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Unit-2

Operational Amplifiers (Op-Amp)

Introduction:-

Operational Amplifier is advanced Amplifier.

* These are more economical & convenient to use.

* Operational Amplifier is a complete ckt.

* They are available as IC's.

* In IC's large value of capacitors are difficult to fabricate.

Ex:- Bypass Capacitors.

* These capacitors are 100-times more than picofarad capacitors.

* So, we have to avoid coupling capacitors. These are direct coupled Amplifier. There are 3 types of coupling.

i) RC Coupled :- widely used.

ii) Transformer Coupled :- have restricted application becoz it requires large area. They are not integrated.

iii) Direct Coupled :- No restrictions. means, the coupling is directly conducting path connected from source to o/p without capacitor.

→ Here freq response will be different & works at lower freq (dc also). and it will amplify equally (or) uniformly. These are available as IC's.

Why these are called Op-Amp?

All operations (differentiations, Integrations) are done. So, it is called Operational Amplifier.

* Operational is nothing but mathematical operations like Sum, difference, multiplication etc. So, they are

called as Operational Amplifier. Simply which perform the mathematical operation.

Integrated ckt Chips (IC's):-

* Integrated ckt is a ckt, in which all the components are fabricated on same chip, that is called Integrated ckt.

Advantages:-

* Before IC's we are using discrete component (resistor, capacitor, etc) which are placed on PCB.

* If any one is damaged then we need to replace it (desoldering). This is the drawback.

* After inventing IC's all components are placed in a single chip.

i) Construct the ckt in small size, hence increase equipment density.

ii) Reduction of cost.

iii) Increased operating speed.

iv) Reduction in power consumption.

Classifications of IC's:-

There are two types of classification.

a) Digital IC's:-

These are concerned with only two levels of voltages & current. These levels are either high level (or) low level.

What are the digital IC's?

Ex:- Logic Gates, Counters, Multiplexer & Shift Register.
etc.

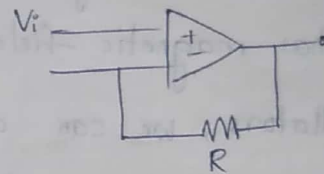
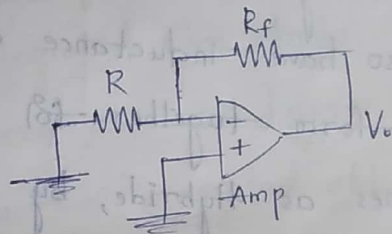
b) Linear IC's:- Linear means "Analog".

In the linear IC's, the electrical signals are Analog in nature. Here we are using only electrical signals.

Ex:- Filters, Modulator (nothing but which converts high freq to low freq), Amplifiers.

* Linear Integrated Ckts contains discrete components along with Operational Amplifiers (transistor) IC 741 based on our requirement.

This is the Linear IC's

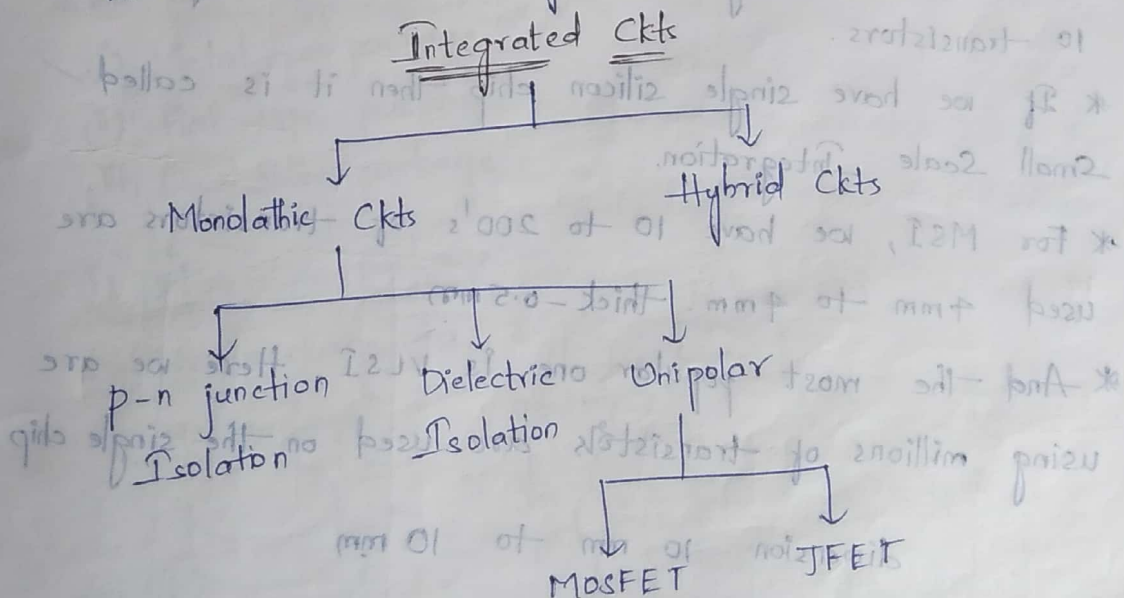


This ' R_f ' forms a specific application that is Amplifier.

* By using planar technology, we can integrate all the discrete components in small chip.

* In planar technology, on the same side of plane we are able to generate Variable Resistor, Capacitors & transistors.

This is "Linear Integrated Ckts"



* Monolithic means 'one single chip', we can build a entire ckt then it becomes monolithic ckt.

* Hybrid means 'Combination', where we have integrated component (IC) apart from discrete components (Capacitors, inductors, resistors), these two forms one ckt

* This is the difference b/w Monolithic & Hybrid ckt.

for Ex:- Making inductance is difficult in IC, because it has magnetic field. Suppose, if we need LC oscillators, we can actually integrate all the components on same silicon chip & also have inductance alone (as a separate unit) then form together for our oscillator. So, here it becomes as Hybrid, by one as integrated component & other as discrete component.

Different IC chips:-

i) SSI

ii) MSI

iii) LSI (or) VLSI

* The SSI is very small, and we are using around 10 transistors.

* If we have single silicon chip then it is called Small Scale Integration.

* For MSI, we have 10 to 200's of transistors are used 4mm to 4mm. thick - 0.5mm

* And the most popular one is VLSI. Here we are using millions of transistors are used on the single chip

dimension 10 mm to 10 mm
thickness 0.5 mm

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* Operational Amplifier is a direct coupled high gain amplifier; high i/p resistance & low o/p resistance.

* Initially, it is used to perform mathematical operation on analog signals. Hence, it was named as operational Amplifier.

* It is available as a Integrated Ckt.

* ~~IC~~ All the components are fabricated on a single ^{silicon} chip, is called. Integrated Ckt

* Packages:-

* Integrated Ckts. looks like a transistor.

* There are 3 different types of packages.

How the integrated ckt mounted for the application:-

* We have to take a small silicon chip, then mount it on package. Take the leads to the pins of package.

This is procedure for mounting for the application.

* By this procedure, externally we can put them in a given ckt & then form a different application.

* The three types of packages are

(i) Metal can package

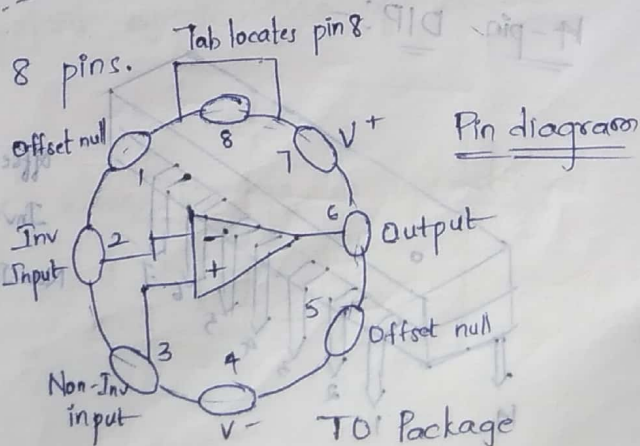
(ii) Flat type package

(iii) Dual Inline package

(i) Metal Can package:-

* This package has 8 pins.

8-pin package

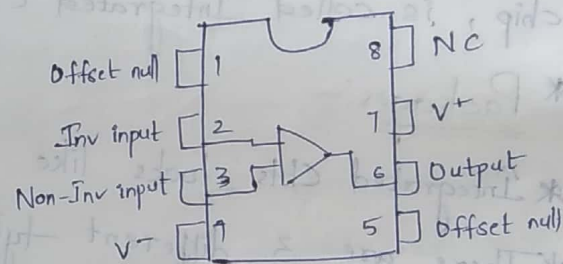


* It is like our SL-100 transistor. (Cylinder Shape).

* It is a 8-pin metal can package with a tab.

* The small projection in the metal can which gives out the idea where from we start from the reference point. This is called 'Tab' which indicates starting point.

(iii) Dual Inline Package:- (DIP)



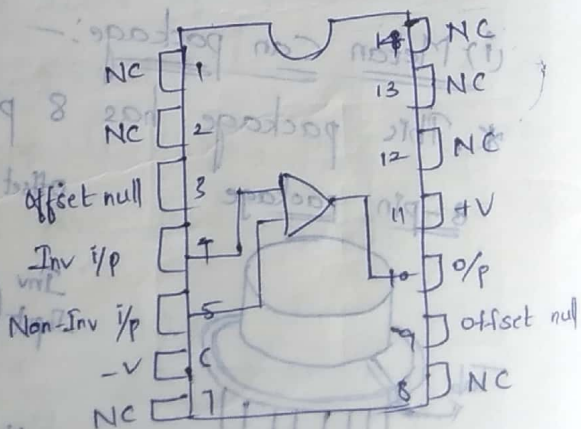
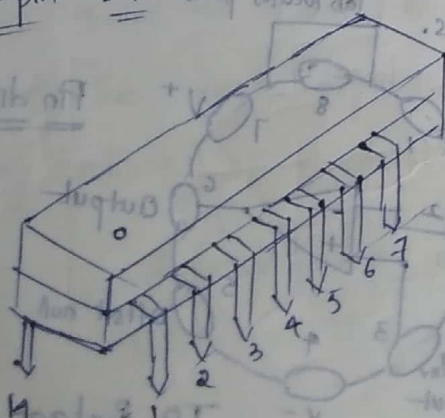
* In laboratories, we use this 8-pin Dual Inline package.

* DIP have two Here, there are two lines of o/p. One line of o/p is one side & other line of o/p is another side. These two lines are parallel to each other.

* As the two lines are exactly opposite to each other. It is called Dual Inline package.

* This is the plastic package because the plastic cover put on the silicon chip.

14-pin DIP:

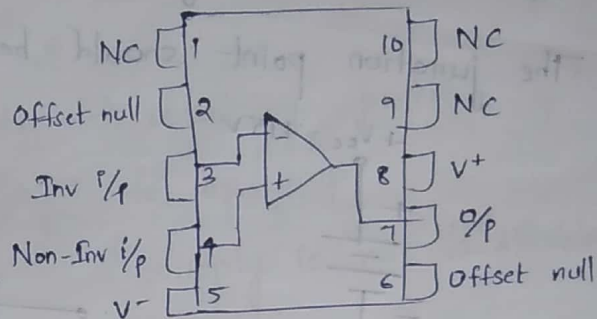
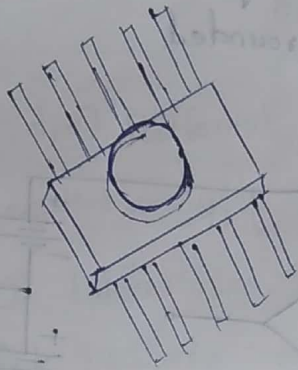


Inv i/p - Inverting i/p

Non-Inv i/p - Non-Inverting i/p

NC - No connection.

(iii) Ceramic slot package:-



Temperature Ranges:-

* There are 3 different temperature grades for 1C741 op-amp.

(i) Military grade:-

* The temperature range is -55°C to $+125^{\circ}\text{C}$.

(ii) Industrial grade:-

* The temperature range is -20°C to $+85^{\circ}\text{C}$.

(iii) Commercial grade:-

* The temperature range is 0°C to $+75^{\circ}\text{C}$.

* This The data sheets for the IC's are provided by the manufactures as they produce it.

* It gives pin diagrams, equivalent ckt's, electrical characteristics & typical applications of the device.

Power Supplies:-

* When In laboratory, when we go to operational amplifier, it require dual supply.

* Dual supply means two supplies.

* Consider 2 two 15 volt batteries, then to interconnect them in series, (fig 1)

Take +ve terminal of one battery connected to the -ve terminal of other battery.

The junction point should be grounded.

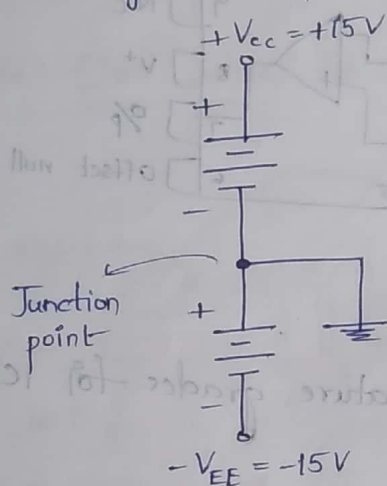
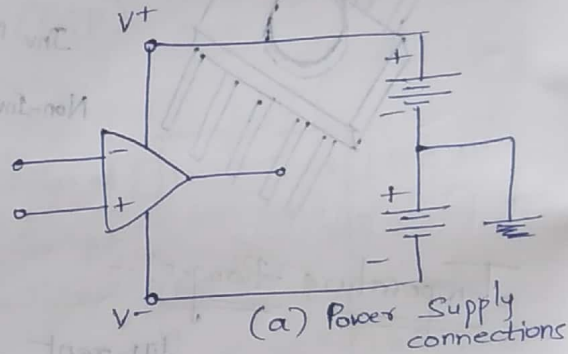


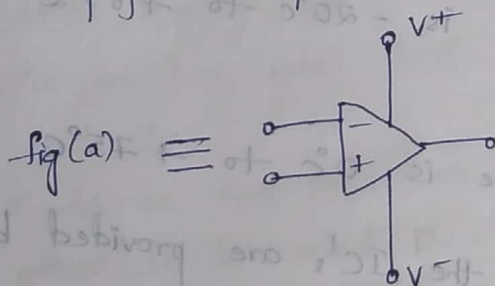
fig-1)



* In fig(a), 7th pin is $+V_{cc}$

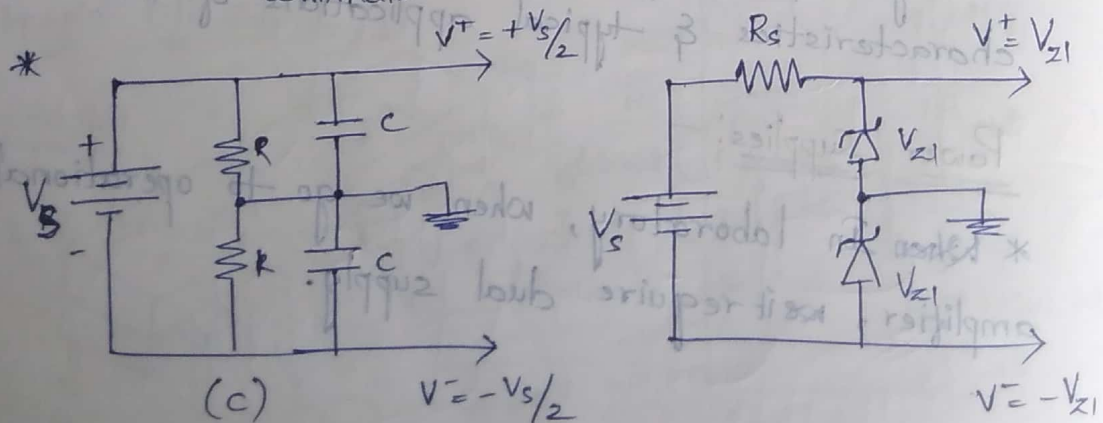
& 4th pin is $-V_{EE}$

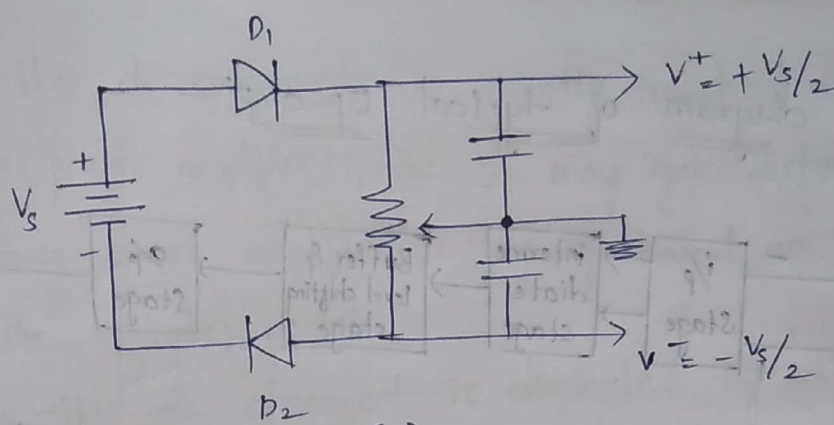
* In fig(a), two batteries are connected in series & junction point is considered as ground.



* fig(b) is the symbolic representation of op-amp with dual supply

fig. (b) Circuit symbol showing power supply terminals





(e)

(c, d, e) Different ckt's for obtaining positive & negative supply voltages for op-amp.

fig(c) * In laboratories, the dual supply is not available. But op-amp requires dual supply.

* If we have one single power supply (V_s), we can put two resistors parallel to V_s and keep the center to ground. in fig(c).

* One End is the half of the voltage ($V_s/2$) & other end is half of the voltage ($-V_s/2$). Capacitors take care of the fluctuations (or) transients in.

Like this, we convert single power supply to dual power supply by using resistors & capacitors combination.

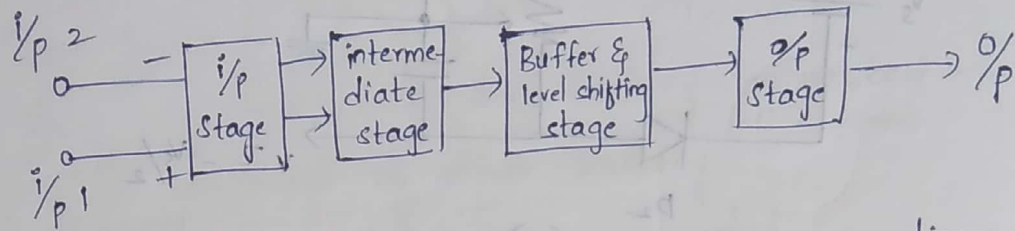
fig(d) * The another way to convert to dual supply is, the same supply voltage is introduced to two Zener diodes.

* Zener diode should be connected to resistor in series.

* The purpose of ' R_s ' is to take care of current limit.

* These two Zener diodes depends on the breakdown voltage.

Block diagram of typical op-amp:



* OP-amp is a direct coupled high gain amplifier.

Usually consists of one or more differential amplifiers & followed by level translator & an o/p stage.

* The o/p stage is generally a push-pull pair amplifier.

* The first stage & intermediate stage is differential amplifier. ($\because$ one or more diff amplifiers).

* This op-amp is available as a single IC package.

* The i/p stage is dual i/p & balanced o/p differential amplifier. with high gain & high i/p resistance.

* Intermediate stage is a multi-stage amplifier because of the no. of stages connected in cascade.

* Intermediate stage is dual i/p & unbalanced o/p differential amplifier to increase gain further.

* The function of intermediate stage is to get a sufficient gain.

* The last stage should be a diff amplifier with unbalanced o/p. because the further stage (level shifter) has one i/p terminal.

* The unbalanced o/p contain dc component

* If this dc component is directly reached to φ stage (power amplifier), the φ may get distorted because power amplifier is purely based on location of the operating point.

* So, this dc component is eliminated by using level shifter (or) level translator.

* Since level shifter is a common collector ckt, it will have very high i/p resistance, which prevents the loading of intermediate stage.

* Because of direct coupling of op-amp, the dc level ~~raises~~ raises from stage to stage.

* The increase in dc level tends to shifting in operating point of next stage.

* To limit level shifters are used to shift dc voltage to zero volts.

* The requirements of good % stage are:

(i) Large % voltage swing capability

(ii) Large % current swing capability

(iii) Low o/p impedance

(iv) Low dc power dissipation.

(v) Short ckt protection.

* The power amplifier is used so that op-amp can drive all type of loads.

* The $\%$ stage will decide the $\%$ resistance of the op-amp.

* (practically = 10°)

Output stage in op-amp:-

* The ϕ/p stage is a complementary symmetrical class-B push-pull amplifier.

* This power amplifier is used so that op-amp can drive all type of loads.

* The ϕ/p stage will decide the ϕ/p impedance of op-amp.

* Good ϕ/p stage is low ϕ/p impedance

* The transistors used here are complement to each other. One is npn & the other is pnp.

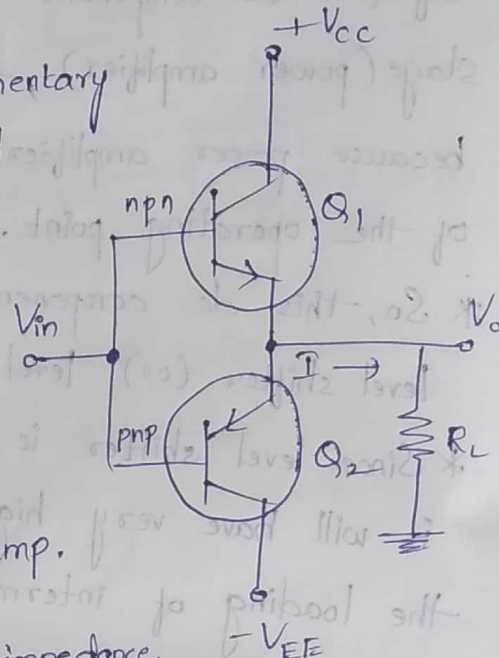
* The one drawback in this ckt is cross-over distortion.

* Here, i/p is coming from level-shifting stage.

If i/p is +ve, Q_1 is turn on & Q_2 is turn off

* The ϕ/p is taken at emitter. It is common collector amplifier. So, whatever i/p is applied, the same i/p is reflected on the ϕ/p . The voltage gain is unity.

* If i/p is -ve, Q_2 is turn on & Q_1 is turn off



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Part-II

Ideal Operational Amplifier:-

Characteristics of Ideal Operational Amplifier:-

1. Infinite Open loop Gain:-

$$A_{OL} = \infty \text{ (ideally)}$$

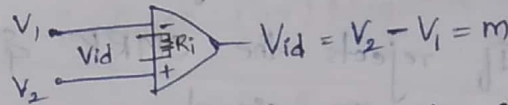
$$A_{OL} = \frac{\phi/p \text{ volt}}{i/p \text{ volt}} = \frac{V_o}{V_2 - V_1}$$

($\because i/p$ of op-amp is difference of 2 i/p 's)

(practically $= 10^6$) *

Since, Gain is ' ∞ ', we can amplify very small values.

2. Infinite i/p resistance: - $R_i = \infty$ (ideally)
practically $= 10^6 \Omega$ (or) $1 M\Omega$.

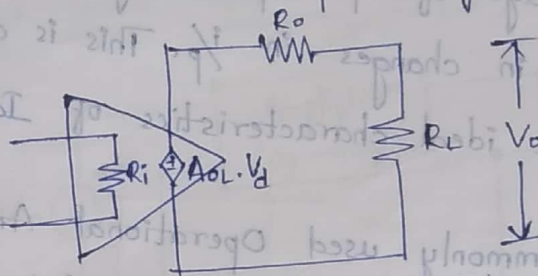


* The op-Amp draws zero current from the i/p source.

* The full voltage source will act as i/p to the amplifier because i/p resistance is infinite.

3. Zero Output Resistance: - $R_o = 0$ (ideally)

But practically minute (small) value.



$$V_o = A_{OL} \cdot V_d \times \frac{R_L}{R_o + R_L}$$

if $R_o = 0$,

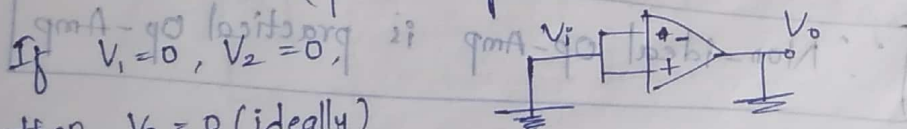
$$V_o = A_{OL} \cdot V_d$$

Therefore, i/p voltage directly appears at o/p and R_o is independent on load resistor (R_L).

