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ECE

ANALOG INTEGRATED CIRCUITS

UNIT-I

- INTRODUCTION
- TRANSISTOR CURRENT SOURCE
- DIFFERENTIAL AMPLIFIERS

Contents

Integrated Circuits :

The term IC means integrated circuit where all the active & Passive components are fabricated on the same chip.

IC is a microscopic array of electronic circuits and components that are diffused (or) implanted on to the surface of single crystal (or) chip of semiconducting material such as silicon.

Advantages :

1. Small size
2. low cost
3. Less weight
4. Fast speed
5. low supply voltages
6. low power consumption
7. Highly reliable
8. Matched devices.

Classifications :

→ Based on function ICs are classified into two types. Those are

i) Digital IC ii) Linear IC.

i) Digital IC :

* These are complete functioning of logic network, Such as Gates, Counters, Multiplexers, Demultiplexers and Shift registers.
* It is a complete predesigned package, and it requires a power-Supply, i/p & o/p
* Digital circuits are primarily concerned with only two Levels of voltage (or) current : 'HIGH' (or) 'LOW'
* These are easy to design & produced in large quantities as a low cost devices.

ii) Linear IC :

* These are equivalents of discrete transistor network, Such as Amplifiers, filters, frequency multipliers and modulators.
* It requires additional external components for Satisfactory operation.

Ex External resistors are necessary to control the voltage gain and frequency responce of an OP-Amp.

→ Based on fabrication ICs are classified into three types. Those are

i) Monolithic ICs → Bipolar ICs, Unipolar ICs

ii) Thick & Thin film ICs

iii) Hybrid ICs

→ Based on number of components used ICs are classified into following types. Those are

i)	Small scale Integration	(SSI)	less than 100	→ 1960-1965
ii)	medium " "	(MSI)	100 - 1000	→ 1965-1970
iii)	Large " "	(LSI)	1000 - 1,00,000 20,000	→ 1970-1980
iv)	Very large " "	(VLSI)	more than 1,00,000 20,000 - 10,00000	→ 1980-1990
v)	Ultra large " "	(ULSI)	more than 1 million $10^6 - 10^7$	→ 1990-2000
vi)	Giant " "	(GSI)	$>10^7$	

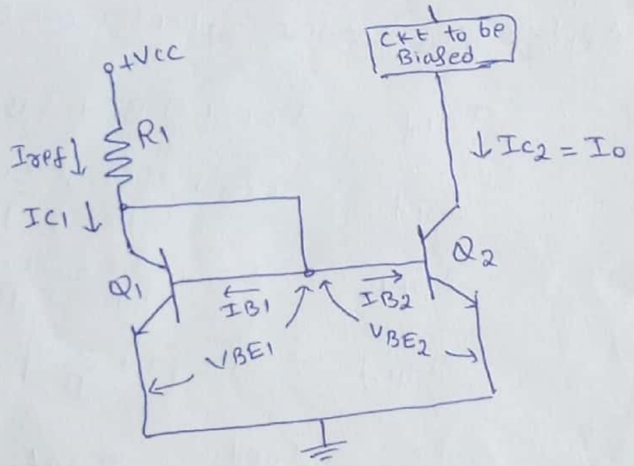
Constant Current Source (or) Current mirror:

→ A current mirror is a circuit whose output current is a replica of the current sent at its input terminal.

→ A constant current source is an electronic circuit that supplies a constant current to the load i.e. independent of the voltage across the load.

→ The constant current sources are widely used in analog integrated circuits as biasing elements and load devices for amplifier stages.

Basic Current Source:



→ In the basic current source circuit, the transistors Q_1 & Q_2 are matched and the bases and emitter of Q_1 & Q_2 are tied together and thus have the same V_{BE}

→ The transistor Q_1 is connected as a diode by shorting its collector to base. The i/p current I_{ref} flows through diode-connected transistor Q_1 and thus establishes a voltage across Q_1. This voltage inturn appears b/w the base & emitter of Q_2.

→ Thus, as long as Q_2 is maintained in the active region, its collector current I_{C2} (I_o) will be approximately equal to I_{ref}. Hence the circuit is often referred to as a current mirror

→ This mirror effect is however valid only for larger values of β.

Analysis:

→ The collector currents I_{C1} & I_{C2} for transistors Q_1 & Q_2 can be approximately expressed as

$$I_{C1} \cong \alpha_F I_{ES}\, e^{V_{BE1}/V_T} \longrightarrow (1)$$

$$I_{C2} \cong \alpha_F I_{ES}\, e^{V_{BE2}/V_T} \longrightarrow (2)$$

$$\frac{(2)}{(1)} \Rightarrow \frac{I_{C2}}{I_{C1}} = \frac{\alpha_F I_{ES}\, e^{V_{BE2}/V_T}}{\alpha_F I_{ES}\, e^{V_{B1}/V_T}} = e^{(V_{BE2}-V_{BE1})/V_T}$$

→ If Q_1 & Q_2 are identical then $V_{BE1} = V_{BE2}$ and $\beta_1 = \beta_2 = \beta$

$$\therefore \frac{I_{C2}}{I_{C1}} = 1 \Rightarrow \boxed{I_{C2} = I_{C1} = I_C = I_O}$$

$\beta = \frac{I_C}{I_B}$

→ Apply KCL at the collector of Q_1

$$I_{ref} = I_{C1} + I_{B1} + I_{B2}$$

$$I_{ref} = I_{C1} + \frac{I_{C1}}{\beta} + \frac{I_{C2}}{\beta}$$

$$I_{ref} = I_C + \frac{I_C}{\beta} + \frac{I_C}{\beta}$$

$$I_{ref} = I_C\left[1 + \frac{2}{\beta}\right]$$

$$\therefore I_C = \frac{I_{ref}}{1+\frac{2}{\beta}} = I_{ref}\cdot\frac{\beta}{\beta+2} \qquad \boxed{\therefore I_C = \frac{\beta}{\beta+2}\cdot I_{ref}} \longrightarrow (3)$$

→ from ckt $I_{ref} = \frac{V_{CC}-V_{BE}}{R_1} \cong \frac{V_{CC}}{R_1}$ $\quad$ | $\because V_{BE} = 0.7V \rightarrow$ very small

from eq (3): for $\beta >> 1$ then $\frac{\beta}{\beta+2} = 1$ $\quad \boxed{\therefore I_O = I_C = I_{ref}}$

for constant R_1

→ Typically I_O varies by 3% for $50 \le \beta \le 200$.

(2)

Ex. 2.10 (67) The current mirror circuit is to provide a 1.0 mA current with $V_{CC} = 10V$. Assume $\beta = 125$ and $V_{BE} = 0.7V$. Determine (a) the value of R_1 (b) the value of R_1 for $I_C = 10\mu A$

Sol Given data

$I_C = 1\,mA$

$V_{CC} = 10V$

$\beta = 125$

$V_{BE} = 0.7V$.

(a)

$$I_C = \frac{\beta}{\beta+2} I_{ref} \Rightarrow I_C = \frac{\beta}{\beta+2}\left[\frac{V_{CC} - V_{BE}}{R_1}\right]$$

$$R_1 = \frac{\beta}{\beta+2}\left[\frac{V_{CC} - V_{BE}}{I_C}\right] = \frac{125}{125+2}\left[\frac{10V - 0.7V}{1\,mA}\right]$$

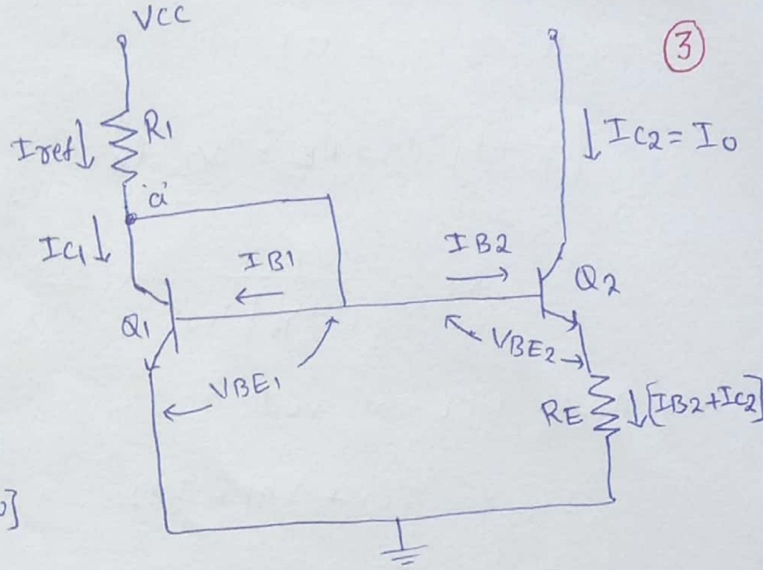
$$\boxed{R_1 = 9.15\,k\Omega}$$

(b) $I_C = 10\mu A$

$$R_1 = \frac{\beta}{\beta+2}\left[\frac{V_{CC} - V_{BE}}{I_C}\right] = \frac{125}{125+2}\left[\frac{10V - 0.7V}{10\,\mu A}\right]$$

$$\boxed{R_1 = 915\,k\Omega}$$

Widlar Current Source :



→ The basic current source has a limitation. Whenever, we need low value current source the value of resistance R_1 is high [Ex. 2.10 page 67 Roy. Chow] and can not be fabricated economically in IC circuits.

→ Therefore, there is a new current source (or) modified current source called Widlar current source, which is used to generate a lower current source.

→ The circuit differ from the basic current source is only in the emitter resistance RE. Due to RE, V_{BE2} is less than V_{BE1} and I_o is smaller than I_{C1}.

Analysis:

→ The ratio of collector currents I_{C1} & I_{C2} using eq (1) & (2) is given by

$$\frac{I_{C1}}{I_{C2}} = e^{(V_{BE1} - V_{BE2})/V_T}$$

taking natural logarithm on both sides

$$\ln\left(\frac{I_{C1}}{I_{C2}}\right) = (V_{BE1} - V_{BE2})/V_T$$

$$V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right) \longrightarrow (i)$$

→ Apply KVL for Emitter base loop

$$V_{BE1} = V_{BE2} + (I_{B2} + I_{C2}) R_E$$

$$V_{BE1} - V_{BE2} = \left(\frac{1}{\beta} + 1\right) I_{C2} R_E \longrightarrow (ii)$$

Equate eq (i) & (ii)

$$\left[\frac{1}{\beta}+1\right] I_{C2} R_E = V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

$$R_E = \frac{V_T}{\left(1+\frac{1}{\beta}\right) I_{C2}} \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

→ Apply KCL at node 'a'

$$I_{ref} = I_{C1} + I_{B1} + I_{B2}$$

$$I_{ref} = I_{C1} + \frac{I_{C1}}{\beta} + \frac{I_{C2}}{\beta}$$

$$I_{ref} = I_{C1}\left[1+\frac{1}{\beta}\right] + \frac{I_{C2}}{\beta} \longrightarrow \text{(iii)}$$

→ In widlar current source $I_{C2} << I_{C1}$, therefore $\frac{I_{C2}}{\beta}$ is neglected in eq (iii).

thus $I_{ref} \cong I_{C1}\left(1+\frac{1}{\beta}\right] \cong I_{C1}\left[\frac{1+\beta}{\beta}\right]$

$$\boxed{\therefore I_{C1} = \left(\frac{\beta}{1+\beta}\right) I_{ref}} \longrightarrow \text{(iv)}$$

Where $I_{ref} = \dfrac{V_{CC}-V_{BE}}{R_1}$

→ for $\beta >> 1$ then $\boxed{I_{C1} \cong I_{ref}}$

Ex. 2.11 (69)

(3-A)

Design a Widlar current Source for generating a constant Current $I_o = 10\,\mu A$. Assume $V_{CC} = 10V$, $V_{BE} = 0.7V$, $\beta = 125$. Use $V_T = 25\,mV$.

