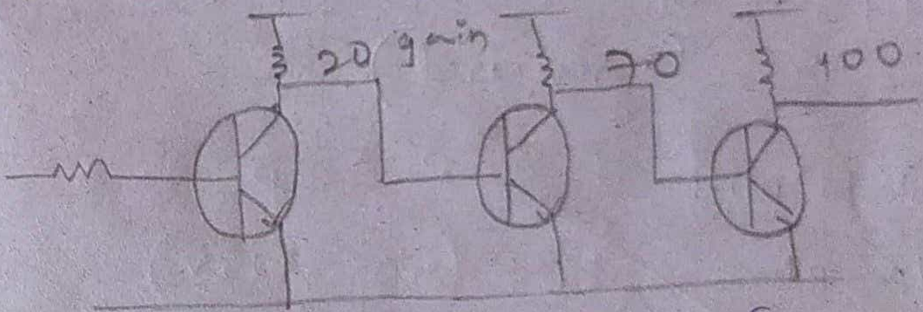
# 04. Operational Amplifier

Introduction :-

① * Operational Amplifier provides much more i/p impedance compared to MOSFET & BJT.

② * It also provides max. gain compared to MOSFET & BJT.

* BLOCK CKT :-




Combination of amplifiers - O.A.

③ Operational Amplifier eliminates noise in input signal unlike MOSFET/ BJT.

∵ it performs mathematical operations.

Definition :- Operational Amplifier is an active device which performs some mathematical operations like addition, subtraction, multiplication, integration & differentiation along with amplifying the signal.

Advantages :

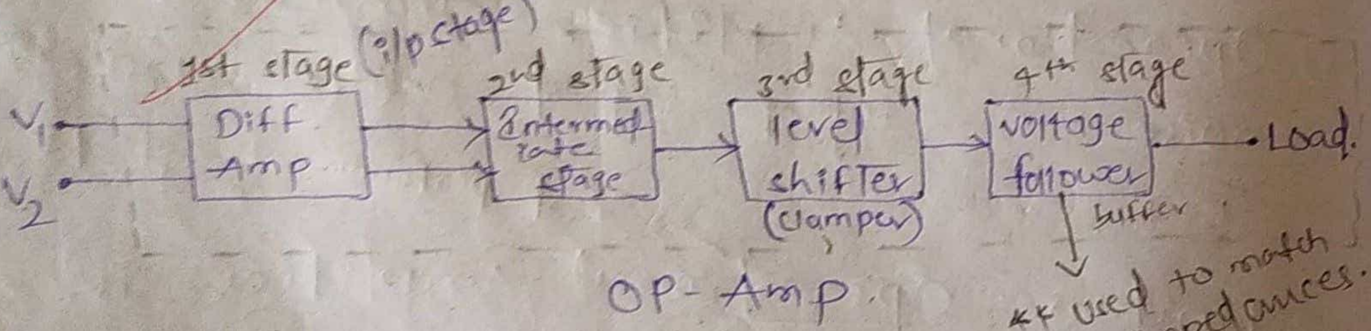
* High i/p impedance
* High gain
* Eliminates noise signal.

IC (Integrated Circuit) : A single silicon chip on which all active & passive elmts are fabricated.

* IC 741 – Operational Amplifier as IC (* reserved).

  7 – total pins
  4 – i/p pins
  1 – o/p pin.

* Block Diagram of OP-Amp.

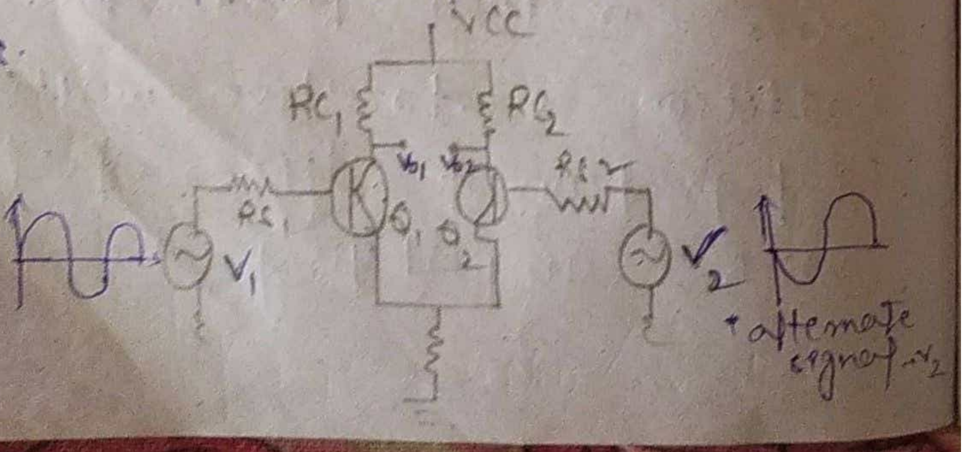



OP-Amp.

1st stage :

Differential Amp : Amplifies difference b/w two i/p signals.

ex: $V_1 = 5$
$V_2 = 3$
$V_1 - V_2 = 2$



Diff-Amp is of 4-types :-

① Dual i/p balanced o/p → o/p at both capacitors
② Dual i/p unbalanced o/p → o/p at any capacitor
③ Single i/p balanced o/p
④ Single i/p unbalanced o/p.

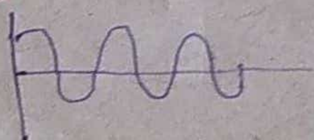
* In this stage we use Dual i/p balanced o/p.

2nd stage :-

$\boxed{\text{intermediate stage}}$

* In this stage we use Dual i/p unbalanced o/p.

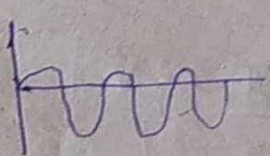
* output



3rd stage :-

$\boxed{\text{level shifter}}$ clamper / DC restorer.

(* high impedance output we get

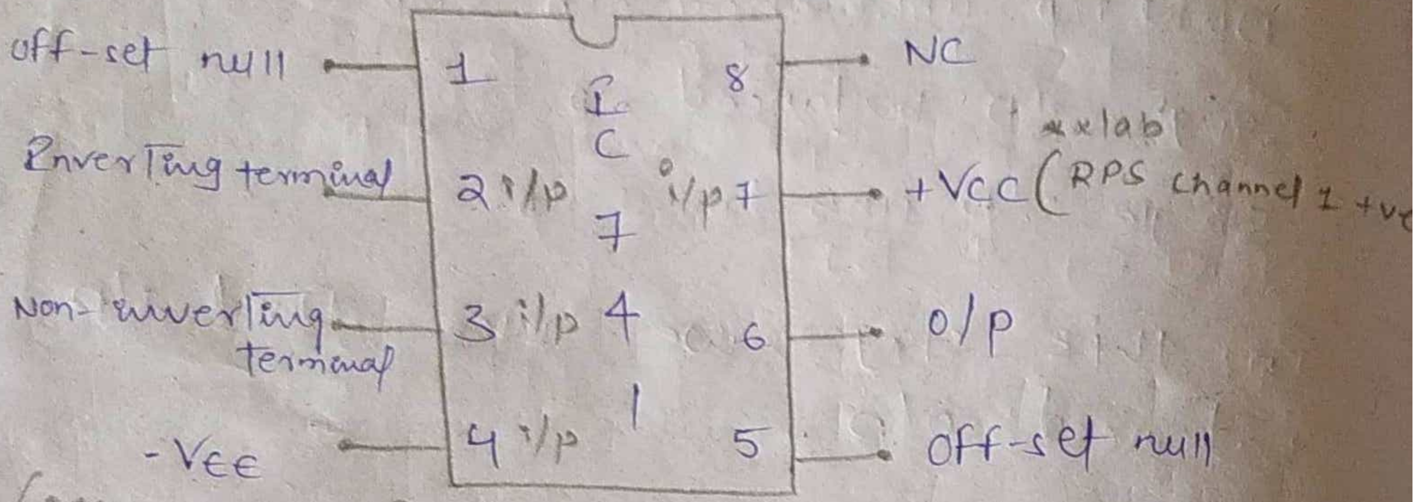


4th stage.

$\boxed{\text{Voltage follower}}$ * Buffer ckt to transform max power.

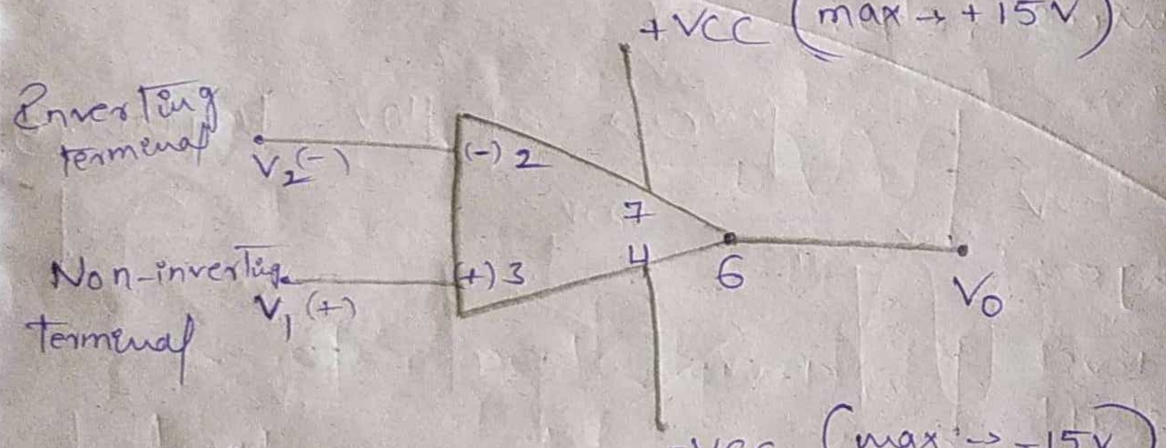
* allows high i/p impedance and gives low o/p impedance signal. Thus satisfies max. power transformation Theorem.

# IC 741 - OP-Amp - Pin diagram :




(RPS - channel 2 -ve)
Magnitude exactly
opp. to VCC

## Symbol Diagram of OP-Amp :

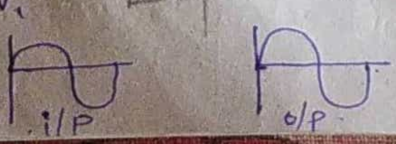



$$V_0 \propto (V_1 - V_2)$$

$$V_0 = \underbrace{A}_{\text{gain}}(V_1 - V_2)$$

case 1 : $V_2 = 0$.


$V_0 = A(V_1 - 0)$
$= A \cdot V_1$
$V_0 = V_1$



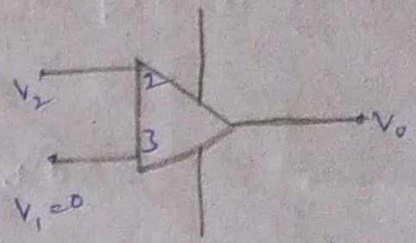

→ Non-inverted (pin-3)

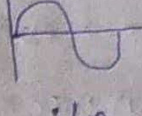
case 2: $V_1 = 0$

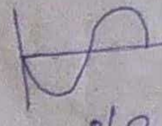
$V_0 = A(0 - V_2)$

$V_0 = -AV_2$

$V_0 = -V_2$



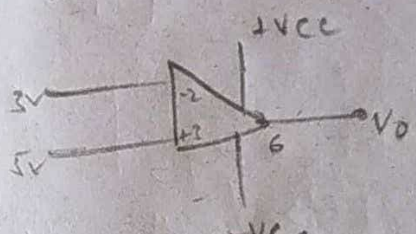




→ ∴ inverted (pin-2)

## Characteristics of OP-Amp:

① Input-offset voltages:

$V_{dc1}$ & $V_{dc2}$ depends on $V_{CC}$ & $V_{EE}$

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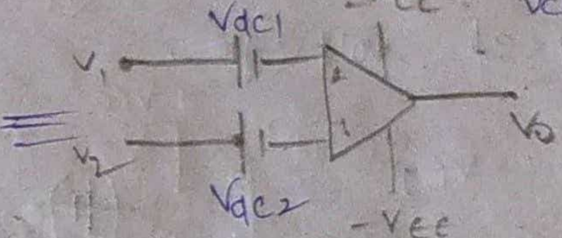



$V_0 = A(V_1 - V_2)$

$V_0 = 2(5-3)$

$V_0 = 4$

$$\boxed{V_{ios} = |V_{dc2} - V_{dc1}|}$$

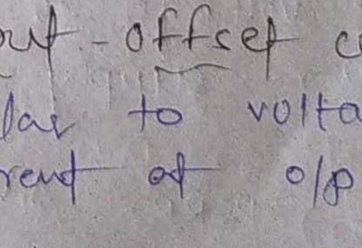
- But we may not get the proper/exact o/p. i.e. unnecessary voltage is present

≡

* To remove the unnecessary voltages we use input-offset voltages - $V_{dc1}$ & $V_{dc2}$ not i/p voltages.