4. Infinite Bandwidth: - $BW = \infty$ (ideally)
practically $= 5 \text{ Hz}$ in open loop

* If $B \cdot W = \infty$ then op-Amp can amplify all frequencies, if it is limited bandwidth then it can amplify only limited freq.

5. Zero offset: (ideally $0V$)
(practically $=$ a few μV)



then $V_o = 0$ (ideally)

But practically o/p volt is not zero.

If $i_p = 0$ then v_p volt = 0. This is called zero-offset.

6. Infinite common mode rejection Ratio (CMRR):-

$$CMRR = \infty \text{ (ideally)}$$

CMRR:- It rejects the CMRR & amplify the difference of the i_p signal.

$$\left(\because 20 \log_{10} 10^6 \right. \\ \left. = 20(6) = 120 \right) \text{ practically } = 10^6 \text{ (or) } 120 \text{ dB}$$

7. Infinite slewrate:- $SR = \infty$ (ideally)

* The v_p voltage of Op-Amp changes within '0' time with response in changes in i_p . This is called slewrate.

These are the ideal characteristics of Ideal Operational Amplifier.

* The most commonly used Operational Amplifier is

"IC741", which has some properties (above one).

* By using -ve fb we can increase the bandwidth

Ex:- 1 % feedback

$$\beta = 0.01$$

$$1 + \beta A_{OL} = 1 + (0.01 \times 10^6) = 10^4$$

$$(\text{Bandwidth})_{\text{with } -ve \text{ fb}} = (B.W)_{w/o \text{ fb}} (1 + A_{OL} \beta)$$

$$= 5 \text{ Hz } (10^4) = 50 \text{ KHz}$$

(practically)

$$\therefore (B.W)_{\text{with } -ve \text{ fb}} = 50 \text{ KHz}$$

$$\Rightarrow A_{CL} = \frac{A_{OL}}{1 + A_{OL} \beta} = \frac{10^6}{10^4} = 100 \text{ (Gain with } -ve \text{ fb)}$$

$\therefore$ Non-ideal Op-Amp is practical Op-Amp

Block diagram representation of feedback configurations:-

We have 2 types of feedback

- Regenerative feedback (or) Positive feedback
- Degenerative feedback (or) Negative feedback.

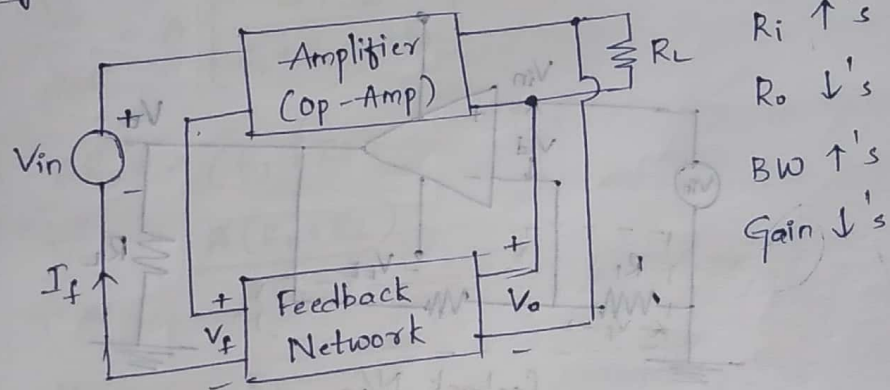
b) Degenerative / Negative feedback:-

* -ve fb is used for Amplifier

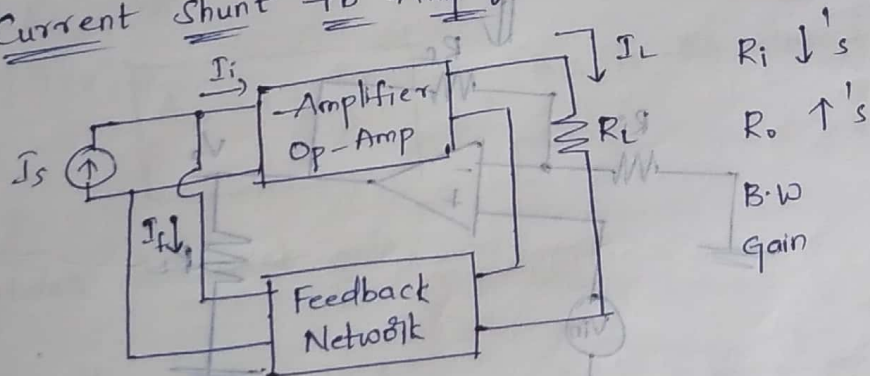
* Degenerative fb used for Amplifier

Types:- (Based on Sampling / Mixing)

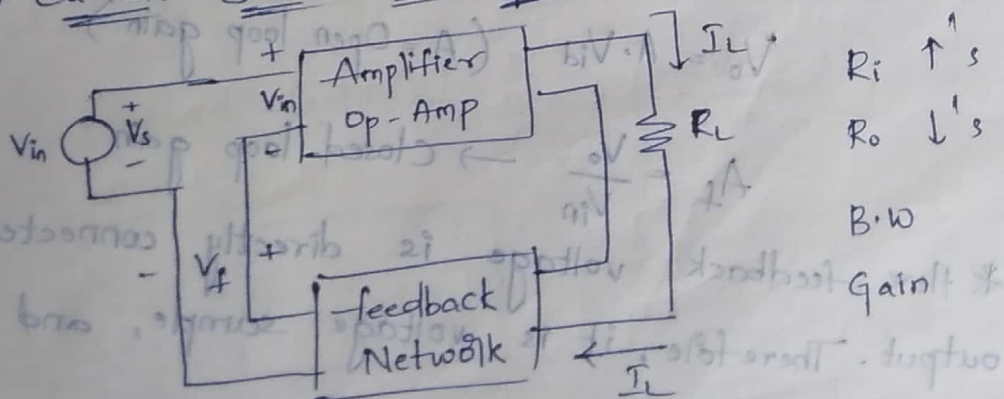
(i) Voltage Series feedback Amplifier:-



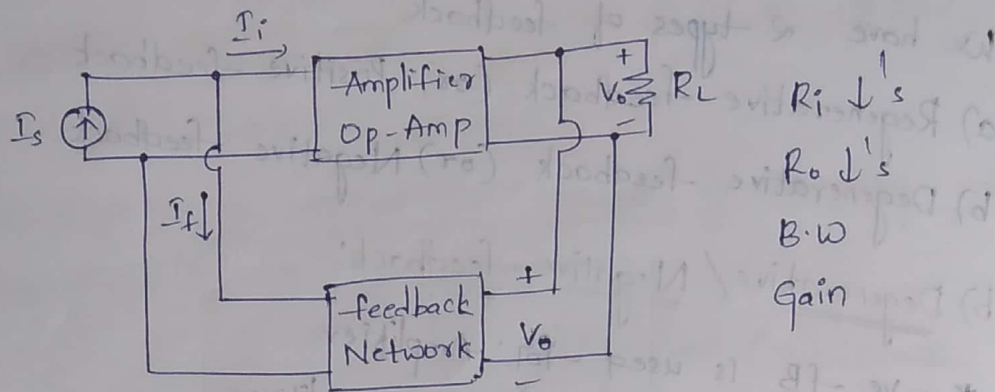
(ii) Current Shunt fb Amplifier:-



(iii) Current Series fb Amplifier:-

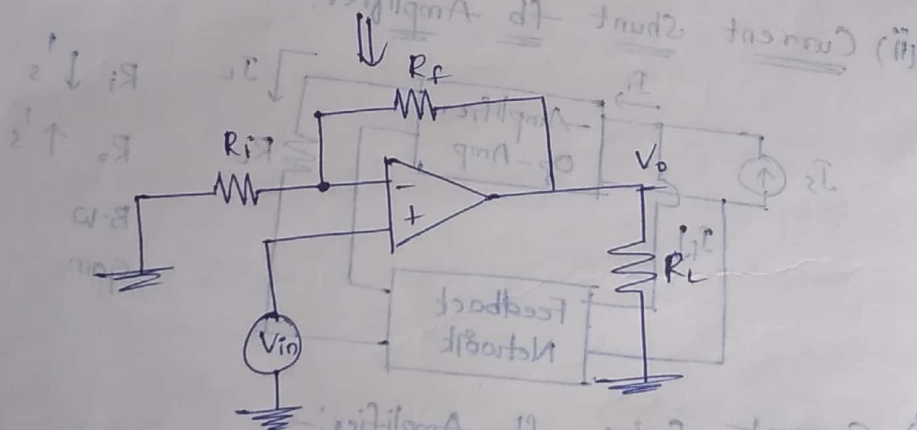
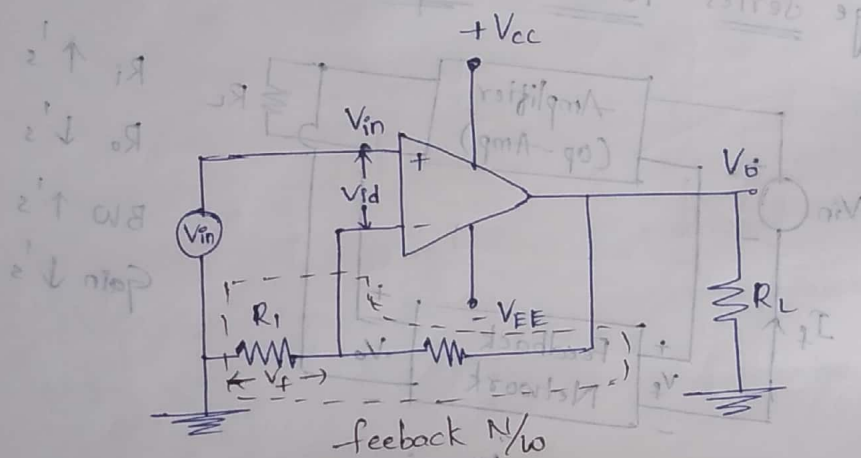


iv) Voltage Shunt fb Amplifier:-



Voltage Series feedback Amplifier:-

* It is also called as "Non-Inverting Amplifier."



$$V_o = A \cdot V_{id} \quad (A = \text{Open loop gain})$$

$$A_f = \frac{V_o}{V_{in}} \rightarrow \text{closed-loop gain}$$

* Here feedback voltage is directly connected to output. Therefore, it is voltage sample, and series mixing.

$$V_o = A V_{id}$$

$$V_o = A (V_1 - V_2) \quad (\because V_1 = V_{in}, V_2 = V_f)$$

$$\text{(feedback Voltage)} \quad V_f = V_o \cdot \frac{R_1}{R_1 + R_f} \quad (\text{voltage division})$$

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

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

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

$$\frac{V_o}{V_{in}} = A \left[\frac{R_1 + R_f}{R_1 + R_f + A R_1} \right]$$

$$\text{as } A R_1 \gg (R_1 + R_f)$$

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

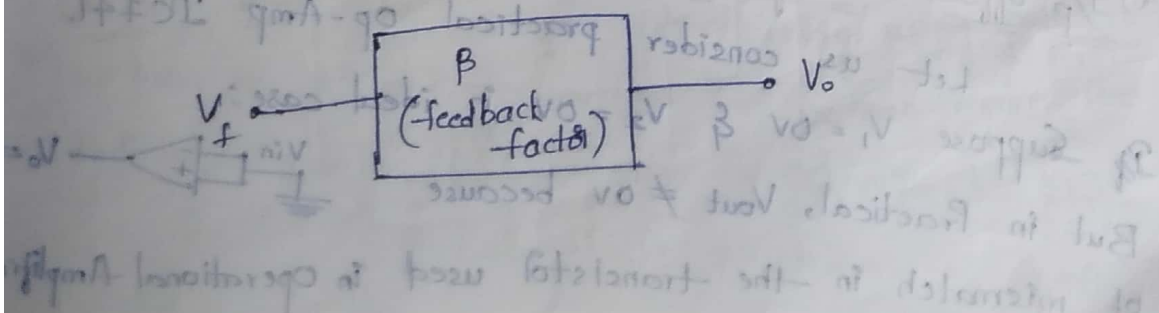
$$\frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}$$

$$\boxed{A_f = 1 + \frac{R_f}{R_1}} \rightarrow \text{This is the closed loop gain}$$

Consider feedback gain,

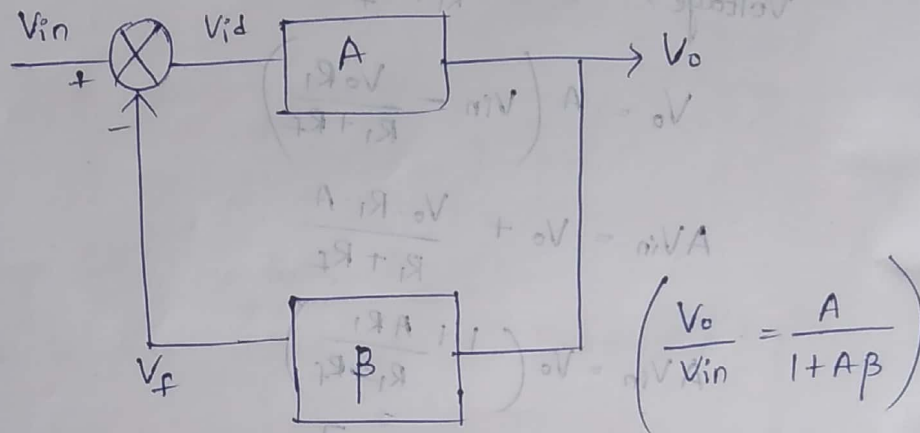
$$\frac{V_f}{V_o} = \frac{R_1}{R_1 + R_f} = \frac{1}{A} \quad (\because V_f = V_o \cdot \frac{R_1}{R_1 + R_f})$$

$$\therefore \text{Feedback factor } (\beta) = \frac{1}{A} \quad (\because \frac{V_f}{V_o} = \frac{1}{A})$$



$$\beta = \frac{V_f}{V_o}$$

Simply,



	Without feedback	With feedback
i/p resistance	R_i	$R_i(1 + A\beta)$
o/p resistance	R_o	$R_o / (1 + A\beta)$
Bandwidth	f_o	$f_o(1 + A\beta)$

Practical Op-Amp Parameters:

It has 2 parameters

(i) DC Parameter

(ii) AC Parameter $= \frac{V}{V_o}$

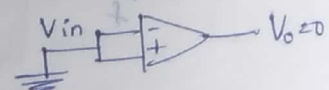
(i) DC Parameter:-

a) I/p offset voltage (V_{io}):-

Let us consider practical op-amp IC 741.

Suppose $V_1 = 0V$ & $V_2 = 0V$ in ideal case:

But in Practical, $V_{out} \neq 0V$ because



of mismatch in the transistor used in Operational Amplifier.

* The differential having 2 transistors are identical but practical not matched. So, that non-zero voltage will appear at o/p when $V_1 = 0$ & $V_2 = 0$ practical.

This non-zero voltage is called o/p offset voltage.

* Hence, a small non-zero voltage must be applied at the difference i/p voltage. This is called i/p offset voltage to make o/p voltage to '0'.

* This "i/p offset volt" is the amount of i/p dc (few μV) voltage that should be applied b/w 2 terminals of Op-Amp. Therefore the o/p offset voltage is '0'.

* If we are not applying these dc voltage (i/p) then even though $V_1 = 0$ & $V_2 = 0 \Rightarrow V_o \neq 0$. This is the "o/p offset voltage".

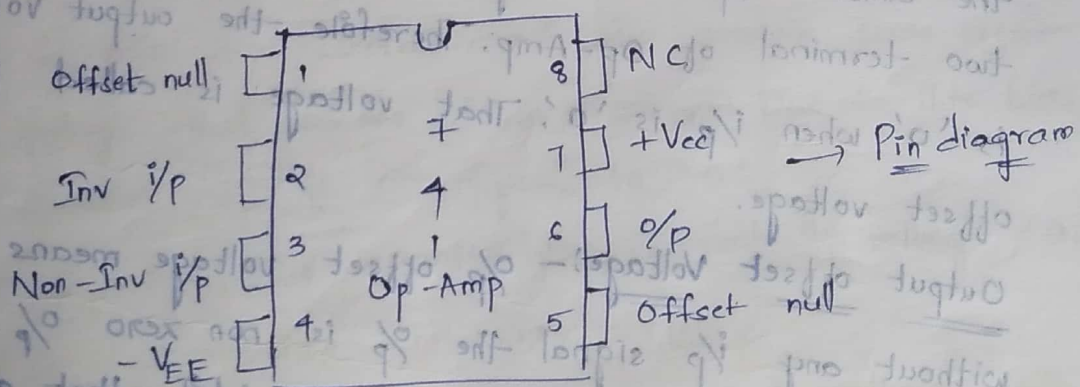
$$\therefore V_{io} = \text{a few } \mu V \quad V_{io} = \text{i/p offset voltage}$$

Ex:- ± 41 Op-Amp $V_{io} = 6 \text{ mV max}$

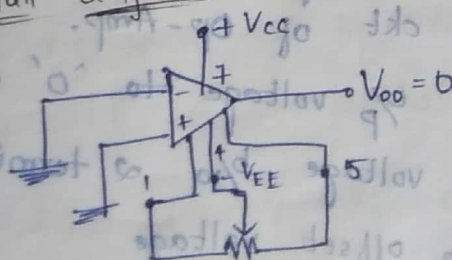
$V_{id} = 6 \text{ mV}$

then $V_{oo} = 0 \text{ V}$

V_{oo} - o/p offset voltage



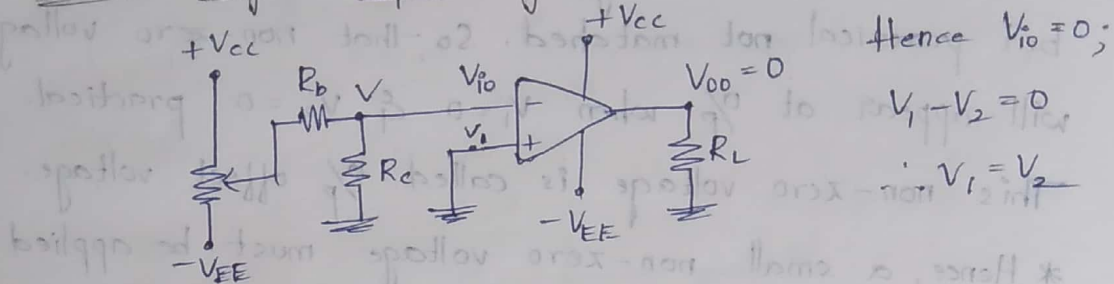
Offset Null adjustment.



By using potentiometer

we can make the o/p 'volt' to zero

Offset Voltage Compensating Network:-



Case (i):- Let us take $V_{oo} = +ve \Rightarrow$ (if $V_1 > V_2$)

increase ' V_2 ' up to V_1 to make V_{oo} to '0'

$\therefore V_{oo}$ becomes '0' $\Rightarrow$ our requirement

Case (ii):- Let us take $V_{oo} = -ve \Rightarrow$ (if $V_1 < V_2$)

So, to make V_{oo} to '0' we need to do the following decrease V_2 up to V_1 to make V_{oo} to '0'

$\therefore V_{oo}$ becomes '0' $\Rightarrow$ Our requirement

$\therefore$ In closed loop,

$$\text{o/p offset voltage} \left[V_{oo} = \left(1 + \frac{R_f}{R_i} \right) V_{io} \right] \rightarrow \text{Practical Eqn}$$

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Practical Op-Amp Parameters - (2-parameters DC, AC)

DC Parameters:-

a) Input offset voltage (V_{io}):- I/p offset voltage means the amount i/p dc voltage should be applied at the two terminal of Op-Amp. Therefore the output voltage is '0' when i/p is '0'. That voltage is called i/p offset voltage.

Output offset voltage:- o/p offset voltage means without any i/p signal the o/p is non zero o/p.

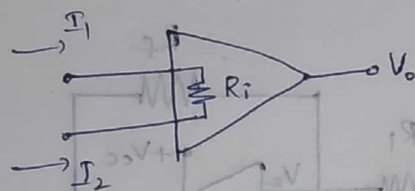
This is due to mismatching of transistor that are used in the internal ckt of Op-Amp.

So, to make the o/p voltage to '0' we need to apply small i/p dc voltage b/w 2 terminal. That voltage is called o/p offset voltage.

b) Input Bias Current (I_B):-

* Now we have operational amplifier having 2 terminals inverting & non inverting terminals.

* Input Bias Current is nothing but the "average of 2 i/p bias current", which are entering into the inverting & non-inverting terminals of Op-Amp.



$$\text{i/p Bias Current } \left\{ \begin{array}{l} I_{B1} \\ I_{B2} \end{array} \right\} I_B = \frac{I_{B1} + I_{B2}}{2}$$

* I_B (i/p Bias current) ideally is '0' i.e., $I_B = I_{B1} = I_{B2} = 0$

* But practically, $I_{B1} \neq I_{B2}$ i.e., I_{B1} & I_{B2} exists internally & may not be equal to I_{B1} & I_{B2} because of internal mismatching

* So, due to internal mismatch $\Rightarrow (I_{B1} \neq I_{B2})$

Ex:- $I_B = 500 \text{ nA}$ max for IC 741 Op-Amp
 $I_B = 75 \text{ nA}$ max for MLM 101A

* So, this Bias current will also produce some offset voltage that means Error current. Due to this bias current o/p is not equal to '0'.

* Therefore, due to this bias current o/p voltage $\neq 0$.

* So, to minimize this bias current,

due to this current the offset voltage will occur. So, we need to introduce a new scheme i.e., difference i/p should be 0 i.e.,

$$I_{B1} = I_{B2} (\because V_1 - V_2 = 0) \Rightarrow V_1 = V_2$$

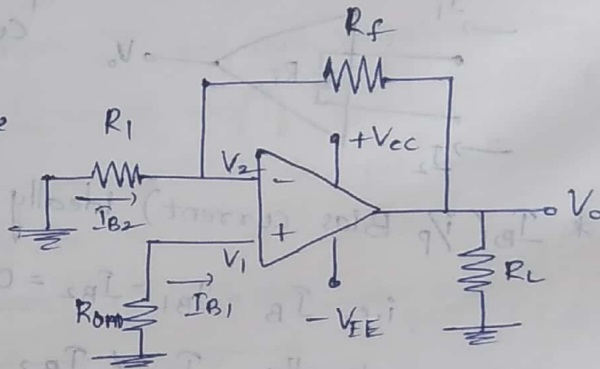
* So, to make difference i_p to '0', we need to introduce one extra resistor at non inverting terminal to make $V_1 = V_2$.

* This resistor is called "offset minimizing resistor" (or) "Compensating resistor".

* By connecting this resistor if $i_p = 0$ then volt (o/p) will be '0'.

Suppose if ' R_f ' is large value, then considering o/p voltage will appear even if i_p is '0' V.

Some non-zero voltage R_{om} = Offset minimizing resistor will appear at o/p.



for ex:- Let us take IC741, having

$I_{B1} = 500 \text{ nA}$ practically ($\because I_{B1} = 0$ ideally)

feedback resistor (R_f) = $2 \text{ M}\Omega$ then the o/p voltage

V_o is, $V_o = 2 \text{ M} \times I_{B1}$ ($\because R_f \times I_{B1}$)

$$= 2 \text{ M} \times 500 \text{ nA}$$

$$\boxed{V_o \approx 1 \text{ V}}$$

Here, without any i/p, o/p is '1V' due to this bias current of op-Amp.

This V_o is called "Offset Voltage" (or) "Error Voltage".

* This '1V' is reduced to '0' by connecting an addition resistor (R_{om}), at the non-inverting terminal from node to ground.

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At 1MHz, the gain is 0dB i.e., '1'

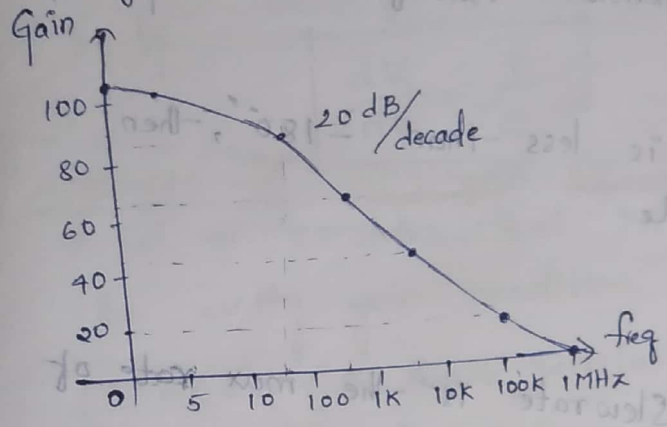
The UGB (Unity Gain Bandwidth) = $1 \times 1\text{MHz} = 1\text{MHz}$.