Sol

For widlar current Source, we must first decide a suitable value for Iref. If we choose $I_{ref} = 1mA$, then

$$R_1 = \frac{V_{CC} - V_{BE}}{I_{ref}} = \frac{10V - 0.7V}{1mA} = \underline{9.3\,K\Omega}$$

$$RE = \frac{V_T}{\left[1 + \frac{1}{\beta}\right] I_{C2}} \ln\left(\frac{I_{C1}}{I_{C2}}\right) = \frac{0.025}{\left(1 + \frac{1}{125}\right) 10\,\mu A} \cdot \ln\left[\frac{1mA}{10\,\mu A}\right]$$

$$\boxed{RE = 11.5\,K\Omega}$$

Therefore, the widlar current source allows the generation of small currents using small resistors.

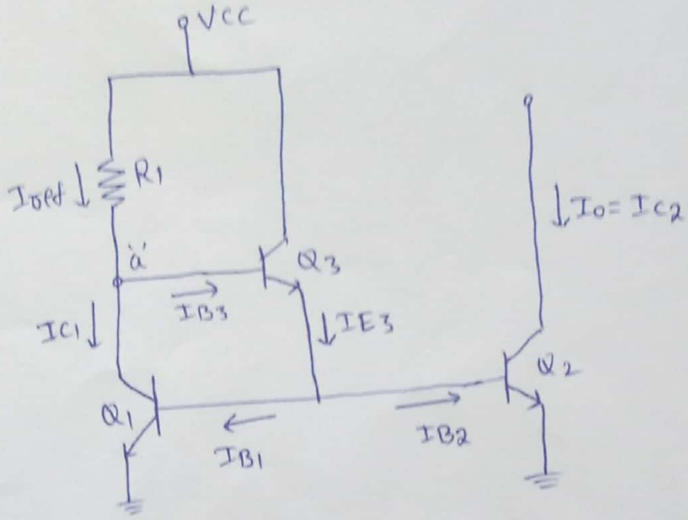
Improved Current Source Circuits :

→ A good current Source must meet two requirements.

(i) The o/p current I_o, should not dependent upon β.

(ii) The o/p resistance of the current source should be very high.

(a) A current Source with Gain :



→ The circuit shown in figure includes a transistor Q_3, whose emitter current supplies the base currents of Q_1 & Q_2.

→ Apply KCL at node a.

$$I_{ref} = I_{C1} + I_{B3}$$

$$I_{ref} = I_{C1} + \frac{I_{E3}}{1+\beta}$$

$$I_{ref} = I_{C1} + \frac{I_{B1}+I_{B2}}{1+\beta}$$

$$I_{ref} = I_{C1} + \frac{2I_B}{1+\beta}$$

$$I_{ref} = I_C + \frac{2I_C}{\beta(1+\beta)}$$

$$I_{ref} = I_C\left[1 + \frac{2}{\beta(1+\beta)}\right]$$

$$\boxed{\therefore I_o = I_C = I_{ref}\,\frac{\beta(1+\beta)}{\beta^2+\beta+2}} \longrightarrow (1)$$

$I_E = I_B + I_C$

$I_E = I_B + \beta I_B$

$I_E = I_B(1+\beta)$

$I_B = \frac{I_E}{1+\beta}$

from ckt

$I_{E3} = I_{B1} + I_{B2}$

If $Q_1 = Q_2$ then

then $I_{B1} = I_{B2}$

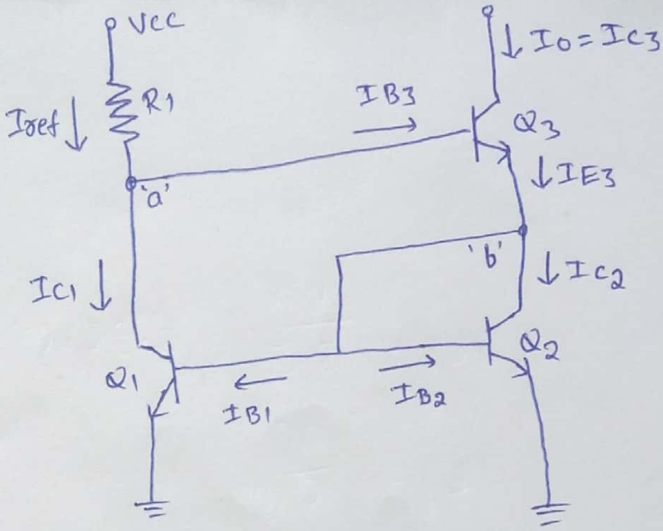
& $I_{C1} = I_{C2} = I_o$

$\beta = \frac{I_C}{I_B} \Rightarrow I_B = \frac{I_C}{\beta}$

where $\boxed{I_{ref} = \frac{V_{CC} - 2V_{BE}}{R_1}}$

→ From eq (1) it is clear that, the o/p current is essentially independent of the β.

Wilson Current Source :



→ This current source provides an o/p current Io, which is very nearly equal to Iref and also exhibits a very high o/p resistance.

→ Q1 & Q2 are Identical

then $V_{BE1} = V_{BE2}$, $I_{C1} = I_{C2}$ and $I_{B1} = I_{B2} = I_B$

→ Apply KCL at node 'b'

$$I_{E3} = I_{C2} + I_{B1} + I_{B2} = I_{C2} + 2I_B = I_{C2} + \frac{2I_{C2}}{\beta} = I_{C2}\left[1+\frac{2}{\beta}\right] \longrightarrow (1)$$

→ We know that from fig

$$I_{E3} = I_{C3} + I_{B3} = I_{C3} + \frac{I_{C3}}{\beta} = I_{C3}\left[1+\frac{1}{\beta}\right] \longrightarrow (2)$$

Equate eq(1) & eq(2)

$$I_{C3}\left[1+\frac{1}{\beta}\right] = I_{C2}\left[1+\frac{2}{\beta}\right]$$

$$I_{C3}\left[\frac{1+\beta}{\cancel{\beta}}\right] = I_{C2}\left[\frac{2+\beta}{\cancel{\beta}}\right]$$

$$I_{C3} = I_o = \left[\frac{2+\beta}{1+\beta}\right] I_{C2}$$

$$\boxed{\therefore \; I_o = \left[\frac{2+\beta}{1+\beta}\right] I_{C1}}$$

→ Apply KCL at node 'a'

$$I_{ref} = I_{C1} + I_{B3} = \left[\frac{1+\beta}{2+\beta}\right] I_o + \frac{I_o}{\beta} = I_o\left[\frac{\beta+\beta^2+2+\beta}{\beta(2+\beta)}\right]$$

$$I_{ref} = I_o\left[\frac{\beta^2+2\beta+2}{\beta^2+2\beta}\right]$$

$$\boxed{\therefore \; I_o = \left[\frac{\beta^2+2\beta}{\beta^2+2\beta+2}\right] I_{ref}}$$ where $$\boxed{I_{ref} = \frac{V_{CC} - 2V_{BE}}{R_1}}$$

Configurations of Differential Amplifier :

→ There are four configurations. those are

i) Dual i/p, Balanced o/p differential amplifier

ii) Dual i/p, unbalanced o/p " "

iii) Single i/p, balanced o/p " "

iv) Single i/p unbalance o/p " "

→ If o/p is taken b/w the two collectors it is called balanced o/p (or) double ended o/p

→ If the o/p is taken b/w one collector with respect to ground it is called unbalanced o/p (or) Single ended o/p.

→ If the Signal is given to both the i/p terminals it is called dual i/p.

→ If the Signal is given to only one i/p terminal and other terminal is grounded it is called Single i/p (or) single ended i/p.

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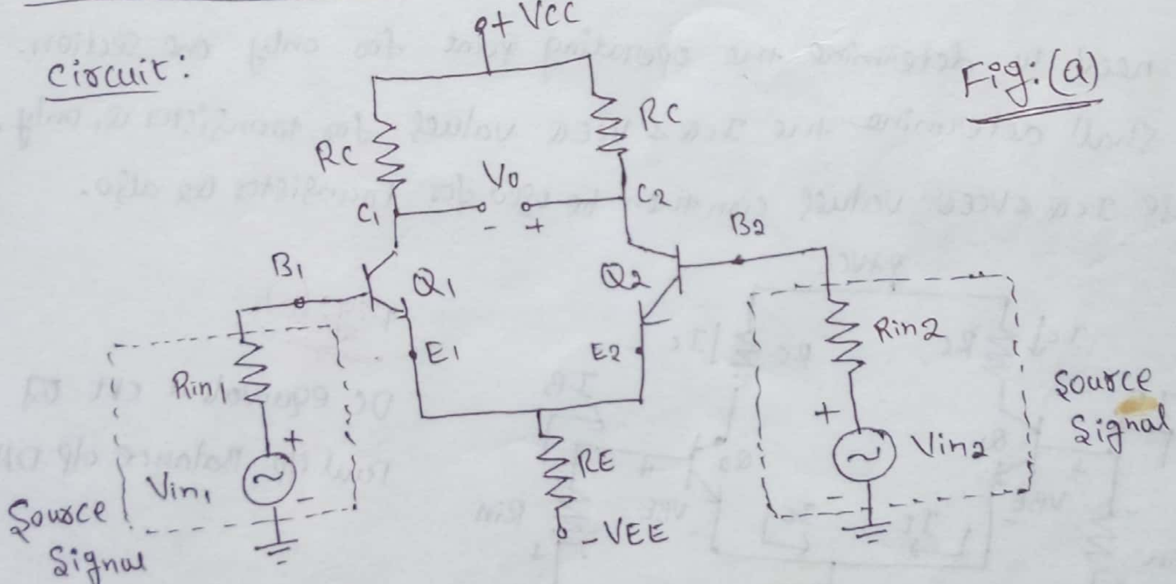
→ In the analysis to follow we use r- Parameters instead of h-Parameters for a number of reasons.

