Unit 3

Syllabus

Operational Amplifiers: Introduction, Op-Amp basic, Practical Op-Amp Circuits (Inverting Amplifier, Non-inverting Amplifier, Unit Follower, Summing Amplifier, Integrator, Differentiator).Differential and Common-Mode Operation, Comparators.

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PAGE No. 1
DATE / / 202

Unit 3

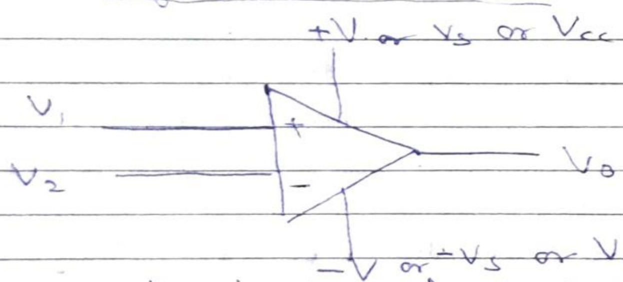
Operational Amplifier (Op-Amp)

An Op Amp is a high gain ($10^5 - 10^6$) amplifier which is used to perform variety of operations such as amplification, addition, subtraction, differentiation, integration etc.

Advantages of ~~opp~~ op-amp

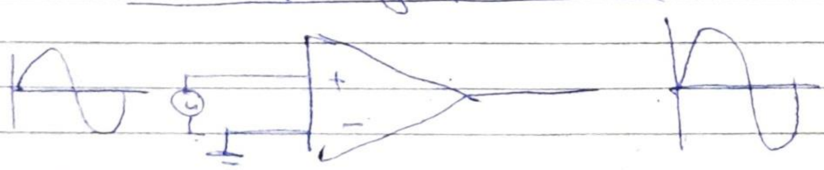
- It has smaller size
- It has less power consumption
- It is easy to replace
- low cost
- high reliability

Symbol and terminals



- The non-inverting i/p terminal is marked as +
- The inverting i/p terminal marked as −
- The positive supply voltage +V
- The negative supply voltage −V
- The o/p terminal V_o

Non inverting i/p terminal



If we connect the i/p s/g to the non-inverting terminal, then the amplified o/p s/g is in phase with the i/p s/g.

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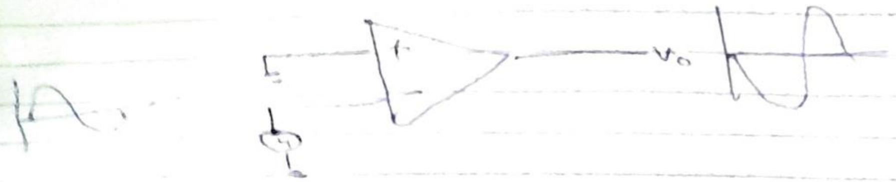
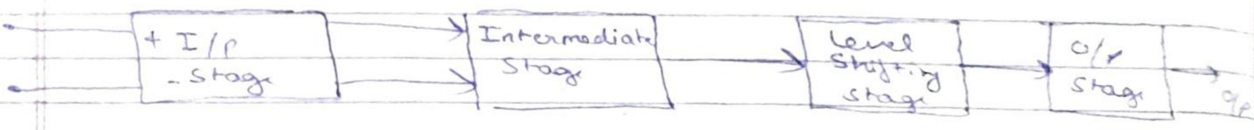
PAGE No. 2

Inverting i/p terminal



If we connect the i/p s/g to the inverting terminal then the amplified o/p s/g is 180° out of phase w.r.t. the i/p s/g

Block diagram of opamp



It basically consists of 4 stages:

(1) I/p stage: It consists of a dual i/p and dual o/p differential amplifier
The 2 i/p are non-inverting and inverting i/p terminal
The stage provides most of the voltage gain of opamp
This stage decide the value of i/p resistance (R_i)

(2) Intermeditate stage: It consists of a dual i/p and single o/p differential amplifier.
It is driven by the o/p of i/p stage
I/p stage alone can't provide high gain so intermediate stage provide the required additional voltage gain

(3) Level shifting stage: As opamp amplifies the dc s/g also and in different cascading stages coupling capacitor are not used hence stage by stage dc level ↑ well above the ground potential
Level shifting stage is used the intermediate stage to shift the dc level to 0 V w.r.t. ground

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PAGE No 3
DATE : / 202

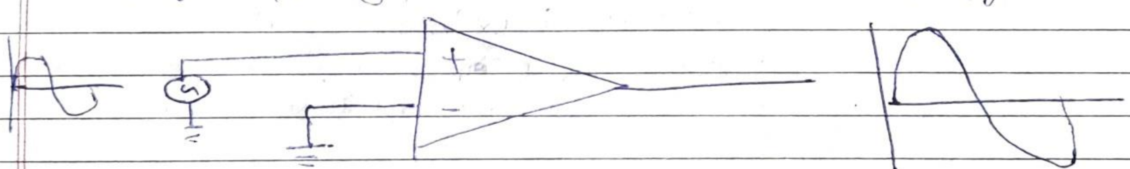
(4) O/P Stage :- This stage ↑ the O/p voltage and raises the current carrying capability of op amp.
It also provides low o/p impedance