By using this frequency & gain values, we can plot Magnitude & Phase response.

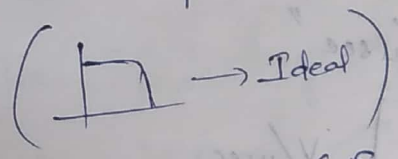
Magnitude Response (freq Vs Gain)
$$1 = \frac{A_{OL}}{\sqrt{1 + \left(\frac{f_{UGB}}{f_0}\right)^2}}$$

as $f_{UGB} \gg f_0$

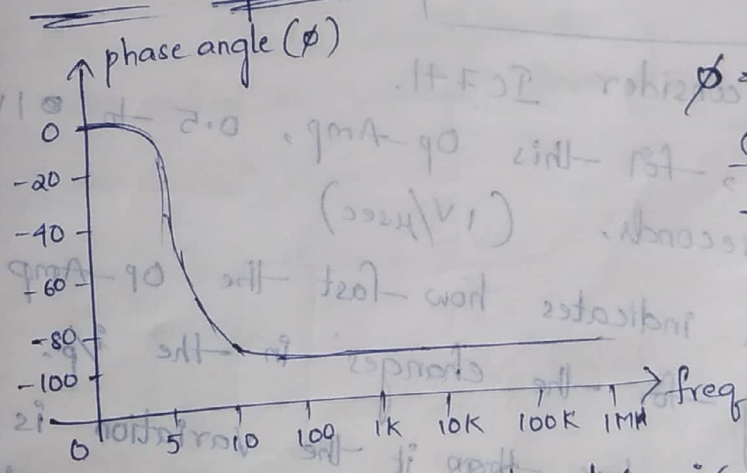
$$\Rightarrow f_{UGB} = f_0 \cdot A_{OL}$$



This is practical response



Phase Response (freq Vs Phase angle)



$$\phi = -\tan^{-1}\left(\frac{f}{f_0}\right)$$

Substitute same freq values.

& plot the response

* The max phase angle b/w i/p & o/p is 90°

So, the o/p lags i/p by 90° .

This is the freq response of Op-Amp.



Imp Stability of Op-Amp:-

* The stable A ckt is said to be stable if the ϕ reaches to a fixed value in a finite time

* For Ex, to get a stable op-Amp, it should have single freq 'fo' (Break (or) Cut-off freq) & "total phase shift never exceed -90° ."

* If these two conditions satisfies then Op-Amp is stable.

* If phase shift is less than -180° , then Op-Amp is unstable

(b) Slewrate:- (SR)

* Mathematically, Slewrate is the max rate of change of ϕ voltage. w.r.to time.

The units of SR is "Volts/ μ sec"

$$SR = \left. \frac{dV_o}{dt} \right|_{\max} \quad V/\mu\text{sec}$$

* Let us consider IC 741.

Practically, for this Op-Amp, 0.5 to 1V per microseconds. ($1V/\mu\text{sec}$)

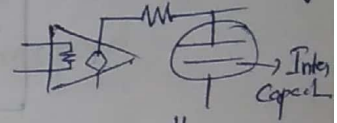
* Generally SR indicates how fast the Op-Amp is responding for the changes in the i/p.

* Within $1\mu\text{sec}$, less than if the variation is 1V, then the Op-Amp is said to be responding.

* If the variation is ^{more than} $1V/\mu\text{sec}$, then Op-Amp will not respond.

* For LH0063C Op-Amp, if the variation is less than $6000\text{V}/\mu\text{sec}$ then Op-Amp will respond.

* The SR occurs because of internal compensating capacitor.



* The internal capacitor prevents the o/p voltage from responding immediately due to fast change in i/p.

$$\frac{dV_c}{dt} = \frac{I}{C}$$

Slewrate for unity gain Op-Amp:-

* Let us consider that SR is calculated under the unity gain condition. & i/p is sinusoidal.

($\because R_f = 0$ (feedback resistance) $\rightarrow$ for unity f/b)

$$A_f = \left(1 + \frac{R_f}{R_i}\right) = 1 + \frac{0}{R_i} = 1$$

(The o/p voltage is replica of i/p voltage.)

$V_{in} = V_p \sin \omega t$ $\rightarrow$ It is a voltage follower i.e. unity gain Op-Amp. (o/p follows i/p).

(Common Collector Amplifier is also called as Voltage follower)

$$\Rightarrow V_o = V_{in}$$

$$\text{Slewrate } \frac{dV_o}{dt} = \frac{dV_{in}}{dt}$$

$$= \frac{d}{dt} V_p \sin \omega t$$

$$= V_p \cdot \omega \cos \omega t$$

$$\therefore \left. \frac{dV_o}{dt} \right|_{\text{Max}} = V_p (2\pi f) (1)$$

(Max Value occurs at '0'.
i.e., $\cos \omega(0) = 1$
($\because \omega = 2\pi f$)

$$\boxed{SR = \frac{2\pi f V_p}{10^6} \text{ V}/\mu\text{sec}} \rightarrow \text{Slewrate under unity gain condition.}$$

Slewrate for non-unity gain Op-Amp:-

* If Op-Amp has non-unity gain i.e, $A > 1$

then

$$SR = \frac{2\pi f V_p \cdot A}{10^6} \text{ V}/\mu\text{sec}$$

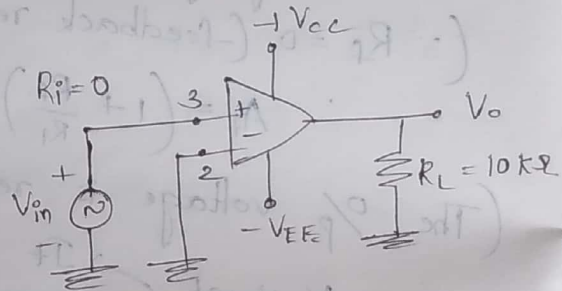
Conclusion:-

* To prevent distortion in the o/p, the i/p signal should not have very large freq for a given peak value V_p .

* Otherwise, the s/p should not have very large peak value V_p for a given freq 'f'.

Example:-

What is the max^{i/p} freq for a given peak voltage V_p to remove distortion in the o/p?



Sol:- This Ckt is Open-loop Configuration

(∵ there is no feedback).

I/p is sinusoidal wave form, & o/p is square wave.

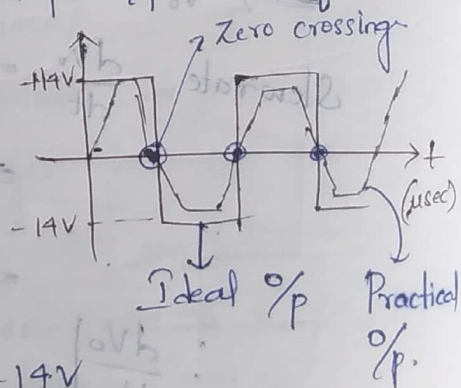
Let us take Op-Amp IC741

for which SR is $0.5 \text{ V}/\mu\text{sec}$

But at every zero crossing it has to from $+14\text{V}$ to -14V

& -14V to $+14\text{V}$.

∴ The total voltage (peak to peak) is '28 volts'.



$$\frac{\Delta V_p \text{ (Peak to Peak)}}{\text{Time}} = \text{SR.}$$

$$T = \frac{28}{0.5} = 56 \mu\text{sec} \quad \left(\because \frac{V}{V/\mu\text{sec}} = \mu\text{sec} \right)$$

∴ Within 56 μsec, the Op-Amp will respond.

$$\therefore f = \frac{1}{T} = \frac{1}{56 \mu\text{sec}}$$

$$f_{\text{max}} = \frac{1}{2 \times 56 \mu\text{sec}} = 8.93 \times 10^3 = 8.93 \text{ KHz.}$$

∴ The % is distorted at $f_{\text{max}} = 8.93 \text{ KHz.}$

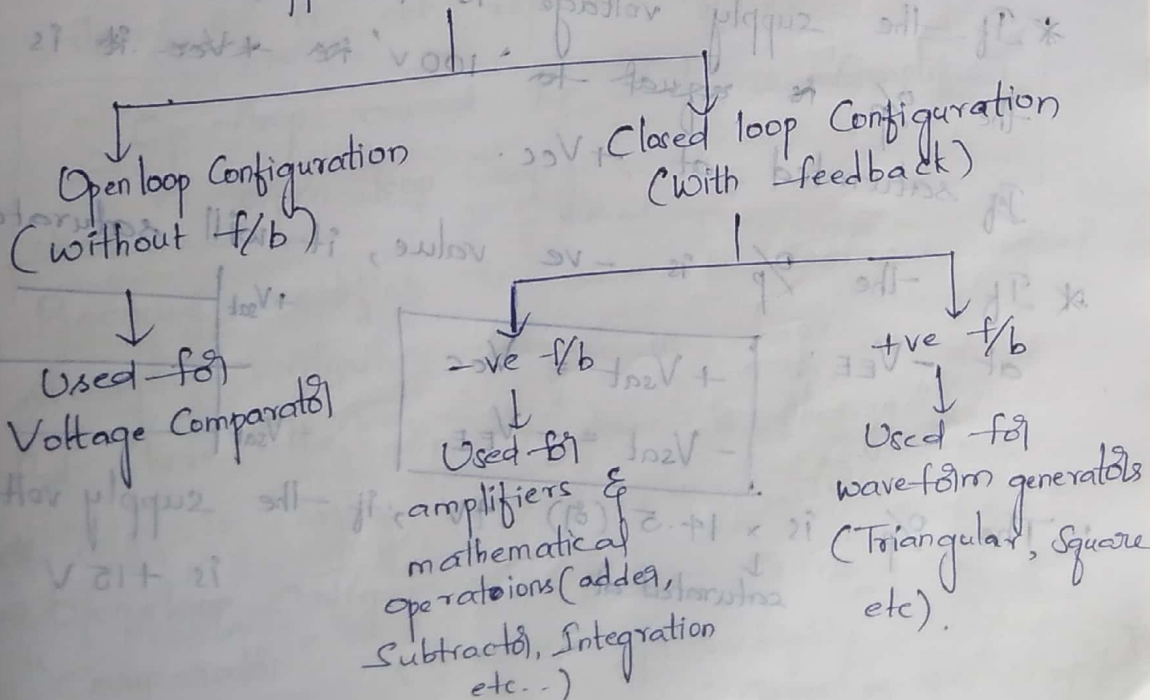
So, to get a perfect square % we need to use Op-Amp with high slewrate (SR).
% signal should have less freq.
i.e., % freq should be less than $f_{\text{max}}.$

for the given peak voltage.

PART-II

Op-Amp Applications

Applications of Op-Amp

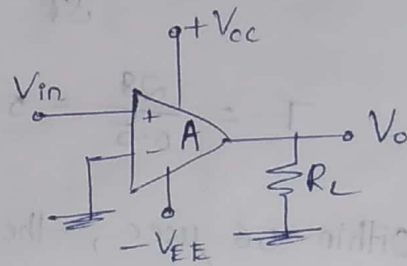


Op-Amps in Open loop Configuration:— (Without f/b).

A = Open loop gain in Op-Amp

for IC741, Op-Amp,

$$A = 10^5 \text{ (or)} 10^6$$

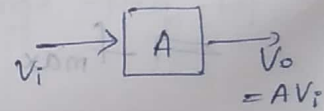


If the $\frac{1}{p}$ V_{in} is +ve or at non-inverting terminal, i.e., $V_{in} = +1 \text{ mV (dc)}$, then $\frac{0}{p}$ is.

$$V_o = AV_i$$

$$= 10^5 \times 1 \times 10^{-3} = 10^2 = 100 \text{ V}$$

$$\therefore V_o = 100 \text{ V}$$



For 1 mV $\frac{1}{p}$, we got 100 V $\frac{0}{p}$.

* The ~~ckt~~ V_o cannot

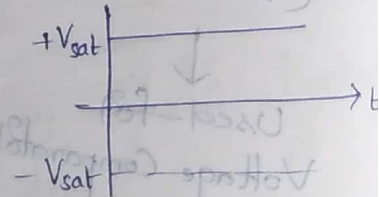
* The $\frac{0}{p}$ voltage (V_o) of ckt cannot exceed the max dc supply voltage.

Here, the dc voltage is available (or) applied to the ckt. Therefore instead of this 100 V , the $\frac{0}{p}$ will be saturated at $+V_{sat}$ with slightly low value.

* If the supply voltage is $+15 \text{ V}$ (or) -15 V then the $\frac{0}{p}$ is equal to 100 V ~~or~~ ~~it is~~ saturated at $+V_{cc}$.

* If the $\frac{0}{p}$ is -ve value, it will saturate at $-V_{EE}$.

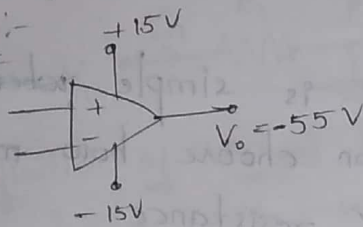
$$\begin{aligned} +V_{sat} &= V_{cc} \\ -V_{sat} &= -V_{EE} \end{aligned}$$



The $\frac{0}{p}$ is $\times 14.5$ (or) 14 V , if the supply voltage is $+15 \text{ V}$.
↓
saturated at

If the supply voltage is $+12V$, then the saturated $\%p$ will be 10.5 (or) $11V$.
 * $\%p$ of a ckt doesn't exceed the supply voltage

Eg:-



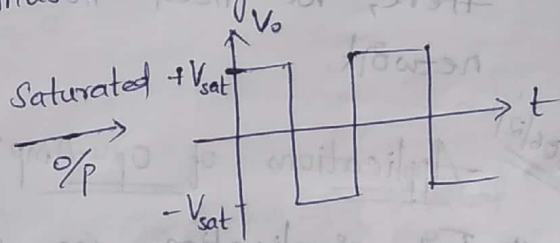
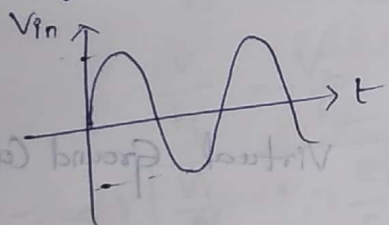
Then, the $\%p$ value is saturated

- at — ?
 (A) $-55V$ (B) $+55V$
 (C) $-15V$ (D) None of these

Sol:- Whatever the $\%p$ voltage, the $\%p$ voltage never exceeds the supply voltage, i.e., $+15V$ (or) $-15V$.
 Here, $\%p$ is $-ve$ value, therefore $\%p$ is saturated at $-V_{EE}$, i.e., $-15V$

Ans:- (C)

* If the i/p is sinusoidal signal,



Here, $\%p$ is not replica of i/p .

$\therefore$ Op-Amp cannot be used as Amplifier.
 in Open loop Configuration.

Because amplifier is used to increase signal strength without change in shape.
 But here, the $\%p$ shape is changed.
 This is highly distorted wave form.

$\Rightarrow$ Open-loop Configuration Op-Amp is used as "Comparator". (Because $\%p$ is highly distorted $\therefore$ cannot be used as Amplifier)

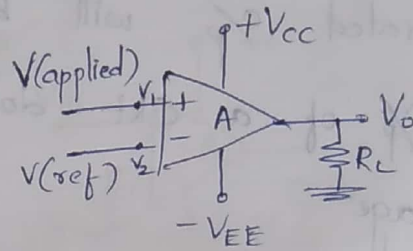
* Comparator compares two voltages

Here, the o/p voltage

$$V_o = A V_{id}$$

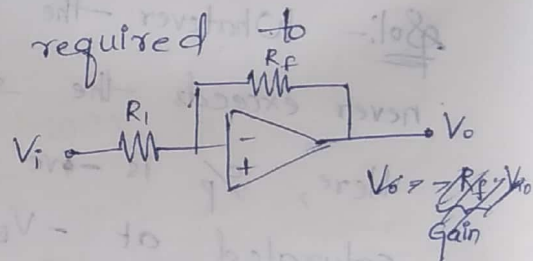
V_{id} - difference i/p voltage

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



* Construction of Amplifier is simple with the Op-Amp. We can choose how much gain required & also i/p resistance.

* Only two resistors are required to design an amplifier.



$$V_o = - \underbrace{\frac{R_f}{R_i}}_{\text{Gain}} \cdot V_i$$

Here, we need not to worry about biasing network.

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Applications of Op-Amp:-

* For simplification, we use Virtual Ground Concept.

Virtual Ground:-

* This name indicates 'not real ground'. It is just an imagination.

* For some purpose, we consider that it is equal to ground.

* Virtual ground indicates voltage at particular node is almost equal to 0V. It is not physically connected to ground.

* At one particular terminal of Op-Amp, the voltage is almost 0V without physically connected.

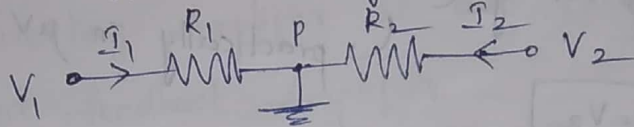
to ground.

* It is useful in the analysis of Op-Amp

* It makes calculations very simple.

* Why we need Virtual Ground:-

* It is applicable only for -ve feedback.



Definition of Virtual Ground:- The technique of making voltage at node 'P' is equivalent to zero without connecting it to any physical ground.

Apply KCL at node 'P',

$$I_1 + I_2 = 0$$

$$\frac{V_1 - V_P}{R_1} + \frac{V_2 - V_P}{R_2} = 0$$

Due to Virtual Ground, $V_P = 0$

$$\frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} = 0$$

$$\frac{V_1}{R_1} = -\frac{V_2}{R_2}$$

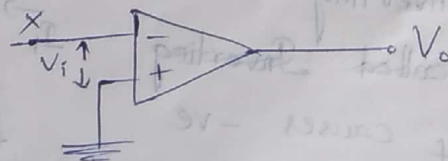
$$\Rightarrow \boxed{\frac{V_1}{V_2} = -\frac{R_1}{R_2}}$$

$\Rightarrow$ Condition for Virtual Ground

* If this condition satisfies, then we can say that voltage at that node is '0'.

Consider Ideal Op-Amp with inverting & non-inverting terminal. (One of the terminal is physically grounded)

$V_x = 0$ ($\because$ Virtual Ground)



Gain of Op-Amp,

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

* An ideal Op-Amp has infinite gain.

$$\therefore \text{The i/p voltage } (V_i) = \frac{V_o}{A} = \frac{V_o}{\infty} = 0.$$

This result ' $V_i = 0$ ' indicates that there is a short ckt b/w two terminals.

$$\text{Difference i/p Voltage } (V_{id}) = V_1 - V_2 \approx 0$$

(practically in μV .)

$$\Rightarrow \boxed{V_1 = V_2}$$

* If there is short ckt b/w two terminals, then i/p $V_i = 0$ (but no real short ckt exists).

* Since one of the terminal is physically grounded & virtual short becomes Virtual Ground.

$$\Rightarrow \boxed{V_x = 0}$$

$\therefore X$ is called as Virtual Ground.

Applications of closed loop Configurations Op-Amp
-ve feedback:-

* Two types of Amplifiers

(i) Inverting Amplifier

(ii) Non-Inverting Amplifier.

(i) Inverting Amplifier:-

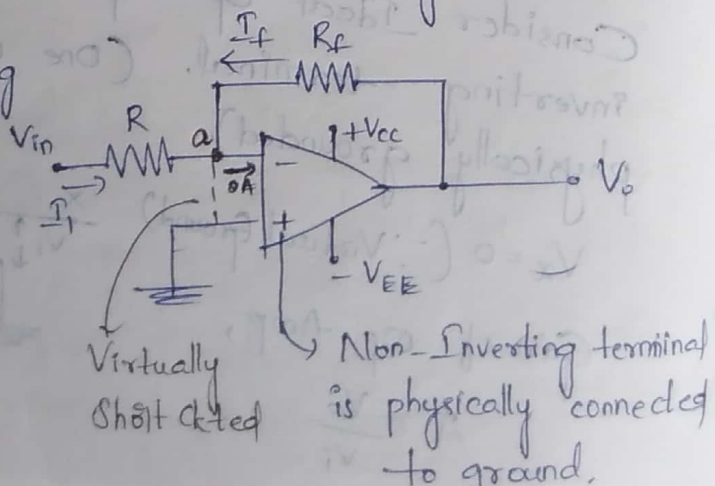
* This Amplifier provides 180° phase shift b/w i/p & o/p.

* i/p signal is connected at Inverting terminal.

* The o/p is returning to inverting terminal

is called Inverting

* R_f causes -ve feedback.



* The feedback component is ' R_f '.

* The feedback component is directly connected to ϕ/p node $\Rightarrow$ It is Voltage Sample.

* The feedback component is directly connected to ϕ/p node $\Rightarrow$ Shunt Mixing.

$\therefore$ Inverting Amplifier is also called as Voltage Shunt feedback Amplifier.

* When ϕ/p voltage is connected to Inverting terminal of Op-Amp then ϕ/p current ' I_1 ' starts flowing into Op-Amp (Ideally Op-Amp).

* Due to this high ϕ/p resistance, this ' I_1 ' current is completely flows into feedback component.

* The point 'a' is virtual Ground potential.

$\therefore$ The current ' I_1 ' will not flow into Op-Amp. It will flow through the R_f w.r. to virtual Ground point 'a'.

* Due to Virtual Ground concept, $V_a = 0$.

R_f causes -ve feedback.

Both inverting & non-inverting terminal are virtually short cktd.

* Since short cktd $\Rightarrow V_1 = V_2 = 0$

(Approximately inverting terminal is equal to non-inverting terminal).

* Zero Current flows into Inverting & Non-inverting terminal of Op-Amp.

* Apply KCL at node 'a'.

$$I_1 + I_f = 0$$

$$I_1 = \frac{V_{in} - V_a}{R}$$

$$I_f = \frac{V_o - V_a}{R_f}$$

Due to Virtual Ground Concept,

$$V_a = 0 \implies I_1 = \frac{V_{in}}{R}, \quad I_f = \frac{V_o}{R_f}$$

$$\implies \frac{V_{in}}{R} + \frac{V_o}{R_f} = 0$$

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

$$V_o = \ominus V_{in} \cdot \frac{R_f}{R} \implies \text{op expression for Inverting Amplifier.}$$

Indicates
-ve phase shift
b/w i/p & o/p.

* For Inv - Amplifier, closed loop gain,

$$A = -\frac{R_f}{R}$$

$$\left(\because A = \frac{V_o}{V_i} \implies V_o = A V_i \right)$$

* This is the voltage shunt feedback Amplifier.

i/p $\Rightarrow$ Shunt Mixing

$\therefore$ i/p resistance is decreased.

o/p $\Rightarrow$ Voltage Sample.

$\therefore$ o/p resistance is decreased.

(ii) Non-Inverting Amplifier:-

* The op doesn't have any phase shift

* Without any phase shift, i/p signal can be amplified

* The i/p signal is applied to non-inverting terminal.

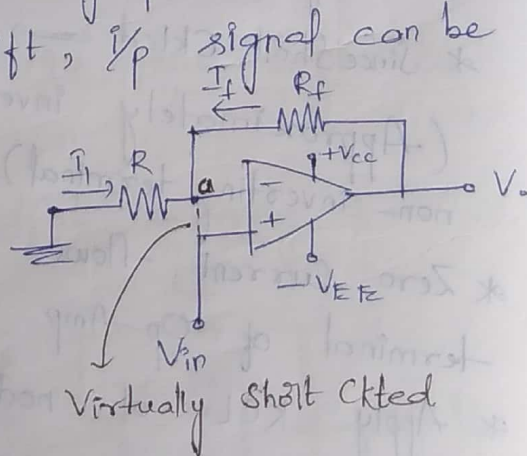
* R_f causes -ve f/b.

* The ' R_f ' is directly

connected to o/p $\Rightarrow$ Voltage Sample

* ' R_f ' is not directly connected to i/p

$\Rightarrow$ Series Mixing.