* The A.C. analysis of differential amplifiers with r- parameters is simpler, more straight forward, and less cumbersome.
* The performance equations obtained are easy to remember since they are not as complex (or) as lengthy as h- parameter equations

① Dual i/p, Balanced o/p Differential Amplifier :

Circuit:

Fig: (a)



→ The two i/p Signals V_{in1} & V_{in2} are applied to the bases B_1 & B_2 of transistors Q_1 & Q_2.

→ The o/p Vo is measured b/w the two collectors, C_1 & C_2 which are at the same dc potential.

→ Because of the equal dc potential at the two collectors with respect to ground, the o/p is referred to as a balance o/p.

DC Analysis :

→ To determine the operating point values (I_{CQ} & V_{CEQ}) for the differential amplifier we need to obtain a dc equivalent circuit.

→ The dc equivalent circuit can be obtained simply by reducing the i/p signals V_{in1} & V_{in2} to zero. The circuit shown in below fig.

→ The internal resistances of of the i/p signals are denoted by Rin because $R_{in1} = R_{in2}$. Since both emitter-biased sections of the differential amplifier are symmetrical.

* We need to determine the operating point for only one section. we shall determine the I_{CQ} & V_{CEQ} values for transistor Q_1 only. These I_{CQ} & V_{CEQ} values can then be used for transistor Q_2 also.

circuit

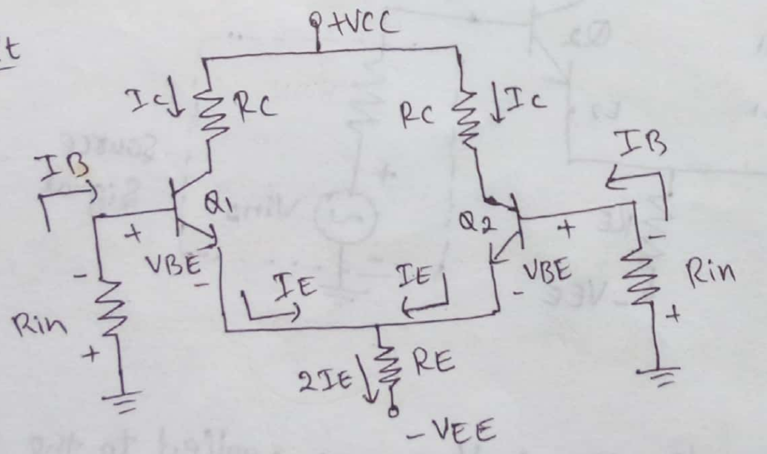


Fig: (b)

DC equivalent ckt of Dual i/p, Balance o/p DA

→ Apply KVL to the Base-emitter loop of the transistor Q_1.

$$-R_{in} I_B - V_{BE} - 2I_E R_E + V_{EE} = 0$$

But we know $\beta = \frac{I_C}{I_B} \Rightarrow I_B = \frac{I_C}{\beta} \Rightarrow I_B = \frac{I_E}{\beta}$ $\quad \because I_E \simeq I_C$

then $$-\frac{R_{in} I_E}{\beta_{dc}} - V_{BE} - 2I_E R_E + V_{EE} = 0$$

$$-I_E\left[\frac{R_{in}}{\beta_{dc}} + 2R_E\right] + V_{EE} - V_{BE} = 0$$

$$I_E\left[\frac{R_{in}}{\beta_{dc}} + 2R_E\right] = V_{EE} - V_{BE}$$

$$I_E = \frac{V_{EE} - V_{BE}}{R_{in}/\beta_{dc} + 2R_E}$$

$$\boxed{\therefore\ I_E \simeq I_C = I_{CQ} = \frac{V_{EE} - V_{BE}}{R_{in}/\beta_{dc} + 2R_E}} \longrightarrow (1)$$

Here $V_{BE} = 0.7V$ for Si & $V_{BE} = 0.2V$ for Ge

Generally $R_{in}/\beta_{dc} << 2R_E$ the $\boxed{I_{CQ} = \frac{V_{EE} - V_{BE}}{2R_E}}$ $\therefore I_E = I_C$

→ By selecting a proper value of R_E, we can obtain a desired value of emitter current for a known value of $-V_{EE}$.

→ The emitter current in transistors Q_1 & Q_2 is independent of collector resistance R_C.

To determine V_{CEQ}:

Assume that the voltage drop across R_{in} is negligibly small. Then the voltage at the emitter of transistor Q_1 is approximately equal to $-V_{BE}$.

→ voltage at collector $V_C = V_{CC} - I_C R_C$

collector-to-emitter voltage $V_{CE} = V_C - V_E$

$$V_{CE} = V_{CC} - I_C R_C - (-V_{BE})$$

$$V_{CE} = V_{CC} + V_{BE} - I_C R_C$$

$$\boxed{\therefore\ V_{CEQ} = V_{CC} + V_{BE} - I_C R_C} \longrightarrow (2)$$

Note: The dc analysis equations (1) & (2) are applicable for all four DA configurations as long as we use the same biasing arrangement for each of them.

AC Analysis :

→ To perform ac analysis to derive the expression for the voltage gain Ad, i/p resistance Ri & o/p resistance Ro of the DA.

1. Set the dc voltages +Vcc & −VEE at zero
2. Substitute the Small-Signal T-equivalent models for the transistors.

Circuit :

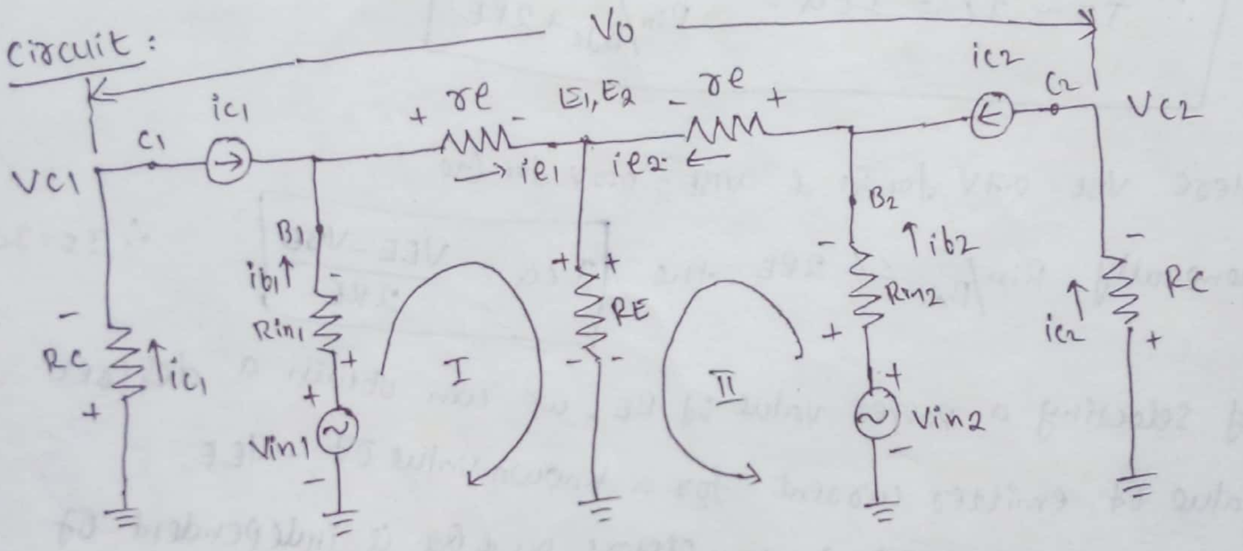
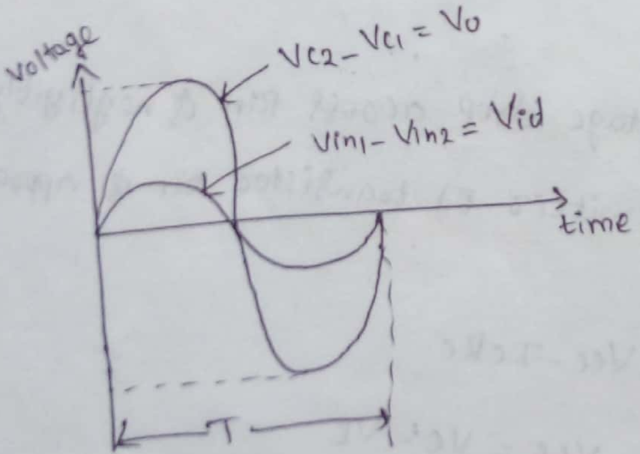


fig (c). AC equivalent circuit of Dual i/p, Balance o/p DA



fig(d). i/p & o/p waveforms

Voltage Gain (Ad) :

→ Note : * $I_{E1} = I_{E2}$; $r_{e1} = r_{e2} = r_e$

* i/p & o/p are out of phase by 180°.

* The voltage at collector C2 is assumed to be more positive with respect to collector C1, even though both of them are negative with respect to ground.

→ Apply KVL to the loop - I.

$$V_{in1} - R_{in1} i_{b1} - r_e i_{e1} - R_E(i_{e1} + i_{e2}) = 0$$

Substitute current relation $i_{b1} = \frac{i_{e1}}{\beta_{ac}}$ yields

$$V_{in1} - \frac{R_{in1} i_{e1}}{\beta_{ac}} - r_e i_{e1} - R_E(i_{e1} + i_{e2}) = 0$$

Generally R_{in1}/β_{ac} value is very small hence neglected

then $V_{in1} - r_e i_{e1} - R_E i_{e1} - R_E i_{e2} = 0$

$$(r_e + R_E) i_{e1} + R_E i_{e2} = V_{in1} \longrightarrow (1)$$

→ Apply KVL to the loop - II.

$$V_{in2} - R_{in2} i_{b2} - r_e i_{e2} - R_E(i_{e1} + i_{e2}) = 0.$$

Substitute current relation $i_{b2} = \frac{i_{e2}}{\beta_{ac}}$ yields

$$V_{in2} - \frac{R_{in2} i_{e2}}{\beta_{ac}} - r_e i_{e2} - R_E(i_{e1} + i_{e2}) = 0$$

Generally R_{in2}/β_{ac} value is very small hence neglected

$$V_{in2} - r_e i_{e2} - R_E i_{e1} - R_E i_{e2} = 0$$

$$R_E i_{e1} + (r_e + R_E) i_{e2} = V_{in2} \longrightarrow (2)$$

→ Equations (1) & (2) can be solved simultaneously for i_{e1} & i_{e2} by using Cramer's rule:

$$i_{e1} = \frac{\begin{vmatrix} V_{in1} & R_E \\ V_{in2} & r_e + R_E \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}} = \frac{(r_e + R_E) V_{in1} - (R_E) V_{in2}}{(r_e + R_E)^2 - (R_E)^2}$$

Similarly

$$i_{e2} = \frac{\begin{vmatrix} r_e + R_E & V_{in1} \\ R_E & V_{in2} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}} = \frac{(r_e + R_E) V_{in2} - (R_E) V_{in1}}{(r_e + R_E)^2 - (R_E)^2}$$