Modes of opamp

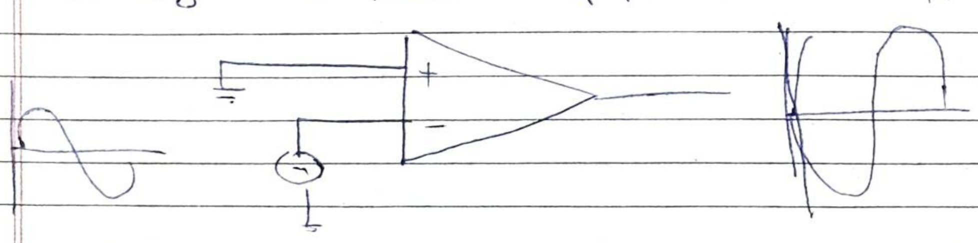
An op amp Can work in 3 modes :-
1. Single ended mode
2. Double ended mode or differential mode
3. Common mode

(1) Single ended mode :- If the i/p s/g is applied only one of the i/p terminals and other i/p terminal is connected to ground, then op-amp is said to be operation in the single ended mode.

(a) If we connect the i/p s/g to the NI terminal then the amplified o/p s/g is in phase with the i/p s/g.



(b) If we connect the i/p s/g to the I terminal then the amplified o/p s/g is 180° out of phase with the i/p s/g



(2) Differential mode : In this mode of operation i/p s/g is applied at both the i/p terminals of opamp. The o/p voltage is directly proportional to the difference b/w 2 i/p voltages i.e.

$$V_o \propto V_1 - V_2$$

$$\boxed{V_o = A_d(V_1 - V_2)}$$

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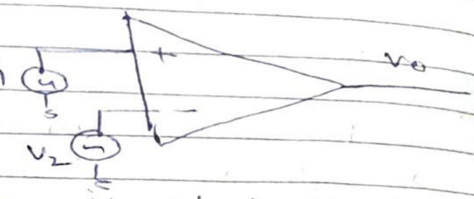
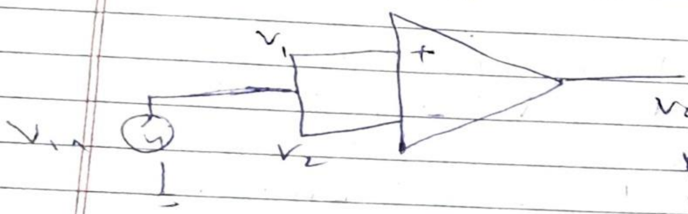
Where A_d is constant of proportionality and is called differential voltage gain or open loop gain (A_v) and $V_1 - V_2 = V_d$ is called differential voltage
so

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



(3) Common mode :- In this mode same i/p s/g is applied to both the i/p terminals i.e. $V_1 = V_2 = V_{in}$



So ideally ~~for~~ $V_o = A_d(V_1 - V_2) = 0$
But practically o/p voltage V_o is proportional to common mode s/g V_c where $V_c = \frac{V_1 + V_2}{2}$

i.e. $V_o \propto V_c$

$$\boxed{V_o = A_c V_c}$$

where A_c is constant of proportionality and is called common mode gain. Thus we find that even if $V_1 = V_2$, there exist some finite o/p voltage practically
The total o/p of any op-amp is

$$\boxed{V_o = A_d V_d + A_c V_c}$$

Common mode rejection ratio (CMRR)

It is the ability of opamp to reject in common mode s/g and is defined as the ratio of A_d to A_c and is denoted by ρ

$$\rho = \left|\frac{A_d}{A_c}\right|$$

Ideally $A_c = 0$ so $\rho = \infty$
CMRR is decible

$$CMRR(dB) = 20 \log_{10}\left|\frac{A_d}{A_c}\right|$$

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PAGE No 5
DATE: / 202

Q For a given opamp CMRR = 10^5 and $A_d = 10^5$ what is the A_c for the amplifier?

Sol
$$A_c = \frac{A_d}{\rho} = \frac{10^5}{10^5} = 1$$

Q Given that CMRR is 1000000 I/p common mode voltage is 12V differential voltage gain is 4000. Calculate o/p common mode voltage