* The Non-inverting Amplifier is also called as Voltage series feedback Amplifier.

* Due to Virtual Ground Concept,

$$V_a = V_{in} \quad \left(\because \text{Inv \& Non-Inv are virtually s.c} \right)$$

Apply KCL at node 'a'.

$$I_1 + I_f = 0$$

$$I_1 = \frac{0 - V_a}{R} = -\frac{V_{in}}{R} \quad \left(\because V_a = V_{in} \right)$$

$$I_f = \frac{V_o - V_a}{R_f} = \frac{V_o - V_{in}}{R_f}$$

$$\Rightarrow -\frac{V_{in}}{R} + \frac{V_o - V_{in}}{R_f} = 0$$

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

$$V_o - V_{in} = \frac{V_{in} \cdot R_f}{R}$$

$$V_o = V_{in} \cdot \frac{R_f}{R} + V_{in}$$

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

% Expression for Non-Inv Amplifier.
(No phase shift).

Closed loop gain of Non-Inv Amp is,

$$A = 1 + \frac{R_f}{R}$$

$$\left(\because V_o = A V_{in} \right)$$

* This is Voltage series Mixing Amplifier.

% $\Rightarrow$ Series Mixing

$\therefore$ % resistance increases.

% $\Rightarrow$ Voltage Sample

$\therefore$ % resistance decreases.

25/06/21 Applications of Op-Amp:-

* Inverting Amplifier (180° phase shift b/w i/p & o/p).

$$\text{Closed loop gain } (A_{CF}) = \frac{-R_f}{R}$$

* Non-Inverting Amplifier (No phase shift)

$$\text{Closed loop gain } (A_{CF}) = \left(1 + \frac{R_f}{R}\right)$$

The o/p exp for Inv-Amplifier

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

The o/p exp for Non-Inv Amplifier

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

Summing Amplifier:-

(a) Inverting Configuration:-

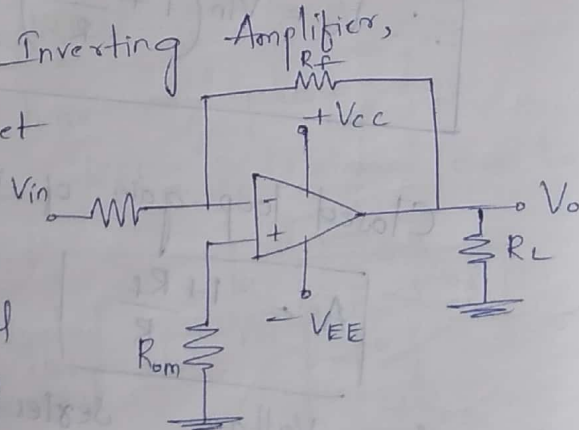
* Here, ^(summing) we attach more than one i/p signal.
But in inverting Amplifier we attach only one i/p signal.

First we draw Inverting Amplifier,

* To make o/p offset voltage zero, we

use extra resistor at Non-Inv terminal

i.e., 'offset minimizing resistor (R_{om})'



* Summing Amplifier is inverting amplifier with more than one i/p.

* If we attach more than one i/p at Inv-terminal

* Suppose 3 i/p's are applied at same Inv-terminal i.e., V_a, V_b & V_c

* Because of these 3 i/p's, 3 i/p voltages are added.

* Due to these 3 voltages, the currents I_a, I_b & I_c flows through corresponding resistors R_a, R_b & R_c .

* Ideal Op-Amp has high i/p impedance. Due to this high i/p resistances, the i/p currents I_a, I_b & I_c flows through the f/b path only.

* The Voltage at x (V_x) = 0. ($\therefore$ Virtual Ground Concept)

Apply KCL at node x ,

$$I = I_f + I_b$$

where, $I = I_a + I_b + I_c$

$$I = \frac{V_a - V_x}{R_a} + \frac{V_b - V_x}{R_b} + \frac{V_c - V_x}{R_c}$$

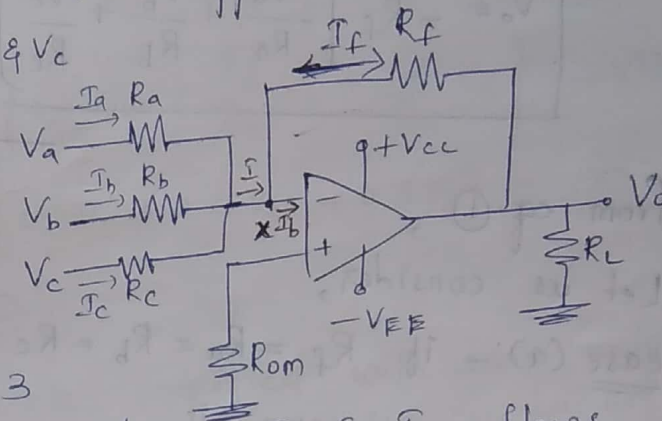
$$I = \frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} \quad (\because V_x = 0)$$

$$\frac{I_f}{R_f} = \frac{V_x - V_o}{R_f} \Rightarrow I_f = \frac{-V_o}{R_f} \quad (\because V_x = 0)$$

Let us consider $I_b \approx 0$ due to high i/p resistance of Op-Amp.

$$\therefore I = I_f$$

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} = \frac{-V_o}{R_f}$$



$$V_o = -R_f \left[\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} \right] \rightarrow \text{Summing Amplifier}$$

①

from eq. ①,

Let us consider,

case (a):- if $R_f = R_a = R_b = R_c = R$, then

the o/p expression is,

$$V_o = - [V_a + V_b + V_c] \rightarrow \text{Summer}$$

180° phase shift

All the i/p signals are added.

Case (b):- if $R_a = R_b = R_c = R$ & R_f is different value i.e., $R_f = \frac{1}{3} R$, then the o/p is

$$V_o = - \frac{R_f}{R} [V_a + V_b + V_c]$$

$$V_o = - \frac{1}{3} [V_a + V_b + V_c] \rightarrow \text{"Averaging ckt"}$$

Case (c):- The o/p expression,

$$V_o = - \left[\frac{R_f}{R_a} V_a + \frac{R_f}{R_b} V_b + \frac{R_f}{R_c} V_c \right] \rightarrow \text{"Summing Amplifier"}$$

This is also called as "Scaling (or) weighted Amplifier". Because at every i/p signal, amplification is done by some different weightage factor.

Ex:- (for Summing Amplifier)

① In the ^{above} ckt. shown, the o/p expression $V_o = - (0.1V_1 + 0.2V_2 + 0.3V_3)$, then find the

values of R_a, R_b, R_c, R_f & R_{om} .

Sol:- % expression of Summing Amplifier

$$\text{is } V_o = - \left[\frac{R_f}{R_a} V_a + \frac{R_f}{R_b} V_b + \frac{R_f}{R_c} V_c \right] \rightarrow \textcircled{1}$$

$$\text{Given, } V_o = - [0.1 V_1 + 0.2 V_2 + 0.3 V_3] \rightarrow \textcircled{2}$$

Comparing $\textcircled{1}$ & $\textcircled{2}$,

Every V_p signal is amplified with some weightage factor.
Choose $R_f = 10 \text{ K}\Omega$ (We can choose any value)

$$A_1 = \frac{R_f}{R_a}$$

$$0.1 = \frac{R_f}{R_a}$$

$$0.1 = \frac{10 \text{ K}}{R_a}$$

$$\Rightarrow R_a = 100 \text{ K}\Omega$$

$$A_2 = \frac{R_f}{R_b}$$

$$0.2 = \frac{R_f}{R_b}$$

$$0.2 = \frac{10 \text{ K}}{R_b}$$

$$\Rightarrow R_b = 50 \text{ K}\Omega$$

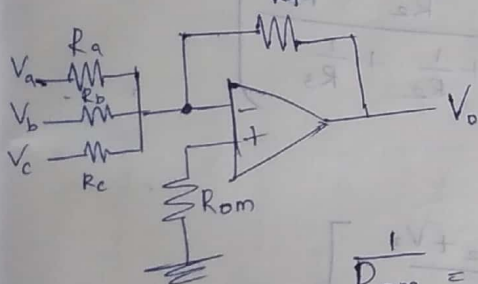
$$A_3 = \frac{R_f}{R_c}$$

$$0.3 = \frac{R_f}{R_c}$$

$$0.3 = \frac{10 \text{ K}}{R_c}$$

$$\Rightarrow R_c = 33.33 \text{ K}\Omega$$

Offset Minimizing Voltage (R_{om}) = $R_a \parallel R_b \parallel R_c \parallel R_f$
Resistance



($\therefore$ All resistors are connected at inverting terminal parallel to each other)

$$\frac{1}{R_{om}} = \frac{1}{100 \text{ K}} + \frac{1}{50 \text{ K}} + \frac{1}{33.33 \text{ K}} + \frac{1}{10 \text{ K}}$$

$$\frac{1}{R_{om}} = 1.6 \times 10^{-4}$$

$$\Rightarrow R_{om} = \frac{1}{1.6 \times 10^{-4}} = 6.25 \text{ K}\Omega$$

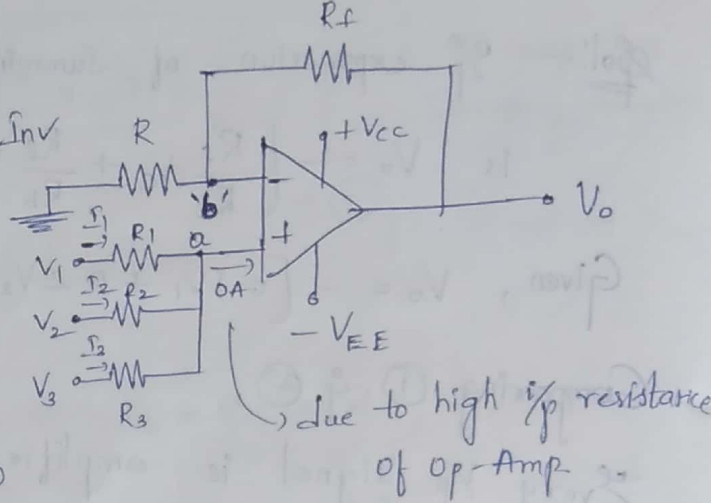
$$\therefore R_{om} = 6.25 \text{ K}\Omega$$

(b) Non-Inverting Configuration:-

The V_p signal is applied at Non-Inv terminal.

* Three i/p 's are applied at Non-Inv terminal

* Here, at Non-Inv terminal.



$$I_1 + I_2 + I_3 = 0$$

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} = 0$$

$$V_a = \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

(The i/p exp for Non-Inv Amplifier)
is $V_o = \left(1 + \frac{R_f}{R}\right) V_a$

$$\Rightarrow V_o = \left(1 + \frac{R_f}{R}\right) \left[\frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \right]$$

If $R_1 = R_2 = R_3 = R = \frac{R_f}{2}$

$$V_o = \left(1 + \frac{2R}{R}\right) \left[\frac{\frac{V_1 + V_2 + V_3}{R}}{\frac{3}{R}} \right]$$

$$V_o = (1+2) \left[\frac{V_1 + V_2 + V_3}{3} \right] = V_1 + V_2 + V_3$$

$$\boxed{V_o = V_1 + V_2 + V_3} \quad (\text{No phase shift})$$

This is the "perfect summer".

* Due to Virtual Ground Concept,

We can say that $V_a = V_b$

$\therefore$ If we find any one voltage, we can find other.

26/06/21

Difference Amplifier:- (Subtractor)

* It is also called a Subtractor.

* It is used to subtract the 2 i/p voltages given to the Op-Amp. Ckt

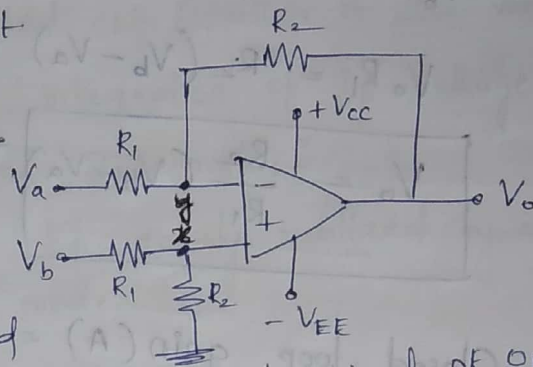
V_a & $V_b \rightarrow$ i/p's

$V_o \rightarrow$ o/p

R_1 & $R_2 \rightarrow$ i/p

resistances connected

to ~~i/p~~ inv & non-inv terminal of Op-Amp



* Find V_a & V_b then equate V_a & V_b to find V_o

$$\Rightarrow V_a = V_b \quad (\because \text{Virtual Ground})$$

By using Voltage division rule, at node 'X',

$$V_x = V_b \times \frac{R_2}{R_1 + R_2} \quad \text{--- (1)}$$

By using Superposition principle, ($\because$ Two voltages are there V_a & V_o)

(i) V_o is grounded,

$$V_{y1} = V_a \times \frac{R_2}{R_1 + R_2}$$

(ii) V_a is grounded,

$$V_{y2} = V_o \times \frac{R_1}{R_1 + R_2}$$

$$\therefore V_y = V_{y1} + V_{y2}$$

$$V_y = \frac{V_a R_2}{R_1 + R_2} + \frac{V_o R_1}{R_1 + R_2}$$

$$V_y = \frac{V_a R_2 + V_o R_1}{R_1 + R_2} \quad \text{--- (2)}$$

As Inv & Non-Inv terminal are virtually short ckted ($\because$ Virtual Ground Concept)

$$\Rightarrow V_x = V_y$$

$$\frac{V_b \cdot R_2}{R_1 + R_2} = \frac{V_a R_2 + V_o R_1}{R_1 + R_2}$$

$$V_b \cdot R_2 = V_a R_2 + V_o R_1$$

$$V_o R_1 = R_2 (V_b - V_a)$$

$$\boxed{V_o = \frac{R_2}{R_1} (V_b - V_a)} \Rightarrow \text{o/p expression of Subtractor}$$

$$\text{Closed loop gain (A)} = \frac{R_2}{R_1}$$

* If ~~$R_f = R$~~ , V_b is not connected, - then the ckt is Inv - Amplifier.

In Inverting mode, the

$$\text{o/p } (V_o) = -\frac{R_f}{R} (V_a) \rightarrow \textcircled{1}$$

In non-Inverting mode, the o/p

$$(V_o) = \left(1 + \frac{R_f}{R}\right) V_x \rightarrow \textcircled{2}$$

If $R_f = R$, then

$$\text{from } \textcircled{1}, V_o = -\frac{R}{R} (V_a) \Rightarrow V_o = -V_a$$

$$\text{from } \textcircled{2}, V_o = \left(1 + \frac{R}{R}\right) V_x \Rightarrow V_o = 2V_x = \frac{2V_b}{2} = V_b$$

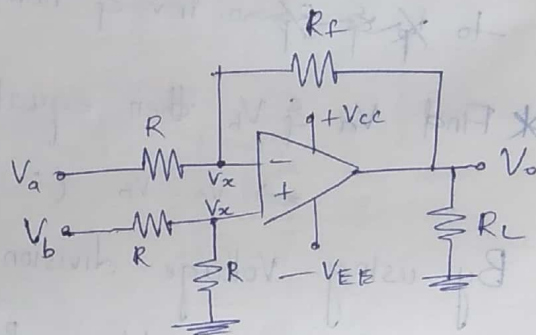
(By voltage division rule,

$$V_x = V_b \times \frac{R}{R+R} = \frac{V_b \times R}{2R} = \frac{V_b}{2})$$

$$\Rightarrow V_o = -V_a \quad \& \quad V_o = V_b$$

perfect

$$\boxed{V_o = V_b - V_a} \Rightarrow \text{Subtractor. (if } R_f = R)$$



The Integrator:— (Integration Amplifier)

* Integrator is used in Analog computer

* It is also called "Integration Amplifier".

Let us take integrated ckt (similar to Inv-Amplifier ckt).

* If the o/p voltage is integration of i/p voltage then

the amplifier is called "Integrator".

* This Integrator can be easily realized by using Op-Amp in inverting mode.

* Replace ' R_f ' by a capacitor

first, we take

Inverting Amplifier.

Principle of Capacitor:—

* The voltage developed across capacitor & charging current relation is

$$i = C \frac{dv}{dt}$$

Charging current (i) gives rate of change of voltage. when capacitor is charged.

∴ The feedback current,

$$I_f = C_f \cdot \frac{d(V_o - V_x)}{dt}$$

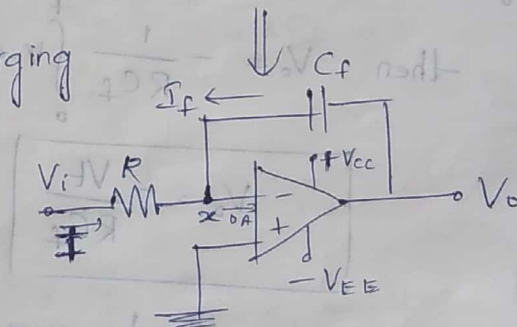
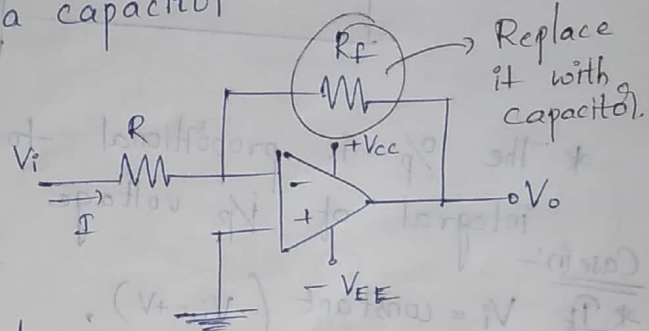
Due to Virtual Ground concept, $V_x = 0$

(∵ Non-Inv terminal is physically grounded)

$$\Rightarrow I_f = C_f \cdot \frac{dV_o}{dt}$$

∴ The i/p current,

$$I = \frac{V_i - V_x}{R} = \frac{V_i}{R} \quad (\because V_x = 0)$$



KCL at node 'x',

$$I_f + I = 0$$

$$C_f \frac{dV_o}{dt} + \frac{V_i}{R} = 0 \Rightarrow \frac{dV_o}{dt} = -\frac{V_i}{RC_f}$$

Integrating on both sides,

$$\int \frac{dV_o}{dt} \cdot dt = -\frac{1}{RC_f} \int V_i \cdot dt + C_1$$

Let $C_1 = 0$,

$$V_o = -\frac{1}{RC_f} \int V_i \cdot dt$$

Integral constant which indicates initial voltage of capacitor ($t=0$)

o/p exp of Integration Amplifier.

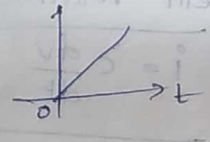
* The o/p is proportional to integral of i/p voltage ($\because RC_f$ is Time Constant)

Case (i):

* If $V_i = \text{constant } (V_i = +V)$,

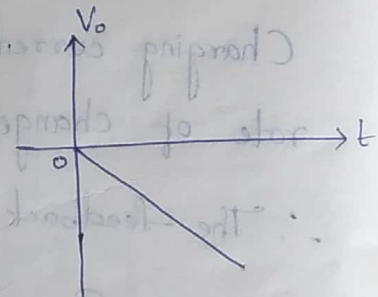
$$\text{then } V_o = -\frac{1}{RC_f} \int V \cdot dt = -\frac{V}{RC_f} [t]$$

$$\therefore V_o = -\frac{Vt}{RC_f}$$



$\therefore$ The o/p will be ramp signal.

where $-\frac{V}{RC_f}$ is slope (-ve slope)

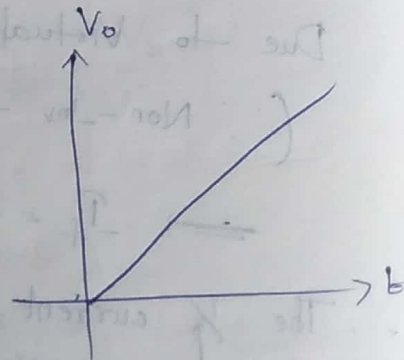


* If $V_i = -V$,

$$\text{then } V_o = -\frac{1}{RC_f} \int (-V) \cdot dt$$

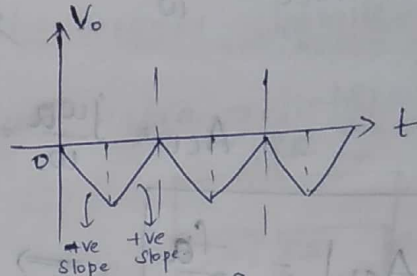
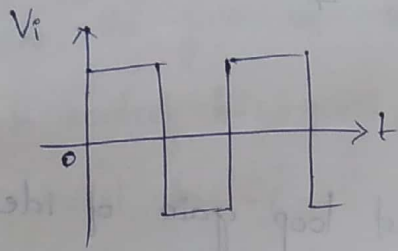
$$\therefore V_o = \frac{Vt}{RC_f}$$

$\therefore$ Slope is +ve ($\frac{V}{RC_f}$)



Case (ii):

* If i/p is a square wave, then the o/p is ramp signal



($\therefore$ for +ve $i/p \Rightarrow o/p$ is -ve
-ve $i/p \Rightarrow o/p$ is +ve)

Case (iii):

If i/p is sinusoidal wave, $V_i = a_0 \sin \omega t$, then $V_o = -\frac{1}{RC_f} \int_0^t a_0 \sin \omega t \cdot dt$

$$V_o = \frac{a_0}{\omega RC_f} [\cos(\omega t) - \cos(0)]$$

$$V_o = -\frac{a_0}{\omega RC_f} \cos \omega t$$

* The o/p depends on freq.

Gain of Integrator:-

$$* \text{Closed loop gain } (A_{CL}) = \frac{V_o}{V_i}$$

* Integrator is same as inverting amplifier but R_f (feedback resistor) is replaced with C_f (Capacitor).

$$\text{Closed loop gain of Inv-Amp} = -\frac{R_f}{R}$$

$$\therefore \text{Closed loop gain of Integrator } (A_{CL}) = \frac{V_o}{V_i} = -\frac{Z_f}{R}$$

$$= -\frac{X_f}{R} = -\frac{1}{\omega RC_f}$$

$$A_{CL} = -\frac{1}{j\omega RC_f} \quad (\because s = j\omega)$$

$$= \frac{j}{\omega RC_f}$$

RC is Time Constant

Replace $\frac{1}{RC_f}$ by ω_b



$$A_{cl} = \frac{j\omega a}{\omega} = \frac{j2\pi f a}{2\pi f} = \frac{jfa}{f}$$

$$\therefore A_{cl} = \frac{j\omega a}{\omega} = \frac{jfa}{f}$$

$$\boxed{|A_{cl}| = \frac{fa}{f}} \Rightarrow \text{Closed loop gain of ideal integrated ckt}$$

Suppose applied freq 'f' is 0, then

$$\Rightarrow |A_{cl}| = \infty$$

If $f_a = f$, (i.e. applied freq 'f' becomes ' f_b ')
 then $|A_{cl}| = \frac{fa}{fa} = 1$

$$\Rightarrow |A_{cl}| = 1 \text{ (Unity) i.e., 0dB}$$

$\therefore f_b$ is called unity gain freq of integrator.

* At which freq the gain becomes unity, then that freq is called unity gain freq.

$$\therefore f_a = \frac{1}{2\pi RC_f}$$

$$\left(\begin{aligned} \therefore \omega_b &= \frac{1}{RC_f} \\ \therefore 2\pi f_a &= \frac{1}{RC_f} \\ \Rightarrow f_a &= \frac{1}{2\pi RC_f} \end{aligned} \right)$$

Drawback:-

* The %p can be non-zero %p even though V_i (i/p voltage) is zero because of gain.

That non-zero %p is called instability of the ckt.

$\therefore$ At $f=0$, the %p is unstable.

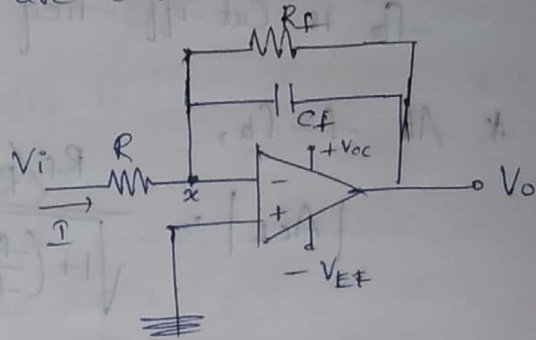
So, this ideal integrated ckt is not practically used.