The o/p voltage $V_o = V_{c2} - V_{c1}$

$$V_o = -R_{c2} i_{c2} - (-R_{c1} i_{c1})$$

$$V_o = R_c i_{c1} - R_c i_{c2} \qquad \because R_{c1} = R_{c2} = R_c.$$

$$V_o = R_c (i_{e1} - i_{e2}) \qquad \because i_c \simeq i_e$$

Substitute current relations i_{e1} & i_{e2} in above equation.

$$V_o = R_c \left[\frac{(r_e + R_E) v_{in1} - (R_E) v_{in2}}{(r_e + R_E)^2 - (R_E)^2} - \left\{ \frac{(r_e + R_E) v_{in2} - (R_E) v_{in1}}{(r_e + R_E)^2 - (R_E)^2} \right\} \right]$$

$$V_o = R_c \left[\frac{(r_e + R_E)(v_{in1} - v_{in2}) + (R_E)(v_{in1} - v_{in2})}{(r_e + R_E)^2 - (R_E)^2} \right]$$

$$V_o = R_c \left[\frac{(v_{in1} - v_{in2})(r_e + R_E + R_E)}{r_e^2 + 2 r_e R_E + \cancel{R_E^2} - \cancel{R_E^2}} \right]$$

$$V_o = R_c \left[\frac{(v_{in1} - v_{in2})(r_e + \cancel{2R_E})}{r_e [r_e + \cancel{2R_E}]} \right]$$

$$\boxed{V_o = \frac{R_c}{r_e} [v_{in1} - v_{in2}]} \longrightarrow (3)$$

$$V_o = \frac{R_c}{r_e} (V_{id}) \qquad \because V_{id} = V_{in1} - V_{in2}$$

$$\frac{V_o}{V_{id}} = \frac{R_c}{r_e} = A_d \qquad \boxed{\therefore A_d = \frac{R_c}{r_e}} \longrightarrow (4)$$

Eq (3) represents DA amplifies the difference b/w two i/p signals.

fig(c): shows the i/p & o/p waveforms of dual i/p, balanced o/p DA.

By defining $V_{id} = V_{in1} - V_{in2}$ as the difference in i/p voltages.

Eq (4) represents voltage gain of differential Amplifier (DA). which is independant of RE.

Input Resistance :

→ Differential i/p resistance is defined as the equivalent resistance that would be measured at either i/p terminal with the other terminal grounded.

* The i/p resistance R_{i1} is seen from the i/p signal source Vin 1 is determined with the signal source Vin 2 set at zero.

* Similarly the i/p resistance R_{i2} is seen from the i/p signal source Vin2 is determined with the signal source Vin1 set at zero.

→ usually the Source resistances Rin1 & Rin2 are very Small and hence will be ignored in the derivation of i/p resistances R_{i1} & R_{i2}.

$$R_{i1} = \left|\frac{V_{in1}}{i_{b1}}\right|_{V_{in2}=0}$$

$$R_{i1} = \left|\frac{V_{in1}}{i_{e1}/\beta_{ac}}\right|_{V_{in2}=0} \qquad \because i_{b1} = i_{e1}/\beta_{ac}$$

Substitute the value of i_{e1} in the above equation

$$R_{i1} = \frac{\beta_{ac} V_{in1}}{\dfrac{(r_e+R_E)V_{in1} - (R_E)(0)}{(r_e+R_E)^2 - (R_E)^2}}$$

$$R_{i1} = \frac{\beta_{ac} \cancel{V_{in1}}}{(r_e+R_E)\cancel{V_{in1}} / (r_e^2 + 2r_eR_E + \cancel{R_E^2} - \cancel{R_E^2})}$$

$$R_{i1} = \frac{\beta_{ac} r_e[r_e+2R_E]}{(r_e+R_E)} \qquad \therefore r_e+2R_E \cong 2R_E \ \& \ r_e+R_E \cong R_E$$

$$R_{i1} = \frac{\beta_{ac} r_e (2\cancel{R_E})}{\cancel{R_E}} \qquad \because r_e << R_E$$

$$R_{i1} = \beta_{ac} r_e \cdot 2 = 2\beta_{ac} r_e$$

$$\boxed{\therefore R_{i1} = 2\beta_{ac} r_e}$$

Similarly $R_{i2} = \left| \frac{V_{in2}}{i_{b2}} \right|_{V_{in1}=0}$

$$R_{i2} = \left| \frac{V_{in2}}{i_{e2}/\beta_{ac}} \right|_{V_{in1}=0}$$

Substitute i_{e2} value in the above equation.

$$R_{i2} = \frac{V_{in2}\,\beta_{ac}}{\frac{(r_e+R_E)V_{in2} - (R_E)(0)}{(r_e+R_E)^2-(R_E)^2}} = \frac{V_{in2}\,\beta_{ac}}{\cancel{V_{in2}}(r_e+R_E) / r_e^2+2r_eR_E+\cancel{R_E^2}-\cancel{R_E^2}}$$

$$R_{i2} = \frac{\beta_{ac}\cdot r_e[r_e+2R_E]}{[r_e+R_E]}$$

$\because r_e+2R_E \cong 2R_E$

$r_e+R_E \cong R_E$

If $R_E >> r_e$

$$R_{i2} = \frac{\beta_{ac}\cdot r_e\, 2\cancel{R_E}}{\cancel{R_E}}$$

$$\boxed{R_{i2} = 2\beta_{ac} r_e}$$

Output Resistance :

It is defined as the equivalent resistance that would be measured at either o/p terminals with respect to ground.

→ The o/p resistance R_{o1} measured b/w collector C_1 & ground is equal to that of the collector resistor R_C.

→ Similarly the o/p resistance R_{o2} measured at collector C_2 with respect to ground is equal to that of the collector resistor R_C.

Thus $\boxed{R_{o1} = R_{o2} = R_C}$

* The current gain of differential amplifier (DA) is undefined. therefore it will not be derived for any of the four configurations.

* Therefore DA is generally used as a voltage amplifier and not as a current (or) Power amplifier.

(2) Dual i/p. Unbalanced o/p Differential Amplifier :

In this configuration two i/p signals are used ; however, the o/p is measured at only one of the two collectors with respect to ground. Hence the o/p is an unbalanced o/p.

Let us assume that the o/p is measured at the collector of transistor Q_2 with respect to ground. See fig: 2(a)

DC analysis :

The dc analysis procedure for the dual i/p, unbalanced o/p DA (Differential Amplifier) is identical to that of the dual i/p - balanced o/p DA because both configurations use the same biasing arrangement.

Therefore
$$I_E = I_{CQ} = \frac{V_{EE} - V_{BE}}{2R_E + R_{in}/\beta_{dc}}$$

$$V_{CE} = V_{CEQ} = V_{CC} + V_{BE} - I_C R_C$$

AC analysis :

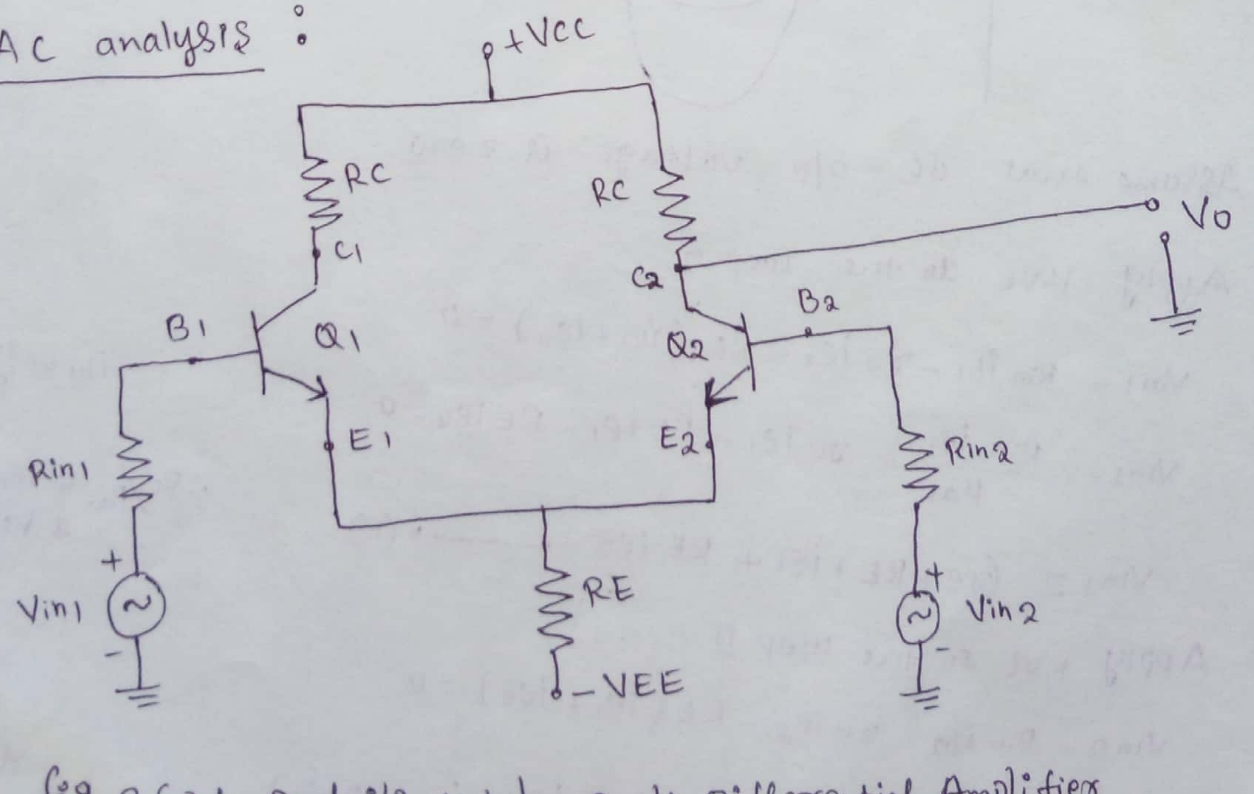
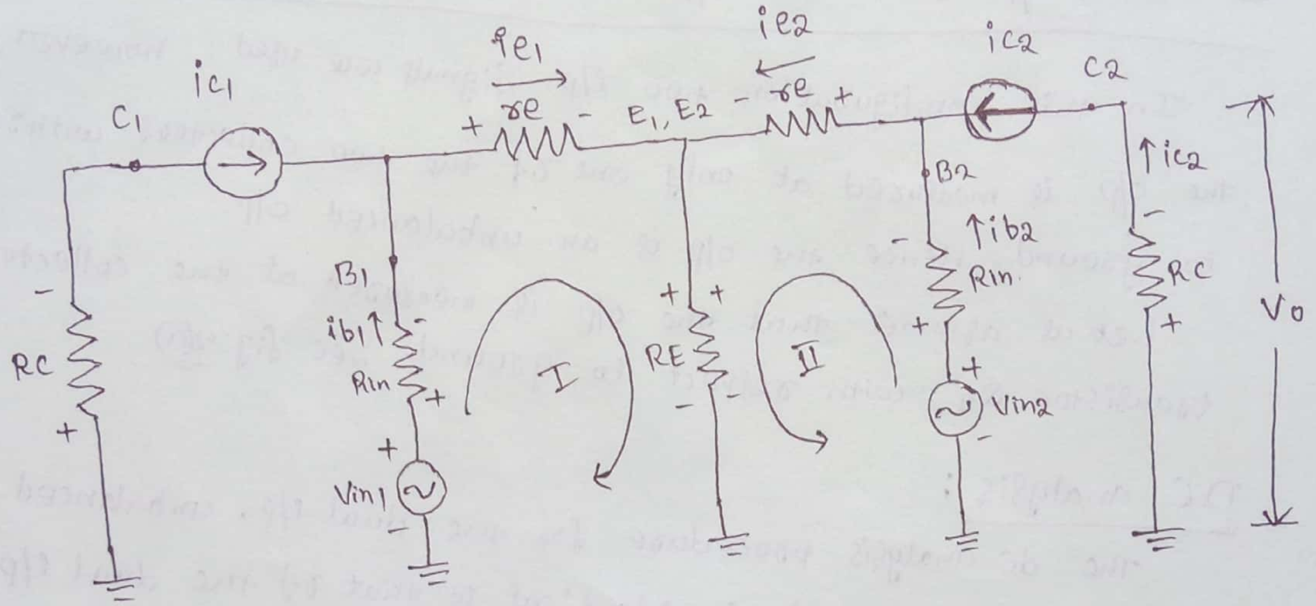
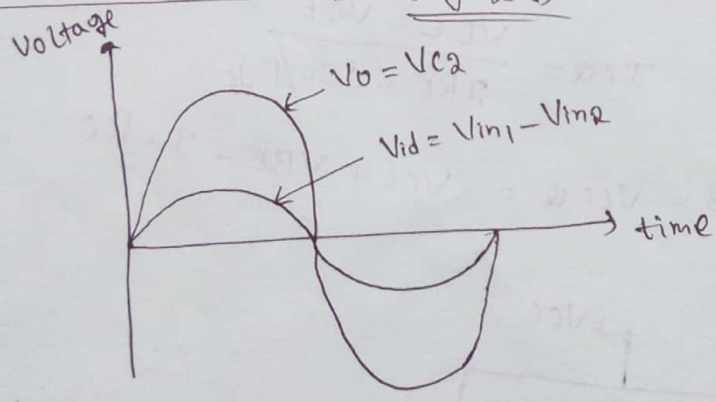


