_\pi}{1+\beta} = \frac{3.1}{1+100} = 30.69\Omega$$

$$A_v = \frac{g_m(R_C \| R_L)}{R_s}\left[R_S \| R_E \| \left(\frac{r_\pi}{1+\beta}\right)\right]$$

$$= \frac{2.223(10\|2)}{1}\left[1\|10\|\frac{3.1K}{1+100}\right] = 1.594$$

$$A_i = g_m\left(\frac{R_C}{R_C + R_L}\right)\left[R_E \| (\frac{r_\pi}{1+\beta})\right] = 0.821$$

$$R_o = R_C = 10K$$

6. The common mode input to a certain differential amplifier, having differential gain of 125 is 4sin 200π t V. Determine the common mode output if CMRR is 60 dB.

Solution:

The CMRR in dB is

$$60 = 20\log\left|\frac{A_d}{A_{cm}}\right| \qquad \text{i.e. } \log\left|\frac{A_d}{A_{cm}}\right| = 3$$

$$\therefore \frac{A_d}{A_{cm}} = 1000$$

$$\text{Now} \quad A_d = 125$$

$$A_{cm} = \frac{A_d}{1000} = \frac{125}{1000} = 0.125$$

Hence the common mode output is

$$= A_{cm}\, V_{cm} = 0.125(4 \sin 200\pi\, t) = 0.5 \sin(200\pi\, t)V$$

TWO MARK QUESTIONS AND ANSWERS

1. Define Diffusion Resistance.

The resistance r_π is called the diffusion resistance or base emitter input resistance.

$$r_\pi = \frac{v_{be}}{i_b} = \frac{V_T}{I_{BQ}} = \frac{\beta V_T}{I_{CQ}}$$

2. What is transconductance?

The parameter g_m is called a transconductance.

$$g_m = \frac{I_{CQ}}{V_T}$$

3.What is loading effect?

1. In CE amplifier, input resistance is not much higher than signal source resistance. Due to this, actual input voltage to the amplifier is reduced. This is called loading effect.

2. To minimize loading effect, $R_i >> R_S$.

4. Explain the meaning of voltage swing limitations.

In a linear amplification process, when symmetrical sinusoidal signals are applied to the input of an amplifier, we get amplified sinusoidal signals at the output. It is possible to obtain maximum output symmetrical swing that amplifier can provide using an a.c load line.If the output exceeds the limit, a portion of the output signal will be clipped resulting signal distortion.

5.What is differential amplifier? What is differential and common mode gain of differential amplifier?

An amplifier which amplifies the difference between the two input voltage signals is called differential amplifier.

The gain with which differential amplifier amplifies the difference between two input signals is called differential gain denoted as A_d.

$$A_d = \frac{V_0}{V_d}$$