* At low freq, we can make it stable by adding extra resistor.

* Capacitor is open ckted at low frequencies, so, the gain of the ckt becomes infinite.

* To control this gain, we use extra resistor ' R_f ' parallel to ' C_f '.

This Ckt is called "practical integrated ckt".



* The gain becomes 0dB i.e., unity at $f = f_b$. To maintain gain even at low freq, we have to reduce the gain. So, we use R_f .

* Because of this R_f , we consider another freq ' f_b ' (Gain limiting frequency).

$$f_b = \frac{1}{2\pi R_f C_f}$$

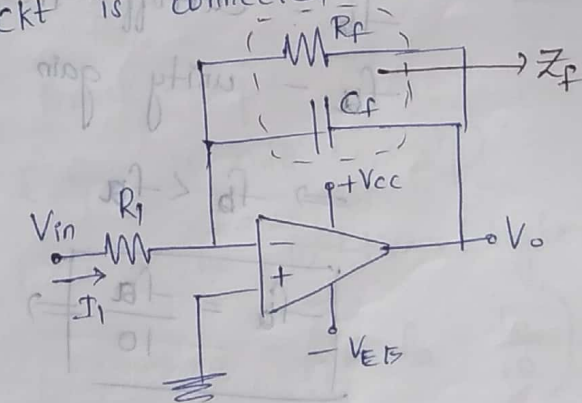
Practical Integrator:-

* The ideal integrated ckt is connected with another resistor ' R_f '.

* Closed loop gain of practical integrator

is,

$$A_{cl} = -\frac{Z_f}{Z}$$



$$Z_f = R_f \parallel \frac{1}{sC_f}$$

$$|A_{cl}| = \frac{R_f/R_1}{\sqrt{1 + \left(\frac{f}{f_b}\right)^2}}$$

Closed loop gain of practical Integrator.

* Even at $f=0$, the gain is finite due to R_f . Therefore, the system is stable at low freq.
 f_b is Cut-off freq (or) Break freq.

* At $f=f_b$,

$$|A_{CL}| = \frac{R_f/R_i}{\sqrt{1 + \left(\frac{f_b}{f}\right)^2}} = \frac{R_f/R_i}{\sqrt{1 + (1)^2}} = \frac{R_f/R_i}{\sqrt{2}}$$

$\therefore$ At $f=f_b$, the gain is constant.

$$|A_{CL}| = \frac{R_f/R_i}{\sqrt{2}}$$

* Up to $f=f_b$, the max gain (or) constant gain.

$$|A_{CL}| \approx \frac{R_f}{R_i}$$

But after f_b , the gain falls at 20 dB/decade

So, practical integrator will act as integrator between f_b & f_a .

f_b - Cutoff freq (or) Break freq

f_a - unity gain freq.

$$\Rightarrow f_b < f_a$$

$$f_b = \frac{f_a}{10}$$

Practically f_b is 10 times less than f_a

$\therefore$ Time period of i/p signal T should be high (or) equal to $R_f C_f$. Then, it acts as a "proper (or) perfect integrated Ckt".

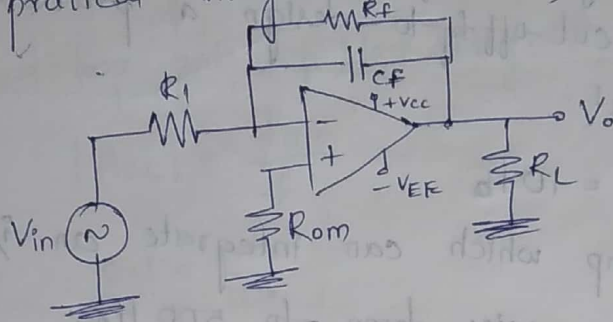
$$\Rightarrow T \geq R_f C_f$$

Applications of Integrated Ckt:-

(a) It is used in Analog computers.

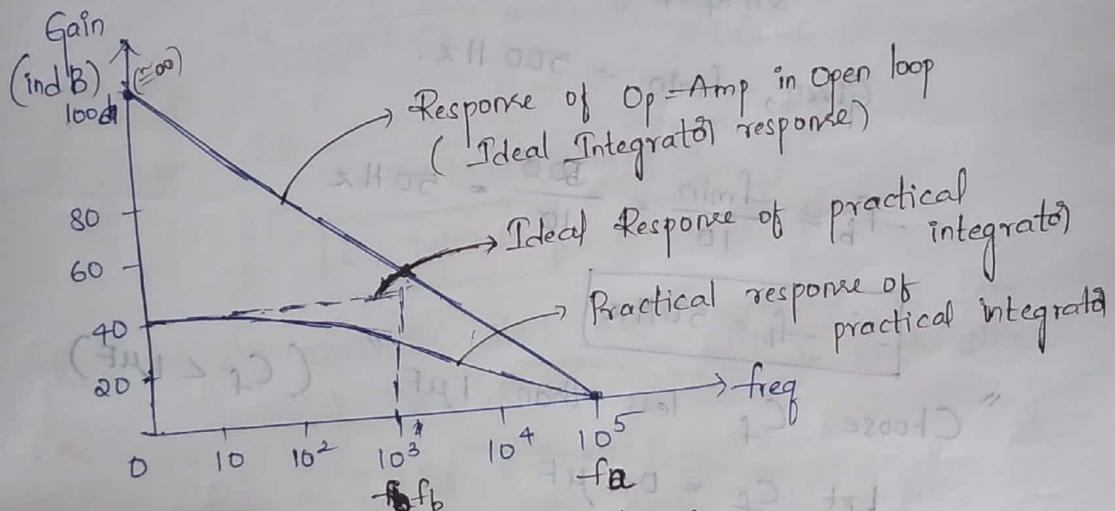
(b) It is used in Analog to digital Converters.

∴ The practical integrated ckt is,



01/07/21

Frequency response of Integrator:-



$f_a \rightarrow$ cut-off freq (or) Break freq

$f_b \rightarrow$ unity gain freq (Gain is 0dB i.e., unity)

* The unity gain freq should be 10 times higher than cut-off freq. $\left(\therefore f_a = \frac{f_b}{10} \right)$

* The i/p signal freq should be 10 times higher than cut-off freq to design practical integrator ckt

$$f_{min} = 10f_b$$

Q). Design a integrator ckt using Op-Amp which can integrate an i/p signal containing frequencies down to 500 Hz. It has a gain of 0.1 at $f = 10\text{kHz}$

Sol:- The i/p signal freq should be 10-times higher-than cut-off freq to design a practical integrator ckt.

$$f_{\min} = 10 f_b$$

Using Op-Amp which can integrate an i/p signal containing frequencies down to 500 Hz.

$$f_b = \frac{1}{2\pi R_f C_f} \Rightarrow \text{Break freq (or) cutoff freq}$$

$$\text{Given, } f_{\min} = 500 \text{ Hz.}$$

$$f_b = \frac{f_{\min}}{10} = \frac{500}{10} = 50 \text{ Hz}$$

$$\therefore f_b = 50 \text{ Hz}$$

"Choose C_f less than $1\mu\text{F}$ " ($C_f < 1\mu\text{F}$)

$$\text{Let } C_f = 0.1\mu\text{F}$$

$$f_b = \frac{1}{2\pi R_f C_f} \Rightarrow R_f = \frac{1}{2\pi f_b C_f} = \frac{1}{2\pi \times 50 \times 0.1\mu}$$

$$R_f = \frac{1}{2\pi \times 50 \times 0.1 \times 10^{-6}} = 31.8 \text{ K}\Omega$$

$$R_f = 31.8 \text{ K}\Omega$$

$$\text{Given, Gain} = 0.1 \text{ at } f = 10\text{kHz}$$

The i/p signal freq is greater than ' f_b ' (Cut-off freq).

We can see in response of integrator ckt i.e, the gain is '1' for $f \geq f_b$.

Here, also $f > f_b \Rightarrow$ Gain is 'unity'.

So, this integrator behaves as ideal integrator.

Closed loop gain of ideal integrator,

$$|A_{CL}| = \frac{f_a}{f}$$

$$0.1 = \frac{f_a}{10K}$$

$$f_a = 1KHz$$

We know,

$$f_a = \frac{1}{2\pi RC_f} \Rightarrow R = \frac{1}{2\pi f_a C_f}$$

$$R = \frac{1}{2\pi \times 1 \times 10^3 \times 0.1 \times 10^{-6}} = 1.5 K\Omega$$

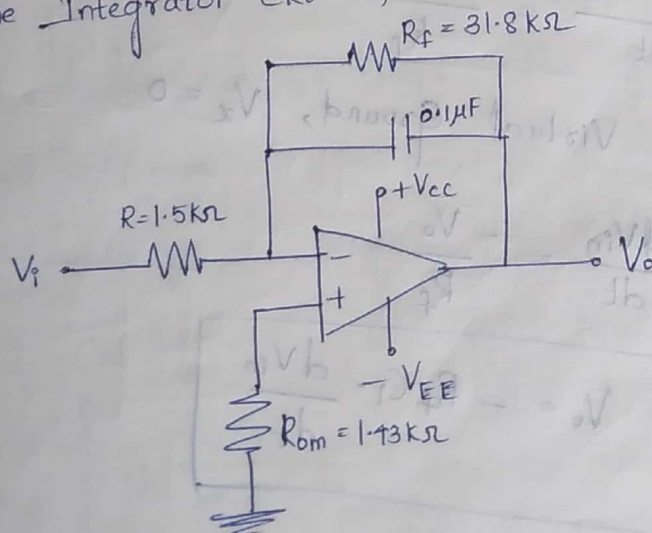
$$R = 1.5 K\Omega$$

R_{om} = All resistors that are connected at In-
terminal which are parallel to each other.

$$R_{om} = R \parallel R_f = 1.5 K \parallel 31.8 K$$

$$R_{om} = 1.43 K\Omega$$

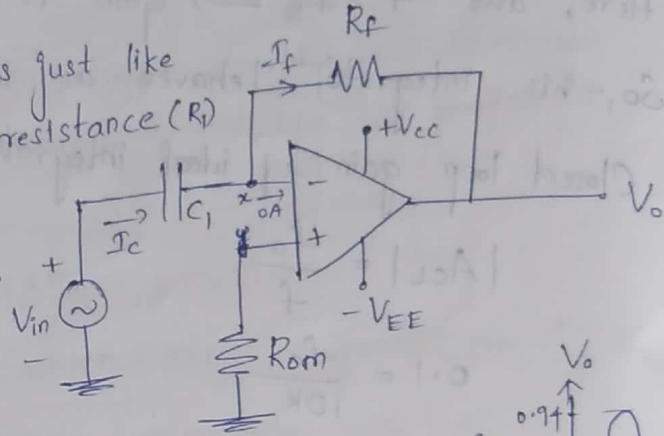
$\therefore$ The Integrator Ckt is,



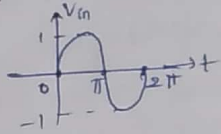
The Differentiator:-

* The o/p waveform is ~~differe~~ derivative of i/p wave form.

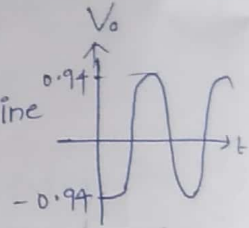
* Differentiator is just like Inv-Amp but i/p resistance (R_i) is replaced with Capacitor (C_i).



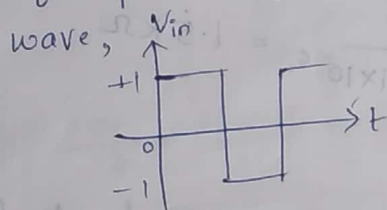
* If i/p is sine wave,



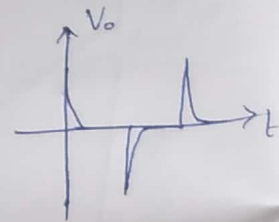
then o/p is cosine



* If i/p is square wave,



then o/p is impulse.



$$V_o = -R_f C_i \frac{dV_{in}}{dt}$$

Proof:-

Here, $I_c = I_f$ ($\because$ KCL at node 'x').

$$C_i \frac{d(V_{in} - V_x)}{dt} = \frac{V_x - V_o}{R_f}$$

Due to Virtual Ground, $V_x = 0$.

$$C_i \frac{dV_{in}}{dt} = -\frac{V_o}{R_f}$$

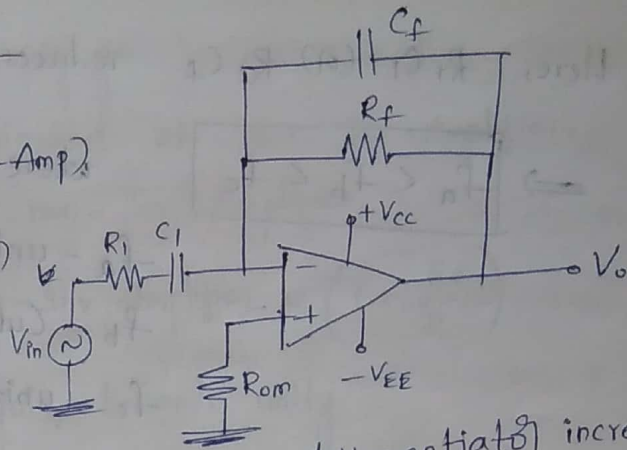
$$\therefore V_o = -R_f C_i \frac{dV_{in}}{dt}$$

Practical Differentiator:-

$$\text{Gain} = -\frac{R_f}{R} \text{ (for Inv-Amp)}$$

Gain of differentiator (ideal)

$$= \frac{R_f}{X_{C_1}}$$



∴ As freq increases, the gain of differentiator increases which makes ckt unstable.

* The ideal differentiator is unstable at high freq.

* As $X_{C_1} \downarrow \Rightarrow \text{frequency} \uparrow$. There is chance of adding high freq noise.

* So, Noise is added at high freq. To avoid this we use extra elements in the ckt such as

R_1 & C_f .

* ' f_a ' is the freq at which gain becomes 0dB i.e., unity.

$$f_a = \frac{1}{2\pi R C_f} \text{ in integrator}$$

$$f_a = \frac{1}{2\pi R_f C_1} \text{ in differentiator. (dbm)}$$

* ' f_c ' is unity gain bandwidth of Op-Amp.

* If applied freq ' f ' varies from 0 to f_b , then gain increases at 20 dB/decade.

* After f_b (cut-off freq), the gain decreases at 20 dB/decade.

Total 40 dB/decade is given by $R_1 C_1$ & $R_f C_f$.

∴ The Cut-off freq ' f_b ' is,

$$f_b = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi R_f C_f}$$

Here, $R_f C_1$ (or) $R_f C_f$ reduces the gain at high freq

$$\Rightarrow f_a < f_b < f_c$$

where,

f_a - unity gain freq

f_b - Cut-off freq

f_c - unity gain bandwidth of op-amp

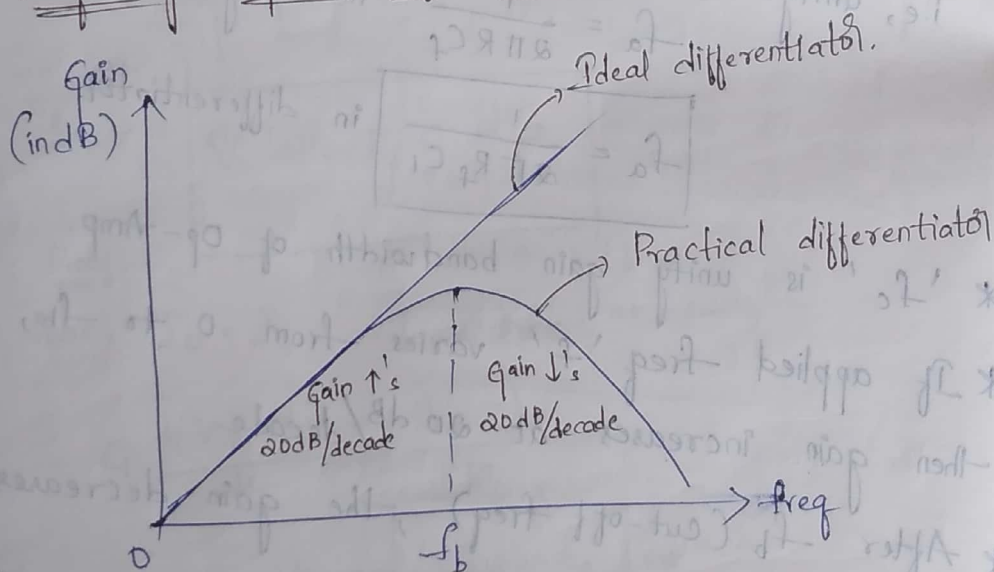
* For the perfect differentiator, the i/p signal time period ' T ' should be greater or equal to $R_f C_1$.

$$T \geq R_f C_1$$

* Cut-off freq should be 20 times of f_a

$$f_b = 20 f_a$$

Frequency response of differentiator:-



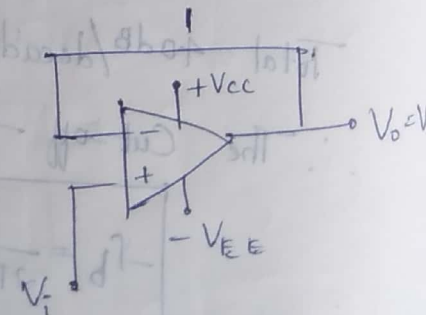
Voltage Follower (Voltage Buffer):-

* It is unity gain Amplifier

* No feedback component

* It has very high resistance (or) impedance

* The o/p voltage is equal



to i/p voltage ($\because$ Unity gain) $\Rightarrow V_o = V_i$

* The i/p signal is applied at Non-Inv Amplifier.

So, it is modified non-Inv Amplifier.

$$\text{Gain of non-Inv Amplifier} = \left(1 + \frac{R_f}{R}\right)$$

* If $R_f = 0$, then gain becomes unity.

(or) If $R = \infty$, then gain becomes unity.

$$\therefore V_o = A V_i \Rightarrow V_o = V_i \quad (\because A = 1)$$

So, Inv-terminal is short ckted with o/p terminal.

Due to Virtual Ground, Inv- & Non-Inv terminal are virtually short ckted.

So, the voltage available at Inv & Non-Inv is ' V_i '.

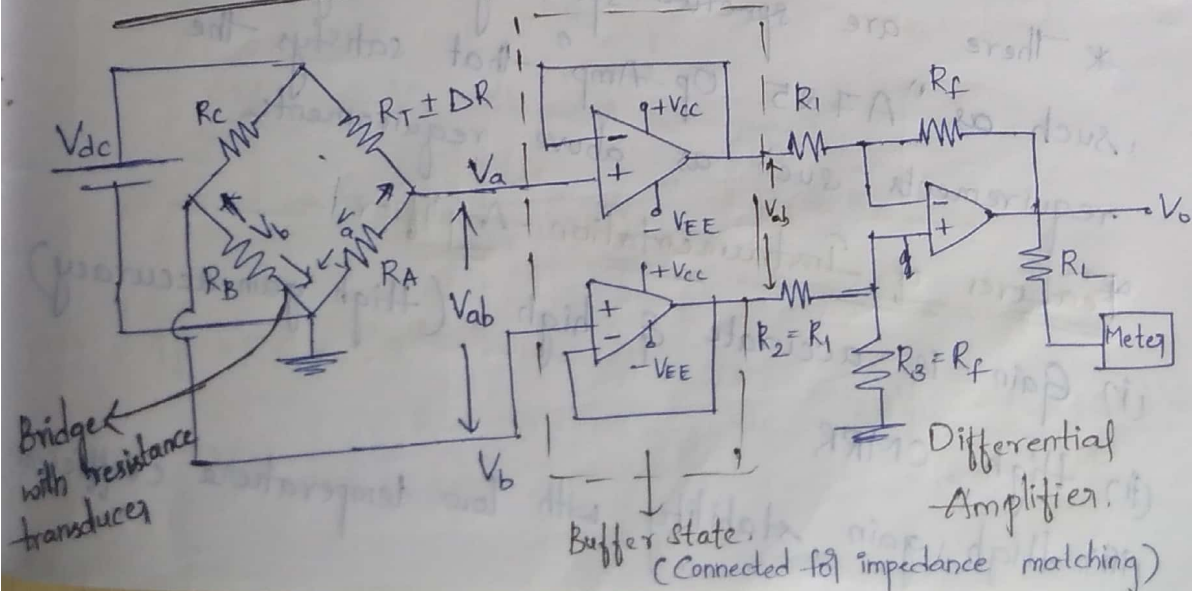
As the gain is '1', the o/p voltage is equal to i/p voltage.

* Whatever changes occur at i/p , that will effect same changes occur at o/p .

* Voltage follower is used in "Sample and Hold ckt".

& "Instrumentation Amplifier".

Instrumentation Amplifier -



* In Instrumentation Amplifier, voltage follower is used.

* In many instrumentation application, we will have very low signals from sensors or transducers.

* We have to amplify that signal either controlling or measurement purpose at the o/p.

* These are used in several applications such as simple motor control, data acquisition & automotive ckt.

* The basic idea behind Ins-Amp is should have high gain & high CMRR.

* The major function of Ins-Amp is for amplifying the low level o/p signals of the transducer. So, then it can drive the indicate (or) display.

* Based upon our requirement, some Ins-Amp have to meet some requirements such as "finite accurate & stable gain", "easy to gain existibility", "high i/p & low o/p impedances", "high CMRR", "lower power consumption", "high slew rate", "low dc offset".

* There are specially designed Op-Amps such as "A725 Op-Amp" that satisfies the requirements such as above requirements.

Features of Instrumentation Amplifier:-

- (i) Gain is accurate & high (High gain accuracy)
- (ii) High CMRR
- (iii) High gain stability with low temperature coefficient

(iv) Low dc offset Voltage

(v) Low % impedance.

* Transducer converts any physical quantity to electrical quantity & vice-versa.

Eg: (Voice to Electrical Signal)

* From the Bridge Ckt, (balanced condition)

$$R_c R_A = R_B R_T$$

$R_T \rightarrow$ Transducer resistance

$\Delta R \rightarrow$ Change in resistance (changes bcoz of parameter variation like temp, etc)

* The Current flows through meter is '0' ($\because$ balanced bridge)
i.e., zero current is drawn from bridge $\Rightarrow V_a = V_b$

By voltage division rule,

$$V_a = \frac{R_A}{R_A + R_T} V_{dc} \quad V_b = \frac{R_B}{R_B + R_c} V_{dc}$$

$\therefore V_{ab} = 0$ ($\because$ balanced bridge). ($\because V_{ab} = V_a - V_b = 0$)

* If there is change in resistance ' ΔR ' (due to parameter variation).

