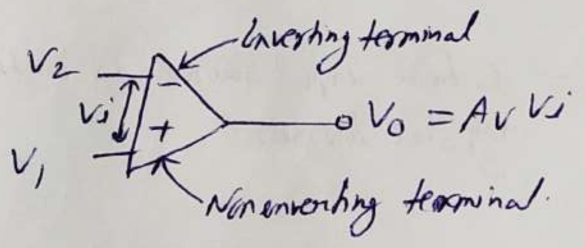
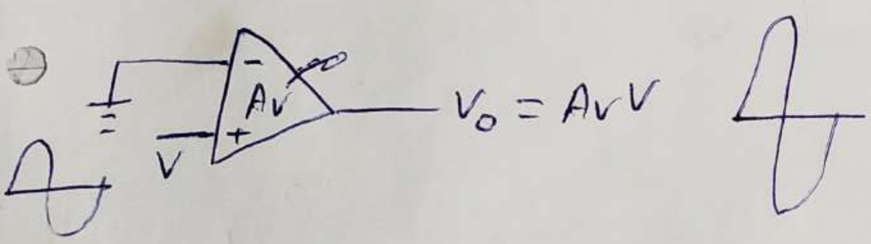
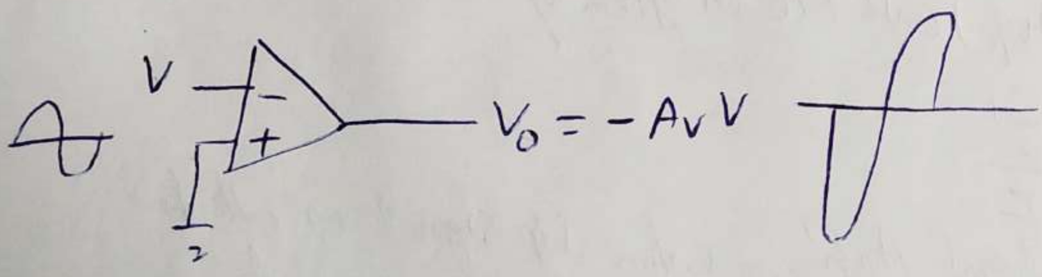
Operational Amplifiers (OP-Amp)

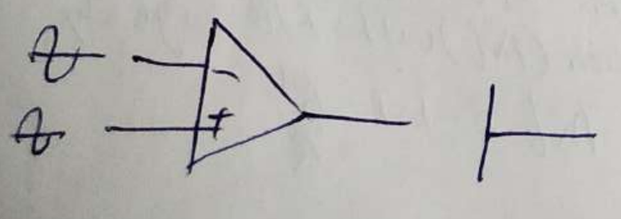
Introduction

- An operational Ampr or OP-Amp is a high gain direct coupled electronic voltage ampr, having differential input and usually a single ended o/p.
- Having different advantages like small size, high reliability, predictably lower cost, temp. tracking and low offset volt. and current.





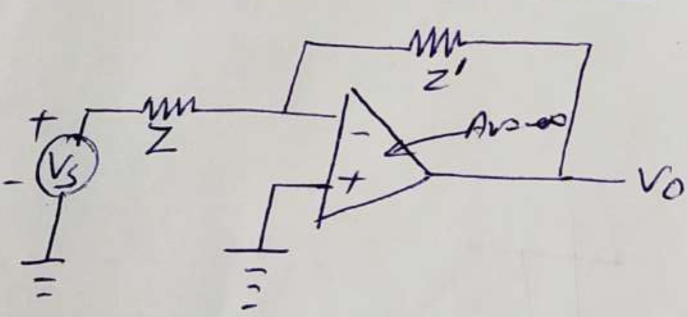




Ideal characteristics

- → Input Resistance $R_i = \infty$
- → O/P Resistance $R_o = 0$
- → Volt. gain $A_v = -\infty$
- → Bandwidth $BW = \infty$
- → $V_0 = 0$ when $V_1 = V_2$ independent of magnitude of V_1
- → Characteristic do not drift with temp.
- → Having CMRR – Common Mode Rejection Ratio $= \infty$
- → Slew rate $= \infty$.