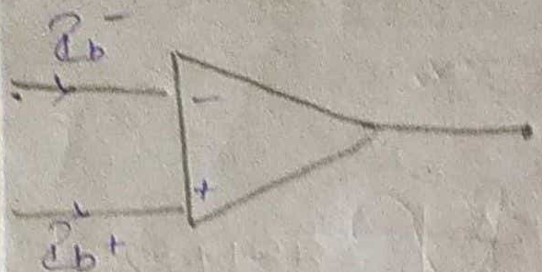
② Input-offset currents:-

- Similar to voltages, to remove unnecessary current at o/p side, we use $I_{b1}$ & $I_{b2}$




$$\boxed{I_{ioc} = |I_{b1} - I_{b2}|}$$

③ Input - bias current :

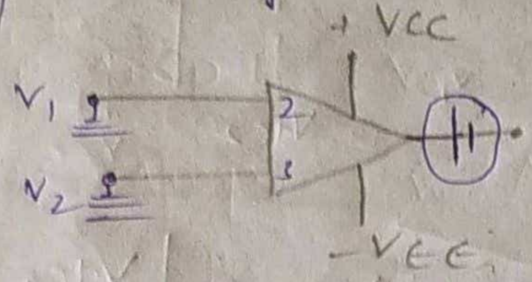



$$i_b = \frac{i_b^+ + i_b^-}{2}$$

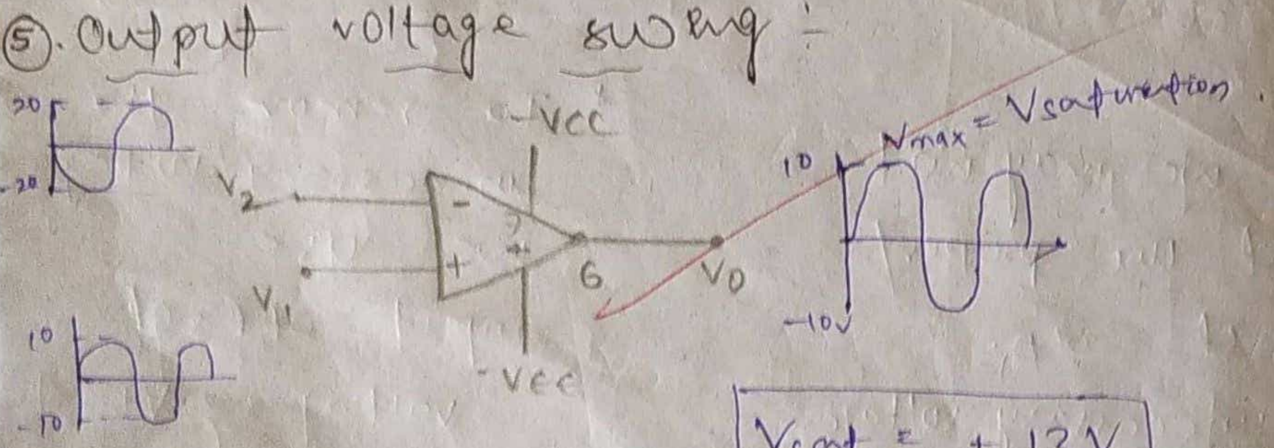
* same concept for removing unnecessary current.

④. Out-put offset voltage :

Some D.C voltage is present at o/p side of OP-Amp is called 'output offset voltage'.




⑤. Output voltage swing :




$$\boxed{V_{sat} = \pm 13V}$$

⑥ Power Supply Rejection Ratio (PSRR) :

Ratio of input offset voltage to the change in +ve power supply.

$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{CC}}\Bigg|_{V_{EE} = constant} \quad \text{(or)} \quad PSRR = \frac{\Delta V_{ios}}{\Delta V_{EE}}\Bigg|_{V_{CC} = constant}$$

ex: $V_{CC} = 8V \rightarrow V_{ios} = 2mV$
$V_{CC} = 9V \rightarrow V_{ios} = 2.5 mV$ } 0.5

$PSRR = \frac{0.5mV}{1V} = 0.5 mV.$

(7) Thermal Drift :

(1) Thermal voltage drift : The max rate of change in $V_{ios}$ due to change in 1 unit temperature.

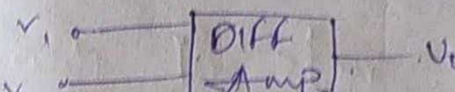
$$\frac{dV_{ios}}{dt}$$

(2) Thermal drift $I_{ios}$ : $\frac{dI_{ios}}{dt}$

(3). Thermal drift $I_b = \frac{dI_B}{dt}$

** ~~$V_{vos}$, $V_{ios}$~~, $I_b$ are not constant. They changes due to temp.

** Differential Amp:



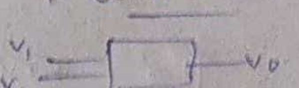
$\boxed{V_1 \neq V_2}$

The o/p, $V_o \propto (V_1 - V_2)$

$V_o = Ad\ (V_1 - V_2)$

$V_o = Ad\ Vd$

* Common mode gain :



$\boxed{V_1 = V_2}$

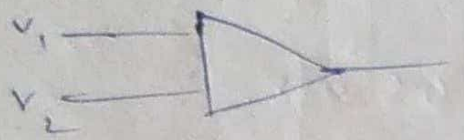
$V_C = \frac{V_1 + V_2}{2}$

$V_o \propto V_C \rightarrow \boxed{V_o = A_C V_C}$

$\boxed{A_C(dB) = 20 \log\left(\frac{V_o}{V_C}\right)}$

** $Ad$ = Differential gain $= \frac{V_o}{Vd} = Ad(dB) = 20\log\left(\frac{V_o}{Vd}\right)$
(decibles) → $\boxed{dB}$

⑧ CMRR (Common mode Rejection Ratio).



$V_o = A_d v_d$ (always for Op-Amp)

$$CMRR = \left| \frac{A_d}{A_c} \right|.$$

* for an ideal OP-Amp, $A_C = 0$.
* for good performance of Diff. amplifier,

$$CMRR = \frac{A_d}{0} = \infty$$

* For Op-Amp, $V_o = A_d V_d$
* for Diff-Amp, $V_o = A_d V_d + A_c V_c$.

$$V_o = A_d V_d \left( 1 + \frac{A_c V_c}{A_d V_d} \right)$$

$$= A_d V_d \left( 1 + \frac{1}{\frac{A_d}{A_c}} \cdot \frac{V_c}{V_d} \right)$$

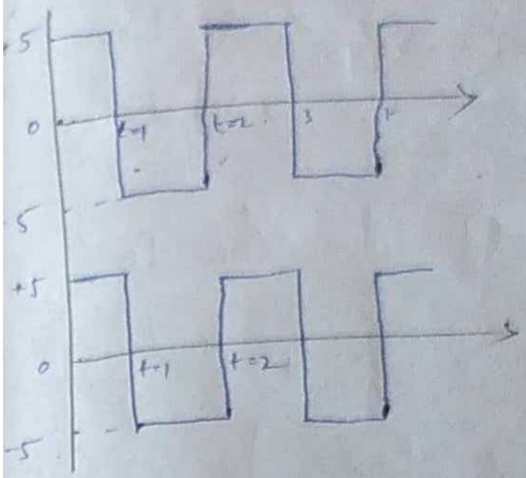
$$\boxed{V_o = A_d V_d \left( 1 + \frac{1}{CMRR} \cdot \frac{V_c}{V_d} \right)}$$

⑨** Slew-Rate: The max. rate of change of o/p voltage with respect to time

* How fast an Op-Amp responding to the input signal is the 'slew-Rate'.

* $\boxed{S = \frac{dV_{o/p}}{dt} \text{ volt/sec.}}$

① Ideal - OP - Amp.

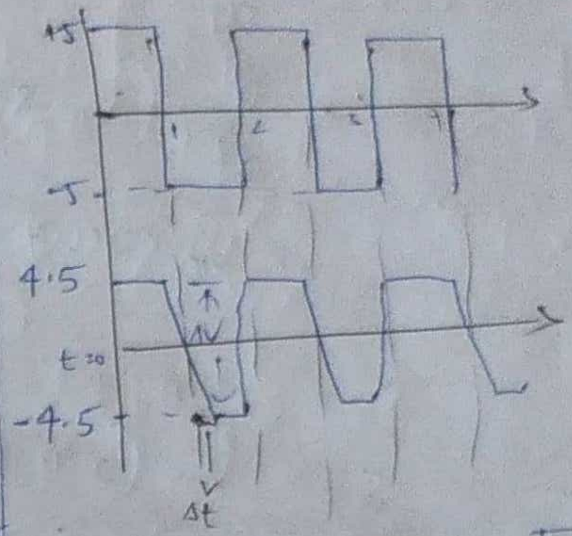


* Ideal op-Amp immediately responds to i/p signal.

* $\Delta t = 0$.

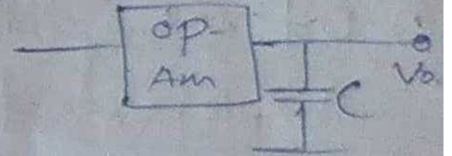
$S = \frac{dV_o}{0} = \infty \Rightarrow$ speedly responding

○ Practical - OP Amp



* There is some Time delay $\Delta t$.

*

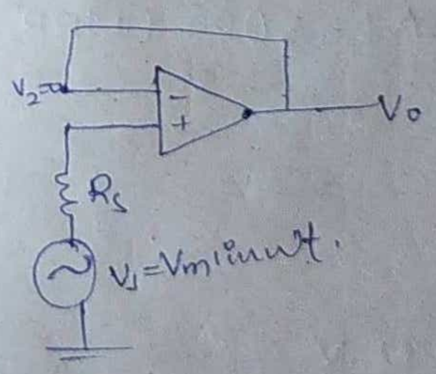


* $$\boxed{S = \frac{d V_{o/p}}{dt} = \frac{I_{c\,max}}{C}}$$

* interms of capacitance.

* Effect of slew on Sinusoidal signal.

* consider ideal op-Amp.



The o/p,

$V_o = A(V_1 - V_2)$

$V_2 = 0$, $V_1 = V_s$, $A = 1$

$V_o = 1(V_s)$

$V_o = V_s = V_m \sin(\omega t)$.

Now, $S = \frac{dV_o}{dt}$

$= \frac{d}{dt}(V_m \sin\omega t)$

$= V_m \cos\omega t \cdot \omega$

$S = V_m \cdot \omega$

$S = V_m (2\pi f)$

$$\boxed{f_{max} = \frac{S_{max}}{2\pi V_m}}$$

* For achieving $S_{max}$, frequency should be max.

Problems:-

① Determine the o/p voltage of Differential Amplifier for i/p of 300 µV & 240 µV. The Diff. gain of the amplifier is 5000 and the value of the CMRR is 100.

Sol:- Given, for Diff. Amp,

$V_1 = 300\,\mu V$, $V_2 = 240\,\mu V$, $A_d = 5000$, $CMRR = 100$

We know that

diff $V_o = A_d V_d + A_c V_c$

$V_d = V_1 - V_2 = 300 - 240 = 60\,\mu V$.

$V_c = \frac{V_1 + V_2}{2} = \frac{300+240}{2} = \frac{540}{2} = 270\,\mu V$.

We know that, $CMRR = \frac{A_d}{A_C}$

$$100 = \frac{5000}{A_C}$$

$$A_C = \frac{5000}{100} = \underline{50}$$

Now, $V_o = A_d V_d + A_c V_c$

$$= (5000 \times 60 \times 10^{-6}) + (50 \times 270 \times 10^{-6})$$

$$= (300000 \times 10^{-6}) + ((27 \times 5) \times 10^{2} \times 10^{-6})$$

$$= (3 \times 10^{-1}) + ((27 \times 5) \times 10^{-4})$$

$$= 0.3135\ V$$

$$V_o = 313.5\ mV$$

② If the base currents for Emitter coupled Transistor of a Diff. Amp is $18\mu A$ & $22\mu A$. Determine
① i/p bias current ② i/p off-set current.