~~V_a~~ $V_a = \frac{R_A \cdot V_{dc}}{R_A + (R_T \pm \Delta R)} \Rightarrow V_a \downarrow$ due to ΔR

$$V_b = \frac{R_B \cdot V_{dc}}{R_B + R_c} \Rightarrow \text{No change}$$

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

$$= \frac{R_A \cdot V_{dc}}{R_A + (R_T \pm \Delta R)} - \frac{R_B \cdot V_{dc}}{R_B + R_c}$$

if $R_A = R_B = R_c = R_T = R$

$$V_{ab} = \frac{R}{2R + \Delta R} V_{dc} - \frac{R}{2R} V_{dc} = \frac{2RV_{dc} - (2R + \Delta R)V_{dc}}{2(2R + \Delta R)}$$

$$V_{ab} = \frac{2RV_{dc} - 2RV_{dc} - \Delta R V_{dc}}{2(2R \pm \Delta R)}$$

$$V_{ab} = \frac{-\Delta R \cdot V_{dc}}{2(2R \pm \Delta R)}$$

This V_{ab} is i/p to difference amplifier.

$$V_o = -\frac{R_f}{R} \cdot V_{ab}$$

$\therefore$ Differential Amplifier (Subtractor)
% is $\frac{R_2}{R_1}(V_2 - V_1)$

$$\Rightarrow -\frac{R_2}{R_1}(V_1 - V_2)$$

$$V_o = -\frac{R_f}{R} \cdot \left(\frac{-\Delta R \cdot V_{dc}}{2(2R \pm \Delta R)} \right)$$

ΔR is neglected ($\therefore$ very small) compared to R in denominator

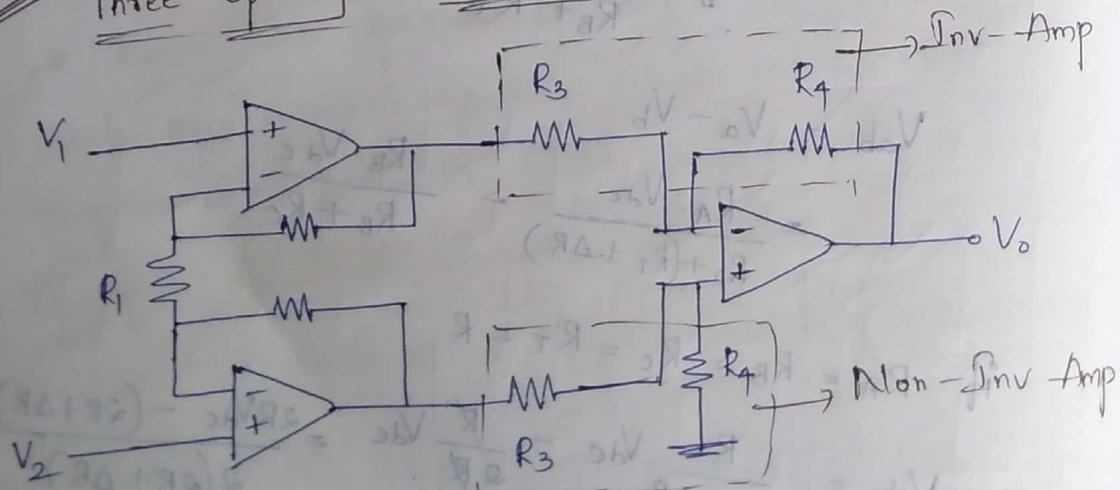
$$V_o \approx -\frac{R_f}{R_1} \cdot \frac{\Delta R \cdot V_{dc}}{4R}$$

$\Rightarrow$ % of Instrumentation Amplifier.

* $V_o \propto \Delta R$ ΔR - Unknown parameter.

* Instrumentation Amplifier is used to measure the physical quantity such as temp, humidity, water flow etc.

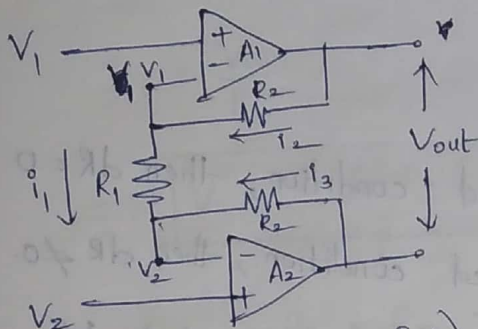
03/07/21 Three Op-Amps Instrumentation Amplifier:-



* R_1 is high i/p resistance (or) impedance.

* Features of Multi-Stage Op-Amp are (i) CMRR, (ii) high i/p impedance, (iii) Gain is more (iv) we can put LPF & HPF at o/p.

Stage ①:-



$$i_1 = \frac{V_1 - V_2}{R_1}$$

i_1, i_2 & i_3 are in series.

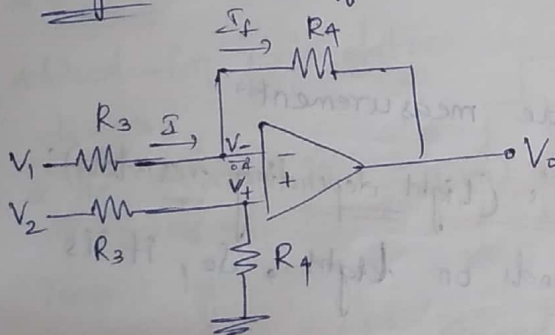
$$\therefore i_1 = i_2 = i_3$$

$$V_o = (V_1 - V_2) \left(1 + \frac{2R_2}{R_1} \right)$$

(Voltages at Inv- & Non-Inv terminals are equal $\because$ SC)

$$\left(\because \text{o/p of Non-Inv-Amp } V_o = \left(1 + \frac{R_f}{R} \right) V_{in} \right)$$

Stage ②:- (Difference Amplifier)



Voltage at non-Inv terminal
 $V = V_+ = V_2 \cdot \frac{R_4}{R_3 + R_4}$

Voltage at Inv-terminal,
 $I = I_+$

$$\frac{V_1 - V_-}{R_3} = \frac{V_- - V_o}{R_4}$$

Due to Virtual Ground Concept, voltage at Inv & Non-Inv terminal are equal.

$$V_+ = V_-$$

$$V_o = -(V_1 - V_2) \cdot \frac{R_4}{R_3}$$

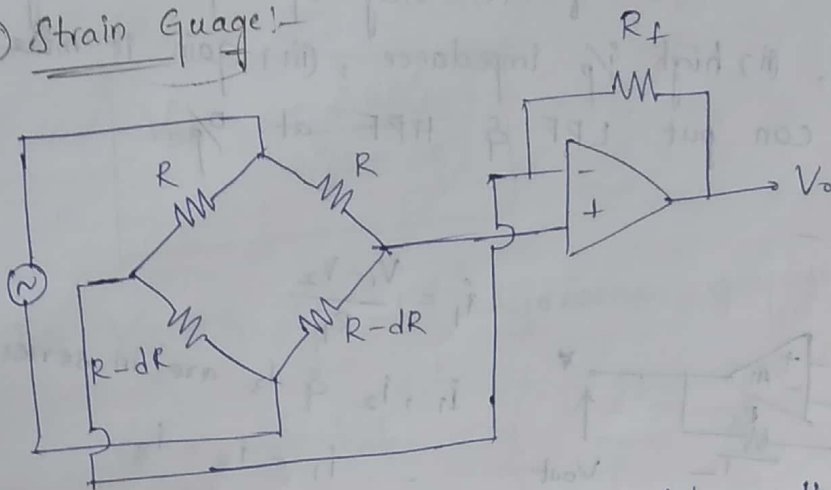
$$\Rightarrow V_o = -(V_1 - V_2) \cdot \left(\frac{R_4}{R_3} \right) \cdot \left(1 + \frac{2R_2}{R_1} \right)$$

$$\therefore V_o = (V_2 - V_1) \left(\frac{R_4}{R_3} \right) \left(1 + \frac{2R_2}{R_1} \right)$$

$\Rightarrow$ o/p of Inv-Amp using 3 op-Amps.

Applications of Ins-Amp:-

① Strain Gauge:-



When bridge is in balanced condition, then $dR = 0$
unbalanced condition, then $dR \neq 0$.

% of difference amplifier is proportional to $1/p$.

When bridge is in balanced, zero current is drawn from the bridge, then % is 'zero'.

② Thermistors:-

* Used for temperature measurement

③ Photo detector & LDR's (Light depending resistors):-

* Here, resistance depends on light, So, it is called LDR.

④ Thermal Conductivity, Measurement of flow:-

These are the applications of Ins-Amps.

Converters:-

(i) Current (I) to Voltage (V) Converter:-

* It is modified ckt of Inv-Amp.

* It takes the current from sensor or transducer & produces a proportional % voltage.

* % - Current & % - Voltage

* The $\frac{V_o}{V_i} = -\frac{R_f}{R_i} (V_i)$

($\therefore$ Inv-Amp)

$$V_o = -\frac{V_i}{R_i} (R_f)$$

$$I_i = \frac{V_i - V_a}{R_i} \quad \left(\text{Due to Virtual Ground } V_a = 0 \right)$$

$$I_i = \frac{V_i}{R_i}$$

$$\Rightarrow \boxed{V_o = -I_i \cdot R_f}$$

$$\frac{V_o}{I_i} = -R_f = R_m \rightarrow \text{Transresistance gain.}$$

So, it is also called as Transresistance Amplifier.

* Actual Ckt of I to V Converter:-

* Used for photo-electric devices.

* The current is proportional to instant light energy

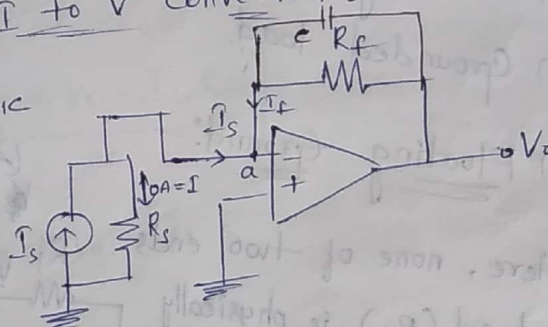
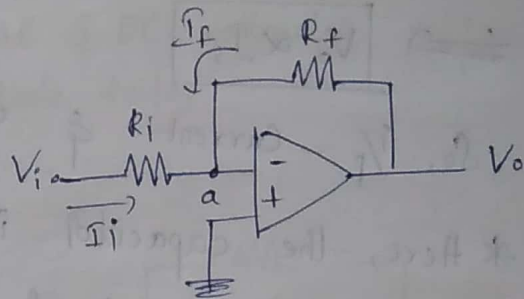
* Due to Virtual Ground, $V_a = 0$
 $I = 0$ as source resistance (R_s) is one end is connected to virtual ground & other end is to physical ground.

$$\therefore I_s + I_f = 0$$

$$I_s + \frac{V_o - V_a}{R_f} = 0$$

$$I_s + \frac{V_o}{R_f} = 0 \quad (\because V_a = 0)$$

$$\frac{V_o}{R_f} = -I_s \Rightarrow \boxed{V_o = -I_s \cdot R_f}$$



$$\Rightarrow \boxed{V_o \propto I_s}$$

So, i_p - Current & v_p - Voltage.
 * Here, the capacitor is used for filtering high freq noise signal.

$$\frac{V_o}{I_s} = -R_f \Rightarrow \text{Transresistance gain.}$$

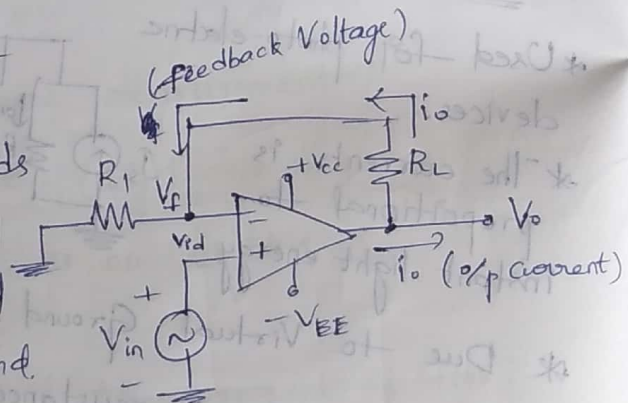
(ii) Voltage (V) to Current (I) Converter -
 * Converts The voltage v_p of a transducer gives is converted to current

Two types of V to I Converter:

- (a) Floating Ground
- (b) Grounded load.

(a) Floating Ground:-

* Here, none of two ends of load (R_L) is physically grounded. So, this load is called Floating ground.



* The v_p current (i_o) is in series in difference v_p voltage (V_{id}).

$\therefore$ It is current-series feedback.

* The v_p voltage V_{in} ,

$$V_{in} = V_{fb} \quad (\because \text{Short Ckt of } V-G)$$

$$V_{fb} = i_o \cdot R_L \Rightarrow i_o = \frac{V_{fb}}{R_L} \Rightarrow \boxed{i_o = \frac{V_{in}}{R_L}}$$

v_p - current
 i_p - Voltage.

* Used for low voltage AC & DC Voltmeter.

* Used for LED's, Zener diode tester

(b) Grounded Load:-

Apply KCL at 1,

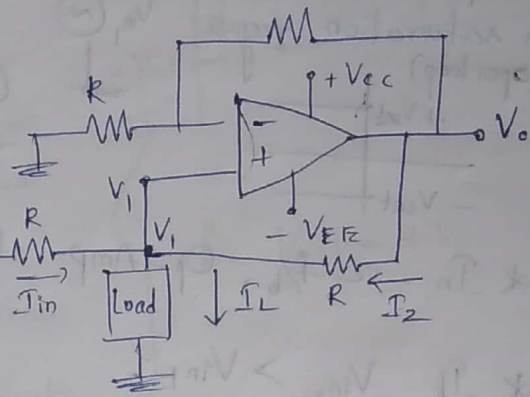
$$-I_L = I_2 + I_{in}$$

$$I_L = \frac{V_{in} - V_1}{R} + \frac{V_o - V_1}{R}$$

$$I_L \cdot R = V_{in} - V_1 + V_o - V_1$$

$$I_L \cdot R = V_{in} + V_o - 2V_1$$

$$V_1 = \frac{V_{in} + V_o - I_L R}{2}$$



(Non-Inv Amp
∴ I_p is applied at Non-Inv terminal)

$$\text{Now } \frac{o/p}{(V_o)} = \left(1 + \frac{R}{R}\right) V_1$$

$$= 2V_1$$

$$= 2 \left[\frac{V_{in} + V_o - I_L R}{2} \right]$$

$$\therefore V_o = V_{in} + V_o - I_L R$$

$$I_L R = V_{in}$$

$$I_L = \frac{V_{in}}{R}$$

$\frac{o/p}{V_o}$ - Voltage

$\frac{i/p}{I_L}$ - Current

05/07/21

Comparators:- (Voltage Comparator)

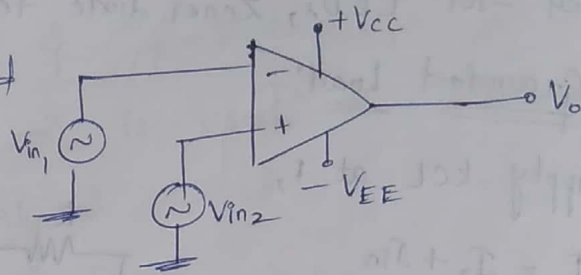
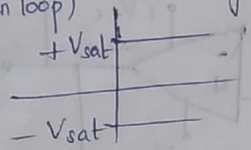
* Comparator is a electronic ckt which compares two different signals. (one voltage is applied voltage & other one is reference voltage).

* Used in digital interfacing, discriminators, voltage level detectors and oscillators.

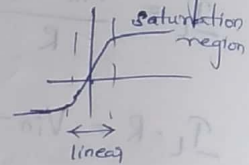
* Open loop Configuration used for Voltage Comparator

$$V_d = V_{in2} - V_{in1}$$

* Op-Amp is operated in saturation region (open loop)



* In -ve f/b, Op-Amp is operated in linear region.



* If $V_{in2} > V_{in1}$,

then $V_d = +ve$ i.e, o/p is $+V_{sat}$

* If $V_{in1} > V_{in2}$,

then $V_d = -ve$ i.e, o/p is $-V_{sat}$

* Let us consider $V_{in2} = V_{ref}$

$V_{in1} \rightarrow$ sinusoidal

then, these two are compared.

* Two Configurations of Comparators

(i) Inverting Configuration

(ii) Non-Inverting Configuration

Comparator Configurations:-

(i) Non-Inverting Configuration:-

* i/p is applied at Non-Inv terminal.

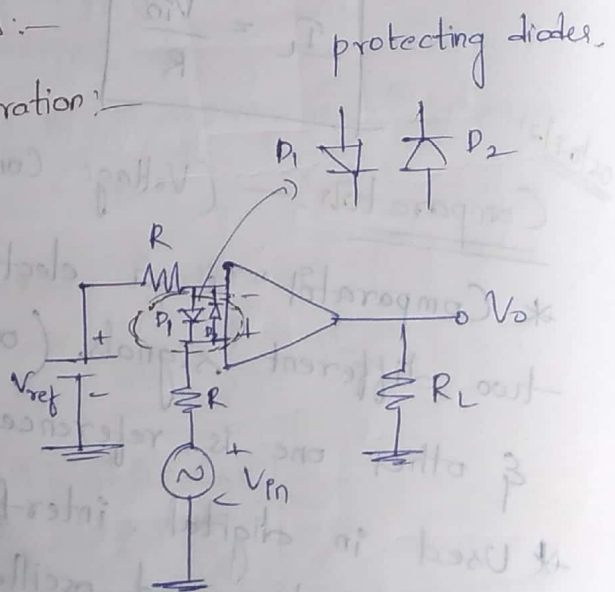
& reference signal is

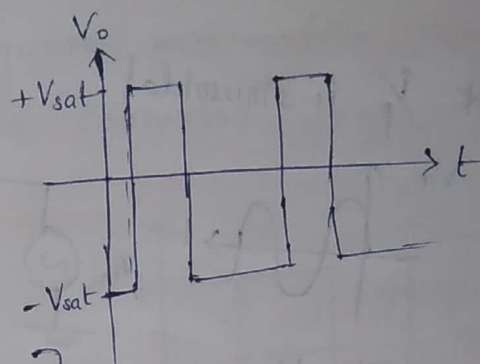
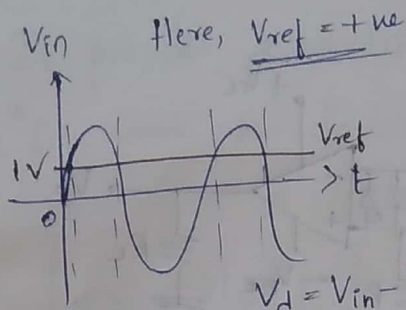
at Inv-terminal.

* Let i/p is sinusoidal

signal & reference

voltage is $1V-0$





If $V_{in} > V_{ref} \Rightarrow V_d = +ve$
i.e., o/p is $+V_{sat}$

$V_{in} < V_{ref} \Rightarrow V_d = -ve$
i.e., o/p is $-V_{sat}$

$V_{in} = 0 \Rightarrow V_o = -V_{sat}$

for $V_{ref} = +ve$

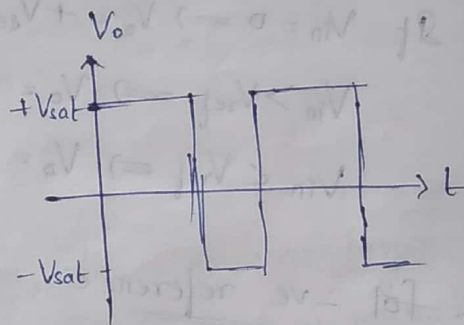
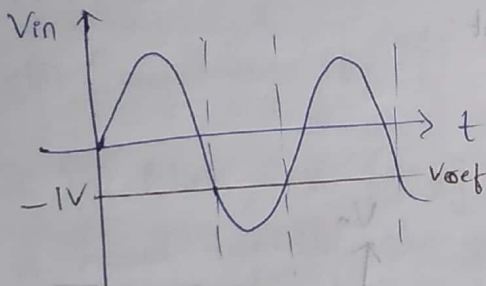
If $V_{in} = 0 \Rightarrow V_o = +V_{sat}$

$V_{in} > V_{ref} \Rightarrow V_o = +V_{sat}$

$V_{in} < V_{ref} \Rightarrow V_o = -V_{sat}$

for $V_{ref} = -ve$

$V_{ref} = -ve$



* We can say that comparator converts analog to digital. (i/p - Sinusoidal, o/p - digital)

* $+V_{sat}$ & $-V_{sat}$ are two levels. These levels are based on reference voltage.

So, It is also called "Voltage-level detector."

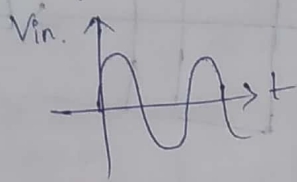
* Diodes are used to clamp the i/p wave-form to $0.7V$ (or) $-0.7V$. These diodes protect the ckt.

(ii) Inverting Configuration:-

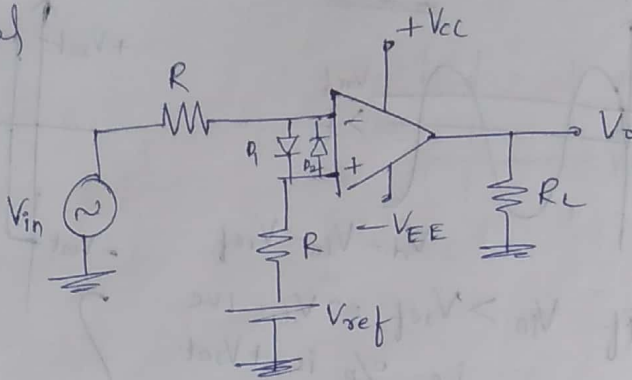
* The reference voltage is applied at Non-Inv terminal

* The i/p is applied at Inv-terminal

* i_p is sinusoidal

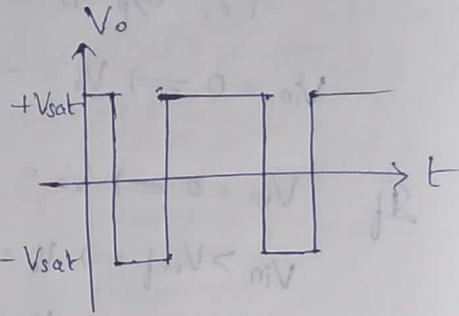
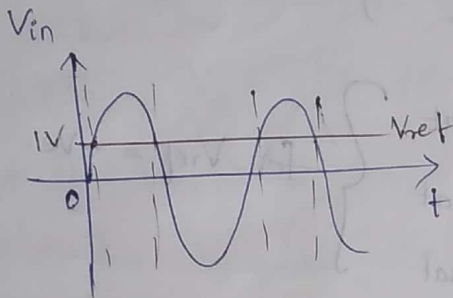


$$V_d = V_{ref} - V_{in}$$



* for +ve reference

$$V_{ref} = 1V$$



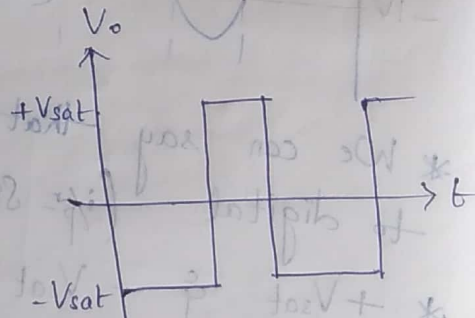
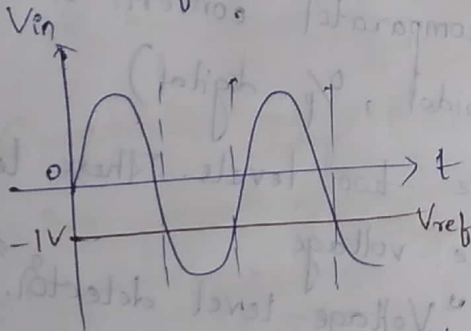
$$\text{If } V_{in} = 0 \Rightarrow V_o = +V_{sat}$$

$$V_{in} > V_{ref} \Rightarrow V_o = -V_{sat}$$

$$V_{in} < V_{ref} \Rightarrow V_o = +V_{sat}$$

* for -ve reference

$$V_{ref} = -1V$$



$$\text{If } V_{in} = 0 \Rightarrow V_o = -V_{sat}$$

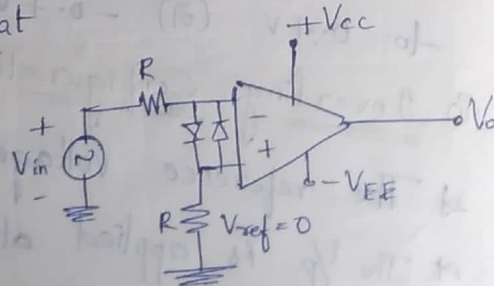
$$V_{in} > V_{ref} \Rightarrow V_o = -V_{sat}$$

$$V_{in} < V_{ref} \Rightarrow V_o = +V_{sat}$$

Zero Crossing detector Ckt:-

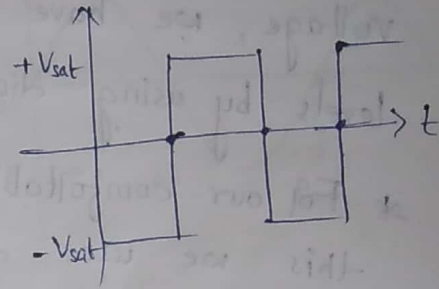
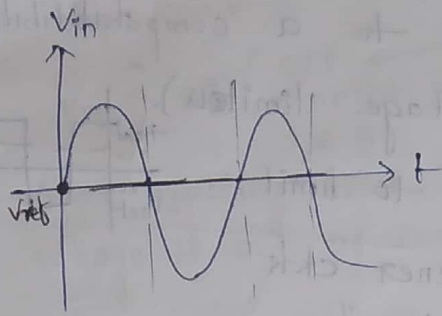
* for zero reference,

This Ckt is also "zero crossing detector"



* It provides symmetrical square wave form

* "Sine wave to Square wave Converter".



$$V_d = V_{ref} - V_{in} = 0 - V_{in} = -V_{in}$$

If $V_{in} = 0 \Rightarrow V_o = 0$

$$V_{in} > V_{ref} \Rightarrow V_o = -V_{sat}$$

$$V_{in} < V_{ref} \Rightarrow V_o = +V_{sat}$$

Characteristics of Comparator:

(i) Speed of Operation

(ii) Accuracy

(iii) Compatibility of %.