fig 2(a) : Dual i/p. unbalance o/p Differential Amplifier

Ac equivalent circuit: fig 2(b)



i/p & o/p wave forms : fig 2(c)



Assume that dc o/p voltage is zero.

→ Apply KVL to the loop I

$$V_{in1} - R_{in}\, i_{b1} - r_e\, i_{e1} - R_E\,(i_{e1} + i_{e2}) = 0$$

$\because i_{b1} \Rightarrow \frac{i_{e1}}{\beta_{ac}}$

$$V_{in1} - \frac{R_{in} \cdot i_{e1}}{\beta_{ac}} - r_e\, i_{e1} - R_E\, i_{e1} - R_E\, i_{e2} = 0$$

$\therefore R_{in}/\beta_{ac}$ is very small & hence neglected.

$$V_{in1} = (r_e + R_E)\, i_{e1} + R_E\, i_{e2} \longrightarrow (1)$$

→ Apply KVL to the loop II

$$V_{in2} - R_{in}\, i_{b2} - r_e\, i_{e2} - R_E\,(i_{e1} + i_{e2}) = 0$$

$$V_{in2} = R_E\, i_{e1} + (r_e + R_E)\, i_{e2} \longrightarrow (2)$$

Equations (1) & (2) can be solved simultaneously for i_{e1} & i_{e2} using Cramer's rule

$$i_{e1} = \frac{\begin{vmatrix} V_{in1} & R_E \\ V_{in2} & r_e+R_E \end{vmatrix}}{\begin{vmatrix} r_e+R_E & R_E \\ R_E & r_e+R_E \end{vmatrix}} = \frac{V_{in1}(r_e+R_E) - V_{in2}(R_E)}{(r_e+R_E)^2 - (R_E)^2}$$

$$i_{e2} = \frac{\begin{vmatrix} r_e+R_E & V_{in1} \\ R_E & V_{in2} \end{vmatrix}}{\begin{vmatrix} r_e+R_E & R_E \\ R_E & r_e+R_E \end{vmatrix}} = \frac{V_{in2}(r_e+R_E) - V_{in1}(R_E)}{(r_e+R_E)^2 - (R_E)^2}$$

The o/p voltage $V_o = V_{c2} = -R_C i_{c2} = -R_C i_{e2}$ $\quad \because i_c \approx i_e$

$$\therefore V_o = -R_C \left[\frac{V_{in2}(r_e+R_E) - V_{in1}(R_E)}{(r_e+R_E)^2 - (R_E)^2} \right]$$

$$V_o = R_C \left[\frac{V_{in1}(R_E) - V_{in2}(r_e+R_E)}{r_e^2 + 2r_eR_E + \cancel{R_E^2} - \cancel{R_E^2}} \right]$$

$$V_o = R_C \left[\frac{V_{in1}(R_E) - V_{in2}(R_E)}{r_e\{r_e+2R_E\}} \right]$$

$\because r_e << R_E$

$r_e+R_E = R_E$

$$V_o = R_C \left\{ \frac{\cancel{R_E}(V_{in1}-V_{in2})}{2r_e\cancel{R_E}} \right]$$

$\therefore r_e+2R_E = 2R_E$

$$V_o = \frac{R_C}{2r_e}(V_{in1}-V_{in2})$$

$$V_o = \frac{R_C}{2r_e} V_{id} \Rightarrow \frac{V_o}{V_{id}} = \frac{R_C}{2r_e} = A_d.$$

$$\boxed{\therefore A_d = \frac{R_C}{2r_e}}$$

$\therefore$ The voltage gain of dual i/p, unbalance o/p DA is half the gain of dual i/p, balanced o/p DA.

Differential i/p Resistance :

The only difference b/w dual i/p, balanced o/p DA & dual i/p unbalanced o/p DA is in the way of o/p voltage measured. However, the i/p resistance seen from either i/p sources does not depend on the way of o/p voltage measured. Therefore, the i/p resistance Ri seen from either i/p source of the dual i/p, unbalanced o/p DA should be same as that of the dual i/p, balanced o/p DA is given by equations

$$\boxed{R_{i1} = R_{i2} = 2\beta_{ac} r_e}$$

Out put resistance :

The o/p resistance R_o measured at collector C_2 with respect to ground is equal to the collector resistor R_C. Thus $\boxed{R_o = R_C}$

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(3). Single i/p, Balanced o/p Differential Amplifier :

In this configuration the single i/p signal is applied to base of transistor Q_1, and the o/p is measured b/w the two collectors, which are at the same dc potential. Therefore, the o/p is said to be a balanced o/p.

Circuit :

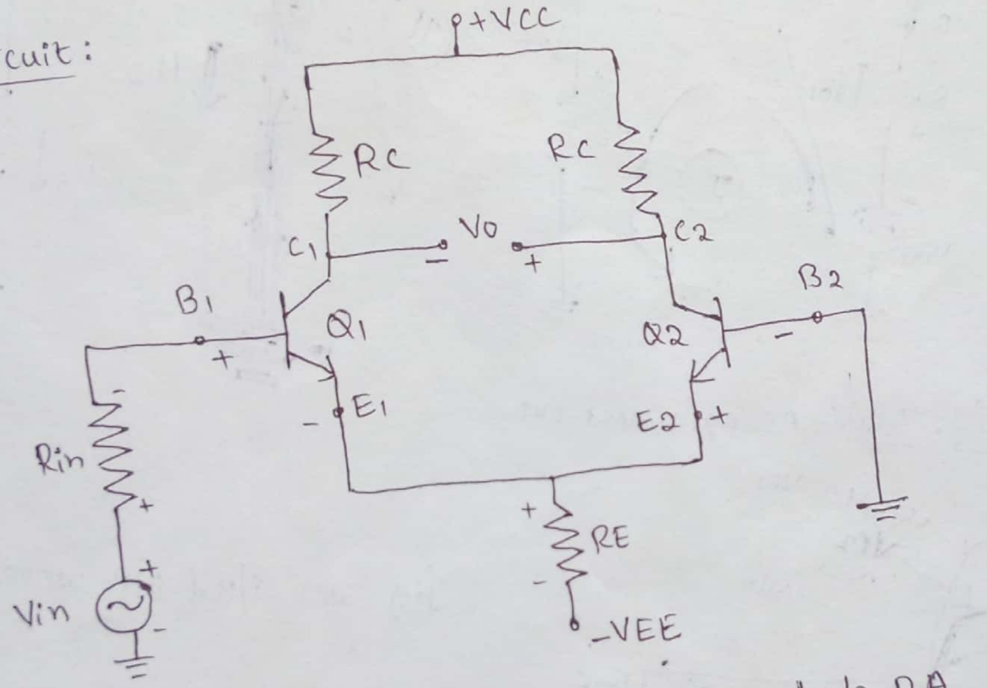


fig. 3(a) Single i/p, Balanced o/p D.A

DC analysis :

The dc analysis procedure for the single i/p, balanced o/p differential amplifier (D.A) is identical to that of the previous two differential amplifier configurations. Because all configurations use the same biasing arrangement

Therefore

$$I_E = I_{CQ} = \frac{V_{EE} - V_{BE}}{2R_E + R_{in}/\beta_{dc}}$$

$$V_{CE} = V_{CEQ} = V_{CC} + V_{BE} - I_C R_C$$

AC analysis :

The a.c equivalent circuit of the single i/p, balance o/p DA with a small-signal T-equivalent model substituted for the transistor is shown in fig. 3(b).