Sol:-


$I_{b_1} = 18\mu A$, $I_{b_2} = 22\mu A$

① I/p bias current $(I_b) = \frac{I_{b_1} + I_{b_2}}{2}$

$$= \frac{22 + 18}{2} = 20\mu A$$

② i/p off-set current $(I_{io}) = |I_{b_1} - I_{b_2}|$

$$= |18 - 22|$$

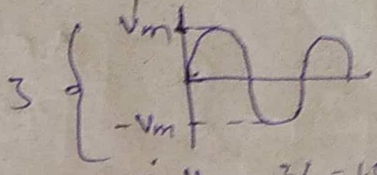
$$= 4\mu A$$

(3) An Op-Amp operates a unity gain buffer with 3V(p-p) square wave i/p. If Op-Amp is ideal with slew rate 0.5 V/μsec. Find the max. frequency of operation.

Sol:- $V(p\text{-}p) = 2V_m$

$V_m = \frac{V(p\text{-}p)}{2}$

$= 3/2 = 1.5\ V.$




$\therefore V_m = 3/2 = 1.5V.$

$f_m = \frac{S}{2\pi V_m}$

$= \frac{0.5}{2\pi \times 1.5 \times 10^{-6}}$

$= 53\ KHz$

we know, $f_{max} = \frac{S_{max}}{2\pi \times V_m}$

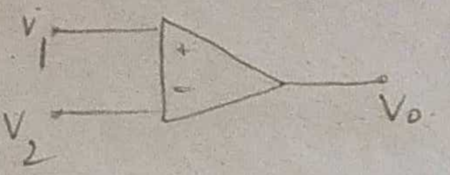
$= \frac{0.5\ V/10^{-6}s}{2\pi \times 1.5}$

$= \frac{0.5}{2\pi \times 1.5 \times 10^{-6}}$

$f_{max} = 53.07\ KHz.$

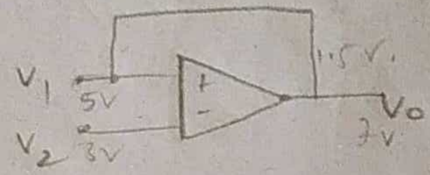
# 05. Applications of OP-Amp.

Open loop OP-Amp

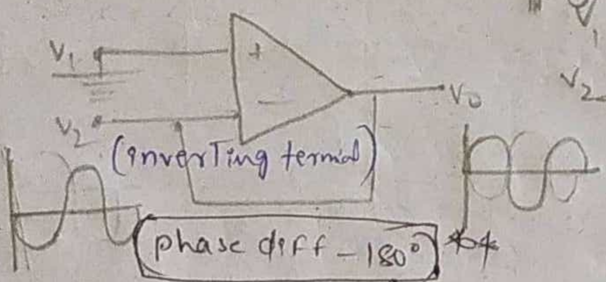



ex:- comparator ckt

closed OP-Amp



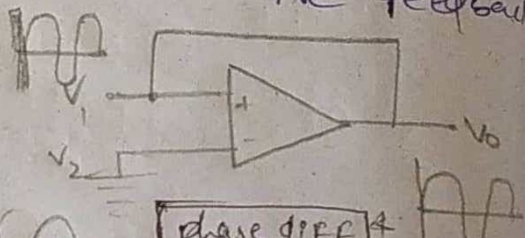

-ve feedback




phase diff - 180° ** out-off phase

ex:- Used in Amplifiers, filters.

+ve feedback




phase diff - 0° ** in-phase

ex:- Schmitt trigger.

** Compared to closed OP-Amp, Open loop OP-Amp gives high gain.

## Open loop OP-Amp :-

① Inverting OP-Amp

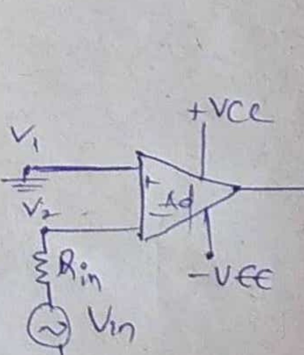
$V_1 = 0$, $V_2 = V_{in}$ ($\because$ considering resistance very small)

We know that

$$V_o = A_d V_d$$

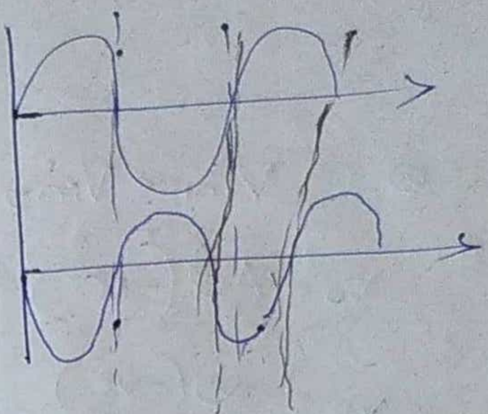
$$= A_d (V_1 - V_2)$$

$$\boxed{V_o = -A_d V_{in}}$$



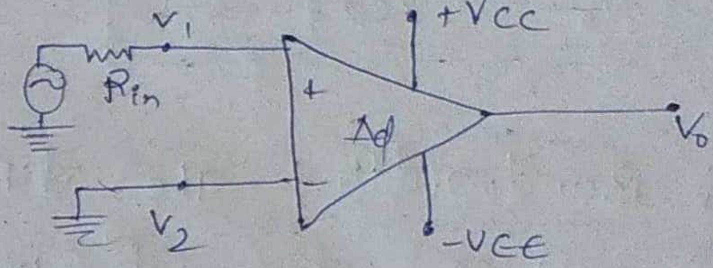

(source connected -ve (inverting terminal)).

wave forms: ($A_d = 1$).



inverted

③ Non Inverting Op-Amp :

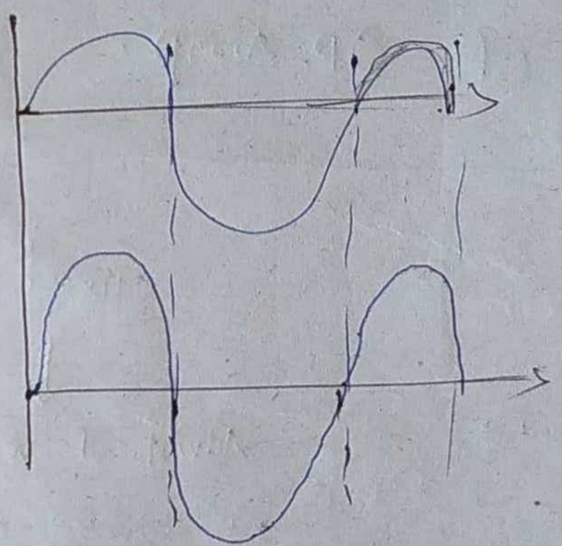



$v_1 = V_{in}$, $V_2 = 0$.

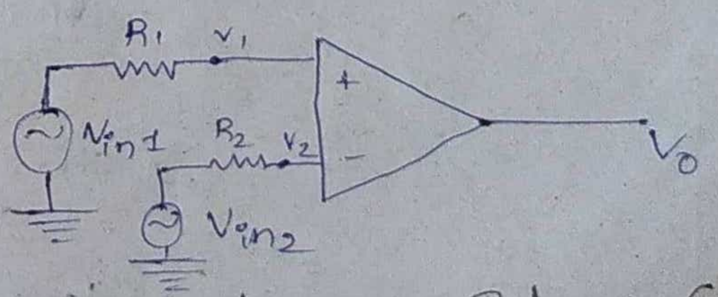
$V_o = A_d (V_{in} - 0)$

$\boxed{V_o = A_d V_{in}}$.

o/p waveforms :



④ Differential Op-Amp :




considering Ideal ($A_d = \infty$).

$V_1 = V_{in1}$ , $V_2 = V_{in2}$ ,

$V_0 = A_d V_d = A_d (V_{in1} - V_{in2})$

case ① : $V_{in1} > V_{in2}$

$V_0 = A_d(+ve)$

$V_0 = \infty(+ve)$ ($\because A_d = \infty$ (ideal))

$\boxed{V_0 = +V_{saturation}}$

case ② : $V_{in1} < V_{in2}$

$V_0 = A_d(-ve)$

$V_0 = \infty(-ve)$

$\boxed{V_0 = -V_{sat}}$

* Bandwidth (space) : The difference b/w Higher cutoff freq & lower cutoff freq.
* Without bandwidth, signal can't be transmitted.

## Applications of OP-Amp

Open loop

* Limitations:

1. Offere max. gain but can't be controlled.
2. Gain is temp dependent
3. Offer small bandwidth

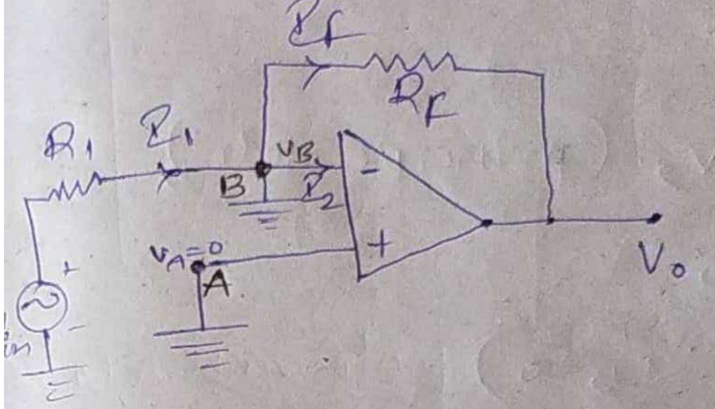
Closed loop.

Advant. of -ve feedback

1. can be controlled
2. Increases bandwidth
3. Offers high i/p impedance
4. Offers low o/p admittance
5. Temp independent

## Virtual Ground Concept :-

** only valid for ideal OP-Amp.




* for ideal OP-Amp :- (non-unity)

Gain $A_d = \infty$

$R_i = \infty$

$CMRR = \infty$

$R_o = 0$

$V_o = A_d V_d$

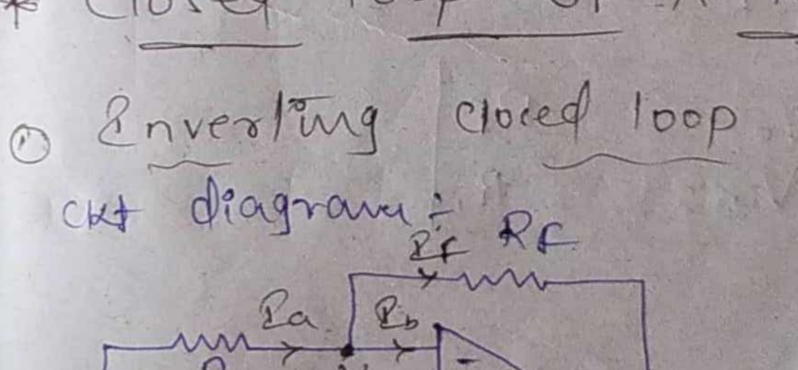
$= A_d (V_B - V_A)$

$V_A -$

## * Closed loop Op-Amp Configurations :-

① Inverting closed loop OP-Amp :-

Ckt diagram :-



calculation of o/p voltage expr:

Acc. to virtual Ground concept

$V_1 = V_2 = 0$.

Apply KCL at $V_2$ (principle node),

$$I_a - I_b - I_f = 0$$

$$I_a - I_f = 0 \quad (\because I_b = 0)$$

$$I_a = I_f$$

$$\frac{V_{in} - V_2^{0}}{R_1} = \frac{V_2 - V_0}{R_f} \quad (\because \text{By ohm's law})$$

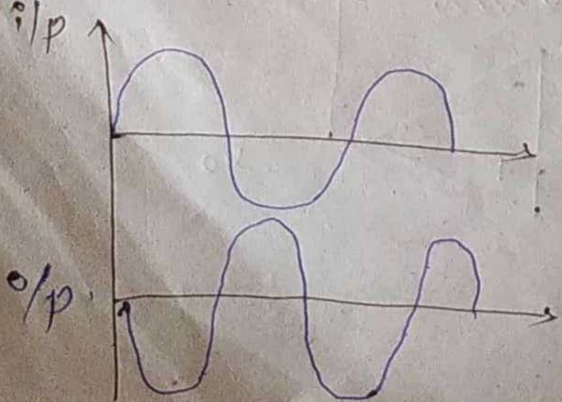
$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_0}{R_f}$$

$$\frac{V_{in}}{R_1} = \frac{-V_0}{R_f}$$

$$\therefore \boxed{V_0 = \frac{-R_f}{R_1} V_{in}}$$

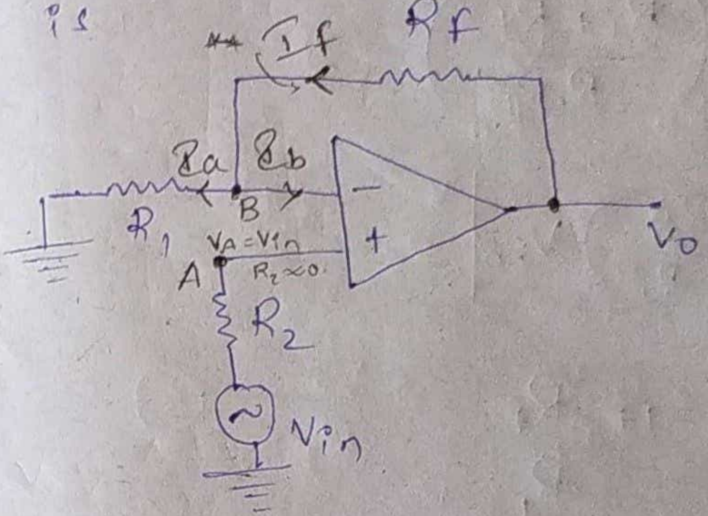
$$\boxed{\text{Gain} = \frac{V_0}{V_{in}} = \frac{-R_f}{R_1}}$$

waveforms:



* Non-Inverting Amplifier:-

The ckt diagram of non-inverting amp is




Calculation of o/p voltage:

⇒ Acc. to virtual Ground concept,

$V_A = V_B = V_{in}$

⇒ Applying KCL at principle (B) node,

$I_f - I_a - I_b = 0 \quad (\because I_b = 0)$.