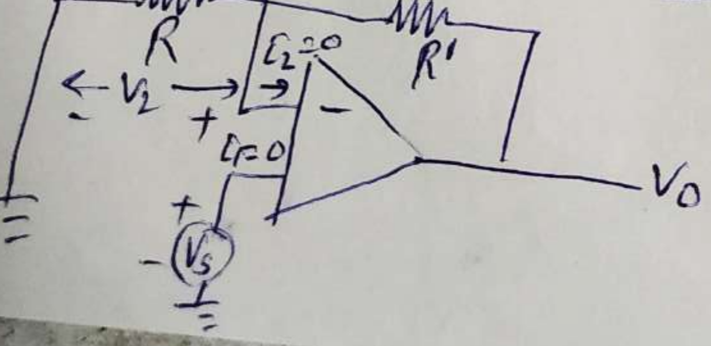
Inverting Operational Amp^r :– when input source is with negative terminal.



Voltage gain (A_{vf}) with F/B is given by

$$A_{vf} = -\frac{Z'}{Z}$$

Non Inverting Operational Amp^r :– when i/p signal is attached with +ve terminal.



Volt. gain (A_{vf}) with F/B is given by.

$$A_{vf} = 1 + \frac{R'}{R}$$

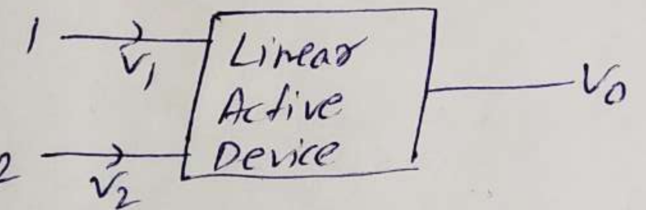
The Differential Ampr

- This ampr is used for amplify difference between ~~two~~ signals.
- $V_0 = A_d (V_1 - V_2)$ —— (I)

A_d — Gain of the differential ampr

- In differential ampr o/p is not only depending upon eq (I) but also upon the average level, called common-mode signal V_c.
- $V_d = V_1 - V_2$ and $V_c = \frac{1}{2}(V_1 + V_2)$ —— (II)

Common Mode Rejection Ratio (CMRR):—



$V_0 = A_1 V_1 + A_2 V_2$ —— (III)

where A_1 is voltage amplification from i/p 1 when i/p 2 is grounded.

A_2 is volt ampm from i/p 2 when i/p 1 is grounded.

from eq (II) we have

$V_1 = V_c + \frac{1}{2} V_d$ and $V_2 = V_c - \frac{1}{2} V_d$ —— (IV)

putting (IV) in (III) we have.

$V_0 = A_d V_d + A_c V_c$; where $A_d = \frac{1}{2}(A_1 - A_2)$ & $A_c = A_1 + A_2$ —— (V)

- Ideally Ad should large & A_c should zero.

- CMRR $\rho = \left| \frac{A_d}{A_c} \right|$ ——— (VI)

from eqn (IV) & (VI) we have.

$$\boxed{V_o = A_d V_d \left(1 + \frac{1}{\rho} \frac{V_c}{V_d}\right)} \quad \text{——— (VII)}$$

- CMRR reflects the merit of differential ampr.