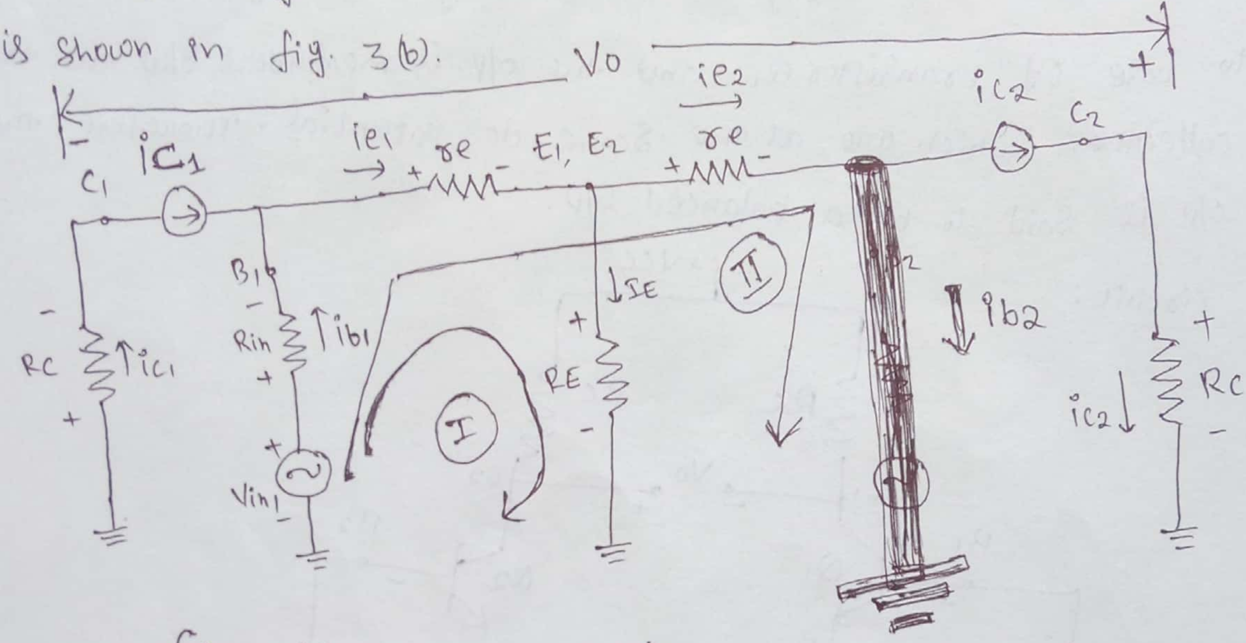


fig. 3(b): AC equivalent ckt.

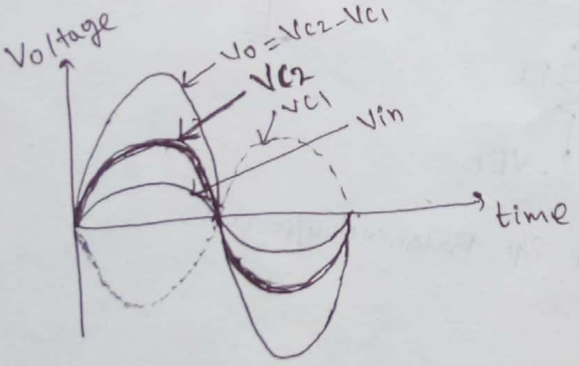


fig. 3(c) i/p & o/p waveforms

→ During the positive half cycle of i/p signal, the base-emitter voltage of Q_1 is positive & that of Q_2 is negative, as shown in fig 3(a). This means that the collector current in Q_1 increases & that in Q_2 decreases from the operating point value I_{CQ}. Hence the current of both sources i_{c1} & i_{c2} are shown to be in the same direction

→ During the negative half cycle of i/p signal, the opposit action takes place. i.e, the collector current of transistor Q_1 decreases and that in transistor Q_2 increases.

→ The polarity of voltage across each collector resistor is consistent with the direction of current sources i_{c1} & i_{c2}. That is voltage across collector resistor of Q_2 is positive and that across the collector of Q_1 is negative with respect to the ground.

→ According to this polarity, the o/p voltage is equal to the voltage at collector C_2 minus the voltage at collector C_1.

Voltage Gain (A_d) :

→ Apply KVL for loop I & II of fig.3(b)

$$V_{in} - R_{in} i_{b1} - r_e i_{e1} - R_E(i_{e1} - i_{e2}) = 0$$

$$V_{in} - R_{in} i_{b1} - r_e i_{e1} - r_e i_{e2} = 0$$

→ Substitute current relations $i_{b1} = \frac{i_{e1}}{\beta_{ac}}$ & $i_{b2} = \frac{i_{e2}}{\beta_{ac}}$

$$V_{in} - \frac{R_{in}}{\beta_{ac}} i_{e1} - r_e i_{e1} - R_E i_{e1} + R_E i_{e2} = 0$$

$$V_{in} - \frac{R_{in}}{\beta_{ac}} i_{e1} - r_e i_{e1} - r_e i_{e2} = 0$$

→ Generally, R_{in}/β_{ac} value is very small; therefor for simplicity we shall neglect it and rearrange the equations as follows.

$$(r_e + R_E) i_{e1} - (R_E) i_{e2} = V_{in} \longrightarrow (1)$$

$$r_e i_{e1} + r_e i_{e2} = V_{in} \longrightarrow (2)$$

Equations (1) & (2) can be solved simultaneously fore i_{e1} & i_{e2} by using Cramer's rule.

$$i_{e1} = \frac{\begin{vmatrix} V_{in} & -R_E \\ V_{in} & r_e \end{vmatrix}}{\begin{vmatrix} r_e + R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{V_{in} r_e + R_E V_{in}}{(r_e + R_E) r_e + R_E r_e} = \frac{(r_e + R_E) V_{in}}{r_e[r_e + 2R_E]}$$

Similarly

$$i_{e2} = \frac{\begin{vmatrix} r_e + R_E & V_{in} \\ r_e & V_{in} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{(r_e + R_E) V_{in} - r_e V_{in}}{(r_e + R_E) r_e + r_e R_E} = \frac{(R_E) V_{in}}{r_e[r_e + 2R_E]}$$

The o/p voltage is

$$V_o = V_{C2} - V_{C1} = R_C\, i_{C2} - (-R_C\, i_{C1})$$

$$V_o = R_C[i_{C2} + i_{C1}] = R_C\{i_{e2} + i_{e1}\} \quad \because i_e \cong i_c.$$

Substitute the i_{e1} & i_{e2} values in the above equations

then $$V_o = R_C\left[\frac{(R_E)\, v_{in}}{r_e[r_e+2R_E]} + \frac{(r_e+R_E)\, v_{in}}{r_e[r_e+2R_E]}\right]$$

$$V_o = R_C\left[\frac{v_{in}(r_e+\cancel{2R_E})}{r_e(r_e+\cancel{2R_E})}\right]$$

$$V_o = \frac{R_C}{r_e} v_{in} \Rightarrow \boxed{\frac{V_o}{V_{in}} = \frac{R_C}{r_e} = A_d}$$

Note: The voltage gain of single-i/p, balanced o/p DA is equal to that of the dual i/p balanced o/p DA

i/p Resistance:

It is seen from the i/p signal source is determined as follows.

$$R_i = \frac{V_{in}}{i_{b1}} = \frac{V_{in}}{i_{e1}/\beta_{ac}} = \frac{V_{in}\beta_{ac}}{i_{e1}} = \frac{\cancel{V_{in}}\cdot\beta_{ac}}{\frac{(r_e+R_E)\cancel{v_{in}}}{r_e(r_e+2R_E)}} = \frac{\beta_{ac}\, r_e(r_e+2R_E)}{r_e+R_E}$$

$$R_i = \frac{\beta_{ac}\, r_e\, 2\cancel{R_E}}{\cancel{R_E}} = 2\beta_{ac} r_e \qquad \because r_e << R_E,\ r_e+R_E \cong R_E,\ r_e+2R_E \cong 2R_E$$

$$\boxed{\therefore R_i = 2\beta_{ac} r_e}$$

o/p Resistance:

→ It is the equivalent resistance that would be measured at either o/p terminal with respect to ground.

→ Therefore, the o/p resistance R_{o1} measured at the collector C_1 & the o/p resistance R_{o2} measured at the collector C_2 are given by equation $\boxed{R_{o1} = R_{o2} = R_C}$

(4). Single i/p. Unbalanced o/p Differential Amplifier:

In this configuration the i/p signal is applied to the base of transistor Q_1, and the o/p is measured at the collector of transistor Q_2.

Circuit:

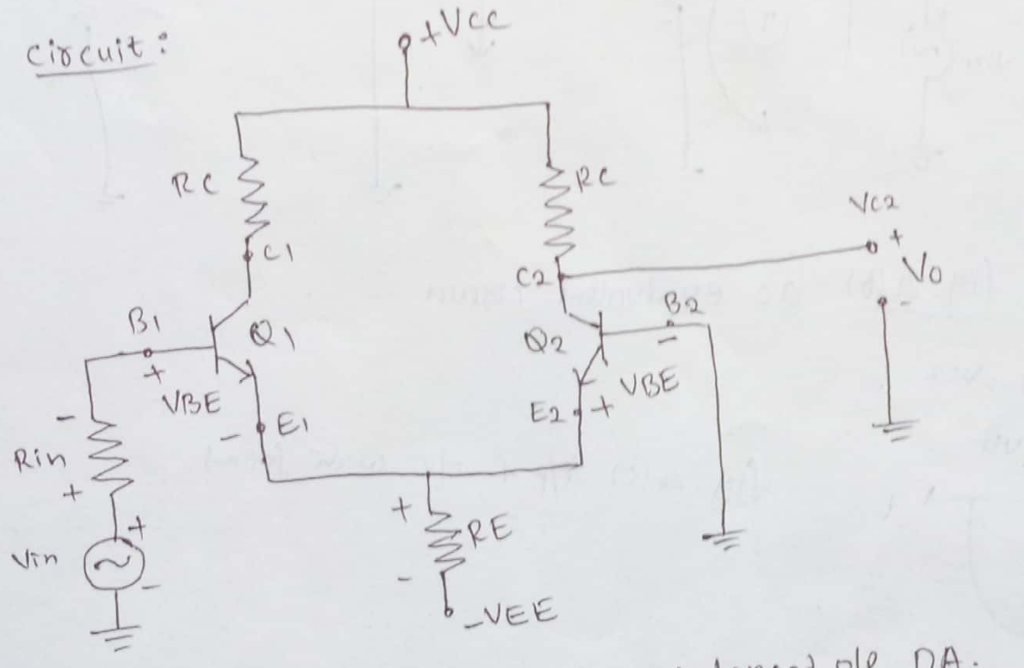


fig. 4(a) Single i/p, unbalanced o/p. DA.

DC analysis:

The dc analysis procedure for the single i/p, unbalanced o/p differential amplifier is identical to that of the previous three differential amplifier configurations. Because all configurations use the same biasing arrangement.

Therefore,

$$I_E = I_{CQ} = \frac{V_{EE} - V_{BE}}{2R_E + R_{in}/\beta_{dc}}$$

$$V_{CE} = V_{CEQ} = V_{CC} + V_{BE} - I_C R_C$$

AC analysis:

The ac equivalent circuit of single i/p, unbalanced o/p differential amplifier with a small-signal T-equivalent model substituted for the transistor is shown in fig. 4(b).