$I_f - I_a = 0$

$I_f = I_a$ — ①

⇒ Acc. to ohm's law,

$I_a = \frac{V_B - 0}{R_1} = \frac{V_{in}}{R_1}$ — ②

$I_f = \frac{V_o - V_B}{R_f} = \frac{V_o - V_{in}}{R_f}$ — ③

sub. eq ② + ③ in ①

$\frac{V_o - V_{in}}{R_f} = \frac{V_{in}}{R_1}$

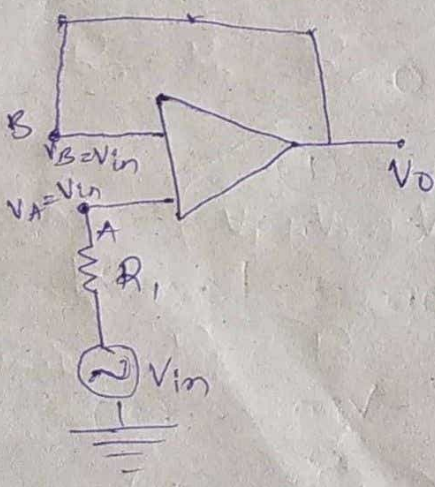
$$\frac{V_o}{R_f} = \frac{V_{in}}{R_1} + \frac{V_{in}}{R_f}$$

$$\frac{V_o}{\cancel{R_f}} = V_{in}\left(\frac{R_1 + R_f}{R_1 \cancel{R_f}}\right)$$

$$\therefore \boxed{V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}}$$

$$\frac{V_o}{V_{in}} = A_f = 1 + \frac{R_f}{R_1}$$ ,,

* Voltage Follower :- (Buffer - doesn't amplify signal).
The ckt in which o/p follows the i/p signal is called 'voltage follower ckt'.




⇒ Acc. to virtual Ground,

$$V_A = V_B = V_{in}$$

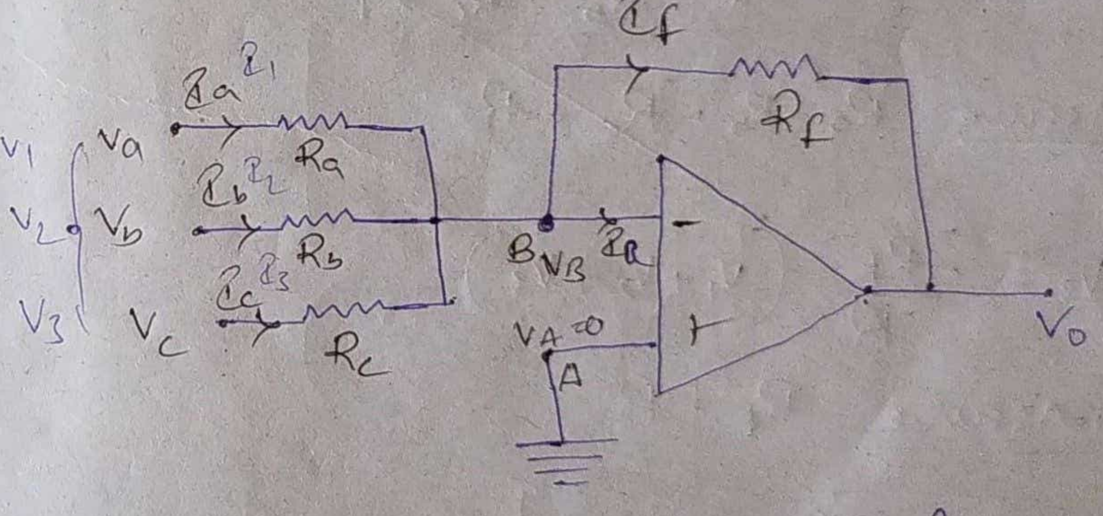
$$\therefore \boxed{V_o = V_{in}}$$

## * Basic Operations of OP-Amp :

* Basically OP-Amp is designed for obtaining max. gain.
* But it also used to perform some operations like :
  - → Addition @ summation — → Inverting Adder; → Non-inverting Adder.
  - → Subtraction @ Difference
  - → Multiplication
  - → Integration Differentiating
  - → Comparator.

## * Inverting Adder :

→ The ckt diagram is



⇒ Acc. to virtual Ground,

$$V_A = V_B = 0$$

⇒ Applying KCL at principle Node,

$$I_1 + I_2 + I_3 - I_f - \underset{0}{I_a} = 0$$

$$I_1 + I_2 + I_3 = I_f \quad \text{—} \ ①$$

$\Rightarrow$ Acc. to ohm's law,

$$i_1 = \frac{V_1 - V_B}{R_a} = \frac{V_1 - 0}{R_a} = \frac{V_1}{R_a} \quad \text{--- (2)}$$

$$i_2 = \frac{V_2 - V_B}{R_b} = \frac{V_2 - 0}{R_b} = \frac{V_2}{R_b} \quad \text{--- (3)}$$

$$i_3 = \frac{V_3 - V_B}{R_c} = \frac{V_3 - 0}{R_c} = \frac{V_3}{R_c} \quad \text{--- (4)}$$

$$i_f = \frac{V_B - V_0}{R_f} = \frac{0 - V_0}{R_f} = \frac{-V_0}{R_f} \quad \text{--- (5)}$$

sub. eq (2) (3) (4) (5) in (1),

$$\frac{V_1}{R_a} + \frac{V_2}{R_b} + \frac{V_3}{R_c} = \frac{-V_0}{R_f}$$

$$\boxed{\therefore V_0 = -R_f\left(\frac{V_1}{R_a} + \frac{V_2}{R_b} + \frac{V_3}{R_c}\right)}$$

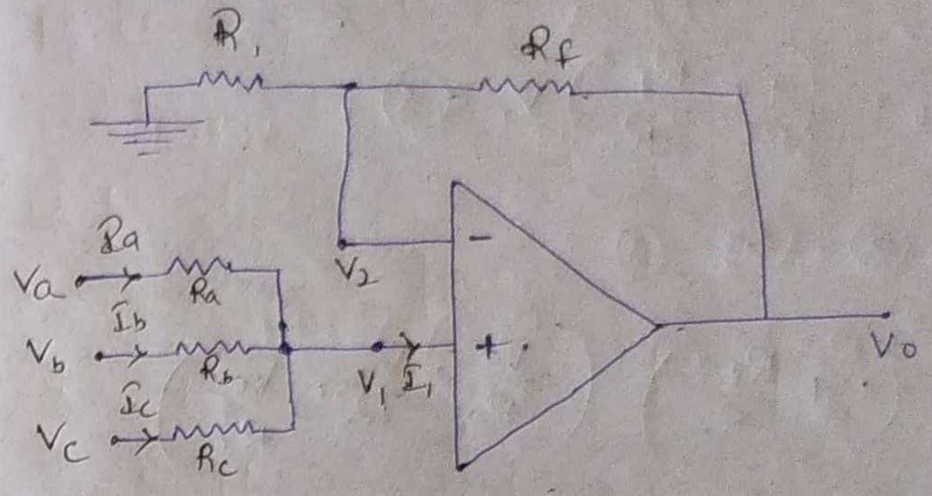
$\Rightarrow$ Assume $R_a = R_b = R_c = R$

$$V_0 = \frac{-R_f}{R}\left(V_1 + V_2 + V_3\right)$$

$\Rightarrow$ Assume $R_f = R$.

$$\boxed{V_0 = -\left(V_1 + V_2 + V_3\right)}$$

* Non-inverting Adder :




* The o/p voltage $V_o$ :

Apply KCL at Node

$$I_a + I_b + I_c - I_1 = 0$$

$$I_a + I_b + I_c = 0 \quad (\because I_1 = 0).$$

$\Rightarrow$ Acc. to ohm's law,

$$I_a = \frac{V_a - V_1}{R_a}, \quad I_b = \frac{V_b - V_1}{R_b}, \quad I_c = \frac{V_c - V_1}{R_c}.$$

$I_a$, $I_b$, $I_c$ sub eq (1)

$$\frac{V_a - V_1}{R_a} + \frac{V_b - V_1}{R_b} + \frac{V_c - V_1}{R_c} = 0$$

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} = \frac{V_1}{R_a} + \frac{V_1}{R_b} + \frac{V_1}{R_c}$$

$$= V_1\left(\frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c}\right)$$

$$\therefore V_1 = \frac{\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c}}{\frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c}} \quad \text{--- (2)}$$

⇒ We know, $v_0$ of non-inverting OP-Amp is

$$v_0 = \left(1 + \frac{R_f}{R_1}\right) v_1 \quad \text{--- (3)}$$

sub eq (2) in (3)

$$\therefore v_0 = \left(1 + \frac{R_f}{R_1}\right) \frac{\left(\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c}\right)}{\frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c}}$$

<u>Assume</u> $R_a = R_b = R_c = R_1 = R$.

$$\therefore V_0 = \left(1 + \frac{R_f}{R}\right) \left[\frac{\frac{V_a}{R} + \frac{V_b}{R} + \frac{V_c}{R}}{\frac{1}{R} + \frac{1}{R} + \frac{1}{R}}\right]$$

$$= \left(1 + \frac{R_f}{R}\right) \left[\frac{\frac{V_a + V_b + V_c}{\cancel{R}}}{\frac{3}{\cancel{R}}}\right]$$

$$V_0 = \left(1 + \frac{R_f}{R}\right) \left(\frac{V_a + V_b + V_c}{3}\right)$$

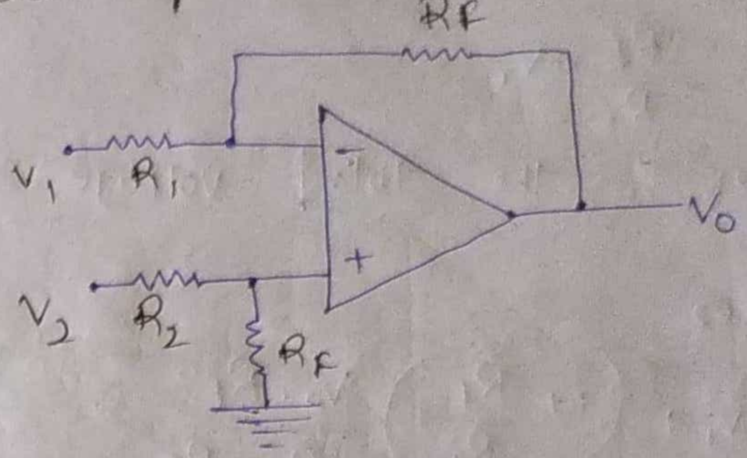
<u>Assume</u> $R = \frac{R_f}{2}$,

$$V_0 = \left(1 + \frac{R_f}{R_f/2}\right) \left(\frac{V_a + V_b + V_c}{3}\right)$$

$$= \cancel{(1+2)} \left(\frac{V_a + V_b + V_c}{\cancel{3}}\right)$$

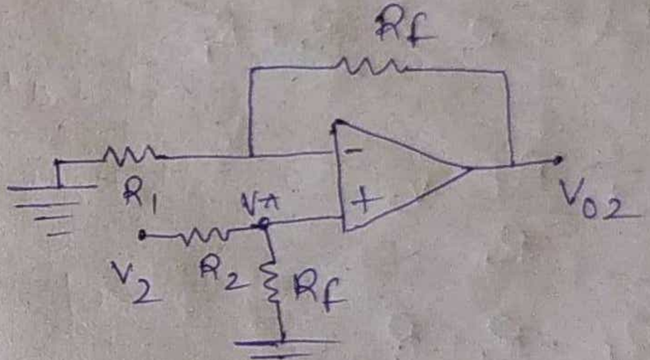
$$\therefore V_0 = V_a + V_b + V_c$$

## Subtractor :




Apply Super position theorem

Step ① : $V_2$ source acting alone, $V_1$ - short circuited.