Sol
$$V_c = 12V$$

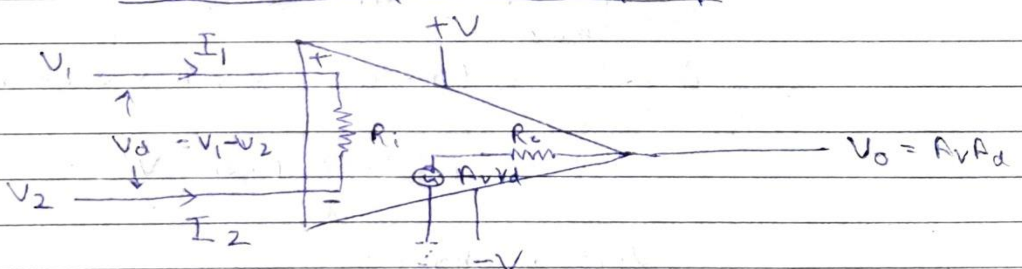
$$A_d = 4000$$

$$CMRR = 1000000 = \frac{4000}{A_c} \Rightarrow A_c = 0.004$$

$$V_o = A_c V_c \Rightarrow 0.04 \times 12$$

$$\boxed{V_o = 0.48V}$$

Characteristics of an ideal opamp



1. ∞ voltage gain ($A_v = \infty$)
2. ∞ i/p resistance ($R_i = \infty$)
3. 0 o/p " ($R_o = 0$)
4. 0 offset voltage (In practical opamp if V_1 and V_2 is 0 then some finite voltage present at o/p. That finite voltage is called offset voltage)
5. ∞ Bandwidth (Bandwidth is the range of freq in which over opamp work as a amplifier)
6. ∞ CMRR

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PAGE No 6
DATE / 202

(7) ∞ Slew rate

$$S = \left.\frac{dV_o}{dt}\right|_{max} = \infty \quad (V/\mu s)$$

(8) 0 power supply rejection ratio (PSRR = 0)
(PSRR is the change in V_o when any fluctuation in i/p Vtg.)

(Q) The output of particular Opamp rises 18V in 12 μS. What is the slew rate?

Sol

$$S = \frac{dV_o}{dt} = \frac{18V}{12\mu s} = 1.5 \ V/\mu s$$

(Q) An opamp amplifier of gain 10 is used to amplify a sinusoidal s/g with a peak amplitude of 0.5V and freq of 25 KHz. What should be the slew rate of the opamp?

Sol

$$V_i(t) = V_m \sin(2\pi f t)$$

$$V_o(t) = A_v V_m \sin(2\pi f t)$$

$$\left.\frac{dV_o}{dt}\right|_{max} = A_v V_m 2\pi f \cos(2\pi f t)$$

$$S = \left.\frac{dV_o}{dt}\right|_{max} = 10 \times 0.5 \times 2 \times \pi \times 25 \times 10^3 \times 1$$

$$= 785714.28 \ V/s$$

Virtual Short:

According to virtual short concept the potential difference b/w 2 i/p terminal of an opamp is almost 0 or both the i/p terminals will be at same potential i.e. $V_d = V_1 - V_2 = 0$

$$V_1 - V_2 = 0$$

$$\boxed{V_1 = V_2}$$

Assume that opamp is ideal. So $R_i = \infty$

Hence $I = \frac{V}{R} \Rightarrow I_1 = I_2 = 0$

Thus voltage drop across R_i ($V_d = IR$) will be 0
So both the i/p terminal will be at same potential

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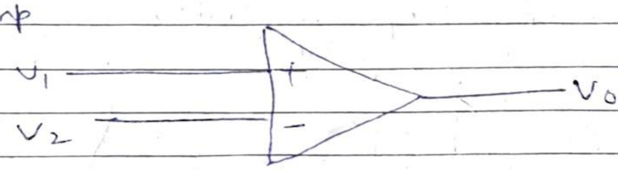
PAGE No 7

Virtual ground

If non-inverting (+) terminal of opamp is connected to ground then due to virtual short existing b/w the 2 i/p terminal, the inverting (-) terminal will also be at ground potential. Hence it is said to "virtual ground"

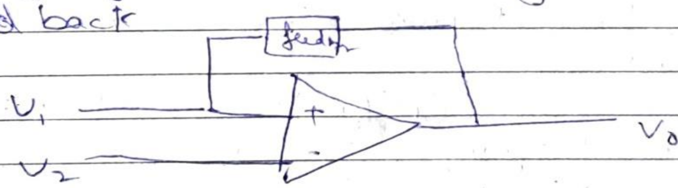
Open and closed loop opamp

→ When there is no feedback in opamp than it is called open loop opamp

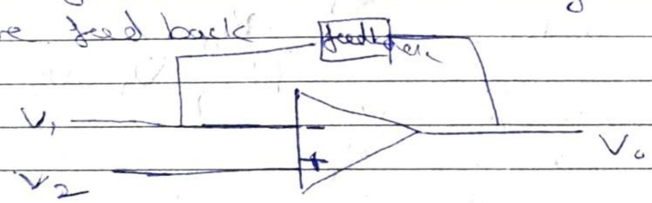


→ When there is some feed back in opamp then it is called ~~a~~ closed loop opamp.
~~Feedback is~~ (When some part of o/p is added to the i/p than it is called feed back)