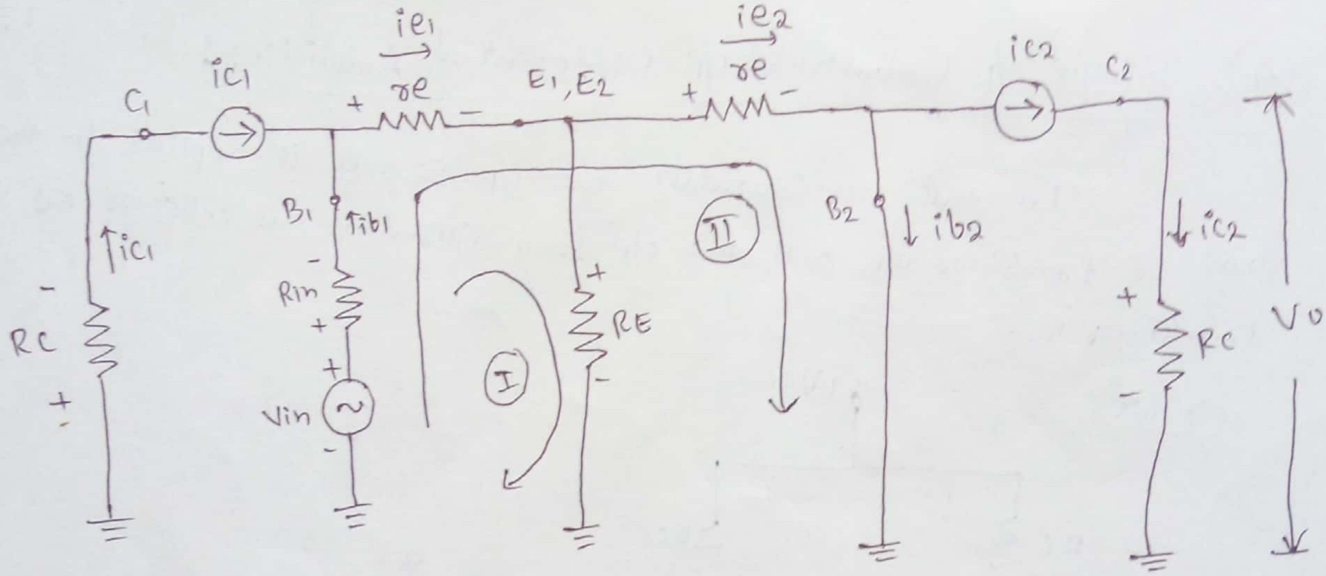


fig. 4(b) ac equivalent circuit

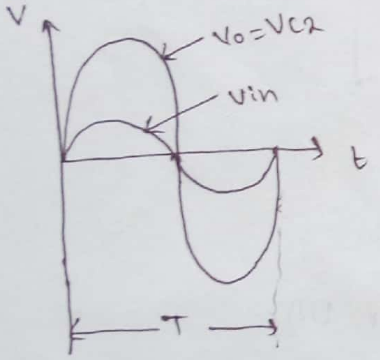


fig. 4(c) i/p & o/p waveforms.

Voltage gain :

→ apply KVL to the loop I & II

$$V_{in} - R_{in} i_{b1} - r_e i_{e1} - R_E (i_{e1} - i_{e2}) = 0$$

$$V_{in} - R_{in} i_{b1} - r_e i_{e1} - r_e i_{e2} = 0$$

→ Substitute current relations $i_{b1} = \frac{i_{e1}}{\beta_{ac}}$ & $i_{b2} = \frac{i_{e2}}{\beta_a}$

$$V_{in} - \frac{R_{in} i_{e1}}{\beta_{ac}} - r_e i_{e1} - R_E i_{e1} + R_E i_{e2} = 0$$

$$V_{in} - \frac{R_{in} i_{e1}}{\beta_{ac}} - r_e i_{e1} - r_e i_{e2} = 0$$

→ Generally, R_{in}/β_{ac} value is very small; therefore for simplicity we shall neglect this value & rearrange the equations as follows

$$(r_e + R_E) i_{e1} - R_E i_{e2} = V_{in} \longrightarrow (1)$$

$$r_e i_{e1} + r_e i_{e2} = V_{in} \longrightarrow (2)$$

equations (1) & (2) can be solved simultaneously for i_{e1} & i_{e2} by using cramer's rule

$$i_{e1} = \frac{\begin{vmatrix} V_{in} & -R_E \\ V_{in} & r_e \end{vmatrix}}{\begin{vmatrix} r_e+R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{V_{in} r_e + V_{in} R_E}{r_e(r_e+R_E)+r_e R_E} = \frac{V_{in}(r_e+R_E)}{r_e[r_e+2R_E]}$$

$$i_{e2} = \frac{\begin{vmatrix} r_e+R_E & V_{in} \\ r_e & V_{in} \end{vmatrix}}{\begin{vmatrix} r_e+R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{V_{in}(r_e+R_E) - V_{in} r_e}{r_e(r_e+R_E)+r_e R_E} = \frac{V_{in}(R_E)}{r_e[r_e+2R_E]}$$

The o/p voltage is

$$V_o = V_{c2} = R_C\, i_{c2} = R_C\, i_{e2}$$

$$V_o = R_C \frac{V_{in}(R_E)}{r_e[r_e+2R_E]}$$

$\because r_e << R_E$

$r_e + 2R_E \cong 2R_E$

$$V_o = R_C \frac{V_{in}(\cancel{R_E})}{r_e(2\cancel{R_E})} = \frac{R_C V_{in}}{2 r_e}$$

$$\frac{V_o}{V_{in}} = \frac{R_C}{2 r_e} = A_d$$

$$\boxed{\therefore A_d = \frac{R_C}{2 r_e}}$$

Note: The voltage gain of single i/p, unbalanced o/p differential amplifier is is half the gain of single i/p balanced o/p differential amplifier.

i/p Resistance :

It is seen from the i/p signal source is determined as fallows

$$Ri = \frac{Vin}{ib_1} = \frac{Vin}{ie_1/\beta ac} = \frac{Vin.\beta ac}{ie_1}$$

$$Ri = \frac{Vin\,\beta ac}{\frac{Vin(re+RE)}{re(re+2RE)}}$$

$$Ri = \frac{\beta ac\; re(re+2RE)}{re+RE}$$

$re << RE$

$$Ri = \frac{\beta ac\; re(2\cancel{RE})}{\cancel{RE}}$$

$\because re+2RE \cong 2RE$

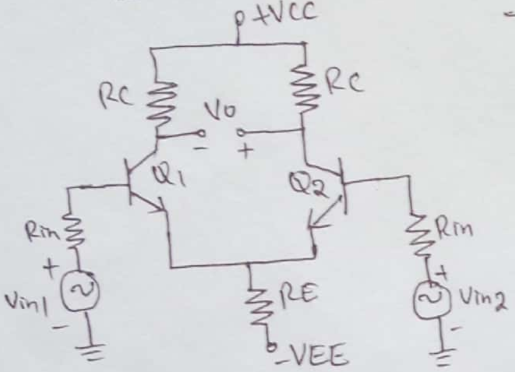
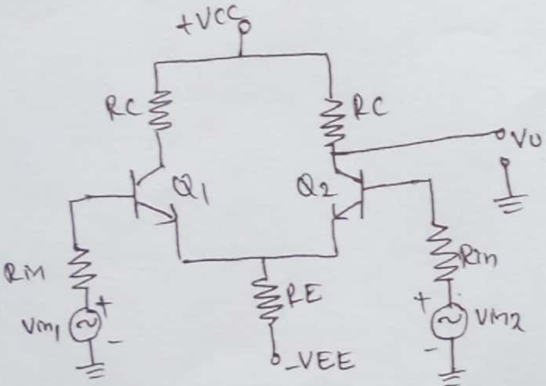
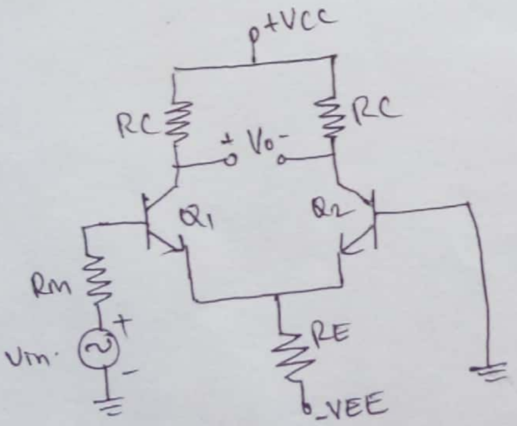
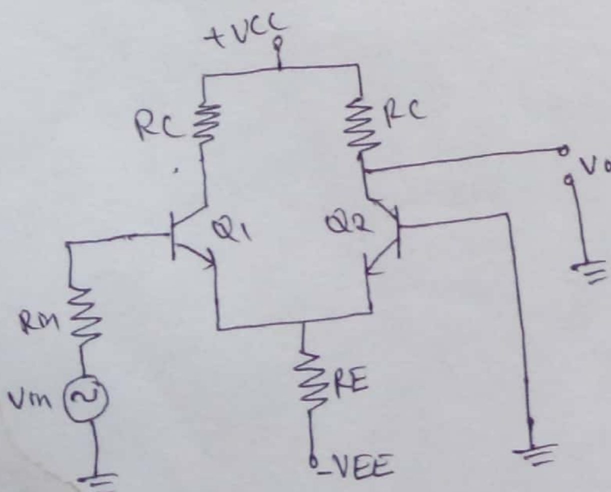
$$\boxed{Ri = 2\beta ac\, re}$$

o/p Resistance :