Apply Voltage Division Rule at $V_A$.

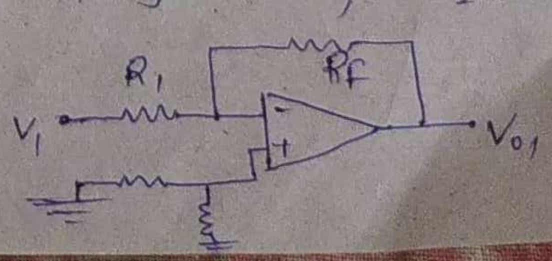
$$V_A = V_2 \frac{R_f}{R_2 + R_f}$$

The non-inv op-Amp o/p volt is

$$V_{o2} = \left(1 + \frac{R_f}{R_1}\right) \cdot V_A$$

$$V_{o2} = \left(1 + \frac{R_f}{R_1}\right) \cdot V_2 \frac{R_f}{R_2 + R_f} \quad \text{— (A)}$$

Step ② : $V_1$ acting alone, $V_2$ - S.C.



We know, inv- OPAmp o/p $V_o$ is

$$V_{o2} = -\frac{R_f}{R_1} \cdot V_1$$

Acc. to SPT, the total voltage

$$V_o = V_{o1} + V_{o2}$$

$$= -\frac{R_f}{R_1} V_1 + \left(1 + \frac{R_f}{R_1}\right) \frac{V_2 \cdot R_f}{R_2 + R_f}$$

Assume $R_1 = R_2$

$$V_o = -\frac{R_f}{R_1} V_1 + \left(\frac{\cancel{R_1 + R_f}}{R_1}\right) \cdot \frac{V_2 \cdot R_f}{\cancel{R_1 + R_f}}$$

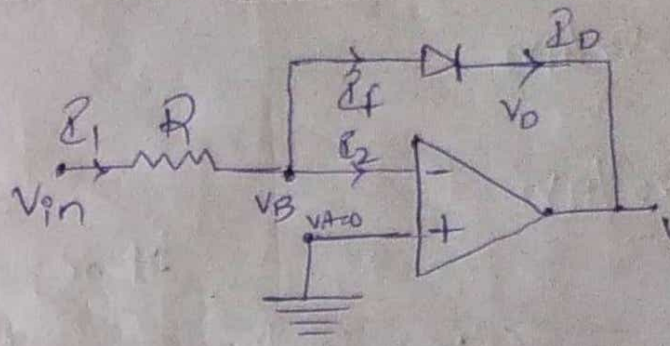
$$V_o = -\frac{R_f}{R_1} V_1 + \frac{R_f}{R_1} V_2$$

Assume $R_f = R_1 = R$

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

$$\boxed{V_o = V_2 - V_1}.$$

# * Logarithmic Amplifier




Calculation of o/p voltage :-

⇒ Acc. to virtual GND,

$$V_A = V_B = 0$$

Apply KCL at principle Node

$$i_1 - i_2 - i_f = 0$$

$$i_1 - i_f = 0 \quad (\because i_2 = 0)$$

$$\boxed{i_1 = i_f} \; \text{—} \; (i)$$

Acc. to ohm's law,

$$i_1 = \frac{V_{in} - V_B}{R} = \frac{V_{in}}{R} \; \text{—} \; (1)$$

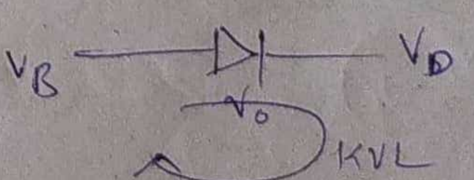
we know the diode current eqn is

$$i_f = I_0 \left( e^{\frac{V_D}{\eta V_T}} - 1 \right)$$

$$i_f = I_0 e^{V_D/\eta V_T} - I_0$$

Assume $I_0 e^{V_D/\eta V_T} >> I_0$

$$i_f = I_0 e^{V_D/\eta V_T} \; \text{—} \; (A)$$




$$-V_B + V_0 + V_D = 0$$

$$V_D = -V_0 \quad (\because V_B = 0)$$

(→ sub. in (A)

$$\Rightarrow i_f = I_0 e^{-V_0/\eta V_T} \; \text{—} \; (B)$$

sub. eq ② ③ in ①

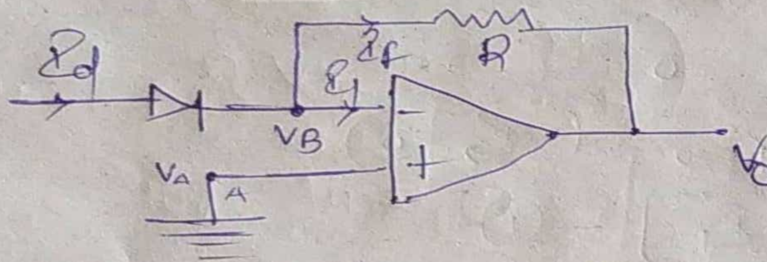
$$\frac{V_{in}}{R} = I_0 e^{-V_0/\eta V_T}$$

$$\frac{V_{in}}{I_0 R} = e^{-V_0/\eta V_T}$$

$$\boxed{-V_0 = \eta V_T \ln\left(\frac{V_{in}}{I_0 R}\right)}$$

Here, $V_0 \propto \ln V_{in}$.

* **Anti Logarithmic Amplifier.**




Acc. to virtual Ground concept

$$V_A = V_B = 0.$$

Apply KCL at principle node,

$$I_d - I_1 - I_f = 0 \qquad (\because I_1 = 0)$$

$$\boxed{I_d = I_f} \quad \text{—①}$$

Acc. to ohms law,

$$I_f = \frac{V_B - V_0}{R} = \frac{-V_0}{R} \quad \text{—②}.$$

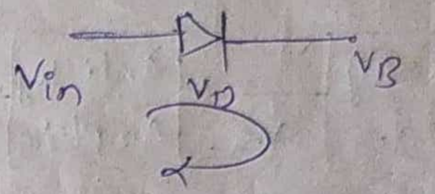
we know that the Diode current eqn.

$$I_d = I_0\left(e^{V_D/\eta V_T} - 1\right)$$

$$= I_0 e^{V_D/\eta V_T} - I_0$$

Assume $I_0 e^{V_D/nV_T} >> I_0$

$$I_d = I_0 e^{V_D/nV_T} \quad \text{—— (A)}$$




Applying KVL in loop

$$-V_{in} + V_D + V_B = 0$$

$$V_D = V_{in} \quad (\because V_B = 0)$$

—— sub. in (A)

$$I_d = I_0 e^{V_{in}/nV_T} \quad \text{—— (B)}$$

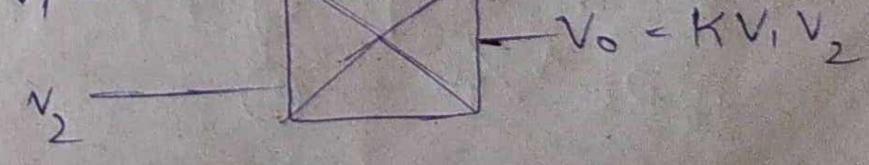
eq (2) (B) sub in (1)

$$I_0 e^{V_{in}/nV_T} = \frac{-V_0}{R}$$

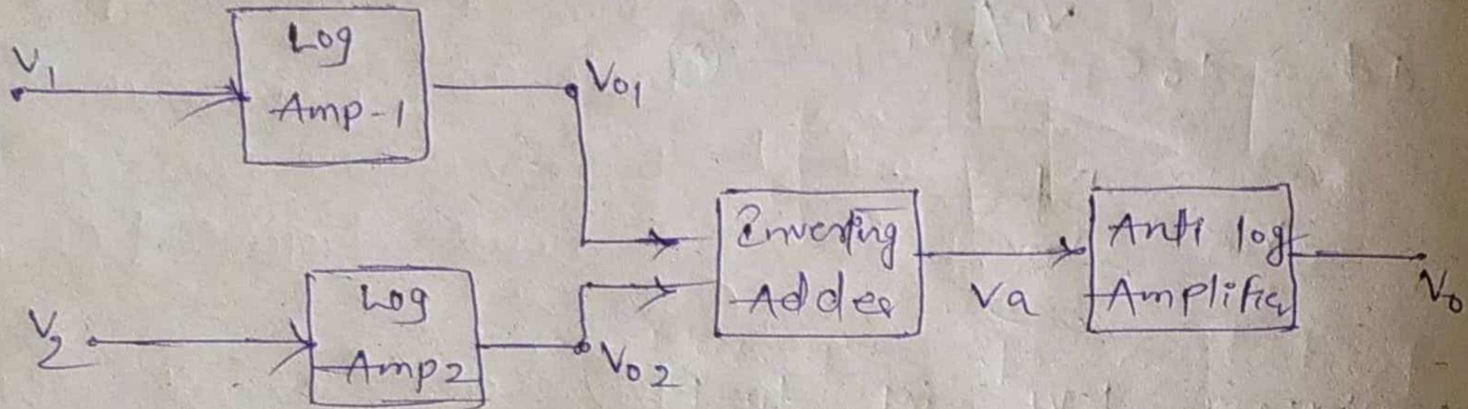
$$-V_0 = I_0 R e^{V_{in}/nV_T}$$

$$\boxed{V_0 = -I_0 R e^{V_{in}/nV_T}}$$

## * Multiplier



→ The Block Diagram of multiplier is




Consider log Amp ①.

The o/p expression of voltage is

$$V_{01} = -\eta V_T \ln\left(\frac{V_1}{I_0 R}\right)$$

consider log Amp ②, The o/p voltage expr

$$V_{02} = -\eta V_T \ln\left(\frac{V_2}{I_0 R}\right)$$

The o/p voltage of inv. adder is

$$V_a = -\left(V_{01} + V_{02}\right)$$

$$V_a = -\left[-\eta V_T \ln\left(\frac{V_1}{I_0 R}\right) - \eta V_T \ln\left(\frac{V_2}{I_0 R}\right)\right]$$

$$V_a = -\eta V_T \left(\ln\left(\frac{V_1 V_2}{I_0^2 R^2}\right)\right) \quad \text{—①}$$

The o/p voltage of Anti-log Amp is

$$V_0 = -I_0 R e^{V_a/\eta V_T} \quad \text{—②}$$

sub. eq ① in ②

$$V_0 = -I_0 R e^{\eta V_T \ln\left(\frac{V_1 V_2}{I_0^2 R^2}\right)}$$

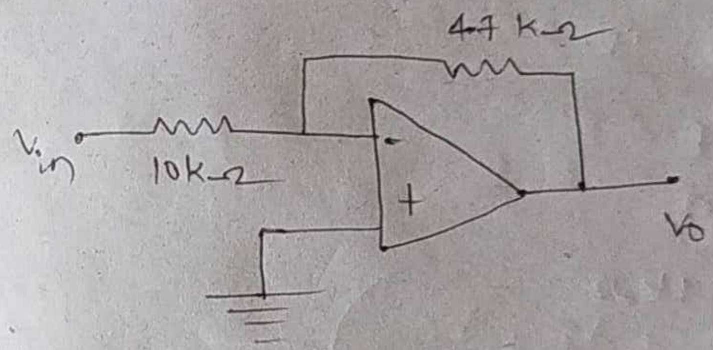
$$V_0 = -\cancel{R_0 R} \cdot \frac{V_1 V_2}{R_0 \times R^2}$$

$$V_0 = -\frac{V_1 V_2}{R_0 R}$$

$$\boxed{V_0 = K\, V_1 V_2}$$ ($\because$ By considering $\frac{-1}{R_0 R}$ as constant).

Problems:-

1) Determine the voltage gain of the following OP-Amp :-




Sol:- The given OP-Amp is an Inv. OP-Amp.