→ When we give feed back at inverting terminal than it called +ve feed back



→ When we give feed back at non-inverting terminal than it called -ve feed back



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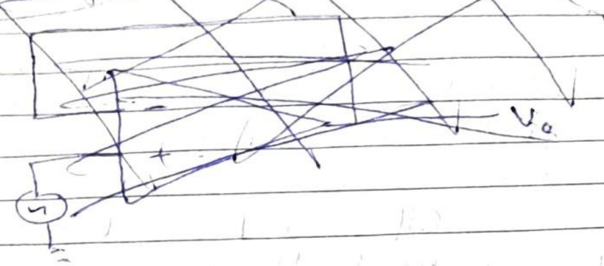
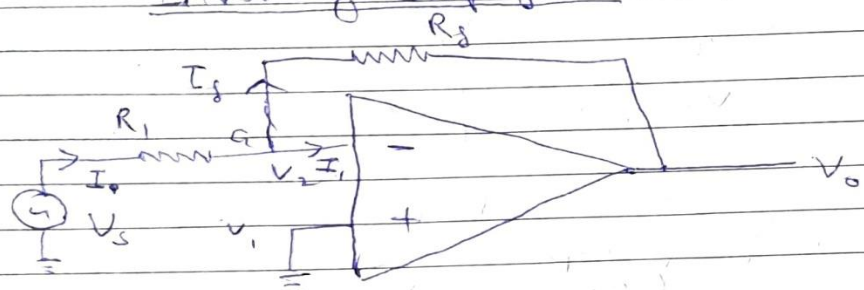
PAGE No 8
DATE / / 202

~~Voltage follower (unit-gain) amplifier~~



Inverting amplifier



The s/g which is to be amplified is applied to the inverting terminal of op-amp
Apply KCL at junction G
we get

$$I = I_1 + I_f$$

For ideal opamp $I_1 = 0$

So $I = I_f$

or $\dfrac{V_s - V_2}{R_1} = \dfrac{V_2 - V_o}{R_f}$ —— (1)

by virtual ground concept $V_1 = V_2 = 0$

$$\frac{V_s}{R_1} = -\frac{V_o}{R_f}$$

$$-\frac{R_f}{R_1} = \frac{V_o}{V_s}$$

$$\boxed{A_{vf} = -\frac{R_f}{R_1}}$$

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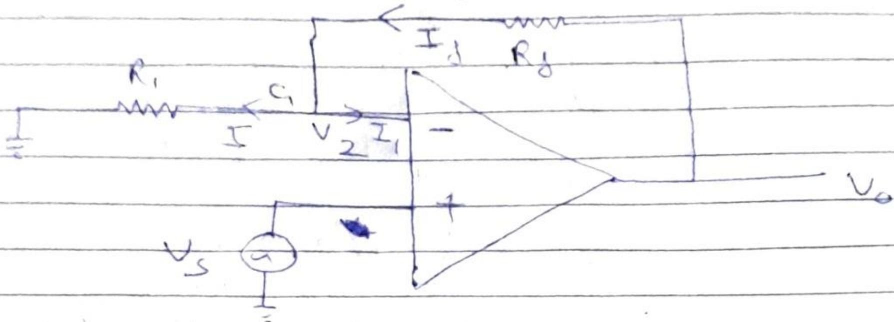
PAGE No 9

Non inverting amplifier



The S/g which is to be amplified is applied to the non-inverting terminal of op amp

Appling KCL at node G

$$I_f = I + I_1$$

for ideal opamp $I_1 = 0$

$$I_f = I$$

$$\frac{V_0 - V_2}{R_f} = \frac{V_2 - 0}{R_1}$$

by virtual ground concept $V_s = V_2$

$$\frac{V_0 - V_s}{R_f} = \frac{V_s}{R_1}$$

$$\frac{V_0}{R_f} - \frac{V_s}{R_f} = \frac{V_s}{R_1}$$

$$\frac{V_0}{R_f} = \frac{V_s}{R_1} + \frac{V_s}{R_f}$$

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

$$\boxed{A_{vf} = \frac{V_0}{V_s} = 1 + \frac{R_f}{R_1}}$$

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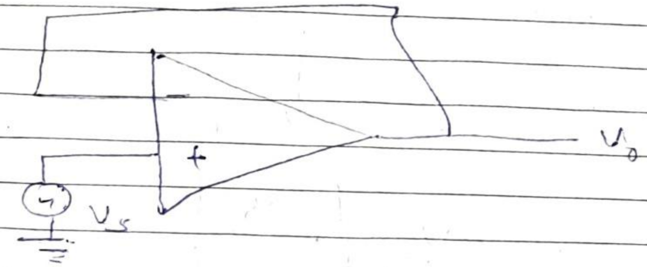
PAGE No 10
DATE: / 202

Unity gain amplifier (Voltage follower)