* In Non-Inv Configuration, the % waveform is ~~slow~~ rapidly changing. So, the speed of operation is improved with ~~the~~ feedback.

* In Inv - Configuration, the % accuracy is based on offset parameters. (gain & CMRR)

* In Zero-Crossing detector, the % of this is suitable for a logic family i.e., TTL.

Limitations of Comparator:

(i) hysteresis

(ii) Unstable

(iii) Incompatibility.

* The $\%$ of Op-Amp as Comparator should be matched with logic family, but due to high voltage, we have to limit to a compatibility levels by using diodes. (Voltage limiters).

* For our comfortable level, to limit this we use diodes, zener ckt

called as "Voltage limiters".

Voltage Limiter:-

* Voltage limiter is the special part of comparator because as the comparator ckt which provides either $+V_{sat}$ (or) $-V_{sat}$. we can limit this to in the $\%$ waveform.

* But, to give this $\%$ to next stage it may not be comfortable with particular logic family such as TTL. (Transistor-Transistor logic).

* Logic family requires only $+5V$ (or) $0V$.

So, to keep the voltage $\%$ within specific limit, the Op-Amp should be used with some external components. such as zener diodes (or) diode.

* Then $\%$ is limited. "Pre-determined values are called Voltage Limiter".

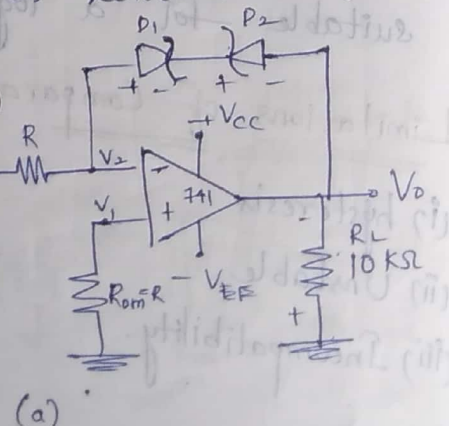
09/07/21

* To keep voltage $\%$ within specific limit, some external components such as zener diodes (or) diode are used.

Ex:-1 (Used only zener diodes)

* i/p is sinusoidal. at Inv-terminal

* During +ve half cycle of i/p , diode D_1 is ON
 D_2 is OFF



* Zener diode acts as normal diode in forward bias.

* $V_{D1} = 0.7V$

$V_{D2} = V_{Z2}$ (OFF means operated in R.B.)

After reaching break down voltage it acts as constant voltage ' V_Z '.

$V_o = -(V_{D1} + V_{Z2})$

$V_o = -(V_{Z2} + V_{D1})$ (Inv-Amp)

* During -ve half cycle,

D_1 is OFF (R.B), D_2 is ON (F.B)

$V_{D1} = V_{Z1}$

$V_{D2} = 0.7V$

$V_o = - (V_{Z1} + V_{D2})$

$V_o = V_{Z1} + V_{D2}$

o/p is limited b/w (Both cycles are limited)

Ex 2:- (Both zener diode & ordinary diode are used)

* i/p is sinusoidal applied at Inv-terminal

* During +ve half cycle,

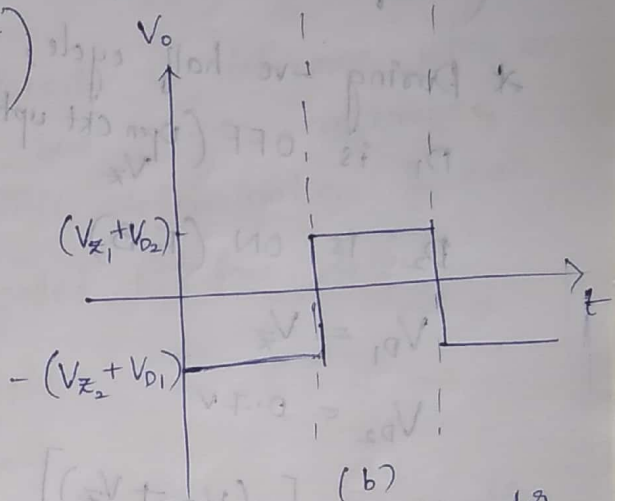
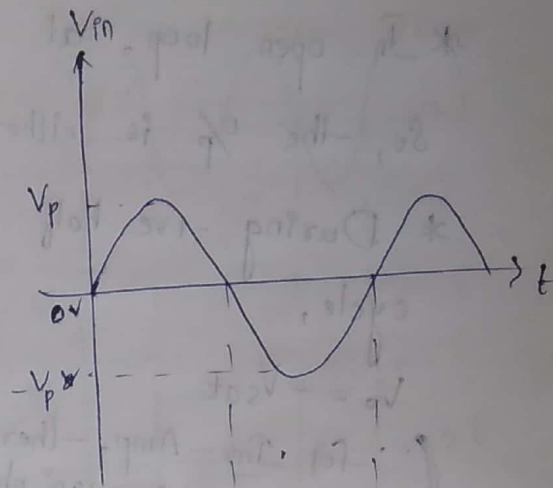
D_1 is ON (F.B)

D_2 is OFF (open ckt) (Ordinary diode)

As D_2 is open ckted,

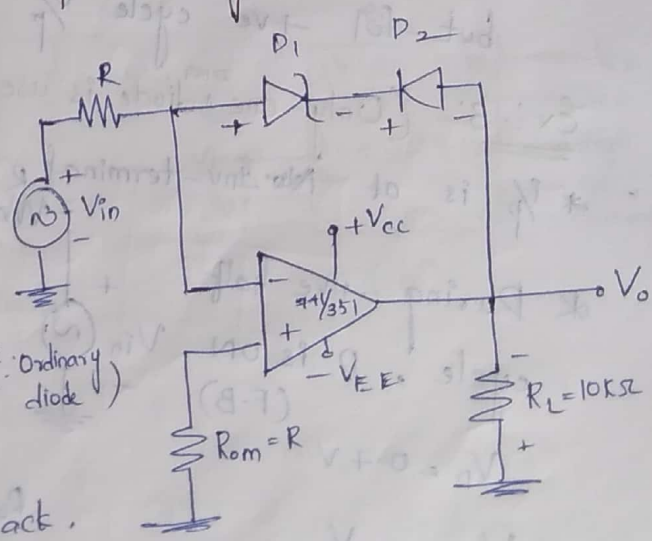
there will be no feedback.

So, it is open loop configuration.



(a) Basic Op-Amp comparator with +ve & -ve o/p voltage limiting
(b) i/p & o/p wave-forms.

$-(V_{D1} + V_{Z2})$ & $(V_{D2} + V_{Z1})$



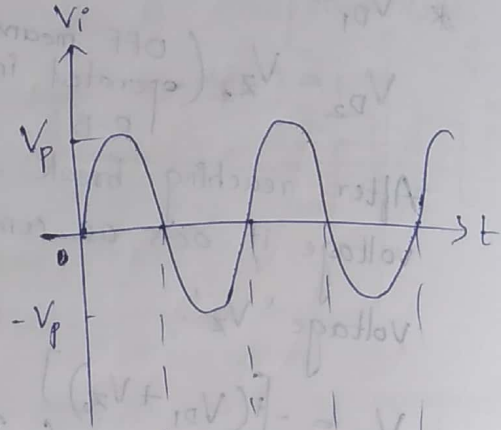
* In open loop, at low freq gain is infinite.

So, the o/p is either $+V_{sat}$ (or) $-V_{sat}$.

* During +ve half cycle,

$$V_o = -V_{sat}$$

($\because$ for Inv-Amp, there will be -ve i.e., 180° phase shift in the o/p)

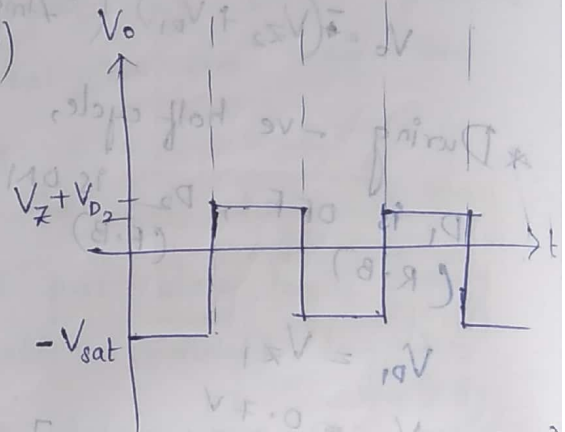


* During -ve half cycle,
 D_1 is OFF (Open ckt upto V_Z)

D_2 is ON (F.B)

$$V_{D1} = V_Z$$

$$V_{D2} = 0.7V$$



$$V_o = -[-(V_{D2} + V_Z)]$$

$$V_o = V_{D2} + V_Z$$

(Only one cycle is limited)

~~o/p is limited by $-V_{sat}$ & $V_{D2} + V_Z$~~

$\therefore$ o/p is limited only for -ve cycle i.e., $V_Z + V_{D2}$

but for +ve cycle o/p is as it is, i.e., $-V_{sat}$

Ex:-3:- (Only one ^{zener} diode is used)

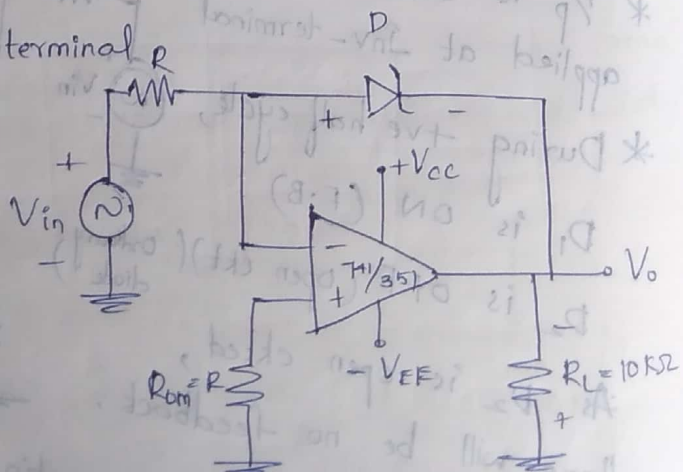
* i/p is at Non-Inv-terminal

* During +ve half cycle, D is ON (F.B)

$$V_D = 0.7V$$

$$V_o = -V_D$$

($\because$ Inv-Amp)



* During -ve half cycle,

D is OFF (R.B)

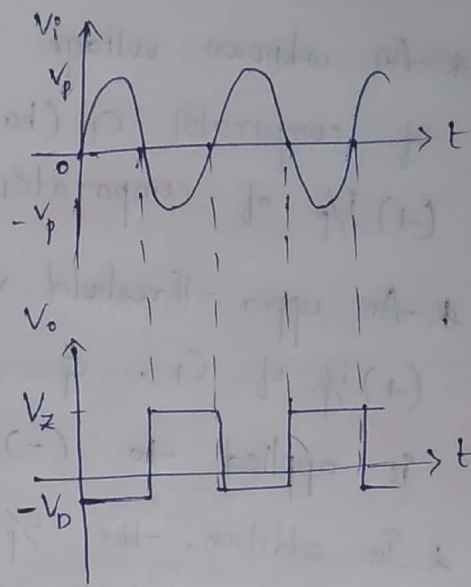
$$V_D = V_Z$$

$$V_D = -[-V_Z] = V_Z$$

∴ O/p is limited b/w

$$-V_D \text{ to } V_Z$$

(Both cycles are limited)



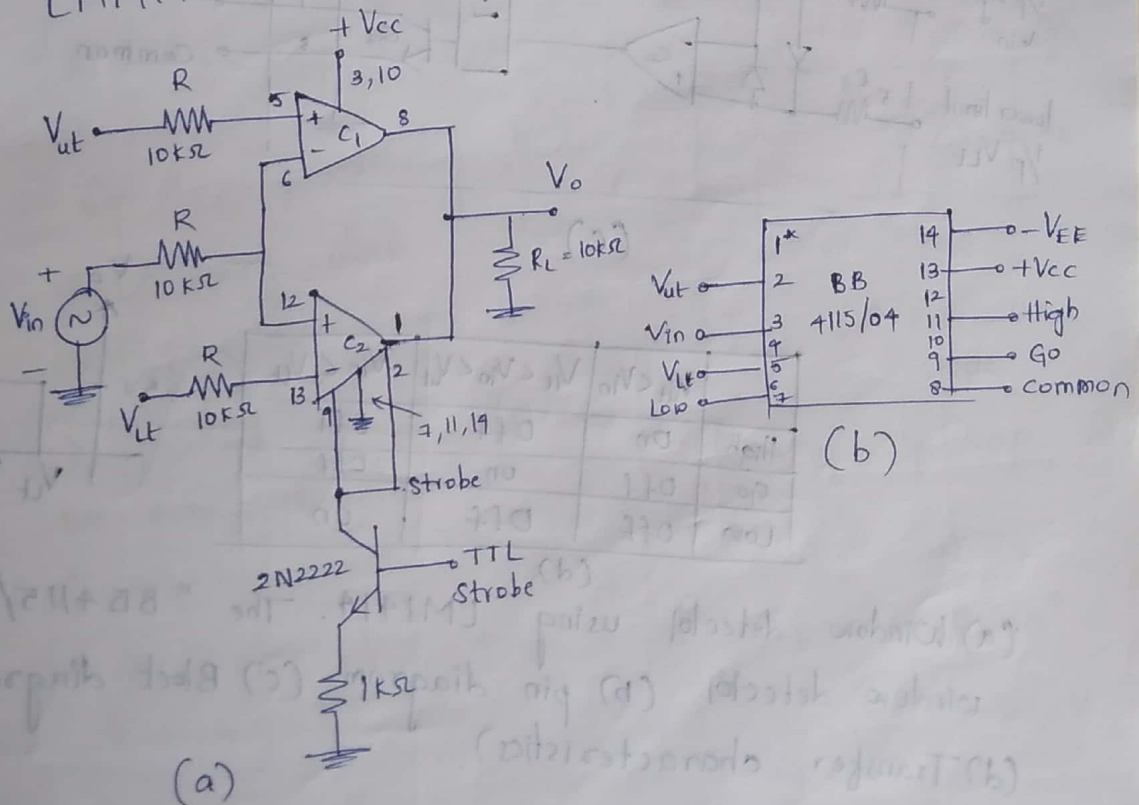
Window detector:-

* Sometimes there is a need to determine when an unknown i/p is between two precise reference thresholds V_{ut} & V_{lt} . This determination can be made by a circuit called window detector.

V_{ut} - Upper threshold

V_{lt} - Lower threshold.

-fig (a) shows the ckt using a dual comparator LM1414.



* An unknown voltage V_{in} is applied to the (-) i/p of comparator C_1 (half of LM1414) & to the (+) i/p of comparator C_2 (remaining half of LM1414).

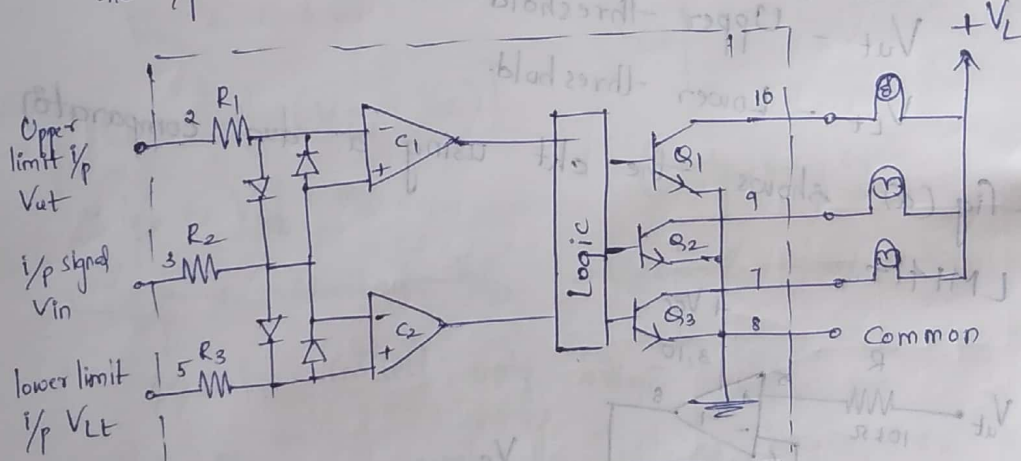
* An upper threshold voltage V_{ut} is applied to the (+) i/p of C_1 , & lower threshold voltage V_{lt} is applied to (-) i/p of C_2 .

* In addition, the o/p's of C_1 & C_2 are connected to form a single o/p V_o .

* When V_{in} is b/w V_{ut} & V_{lt} ,

the o/p V_o is 'high'.

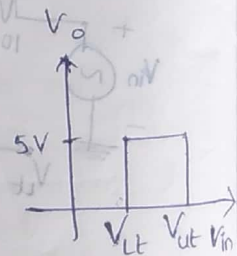
* When V_{in} goes above V_{ut} or drops below V_{lt} , the o/p V_o switches 'low' to '0V'.



(c)

	$V_{ut} < V_{in}$	$V_{lt} < V_{in} < V_{ut}$	$V_{in} < V_{lt}$
High	On	Off	Off
Go	Off	On	Off
Low	Off	Off	On

(d)



(a) Window detector using LM1414. The "BB4115/04" window detector (b) pin diagram (c) Block diagram. (d) Transfer characteristics).

Applications of Window detector:

- * Industrial areas
- * Level detector
- * Digital computers
- * Production line testing

Precision Rectifiers:

- * Function of ordinary diode

if i/p Voltage (V_{in}) $\geq$ Cut-in Voltage (V_r), then diode becomes "conduction state". ($V_{in} \geq V_r$)

if $V_{in} < V_r$, the diode remains "OFF state." (open ckt)

- * Diodes used as rectifiers. for ^{strong} ac signal, which converts ac signal to pulsating dc.

* If ac signal has same value i.e., in order of mV (or) μV , then this type of ordinary diode cannot rectify this weak ac signal.

So, we need to use "precision rectifier".

- * These can rectify very weak ac signal.

* Precision diode consists of Op-Amp & ordinary diode.

* Ordinary diode cannot rectify below cut-in voltage

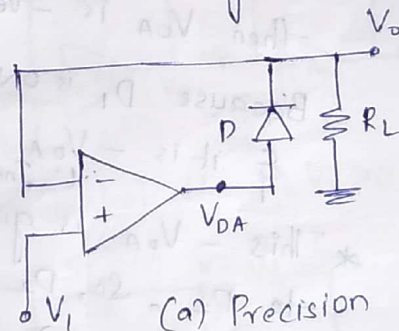
(V_r) So, to make diode ideal

we need to place in-feedback path of Op-Amp. So, cut-in voltage is reduced by $\frac{V_r}{A_{OL}}$

A_{OL} - Open loop gain of Op-Amp $\approx 10^6$ (or) 10^4

$$\therefore \frac{V_r}{A_{OL}} = \frac{0.6}{10^6} \approx 0.6 \mu V \quad (a) \quad \frac{V_r}{A_{OL}} = \frac{0.6}{10^4} \approx 60 \mu V$$

($\therefore$ Negative $\frac{1}{b}$ reduces gain by $1+A_{\beta}$ times $\approx A_{OL}$)



(a) Precision diode

* If i/p is greater than $60\mu V$, it is allowed (D is ON)
 less than $60\mu V$, it is not allowed (D is OFF)

* So, i/p should be greater than $60\mu V$.

* Precision diode is capable of rectifying i/p signal in order mV.

* If $V_i > \frac{V_r}{A_{OL}}$, then D_1 is ON

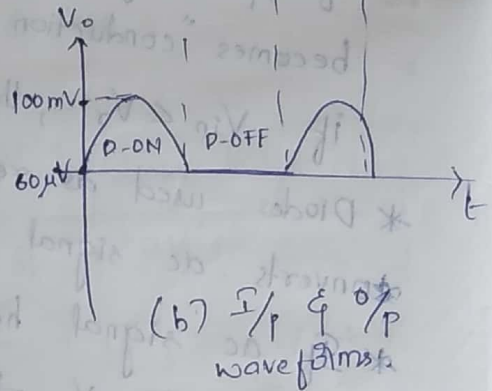
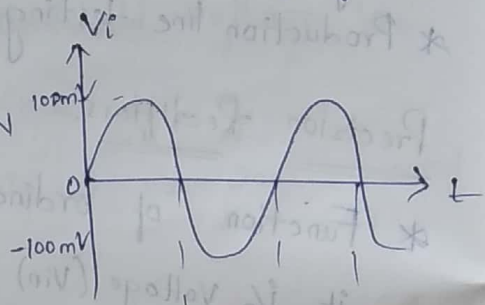
$$V_o = V_i \text{ (Voltage follower)}$$

Due to Virtual Short Ckt,
 V_i appears at Inv-terminal

* If $V_i < \frac{V_r}{A_{OL}}$ ($60\mu V$), then

D is OFF (R.B $\Rightarrow$ Open Ckt)

$$V_o = 0$$



(a) Half-Wave Rectifier:-

* If i/p is +ve, ($V_i \rightarrow +ve$)
 ($V_i > 0$)
 then V_{OA} is -ve

Because D_1 is ON (F.B) (S.C)
 & it is $-V_{OA}$ ($\because$ Inv-Amp)

* This $-V_{OA}$ is given to D_2 , So, D_2 is in R.B (O.C)

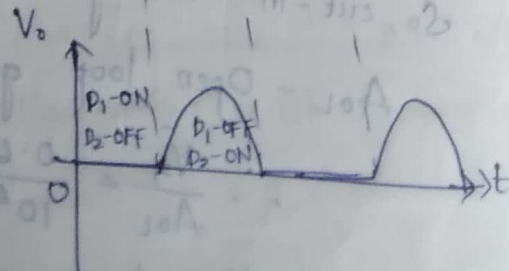
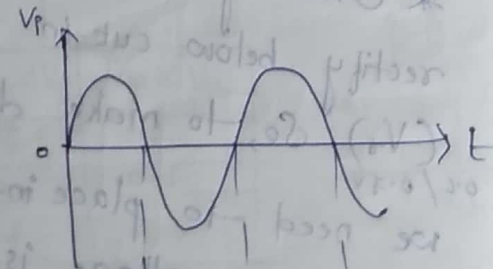
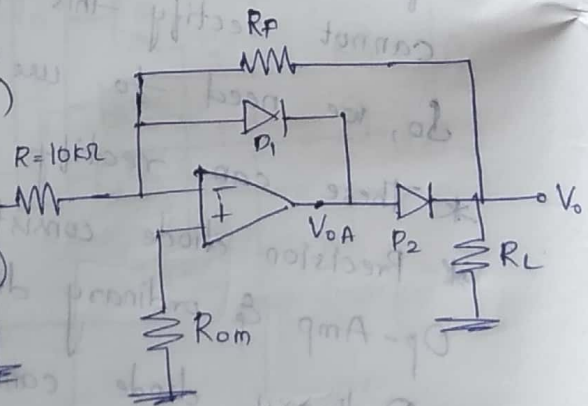
$$\Rightarrow V_o = 0 \text{ (Closed loop)}$$

* If V_i is -ve ($V_i < 0$)

then D_1 is OFF (O.C)

So, $-(-V_{OA}) = V_{OA}$ is given

to D_2 , So, D_2 is ON (S.C)



$$\therefore V_o = -\frac{R_f}{R_i} V_i$$

Here, V_i is -ve

$$\therefore V_o = \frac{R_f}{R_i} V_i$$

$$\Rightarrow V_o = \frac{10K}{10K} V_i \Rightarrow V_o = V_i$$

$$V_o = V_i$$

($\because R_f = R_i = 10K\Omega$)
(Closed loop)

$\therefore$ This ckt is changing from Open loop to closed loop & closed to open & repeats.

* This ckt will have high slew rate.