Given $R_1 = 10k\Omega$, $R_f = 47k\Omega$

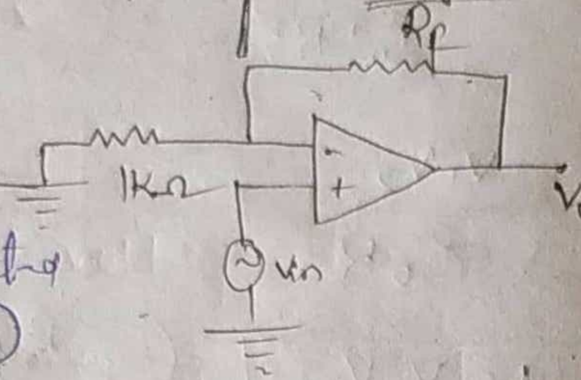
We know that, The o/p volt of Inv. OP-Amp is

$$V_0 = -\frac{R_f}{R_1} \cdot V_{in}$$

$$\frac{V_0}{V_{in}} = -\frac{47 \times 10^3 \Omega}{10 \times 10^3 \Omega}$$

$$\boxed{\frac{V_0}{V_{in}} = -4.7}$$

2) The Gain offered by the Op-Amp is 61 Determine feedback resistor $R_f$




Sol: The Given OP-Amp is an non-inverting OP-Amp (∵ source connected to +ve)

We know, o/p volt is

$$V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

$$\frac{V_0}{V_{in}} = \left(1 + \frac{R_f}{R_1}\right)$$

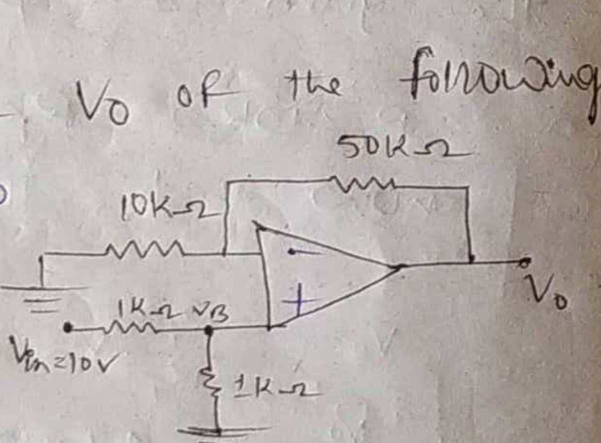
$$A_d = 1 + \frac{R_f}{1 \cdot 10^3}$$

$$61 = \frac{1k\Omega + R_f}{1k\Omega}$$

$$R_f = 61k\Omega - 1k\Omega$$

$$\boxed{R_f = 60k\Omega}$$

3) Find the o/p voltage $V_0$ of the following OP-A




Sol: The Given OP-Amp is an non-inverting with i/p volt - $V_B$.

Given, $R_1 = 10k\Omega$, $R_f = 50k\Omega$

$$V_0 = \left(1 + \frac{R_f}{R_1}\right) V_B$$

$$= \left(1 + \frac{50}{10}\right) \cdot 5$$

$$= (1+5) \, 5$$

$$V_0 = 30V$$

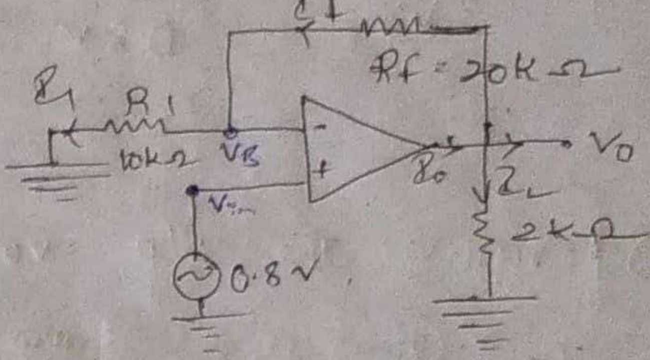
calc. of VB:

Apply Volt. div. rule

$$V_B = 10 \cdot \frac{1}{1+1} = \frac{10}{2}$$

$$= 5V$$

4) The non-inverting OP-Amp as shown in figure




Determine

(1) $A_d$

(2) $V_o$

(3) $i_L$

(4) $i_o$

(5) $i_1$

sol:- Given, $R_f = 20k\Omega$, $R_1 = 10k\Omega$, $V_{in} = 0.8V$

Acc. to virtual Ground concept,

$$V_A = V_B = 0.8V.$$

(5) $i_1$

$$i_1 = \frac{V_B - 0}{R_1} = \frac{0.8}{10.10^3} = \frac{0.8}{10^5} = \frac{80}{10^6} = \underline{80\mu A}.$$

(2) we know o/p volt. of non-inverting OP-Amp

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_{in}$$

$$= \left(1 + \frac{20}{10}\right)0.8 = (1+2)0.8 = (3 \times 0.8)$$

$$V_o = 2.4V.$$

$$* \; i_f = \frac{V_o - V_B}{R_f} = \frac{2.4 - 0.8}{20.10^3} = \frac{1.6}{2.10^4} = \frac{8}{10^5} = 80\mu A.$$

$$(3) \; i_L = \frac{V_o}{R_L} = \frac{2.4}{2.10^3} = \frac{1.2}{10^3} = \frac{12}{10^4} = 1.2mA.$$

(4) Apply KCL at o/p side

$$i_o - i_f - i_L = 0$$

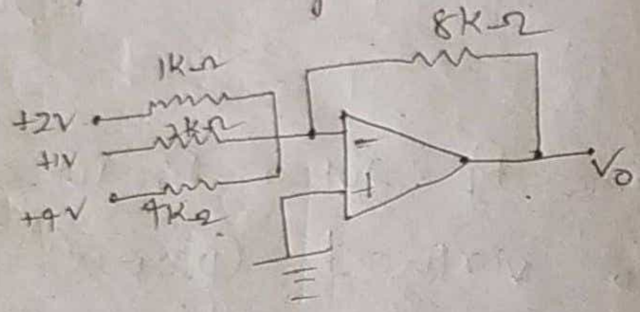
$$i_o = i_f + i_L = 80 \times 10^{-6} + 1.2 \times 10^{-3}$$

$$i_o = 1.28mA.$$

④ $A_d = \frac{V_o}{V_{in}} = \frac{2.4V}{0.8V} = \underline{\underline{3}}$

⑤ Determine the o/p voltage for the following

Sol: The Given Op-Amp is an inverting adder.




Given, $R_1 = 1K\Omega$, $V_1 = 2V$,

$R_2 = 2K\Omega$, $V_2 = 1V$,

$R_3 = 4K\Omega$, $V_3 = 4V$,

$R_f = 8K\Omega$

$$\therefore V_o = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

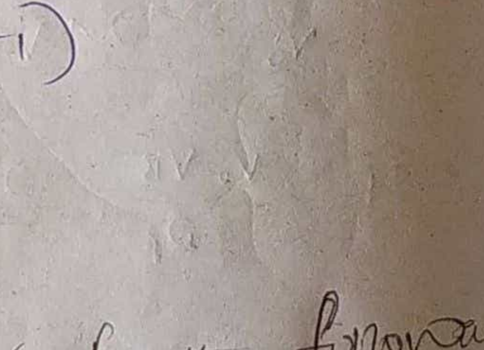
$$= -8K\Omega\left(\frac{2}{1} + \frac{1}{2} + \frac{4}{4}\right)$$

$$= -8K\Omega(2+0.5+1)$$

$$= -8(3.5)$$

$$V_o = -28V$$

⑥ Determine o/p voltage $V_o$ for the following ckt.




Sol: Given, $R_f = 5K\Omega$, $R_1 = 1K\Omega$,

we want $V_A$:-

Apply KCL at Node $V_A$

$I_1 + I_2 - I_a = 0 \quad (\because I_a = 0)$.

$$I_1 + I_2 = 0$$

$$\frac{1 - V_A}{1} + \frac{3 - V_A}{2} = 0$$

$$\frac{1}{1} + \frac{3}{2} = \frac{V_A}{1} + \frac{V_A}{2}$$

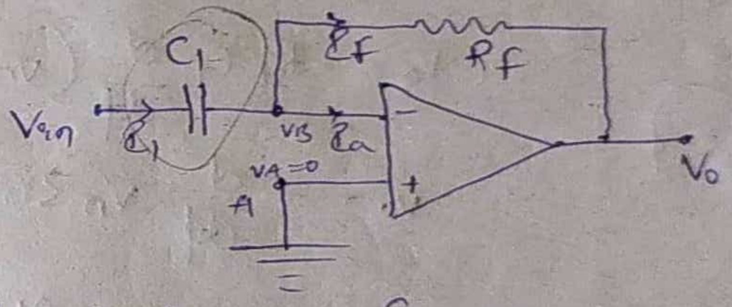
$$\left(\frac{2+3}{\cancel{2}}\right) = \left(\frac{2V_A + V_A}{\cancel{2}}\right)$$

$$5 = 3V_A$$

$$\boxed{V_A = 5/3\ V}$$

* **OP-Amp as Differentiator :**

The ckt diagram for Diff. is




* **calculation of Vo :**

Acc to V.G.C,

$$V_A = V_B = 0$$

⇒ Apply KCL at node B.

$$I_1 - I_a - I_f = 0$$

$$I_1 - 0 - I_f = 0 \quad (\because I_a = 0)$$

$$I_1 = I_f \quad \text{—— (1)}$$

⇒ Acc. to ohm's law,

$$I_1 = C_1 \frac{d}{dt}\underbrace{(V_{in} - V_B)}\ \text{if voltages present.}$$

$$I_1 = C_1 \frac{d}{dt} V_{in} \quad \text{—— (2)}$$


$$I = C \cdot \frac{d\,V_{in}}{dt}.$$

$$\Rightarrow i_f = \frac{V_B - V_o}{R_f} = \frac{0 - V_o}{R_f} = \frac{-V_o}{R_f} \quad \text{— (3)}$$

sub eq (2) (3) in eq (1)

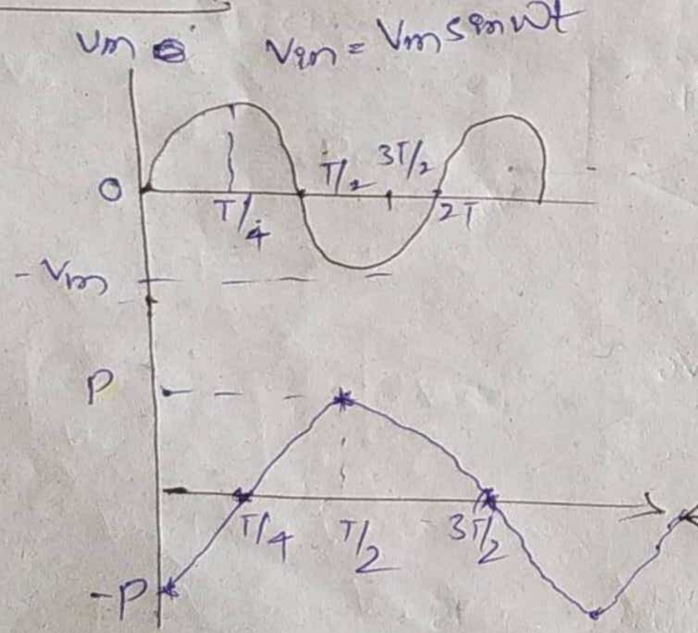
$$C_1 \frac{d}{dt} V_{in} = \frac{-V_o}{R_f}$$

$$-V_o = R_f C_1 \frac{d}{dt} V_{in}$$

$$\boxed{V_o = -R_f C_1 \frac{d}{dt} V_{in}}$$

$$V_o \propto \frac{d}{dt}(V_{in})$$

Wave forms :




$$V_o = -R_f C_1 \frac{d}{dt}(V_m \sin\omega t)$$

$$V_o = -\frac{d}{dt} V_m \sin\omega t$$

$$V_o = -V_m \cos\omega t \cdot \omega$$

$$= -V_m \omega \cos\omega t$$

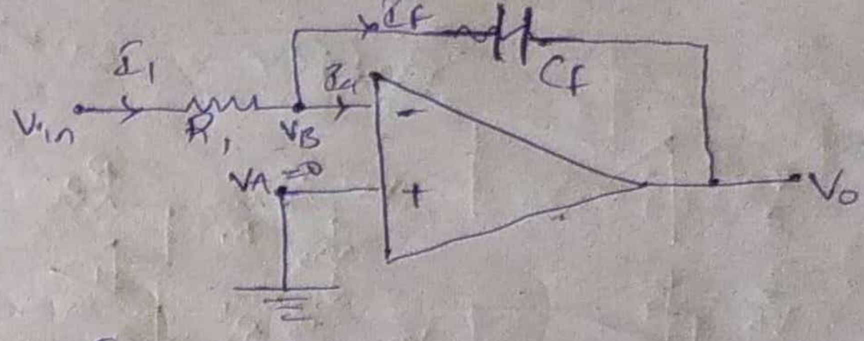
$$\boxed{V_o = -P\cos\omega t}$$

$t = 0$

at $t = T/4$

$t = T/2$

# OP-Amp as Integrator :




## Calc. of $V_0$ :

Acc. to V.G.C,

$V_A = V_B = 0$

⇒ Appy KCL at Node (B) :