In non-inverting amplifier $R_1 = \infty$ $R_f = 0$

So $A_{vf} = 1 + \frac{R_f}{R_1}$

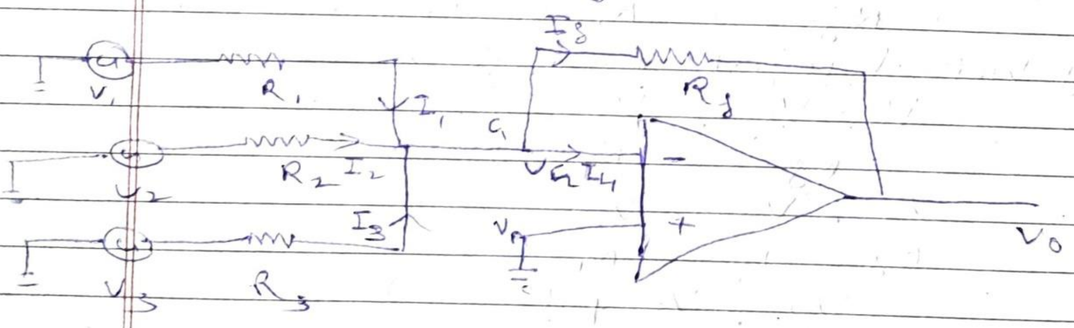
$= 1 + \frac{0}{\infty}$

$\boxed{A_{vf} = 1}$

or

$\boxed{V_o = V_s}$

Summing Amplifier (adder opamp)



An adder is a circuit which adds all the i/p s/g to produce their addition at the o/p

applying KCL at node a

$I_1 + I_2 + I_3 = I_f + I_4$

For ideal opamp $I_4 = 0$

So $I_1 + I_2 + I_3 = I_f$

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} = \frac{V_2 - V_0}{R_1}$$

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PAGE No 11
DATE / 202

by virtual ground $V_G = V_A = 0$

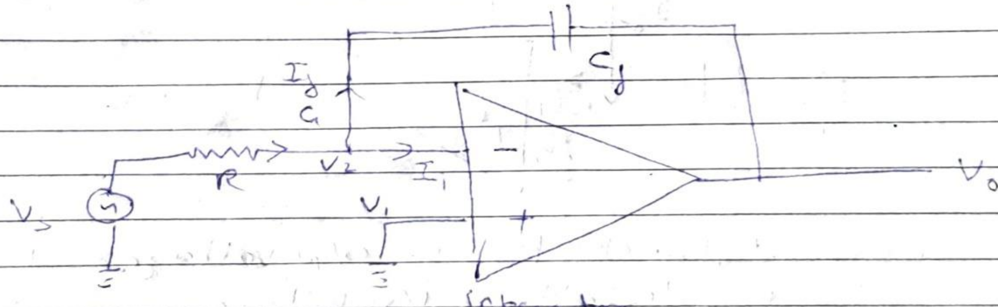
So $\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_0}{R_f}$

$$V_0 = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

If $R_1 = R_2 = R_3 = R_f$

$$V_0 = -(V_1 + V_2 + V_3)$$

Integrator opamp ckt



The ckt diagram of opamp as shown in fig. Integrator ckt produces the o/p voltage which is time integral of i/p voltage.

Appling KCL at node G

$$I = I_1 + I_f$$

But for ideal opamp $I_1 = 0$

$$I = I_f$$

$$\frac{V_s - V_2}{R} = \frac{d}{dt}(C_f V)$$

$$= C_f \frac{dV}{dt}$$

$$= C_f \frac{d}{dt}(V_2 - V_0)$$

By virtual ground $V_2 = 0$

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

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PAGE No 12
DATE: / / 202

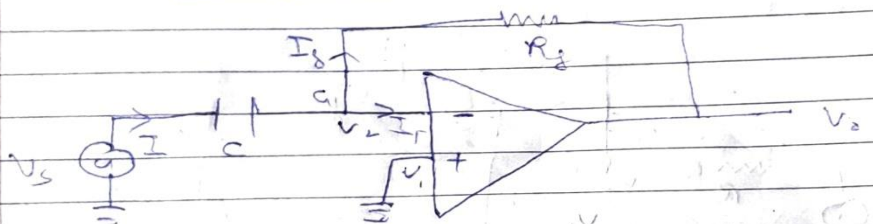
$$\frac{dV_o}{dt} = -\frac{1}{RC_f} V_s$$

Integration both side

$$\int_0^t \frac{d}{dt} V_o \, dt = -\frac{1}{RC_f} \int_0^t V_s \, dt$$

$$\boxed{V_o = -\frac{1}{RC_f} \int_0^t V_s \, dt}$$

Differentiator opamp



Differentiator ckt produces o/p voltage which is proportional to the time derivative of i/p voltage