The Emitter - Coupled Differential Amplifier

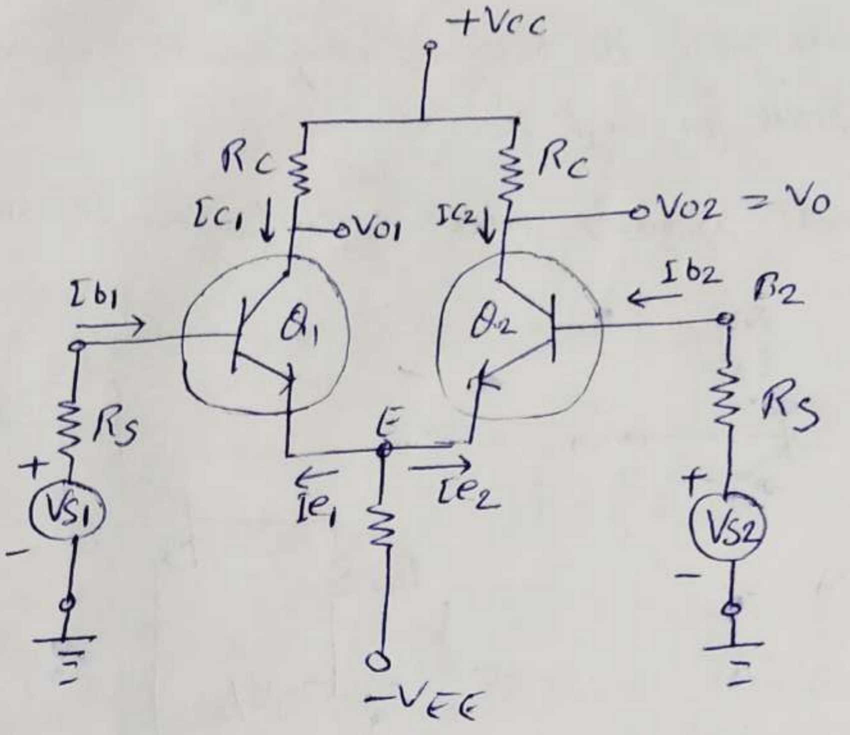


Fig:- Symmetrical Emitter coupled difference ampr.

- The above figure shows emitter coupled difference ampr, having two different but similar transistors Q_1 & Q_2 connected through emitter. Input signal in terms of voltage are fed through base of both transistor.
- The circuit can be used as a difference ampr if and only if emitter resistance Re should be very high.
- Consider $V_{S_1} = V_{S_2} = V_S$ then $V_d = V_{S_1} - V_{S_2} = 0$ and $V_0 = A_c V_c \simeq A_c V_S$

- If $Re = \infty$ than $Ie = 0$, hence $Ic_1 = Ic_2 = 0$. Now if $Ib_2 << Ic_2$ than $Ic_2 \cong Ie_2$ and it follows $V_o \approx 0$. Hence Common mode gain A_C becomes very small and resulting a high CMRR for high Re.

- Now due to symmetry above circuit can be breakup as follow

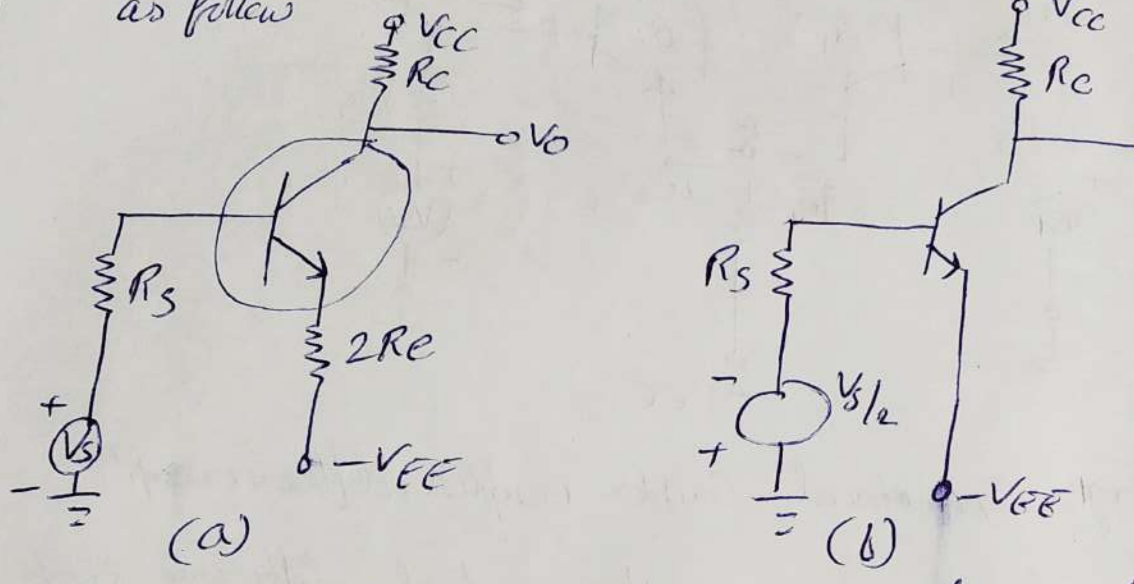


Fig- Equivalent circuit for a symmetrical differential ampr for determining (a) The common mode gain Ac (b) difference gain Ad.