(b) Full Wave Rectifier:-

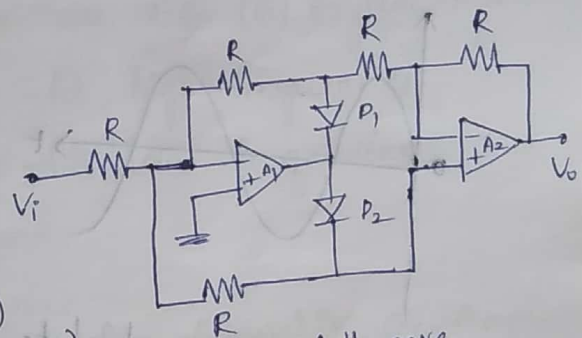
* If $V_i > 0$, then

D_1 is ON (s.c)

D_2 is OFF (o.c)

$$V_x = -V_i \quad (\because \text{Inv-Amp})$$

$$(V_o = -\frac{R_f}{R_i} V_i = \frac{R}{R} V_i = V_i)$$



(a) Precision full-wave rectifier.

* $-V_i$ is given to second op-amp.

$$V_o = -\frac{R_f}{R} (-V_i)$$

$$= \frac{R}{R} V_i = V_i$$

$$V_o = V_i$$

* If $V_i < 0$, then

D_1 is OFF (o.c)

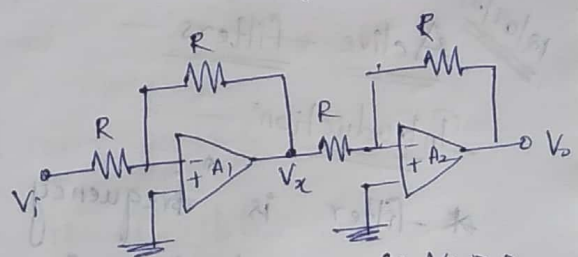
D_2 is ON (s.c)

(KCL at α ,

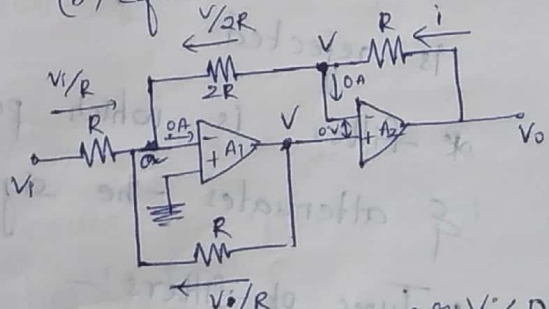
$$\frac{V_i}{R} + \frac{V}{R} + \frac{V}{2R} = 0$$

$$\Rightarrow 2V_i + 2V + V = 0$$

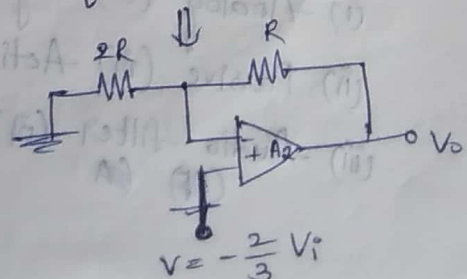
$$3V = -2V_i \Rightarrow V = -\frac{2}{3} V_i$$



(b) Equivalent ckt for $V_i > 0$



(c) Equivalent ckt for $V_i < 0$



Equivalent ckt is like non-Inv Amplifier
 $\therefore$ i/p is applied at non-Inv terminal).

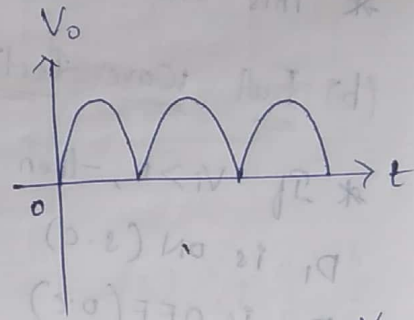
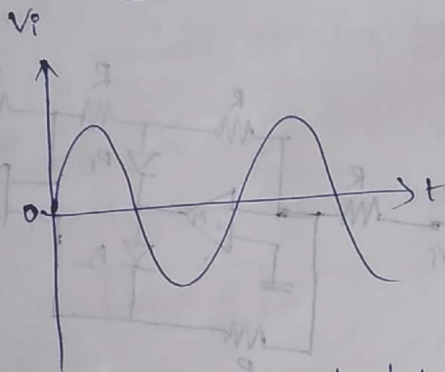
$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_i$$

$$= \left(1 + \frac{R}{2R}\right) \left(-\frac{2}{3} V_i\right)$$

$$= \left(\frac{3}{2}\right) \left(-\frac{2}{3} V_i\right) = -V_i = -(-V_i) = V_i$$

(as i/p is -ve i.e., $-V_i$)

$$\therefore V_o = V_i$$



$\therefore$ It gives absolute o/p.

+ve cycle $\Rightarrow V_o = V_i$
 -ve cycle $\Rightarrow V_o = -V_i$

12/07/21

Active filters:-

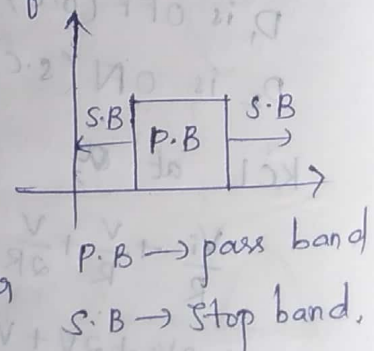
Introduction:-

* filter is "frequency selective ckt"
 i.e., selected freq is allowed & remaining freq is rejected.

* filter is which passes specific band of frequency & attenuates the signals of freq outside the band.

* Types of filters:-

- (i) Analog (or) digital filter
- (ii) Passive (or) Active filter
- (iii) Audio filter (or) Radio freq filter



- * Analog filters ^{passer} analog signals. (process on analog).
- * Digital filters are process of analog ^{signals} using digital techniques.

(ii) Passive (or) Active filters:-

* Passive components are used in Passive filters such as R, L, C.

* Active elements are used in Active filters such as transistor, Op-Amps etc.

(iii) Audio (AF) filter (or) Radio (RF) filter:-

* For low frequencies we use RC filters.

For high frequencies we use LC (or) Crystal filters.

* RF filters are used for high frequencies

* AF filters are used for low frequencies

Active filters:-

* Active filters are used for transistor, Op-Amps along with active elements, we use passive elements also (R, L, C).

Advantages of Active filters over passive filters:-

(i) Gain & freq adjustment is flexible

(ii) No loading problem because of high i/p & low o/p impedance of Op-Amp.

(iii) Less cost & no need of use of inductor.

(∵ Inductor is costly because it effects other elements with its magnetic field).

(iv) Size & weight is also reduced.

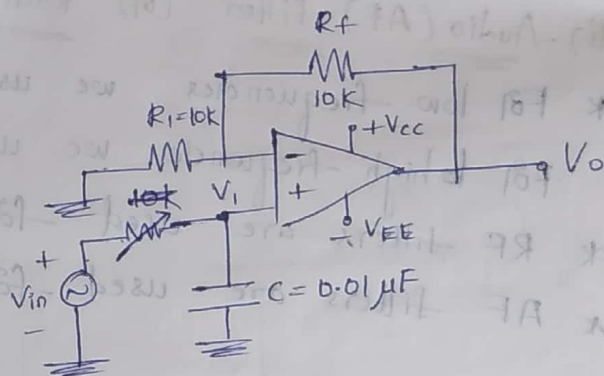
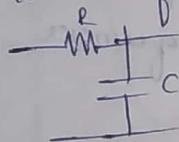
These are used in communications & signal processing.

- * General type of filters used in signal processing are,
- (i) Low pass filter
 - (ii) High pass filter
 - (iii) Band pass filter
 - (iv) Band stop filter
 - (v) All pass filter

(i) Low pass filter:- (First order Butter worth LPF):-

Consider Non-Inv Amp ckt,

* LPF allows only low frequencies.



By voltage division rule,

At +ve terminal,

$$V_1 = \frac{-jX_c}{R - jX_c} \cdot V_{in} \quad \left(\because X_c = \frac{1}{2\pi fC} \right)$$

$$= \frac{-j\left(\frac{1}{2\pi fC}\right)}{R - j\left(\frac{1}{2\pi fC}\right)} \cdot V_{in} = \frac{-j}{2\pi fCR + -j} \cdot V_{in}$$

$$\Rightarrow \frac{V_1}{V_{in}} = \frac{-j}{-j + 2\pi fCR} = \frac{-j}{-j(1 + j2\pi fCR)} = \frac{1}{1 + j2\pi fCR}$$

$$V_1 = \frac{1}{1 + j2\pi fCR} \cdot V_{in}$$

% of Non-Inv Amp,

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1$$

$$\Rightarrow V_o = \underbrace{\left(1 + \frac{R_f}{R}\right)}_{A_{CL} \text{ (or) } A_F} \left(\frac{V_{in}}{1 + j2\pi fRC} \right)$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{A_F}{1 + j2\pi fRC}}$$

Magnitude response:-

$$\left| \frac{V_o}{V_{in}} \right| = \left| \frac{A_F}{1 + j2\pi fRC} \right| \Rightarrow \left| \frac{V_o}{V_{in}} \right| = \left| \frac{A_F}{1 + j \frac{f}{f_H}} \right|$$

$$\text{where, } f_H = \frac{1}{2\pi RC}$$

f_H - higher cut-off freq.
(or) Break freq (or) Corner freq

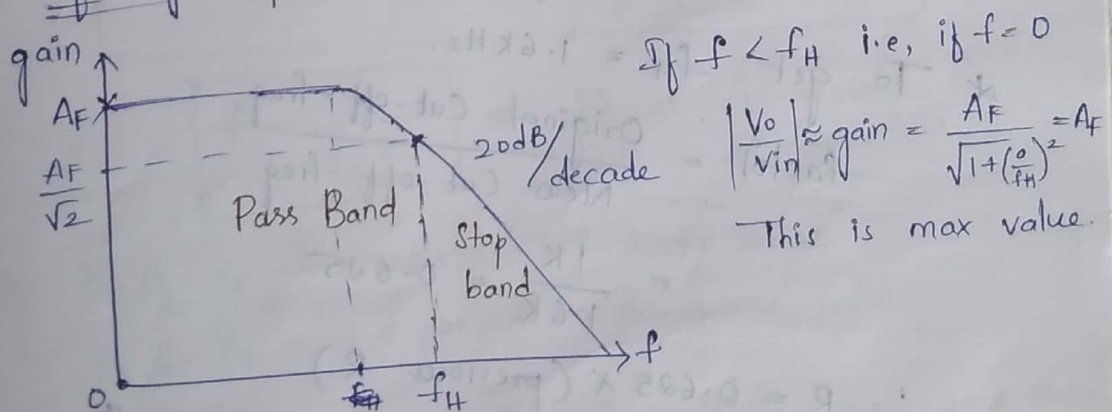
$$\left(\because 2\pi RC = \frac{1}{f_H} \right)$$

$$\boxed{\left| \frac{V_o}{V_{in}} \right| = \frac{A_F}{\sqrt{1 + \left(\frac{f}{f_H}\right)^2}}}$$

phase response:-

$$\boxed{\phi = -\tan^{-1} \left(\frac{f}{f_H} \right)}$$

Frequency response:-



$$\text{If } f = f_H, \left| \frac{V_o}{V_{in}} \right| = \text{gain} = \frac{A_F}{\sqrt{1 + \left(\frac{f_H}{f_H}\right)^2}} = \frac{A_F}{\sqrt{2}} = 0.707 A_F$$

If we apply log on both sides we get, -3 dB
($\because \log(\frac{1}{\sqrt{2}})$)

$$\text{If } f > f_H \Rightarrow \left| \frac{V_o}{V_{in}} \right| \approx \text{gain} < A_F$$

i.e, $f = \infty$

At $f = \infty \Rightarrow$ Gain is '0'.

Designing of first order Butter worth LPF:

* Let f_H (cut-off freq) = 10 KHz.

Pass band gain = 2

Choose Capacitor value $< 1 \mu F$

Let $C = 0.01 \mu F$

$$f_H = \frac{1}{2\pi RC} \Rightarrow R = \frac{1}{2\pi f_H C} = \frac{1}{2\pi \times 10 \times 10^3 \times 0.01 \times 10^{-6}}$$

$$R = 15.9 K\Omega$$

So, Here, 20 K Ω potentiometer should be used. (15.9 K Ω resistor is not available in lab.)

To get pass band gain = 2

Gain of Non-Inv Amp is,

$$1 + \frac{R_f}{R_1} = 2$$

$\therefore$ To get P.B gain = 2, $R_f = R_1$

We can take any value.

* To get $f_H = 1.6 KHz$.

$$\text{factor} = \frac{\text{Original Cut-off freq}}{\text{New Cut-off freq}}$$

$$= \frac{1 K}{1.6 K} = 0.625$$

$$R = 0.625 \times (\text{previous } R)$$

$$= 0.625 \times 15.9 K\Omega = 9.94 K\Omega$$

Here, 10 K Ω potentiometer should be used

15/07/21

Second order Butterworth with LPF:-

* By addition of one more section of RC network to the first order LPF, converts to second order LPF.

* In second order LPF, gain roll-off is at -40dB/decade

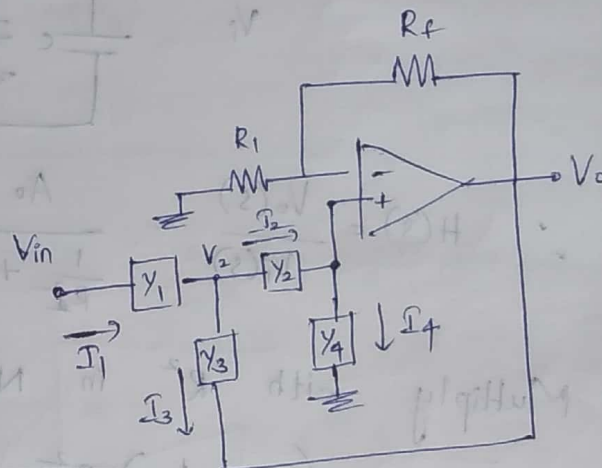
In first order, gain roll-off is at -20dB/decade .

* In order to improve the filter response, second order LPF is used.

* It consists of two RC pairs

* General second order LPF is also called as "Sallen-Key".

* Gain of the ckt (A),



$$A = A_F = \frac{A_F \cdot Y_1 Y_2}{Y_1 Y_2 + Y_2 Y_3 (1 - A_F) + Y_4 (Y_1 + Y_2 + Y_3)}$$

$$f = \frac{1}{2\pi RC}$$

$\Rightarrow$ for similar resistors & capacitors.

* Y_1 & $Y_2 \rightarrow$ resistors with same value

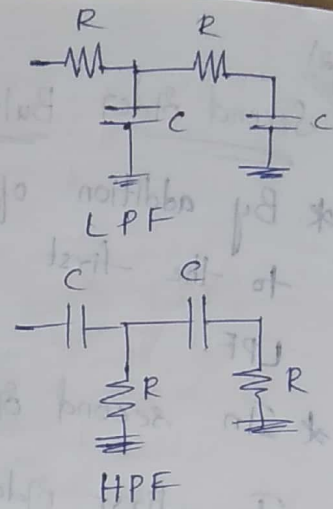
Y_3 & $Y_4 \rightarrow$ capacitors with same value

* If the dissimilar capacitors & resistors are used, then

$$f = \frac{1}{2\pi \sqrt{R_x R_y C_x C_y}}$$

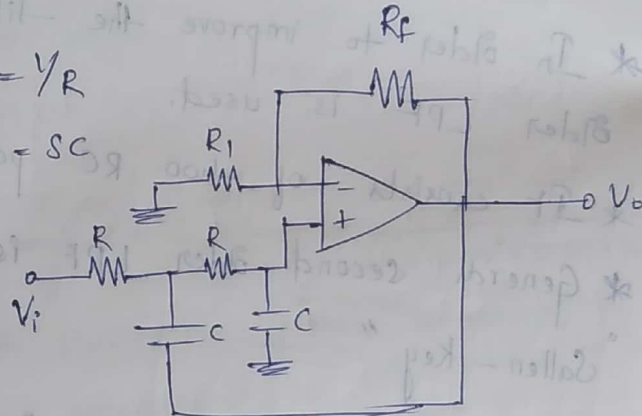
* For LPF,

	Y_1	Y_2	Y_3	Y_4
LPF	$1/R$	$1/R$	SC	SC
HPF	SC	SC	$1/R$	$1/R$



Second order LPF:-

* Replace $Y_1 = Y_2 = 1/R$
 $Y_3 = Y_4 = SC$



$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{A_0 \times \frac{1}{R^2}}{\frac{1}{R^2} + \frac{SC}{R}(1-A_0) + SC\left(\frac{2}{R} + SC\right)}$$

Multiply with R^2 in Num & denominator

$$H(s) = \frac{\left(A_0 \times \frac{1}{R^2}\right) R^2}{\left[\frac{1}{R^2} + \frac{SC}{R}(1-A_0) + SC\left(\frac{2}{R} + SC\right)\right] R^2}$$

$$H(s) = \frac{A_0}{1 + SC R(3-A_0) + S^2 R^2 C^2} \quad \text{--- (2)}$$

We know, general form of second order system,

$$H(s) = \frac{A_0 \cdot \omega_n^2}{s^2 + \alpha \omega_n s + \omega_n^2}$$

A_0 = gain, α = damping coefficient
 ω_n = natural freq of oscillations

$$\omega_n^2 = \frac{1}{RC^2} \Rightarrow \omega_n = \frac{1}{RC}$$

$$\alpha = \frac{(3-A_0)}{RC}$$

put $s = j\omega$ in (2)

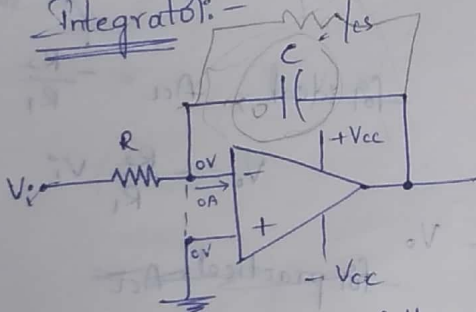
$$H(j\omega) = \frac{A_0}{1 + j\alpha\left(\frac{\omega}{\omega_n}\right) + j^2\left(\frac{\omega}{\omega_n}\right)^2}$$

$$|H(j\omega)| = \frac{A_0}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(\alpha \frac{\omega}{\omega_n}\right)^2}}$$

$$= \frac{A_F}{\sqrt{1 + \left(\frac{f}{f_H}\right)^4}}$$

$$A_F = 1 + \frac{R_F}{R_1}$$

Integrator:-



This is low pass filter

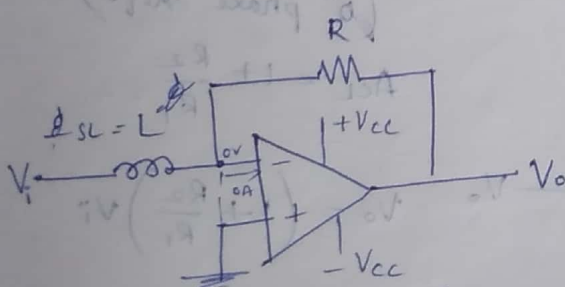
$$\left(\begin{array}{l} \omega = 0 \Rightarrow A_{CL} = \infty \\ \omega = \infty \Rightarrow A_{CL} = 0 \end{array} \right)$$

$$\frac{0 - V_i}{R} + \frac{0 - V_o}{\frac{1}{Cs}} = 0$$

$$\Rightarrow -\frac{V_i}{R} = V_o \cdot Cs \Rightarrow \frac{V_o}{V_i} = -\frac{1}{RCs}$$

$$A_{CL} = \frac{V_o}{V_i} = -\frac{1}{RCj\omega}$$

$$V_o(t) = -\frac{1}{RC} \int V_i(t) \cdot dt$$



This is low pass filter

$$\left(\begin{array}{l} \omega = 0 \Rightarrow A_{CL} = \infty \\ \omega = \infty \Rightarrow A_{CL} = 0 \end{array} \right)$$

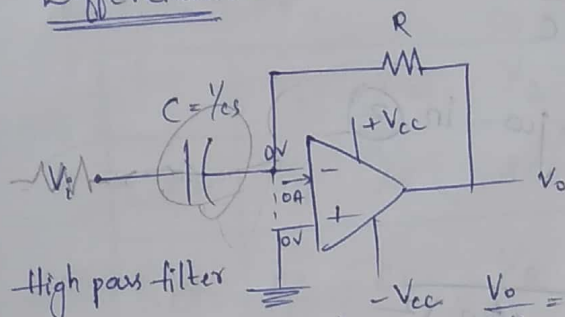
$$\frac{0 - V_i}{sL} + \frac{0 - V_o}{R} = 0$$

$$-\frac{V_i}{sL} = \frac{V_o}{R} \Rightarrow \frac{V_o}{V_i} = -\frac{R}{sL}$$

$$A_{CL} = \frac{V_o}{V_i} = -\frac{R}{Lj\omega}$$

$$V_o(t) = -\frac{R}{L} \int V_i(t) \cdot dt$$

Differentiator:-



$$\frac{0 - V_i}{1/sC} + \frac{0 - V_o}{R} = 0$$

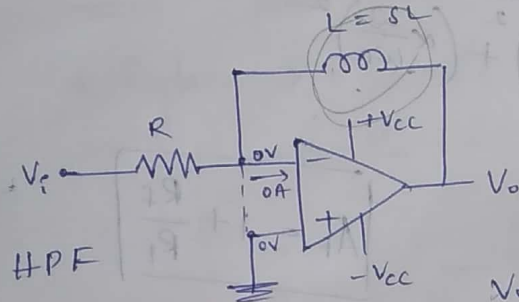
$$-V_i CS = \frac{V_o}{R} \Rightarrow \frac{V_o}{V_i} = -RCS$$

High pass filter

$$\left(\begin{array}{l} \omega = 0 \Rightarrow A_{CL} = 0 \\ \omega = \infty \Rightarrow A_{CL} = \infty \end{array} \right)$$

$$\frac{V_o}{V_i} = A_{CL} = -RCS = -RCj\omega$$

$$\therefore V_o(t) = -RC \frac{d}{dt} V_i(t)$$



$$\frac{0 - V_i}{R} + \frac{0 - V_o}{sL} = 0$$

$$-\frac{V_i}{R} = \frac{V_o}{sL} \Rightarrow \frac{V_o}{V_i} = \frac{sL}{R}$$

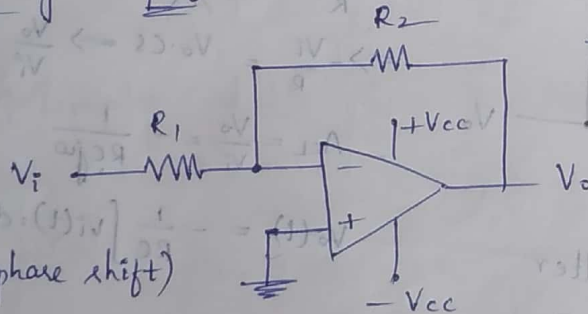
H.P.F

$$\left(\begin{array}{l} \omega = 0 \Rightarrow A_{CL} = 0 \\ \omega = \infty \Rightarrow A_{CL} = \infty \end{array} \right)$$

$$\frac{V_o}{V_i} = A_{CL} = \frac{sL}{R} = \frac{L}{R} j\omega$$

$$\therefore V_o(t) = -\frac{L}{R} \frac{d}{dt} V_i(t)$$

Inverting Amplifier:-



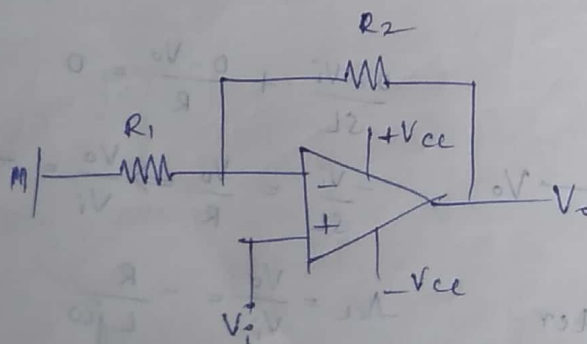
(180° phase shift)

for ideal, $A_{CL} = -\frac{R_2}{R_1}$

$$V_o = -\frac{R_2}{R_1} V_i$$

for practical, $A_{CL} =$

Non-Inverting:-



(0° phase shift)

$$A_{CL} = 1 + \frac{R_2}{R_1}$$

$$V_o = \left(1 + \frac{R_2}{R_1} \right) V_i$$