Appling KCL At node G_1

$$I = I_f + I_1$$

But for ideal opamp $I_1 = 0$

$$I = I_f$$

$$\frac{d}{dt} CV = I_f$$

$$C \frac{d}{dt}(V_s - V_2) = \frac{V_2 - V_o}{R_f}$$

But $V_2 = 0$

$$C \frac{d}{dt} V_s = -\frac{V_o}{R_f}$$

$$\boxed{V_o = -R_f C \frac{d}{dt} V_s}$$

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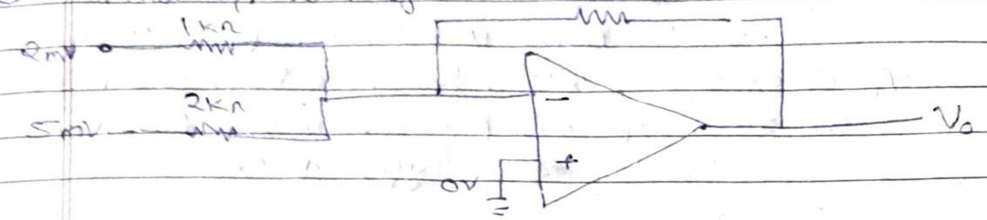
PAGE No 13
DATE : / 202

Q Find O/P voltage :-

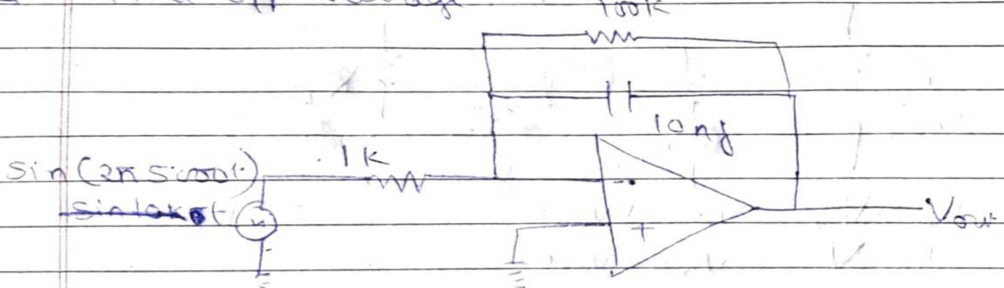


$$V_o = -\left(\frac{10k}{1k} \times 2mV + \frac{10k}{2k} 5mV\right)$$

$$= -(20m + 25m)\ V$$

$$\boxed{V_o = -45\ mV}$$

Q Find O/P voltage :-



$$V_{out} = -\frac{1}{RC_f} \int v_{in}(t)\, dt$$

$$= \frac{1}{1k \times 10n} \int \sin(2\pi\, 5000t)\, dt$$

$$= \frac{10^5}{2\pi\, 5000} \left(\cos 2\pi\, 5000t\right)$$

$$= 3.18 \cos(2\pi\, 5000t)$$

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PAGE No 14
DATE / 202

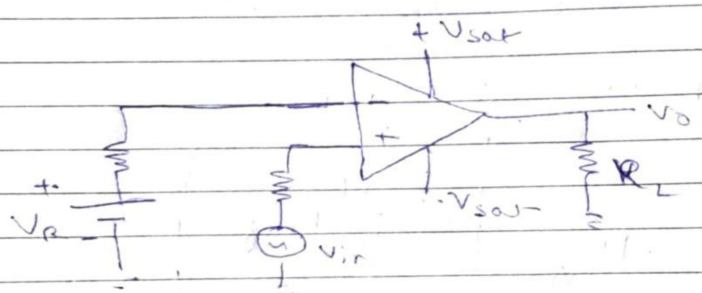
Comparator

A comparator as its name implies compares a s/g voltage on one i/p of an opamp with a known voltage called reference voltage on the other i/p and produces an o/p based on the comparision. ~~Comparator~~ are Types of Comparator

(1) Inverting Comparator
(2) Non-inverting comparator

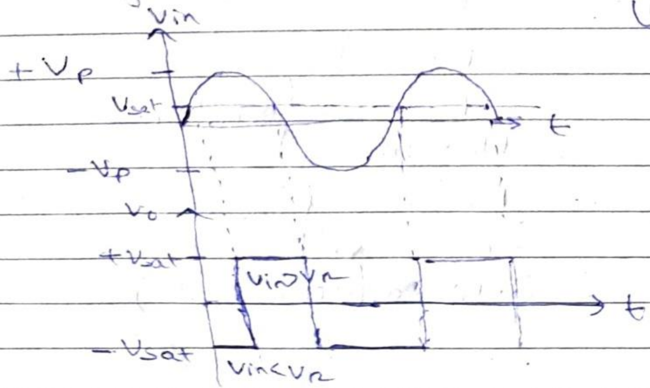
Non inverting comparator

(a). with +ve reference voltage



If $V_{in} > V_R$ $V_o = +V_{sat}$
$V_{in} < V_R$ $V_o = -V_{sat}$

Thus V_o changes b/w $+V_{sat}$ and $-V_{sat}$



Let $V_{sat} = 2V$
$V_{in} = 5V$

(b) with -ve reference voltage :