Now $$A_C = \frac{V_O}{V_S} = \frac{(2h_{oe}R_e - h_{fe})R_C}{2R_e(1+h_{fe}) + (R_S + h_{ie})(2h_{oe}R_e + 1)} \quad \text{— (VII)}$$

(neglecting hre and considering hoe Re << 1).

Setting $V_{S1} = -V_{S2} = V_S/2$, from fig 1 we have if $V_{S1} = -V_{S2}$ than $Ie_1 = -Ie_2$, drop across Re is zero and E is grounded for small-signal operation.

Hence differ gain Ad through Fig 2(b) can be given by.

$$A_d = \frac{V_o}{V_s} = \frac{1}{2}\frac{h_{fe} R_C}{R_S + h_{ie}} \quad \text{— (IX)} \quad (\text{provided } h_{oe}R_C \ll 1)$$

- Again if operating current of transistors are allowed to decrease, results higher hie & lower hfe and finally decreases CMRR.
- To maintain Q point at the proper point on load line, if Re get increased than at the same time V_{EE} must become larger, hence Q point can't be shifted.

⇨ Differential Ampr Supplied with a Constant Current

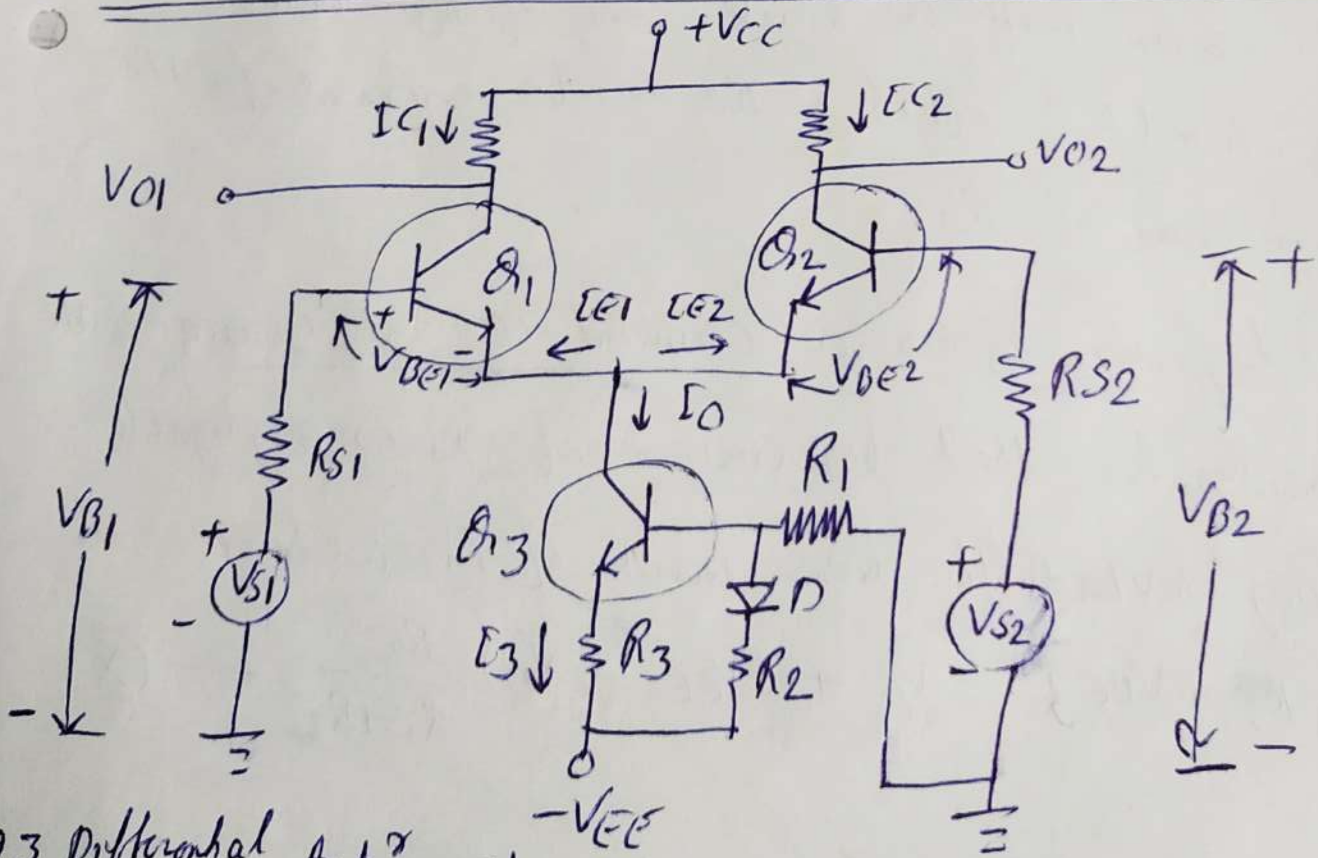


Fig 3 Differential Ampr with constant current stage in emitter circuit.

- As we know for an ideal OP-Amp CMRR should be ∞, for the same A_C (Common mode gain) should be minimum, $\because$ as $CMRR = \left|\frac{A_d}{A_C}\right|$. Now from the previous discussion we found that higher the value of Re reflects lower A_C and hence finally higher CMRR.

- In this continuation 'Re' is generally replaced by a transistor circuit as shown in Fig 3.

- In the Fig 3 R_1, R_2 and R_3 are adjusted in such a fashion that the same quiscent condition for Q_1 & Q_2 as the original circuit is obtained.

- Due to operation of circuit overall 'Re' shows a higher value for Q_1 & Q_2 with a small value of R_3. Hence it can be concluded that effectively Re can be encreased for the lesser value of R_3.