$i_1 - i_a - i_f = 0$

$i_1 - 0 - i_f = 0 \quad (\because i_a = 0)$

$i_1 = i_f$ —— (1)

Acc. to ohms law,

$i_1 = \frac{V_{in} - V_B}{R_1} = \frac{V_{in} - 0}{R_1} = \frac{V_{in}}{R_1}$ —— (2)

$i_f = C_f \frac{d}{dt}(V_B - V_0)$

$i_f = C_f \frac{d}{dt}(-V_0)$

$i_f = -C_f \frac{d}{dt}(V_0)$ —— (3)

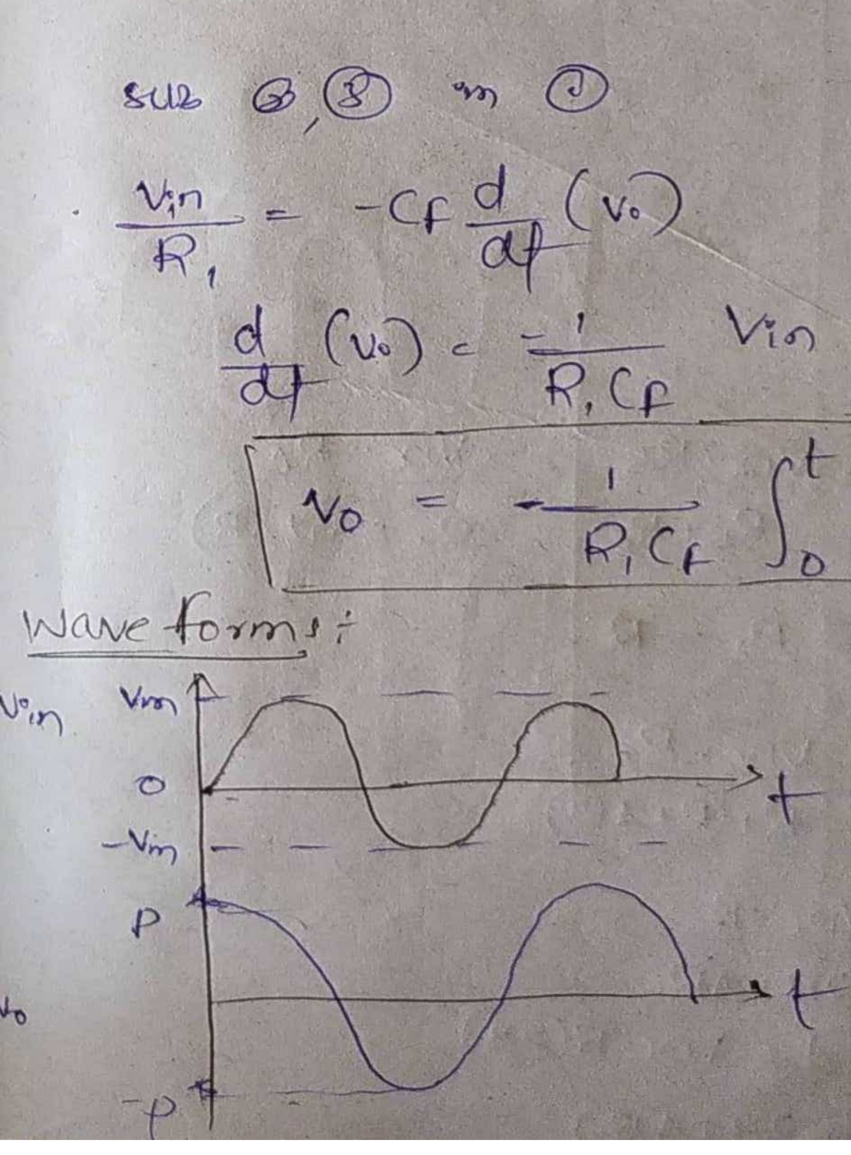
sub (2), (3) in (1)

$\frac{V_{in}}{R_1} = -C_f \frac{d}{dt}(V_0)$

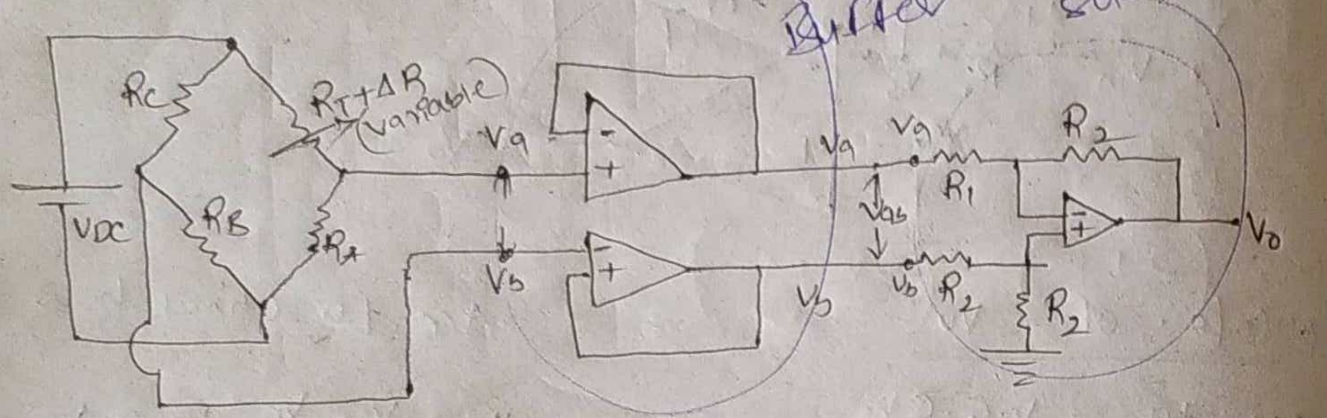
$\frac{d}{dt}(V_0) = \frac{-1}{R_1 C_f} V_{in}$

$$\boxed{V_0 = \frac{-1}{R_1 C_f} \int_0^t V_{in}\, dt}$$

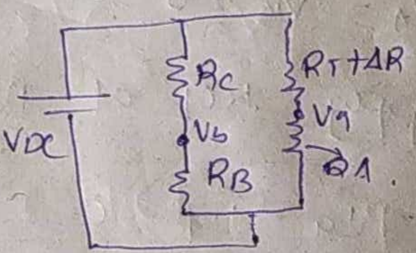
## Wave forms :



# Instrumentation Amplifier :




## * Calculation of $V_o$ :

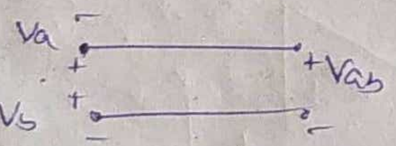



Apply VDR,

$$V_a = \frac{V_{DC} \cdot R_A}{R_A + (R_T + \Delta R)}$$

$$V_b = \frac{V_{DC} \cdot R_B}{R_B + R_C}$$

## * Cal. of $V_{ab}$




$$-V_b + V_a + V_{ab} = 0$$

$$V_{ab} = V_b - V_a = \frac{V_{DC} \cdot R_B}{R_B + R_C} - \frac{V_{DC} \cdot R_A}{R_A + (R_T + \Delta R)}$$

Assume $R_A = R_B = R_C = R_T = R$.

$$V_{ab} = \frac{V_{DC} \cdot R}{R + R} - \frac{V_{DC} \cdot R}{R + (R + \Delta R)}$$

$$= \frac{V_{DC} \cdot R}{2R} - \frac{V_{DC} \cdot R}{2R + \Delta R}$$

$$= \frac{V_{DC} R(2R + \Delta R) - V_{DC} R(2R)}{2R(2R + \Delta R)}$$

$$= \frac{\cancel{V_{DC} \cdot 2R^2} + V_{DC} \cdot R \Delta R - \cancel{V_{DC} \cdot 2R^2}}{\cancel{2R}(2R + \Delta R)}$$

$$V_{ab} = \frac{V_{DC} \cdot \Delta R}{2(2R + \cancel{\Delta R})}$$

$R >>> \Delta R$.

$$V_{ab} = \frac{V_{DC} \cdot \Delta R}{2 \cdot 2R} = \frac{V_{DC} \cdot \Delta R}{4R}.$$

The o/p of subtractor is

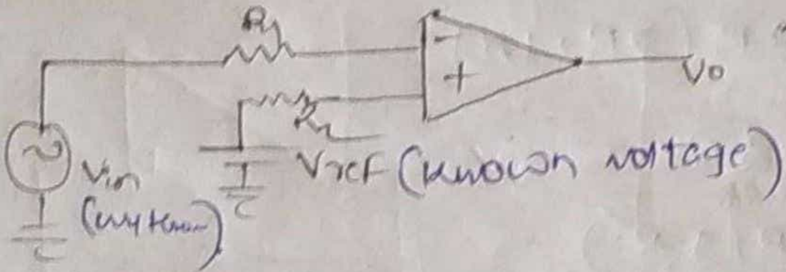
$$V_0 = \frac{R_2}{R_1}(V_b - V_a)$$

$$= A \cdot V_{ab}$$

$$\boxed{V_0 = A \cdot \frac{V_{DC} \cdot \Delta R}{4R}}$$

$\therefore$ $\boxed{V_0 \propto (\Delta R).}$ ** $\Delta R = 0 \Rightarrow V_0 = 0.$

## * Comparator :

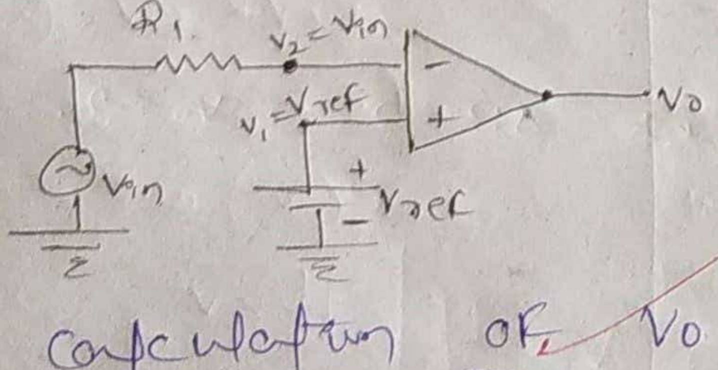


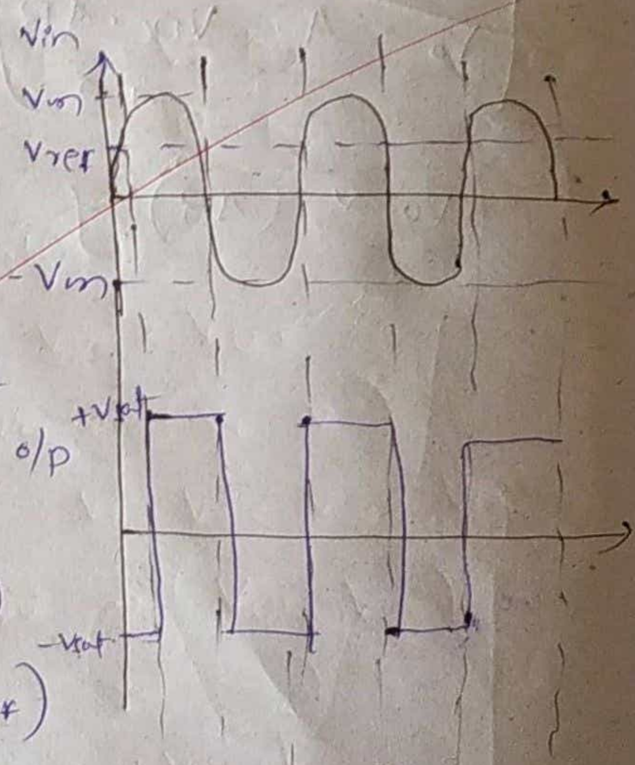

comparator

- Inverting
  - +ve reference
  - -ve reference
- Non-inverting.
  - +ve ref.
  - -ve ref.

## * Inverting comparator with +ve Reference :

The ckt diagram shown is




### Calculation of Vo :

① $V_{in} > V_{ref}$ .

$V_o = A_d(V_1 - V_2)$

$V_1 = V_{in}$ , $V_2 = V_{ref}$ ,

$V_o = A_d(V_{in} - V_{ref})$

$= \infty(5-3)$

$= \infty(+ve)$

$V_o = +V_{saturation}$

$V_{in} < V_{ref}$ .