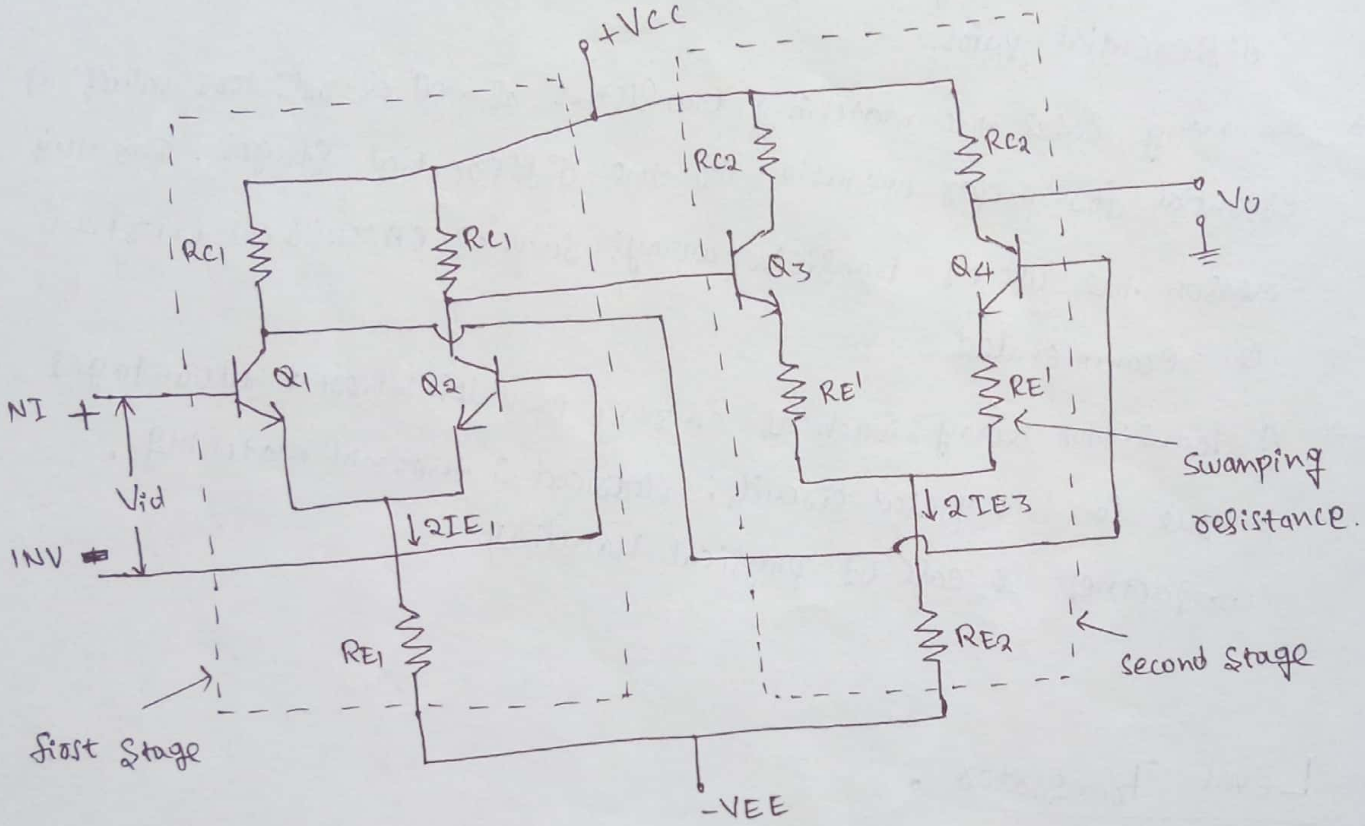
The o/p resistance Ro measured at collector C2 with respect to ground is equal to the collector resistor RC.

$$\boxed{\therefore\ Ro = RC}$$

Properties of Differential amplifier configurations :

Configuration	Circuit	Voltage gain	i/p resistance	o/p resistance
1. Dual i/p, balanced o/p		$A_d = \frac{R_C}{r_e}$	$R_{i1} = 2\beta_{ac} r_e$ $R_{i2} = 2\beta_{ac} r_e$	$R_{o1} = R_C$ $R_{o2} = R_C$
2. Dual i/p, unbalanced o/p		$A_d = \frac{R_C}{2r_e}$	$R_{i1} = 2\beta_{ac} r_e$ $R_{i2} = 2\beta_{ac} r_e$	$R_o = R_C$
3. Single i/p, balanced o/p		$A_d = \frac{R_C}{r_e}$	$R_i = 2\beta_{ac} r_e$	$R_{o1} = R_C$ $R_{o2} = R_C$
4. Single i/p, unbalanced o/p		$A_d = \frac{R_C}{2r_e}$	$R_i = 2\beta_{ac} r_e$	$R_o = R_C$

Cascaded Differential Amplifier Stages :



→ The two stage differential amplifier can be cascaded in series is shown in above figure.

→ The first stage is a dual-i/p, balanced-o/p differential amplifier, The Second stage is a dual-i/p, unbalanced-o/p differential amplifier, driven by the first D.A.

→ The first stage uses an emitter resistance R_{E1}, which carries a current $2I_{E1}$, where I_{E1} is emitter current of Q_1, which is same as emitter current of Q_2 as the transistors are perfectly matched.

→ The second stage uses a pair of swamping resistances and an emitter resistance R_{E2}. This carries a current $2I_{E3}$, where I_{E3} is emitter current of Q_3 which same as emitter current of Q_4 as the two transistors are pefectly matched.

→ A Single-ended o/p is taken from this second Stage. Both Stages use the emitter biasing technique to set-up the emitter currents in the differential pairs.

→ In many cases the matching transistors as well as resistors values is essential for proper operation of the differential Stages. For this reason the use of transistor arrays such as CA 3086 (or) LM3146 is recommended

→ A transistor array such as CA 3086 provides inherent advantages unique to integrated circuits: electrical & thermal matching, compactness & ease of physical handing

Level Translator :

The main purpose of Level translator is to Shift the o/p dc level towards the ground, with minimum change in the ac Signal

Because of the direct coupling, the dc level at emitter rises from Stage to Stage. This increase dc level tends to Shift the operating Point of the Succeeding Stages and, therefore limits the o/p voltage Swing and may even distort the o/p Signal.

Therefore in the cascaded differential amplifier, to shift the o/p dc level down to zero volts, the second (or) final Stage must be fallowed by a level translator circuit.

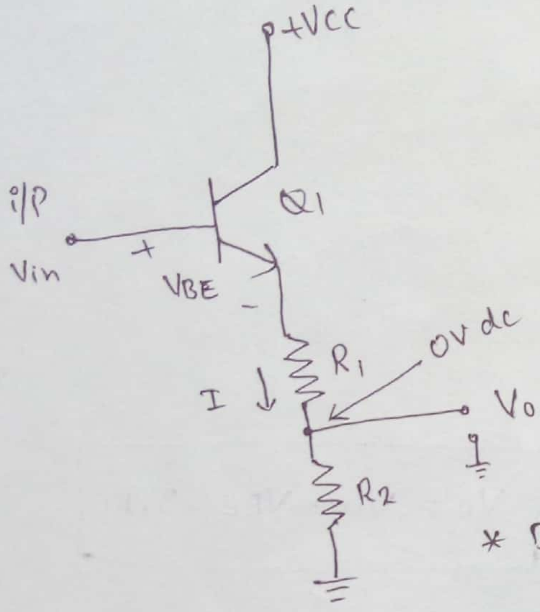
There are variety of translator circuits, those are

a) Emitter fallower with voltage divider

b) " " " constant current bias

c) " " " current mirror

(a) Emitter follower with voltage divider :



Apply KVL to B-E loop

$V_{in} - V_{BE} - I(R_1+R_2) = 0$

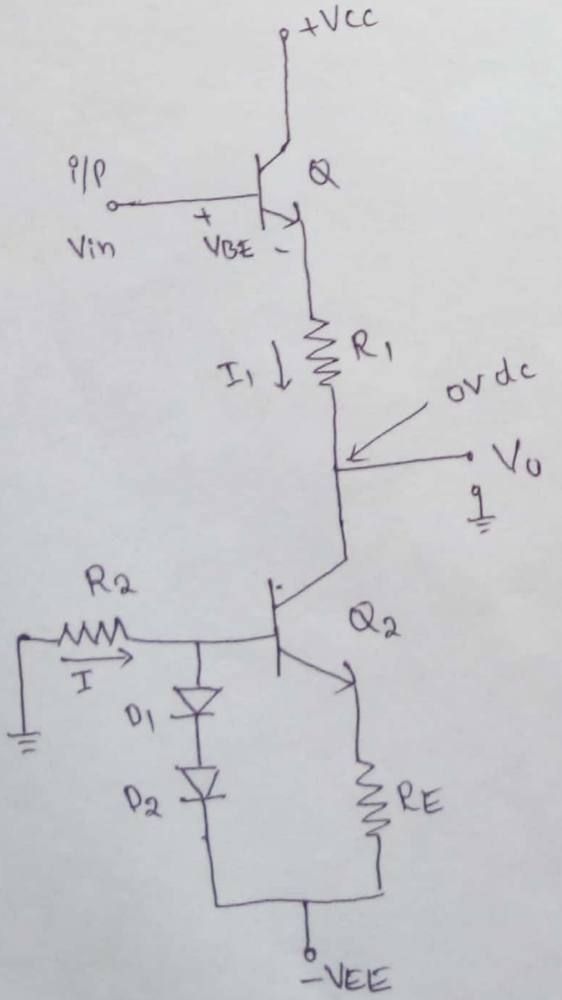
$I = \dfrac{V_{in} - V_{BE}}{R_1+R_2}$

o/p voltage $V_o = I R_2$

$$\boxed{V_o = \frac{(V_{in} - V_{BE}) R_2}{R_1+R_2}}$$

* By proper selection of R_1 & R_2, Level at V_o can be controlled.

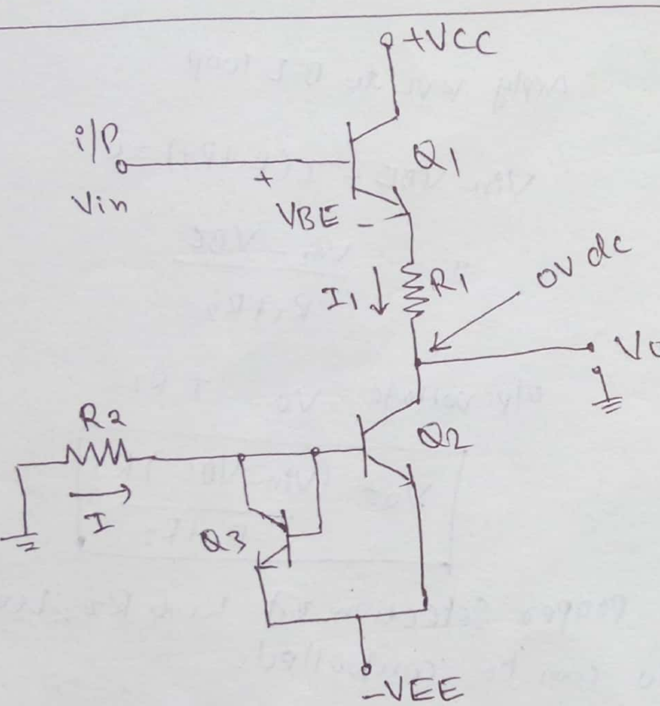
(b) Emitter follower with constant current bias :



$$\boxed{V_o = V_{in} - V_{BE} - I_1 R_1}$$

* choosing proper values of I_1 & R_1 the o/p V_o can be brought to 0 V level

(C) Emitter follower with current mirror :



$$V_o = V_{in} - V_{BE} - I_1 R_1$$

Choosing proper values of I_1 & R_1 the o/p voltage V_o can be brought to 0V level

IC Features and Difference b/w AIC & DIC

1. Input Offset Voltage.
2. Input Offset Current.
3. Input Bias Current.
4. Differential Input Resistance.
5. Input Capacitance.
6. Input Voltage Range.
7. Common Mode Rejection Ratio (CMRR) .
8. Supply Voltage Rejection Ratio (SVRR).

Specifications of Differential Amplifiers

1. High differential voltage gain
2. Low common mode gain
3. High CMRR
4. High input resistance
5. Low output resistance
6. Low offset voltage
7. Low offset current
8. Large bandwidth
9. Two input terminals