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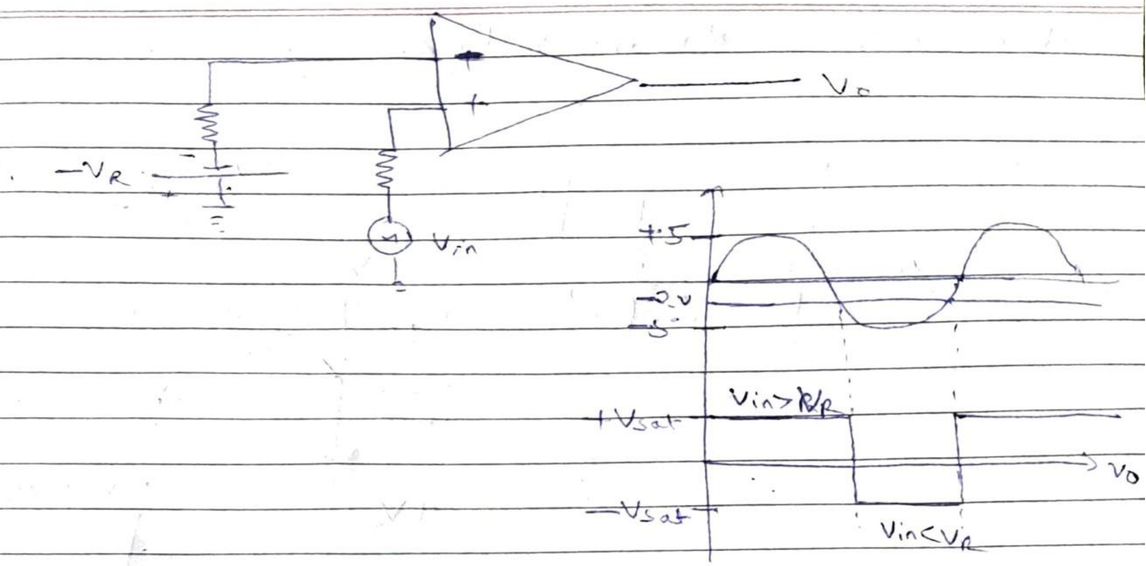
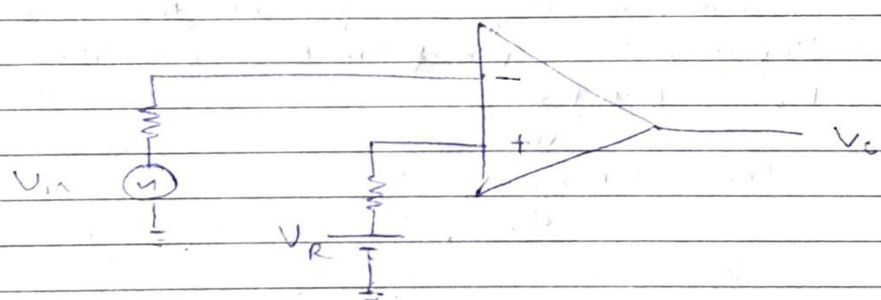
PAGE No 15
DATE : / 202



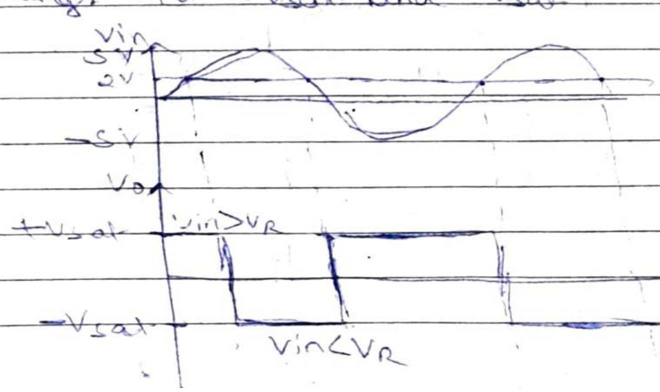
Inverting Comparator

(a) with the Reference voltage



If $V_{in} > V_R$ then $V_o = -V_{sat}$
$V_{in} < V_R$ then $V_o = +V_{sat}$

Thus V_o changes b/w $+V_{sat}$ and $-V_{sat}$. Let $V_{sat} = 2V$, $V_{in} = 5V$