- Now to justify Q_3 as a constant current source with a consideration that base current of Q_3 is negligable. Applying KVL to the base circuit of Q_3 we have

$$I_3 R_3 + V_{BE3} = V_D + (V_{EE} - V_D)\frac{R_2}{R_1 + R_2} \quad \text{—— (X)}$$

where $V_D \longrightarrow$ diode volt.

Hence, $I_0 \simeq I_3 = \frac{1}{R_3}\left(\frac{V_{BE} R_2}{R_1+R_2} + \frac{V_D R_1}{R_1+R_2} - V_{BE3}\right)$ — (X1)

If the circuit parameters are chosen such that

$$\frac{V_D R_1}{R_1+R_2} = V_{BE3}$$

then $\boxed{I_0 = \frac{V_{BE} R_2}{R_3(R_1+R_2)}}$ — (X11)

- Now current I_0 is endependent of signal voltages V_{S1} & V_{S2} than Q_3 acts to supply the difference Ampr consisting of Q_1 & Q_2 with constant current I_0.
- Due to diode D, I_0 is endependent of temp. change, ~~in~~ as to the absence of D, V_{BE3} decreases approximately 2.5mV/°C and hence a effective change in I_0 can be reflected. Hence diode make eqn X11 to be as a const. current source.
- Also $\frac{R_1}{R_1+R_2}$ is chosen experimentally so that I_0 (in eqn X11) is almost endependent of T.
- As under the above condition $A_C = 0$. Assume that $V_{S1} = V_{S2} = V_S$ so due to symmetry of circuit $I_{C1} = I_{C2}$ and $I_{C1} + I_{C2} = 0$ if I_0 = const, also $I_{C1} = I_{C2} = 0$ and $A_C = V_{O2}/V_S = -I_{C2} R_C/V_S = 0$.

Practical Considerations

- Differential ampr are often used as in DC application. As it is known fact that h_{FE}, V_{BE} & I_{CBO} are temp. dependent quantity. So a little change in characteristics can effectively change the overall behaviour. Hence it is required to construct a difference ampr with Q_1 & Q_2 having almost identical characteristics. Hence effective change in any one parameter of one transistor can be countered by the other one.