$V_o = -A_d(V_1 - V_2)$

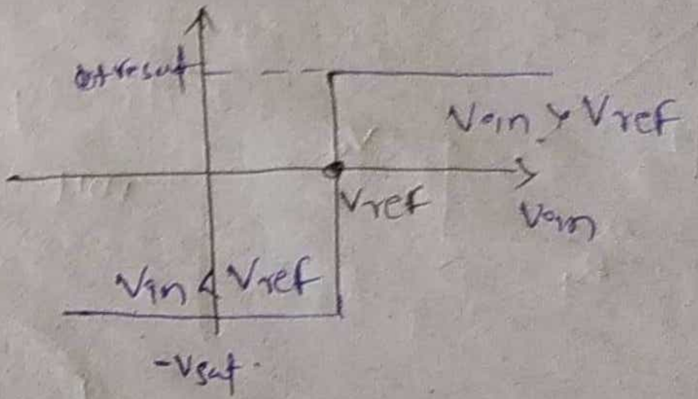
$= \infty(V_{in} - V_{ref})$

$= \infty(-5-3)$

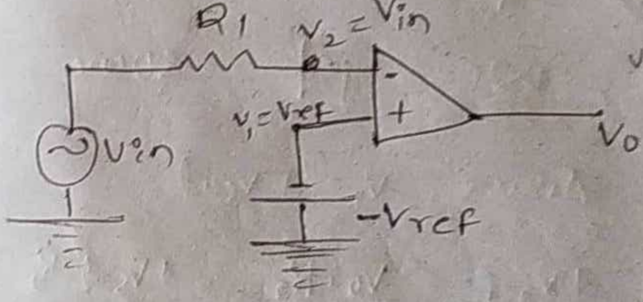
$= \infty(-ve)$

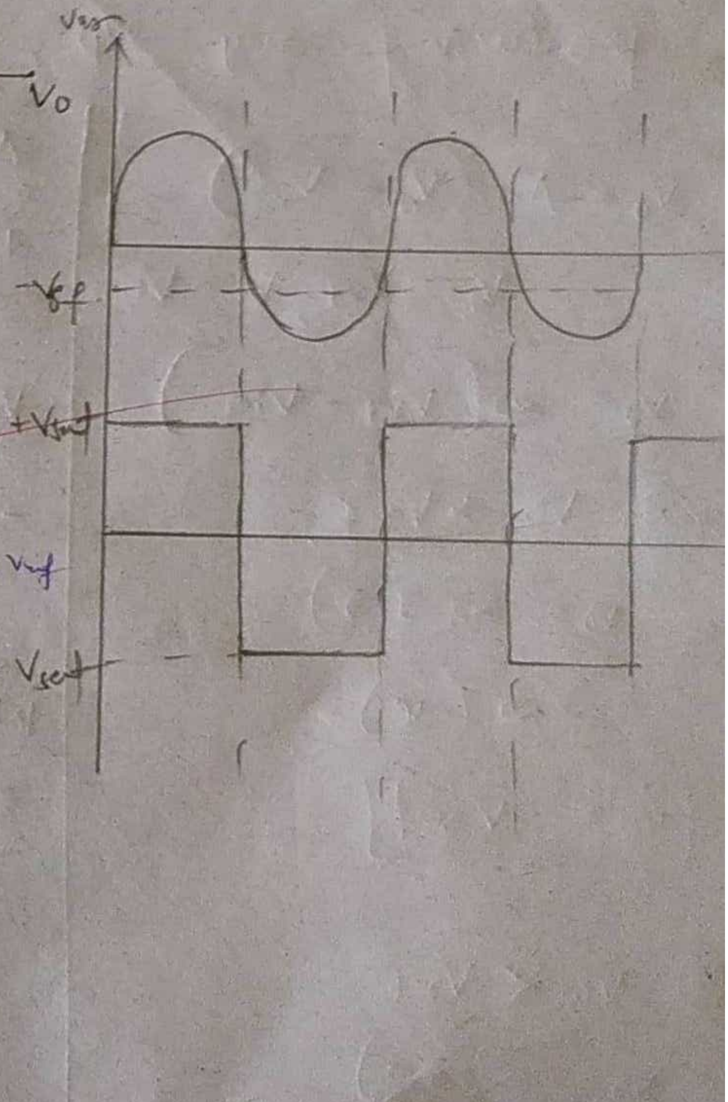
$V_o = -V_{sat}$ .

## voltage Transformer curve




## * Inverting Comparator with -ve Reference




$V_{in} > V_{ref}$

$V_0 = A_d(V_{in} - V_{ref})$

$= A_d(\overset{V_1}{5} - \overset{-V_2}{(-3)})$ , $V_1 = V_{in}$ , $V_2 = V_{ref}$

$= \infty(+ve)$

$V_0 = +V_{sat}$

$V_{in} < V_{ref}$

$V_0 = A_d(V_1 - V_2)$

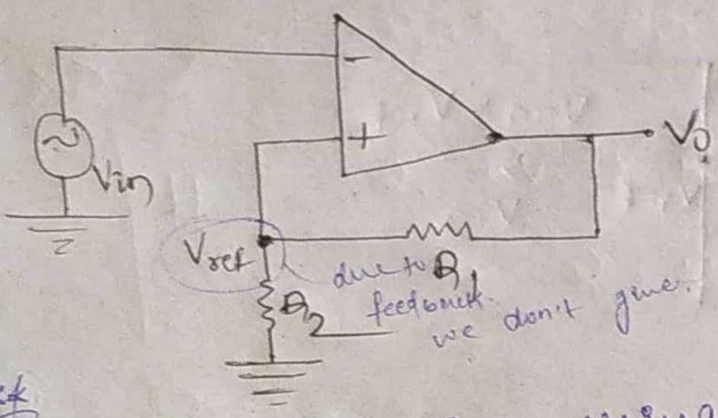
$V_0 = \infty(V_{in} - V_{ref})$

$= \infty(-5-(3))$

$= \infty(-ve)$

$V_0 = -V_{sat}$ .

# * Inverting SCHMITT TRIGGER : (Regenerative comparator)




* Initially $V_0$, off ref voltages.

** In this we are using +ve feedback.

** Advantage of +ve feedback is without producing any i/p, we get some o/p.

$V_0 = A_d(V_+ - V_-)$

$V_+ = V_{ref}$, $V_- = V_{in}$

$V_0 = \infty(V_{ref} - V_{in})$

(2) $V_{in} > V_{ref}$

$V_0 = \infty(3-5)$

$= \infty(-ve)$

$\boxed{V_0 = -V_{sat}}$

(3) $V_{in} < V_{ref}$

$V_0 = \infty(3-2)$

$= \infty(+ve)$

$\boxed{V_0 = +V_{sat}}$.

Assume $V_0 = +V_{sat}$,

$+V_{ref} = \frac{V_0 \cdot R_2}{R_1 + R_2} = \frac{+V_{sat} R_2}{R_1 + R_2} = V_{UT}$ upper Threshold

$V_0 = -V_{sat}$

$-V_{ref} = \frac{V_0 \cdot R_2}{R_1 + R_2} = \frac{-V_{sat} R_2}{R_1 + R_2} = V_{LT}$

Working :

(1) $V_{in} < V_{UT}$

$V_0 = A_d(V_+ - V_-)$

$V_+ = V_{UT}$, $V_- = V_{in}$

$V_0 = \infty(V_{UT} - V_{in})$

$= \infty(3-2) = \infty(+ve)$

$\boxed{V_0 = +V_{sat}}$.

(i) $V_{in} > V_{UT}$.

$$v_0 = \infty(V_{UT} - V_{in})$$
$$= \infty(3-5)$$
$$= -\infty$$
$$\boxed{v_0 = -V_{sat}}$$

(ii) $V_{in} > V_{LT}$

$$\boxed{V_0 = -V_{sat}}$$

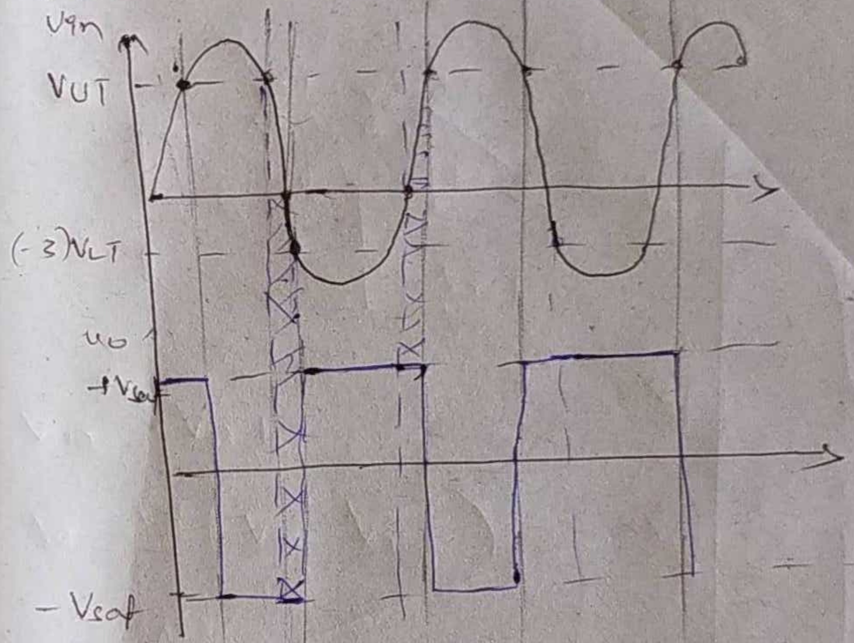
$\because V_0 = \infty(V_{LT} - V_{in})$
$$= \infty(-3-2)$$
$$\boxed{V_0 = -V_{sat}}$$

(iii) $V_{in} < V_{LT}$

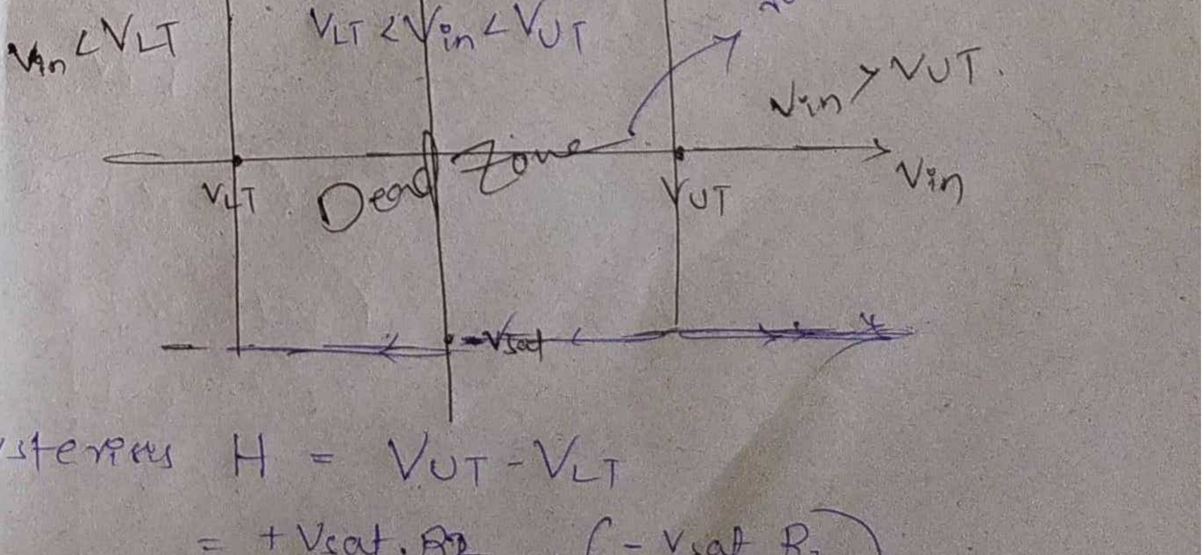
$$\boxed{V_0 = +V_{sat}}$$

$$v_0 = \infty(V_{LT} - V_{in})$$
$$= \infty(-3-(-4))$$
$$\boxed{V_0 = +V_{sat}}$$

Waveforms :-




Characteristic :-




Hysteresis $H = V_{UT} - V_{LT}$

$$= \frac{+V_{sat} \cdot R_2}{R_1 + R_2} - \left( \frac{-V_{sat} R_2}{R_1 + R_2} \right)$$

$$= \frac{+V_{sat} R_2}{R_1 + R_2} + \frac{V_{sat} R_2}{R_1 + R_2}$$

$$\boxed{H = 2 \cdot \frac{+V_{sat} R_2}{R_1 + R_2}}$$