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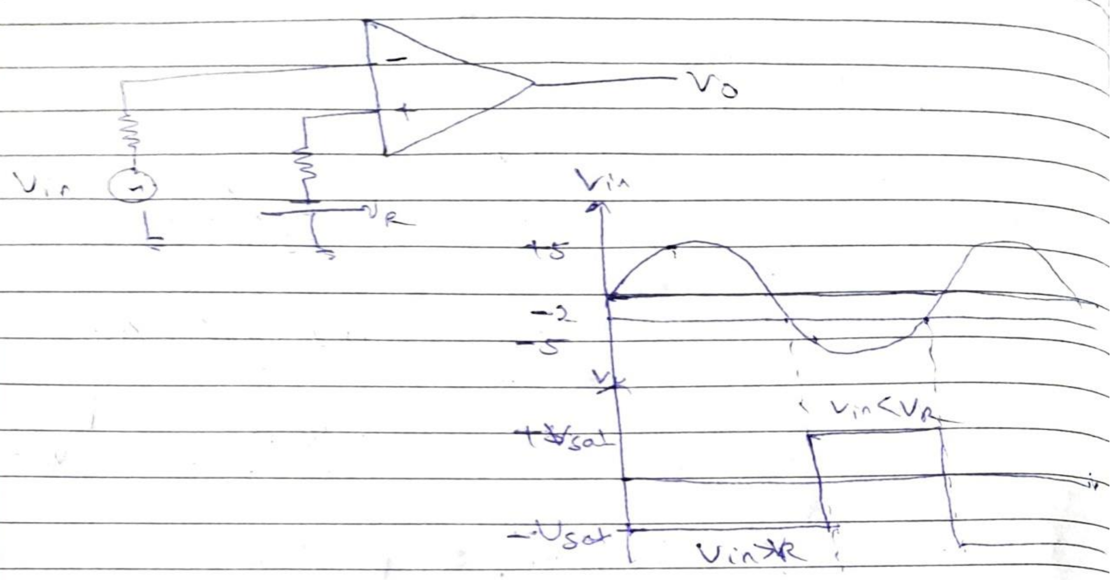
PAGE No 16
DATE : / 202

(b) With -ve Reference voltage :-



Q Design a non-inverting amplifier ckt that is capable of providing a voltage gain of 10. Assume an ideal opamp.

Sol

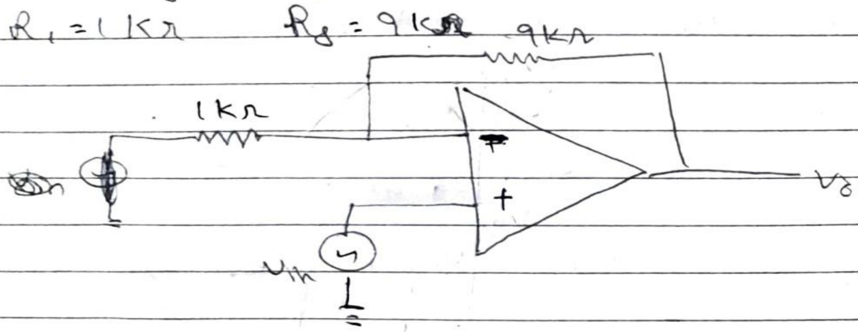
$$A_{vf} = 1 + \frac{R_f}{R_1}$$

$$10 = 1 + \frac{R_f}{R_1}$$

$$\frac{R_f}{R_1} = 10$$

$$R_f = 10 R_1$$

let $R_1 = 1\,k\Omega$ $\quad R_f = 9\,k\Omega$



PAGE No 17
DATE / 202

Q In an opamp used as differentiator $R = 1\,M\Omega$ and $C = 1\,\mu F$. If $V_{in} = 2\sin 1000\pi t$ mV calculate the o/p voltage

Sol
$$V_o = -RC\frac{d}{dt}(V_{in})$$
$$= -10^6 \times 10^{-6}\frac{d}{dt}(2\sin 1000\pi t)\ mV$$
$$= -6.28\cos(1000\pi t)\ mV$$

Q Design an adder ckt using an opamp to get the o/p expression as under $V_o = -(V_1 + 10V_2 + 100V_3)$. It is given that $R_f = 100\,K\Omega$

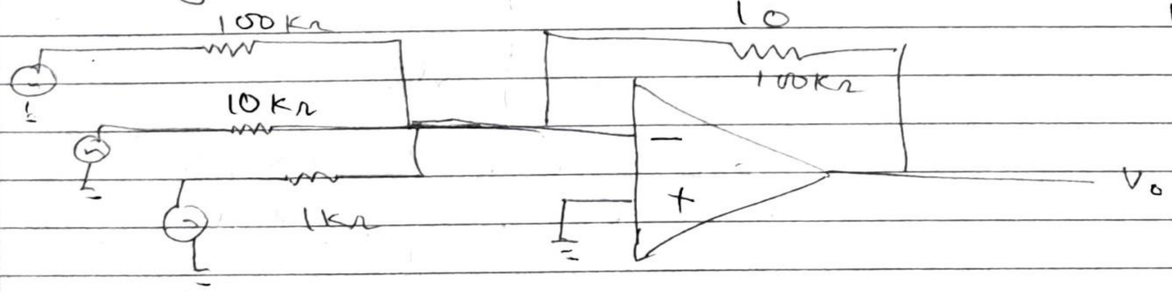
Sol
$$V_o = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right] = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right] \quad \text{—(1)}$$

and $V_o = -(V_1 + 10V_2 + 100V_3)$ —(2)

Compare eq (1) and (2)

$$\frac{R_f}{R_1} = 1, \quad \frac{R_f}{R_2} = 10 \quad \frac{R_f}{R_3} = 100$$

$R_1 = R_f = 100\,K\Omega$, $R_2 = \frac{R_f}{10} = 10\,K\Omega$ $R_3 = \frac{R_f}{100} = 1\,K\Omega$



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