- Differential ampr can be cascaded to obtain larger amplification for the difference signal.

- The differential ampr may be used as an emitter-coupled phase inverter. For this one base is excited whereas other is not. The o/p volt from collectors are equal in magnitude and 180° out of phase.

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Transfer Characteristics of a Differential Ampʳ

- This is graph between I_C & $V_{B1} - V_{B2}$ or normalized value of both ie I_C/I_O and $V_{B1} - V_{B2}/V_T$
- Consider Fig 3, when $V_{B1} <$ Q_1 cutoff than Q_1 would be OFF and all the current I_O will flow through Q_2. ~~for V_{B1}~~
- As V_{B1} increases than cutoff value than Q_1 will conduct and flow of current through Q_2 will decreases, but the overall sum up current will be I_O.
- The total range of volt. for which the conduction take place may be denoted by $\Delta V_O = R_C I_O$, can be adjusted through an adjustment of I_O.
- Now from Fig 3

$$\left.\begin{aligned} I_{E1} + I_{E2} &= -I_O \\ V_{B1} - V_{B2} &= V_{BE1} - V_{BE2} \end{aligned}\right\} \text{— (XIII)}$$

- Now $I_E = I_S e^{V_{BE}/V_T}$ —— (XIV)

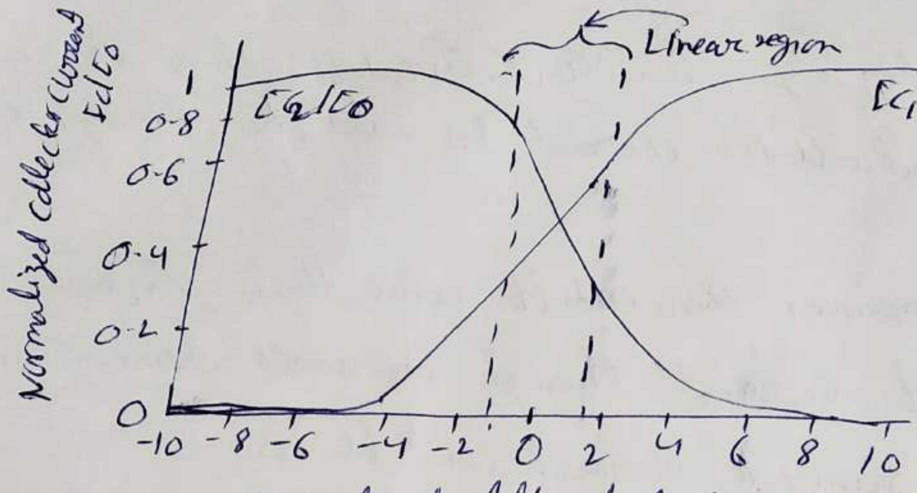
where I_S — Terms of Ebers-Moll parameters.

- If Q_1 & Q_2 are matched then from (XIII) & (XIV)

$$I_{C1} \simeq -I_{E1} = \frac{I_O}{1 + \exp[-(V_{B1} - V_{B2})/kT]} \quad \text{—(XV)}$$

Also $I_{C2} = -I_{E2} = \dfrac{I_0}{1+\exp[-(V_{B2}-V_{B1})/V_T]}$ — (XVI)

So eq graph (XV) & (XVI) can be shown as



Normalized differential i/p volt $(V_{B1}-V_{B2})/V_T$

Fig :- Transfer characteristic of basic differential amp^r ckt.

Now differentiate (XVI) w.r.t $V_{B1}-V_{B2}$ we get transconductance g_{md} of the differential Amp^r.

$$\frac{dI_{C1}}{d(V_{B1}-V_{B2})} = g_{md} = \frac{I_0}{4V_T} \quad \text{— (XVII)}$$

where g_{md} is evaluated at $V_{B1}=V_{B2}$. From (XVII) we can conclude that for same value of I_0 the effective transconductance of differential amp^r is one forth that of a single transistor.