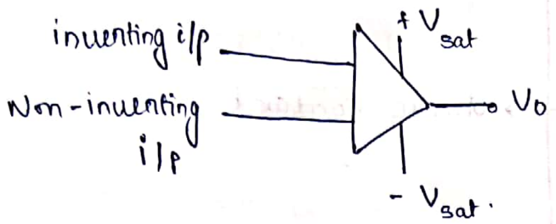
Op - Amp

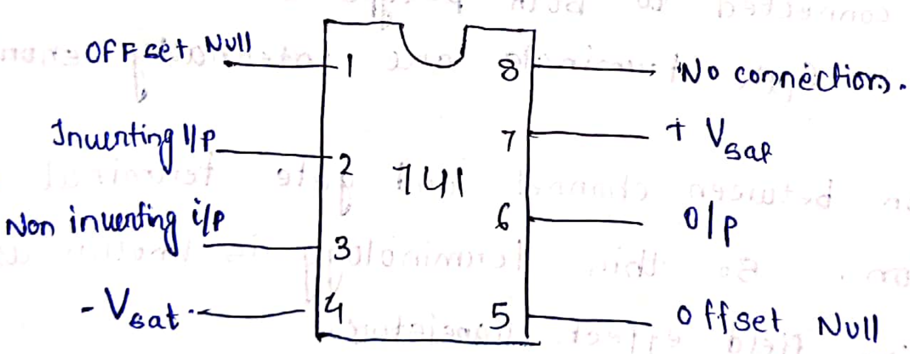
Circuit Diagram



Pin Diagram of Op. Amp.

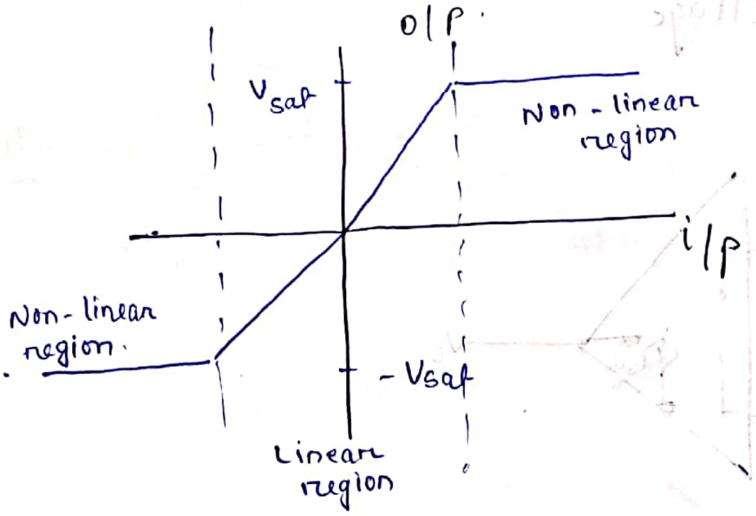
Op - Amp is an 8 pin I.C.

Its IC number is 741



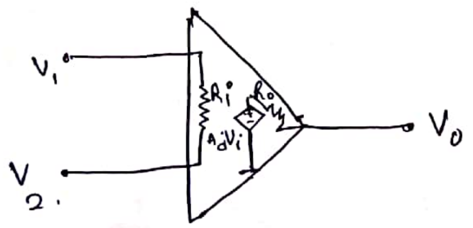
Transfer characteristics of Op-Amp.

It is the characteristics curve between i/p and o/p.



In case of Op-Amp, o/p voltage lies between -Vsat to +Vsat —— $(-V_{sat} \leqslant V_0 \leqslant +V_{sat})$

Characteristics of Ideal Op-Amp.



$\boxed{V_i = V_1 - V_2}$

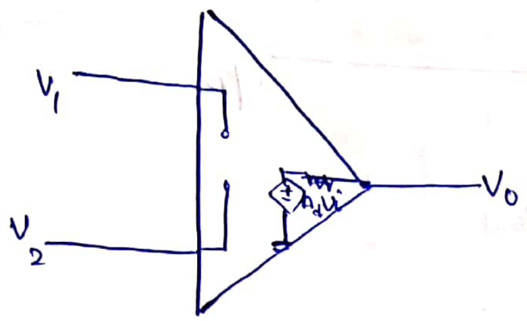
R_o = output impedance of Op-Amp
R_i = i/p impedance of Op-Amp
A_d = voltage gain of Op-Amp
V_i = voltage difference between inverting and non-inverting terminal.

1. I/P impedance of ideal Op-Amp is infinite.
2. O/P impedance of Op-Amp is zero.
3. voltage gain of Op-Amp is very high.

5. CMRR (common mode rejection ratio) is infinite.

6. slew rate is very less (i.e. 0)

7. No offset voltage.



* Application of Op-Amp in Linear region.

1. Inverting Amplifier ($+V_{sat} \geq V_0 \geq -V_{sat}$)
2. Non-Inverting Amplifier.
3. Summing Amplifier
4. Differential Amplifier
5. Differentiator
6. Integrator.

* Virtual Ground :

In case of ground, potential at any point on the ground is 0 volt & potential difference will be 0 V & maximum current is going into the ground.

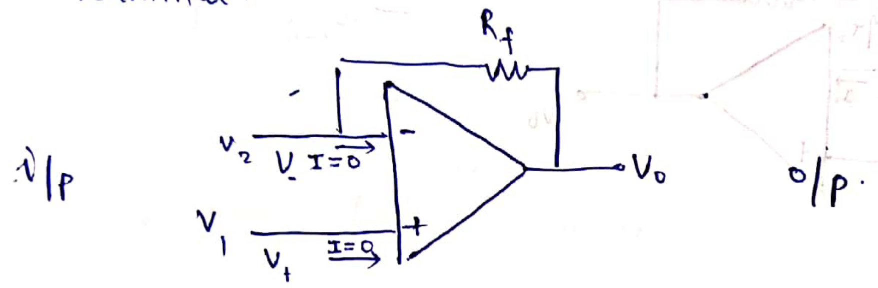
~~In case of ground, potential at any point~~

But in case of virtual ground in op-Amp. Potential at non-inverting terminal is equal to potential at inverting terminal. (~~not vice-versa~~)

Hence p.d between non-inverting and inverting terminal is 0, and no current is flowing between inverting & non-inverting terminal.

Condition for virtual ground in Op-Amp.

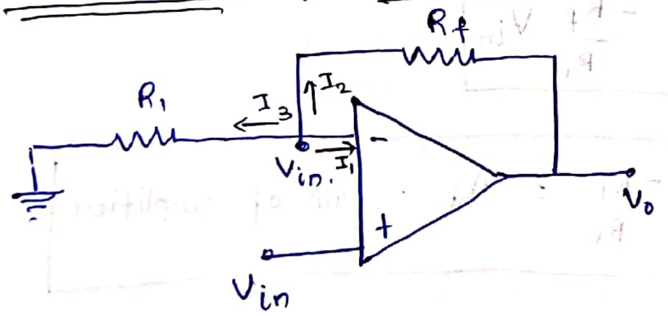
1. There should be a negative feedback from o/p to inverting terminal.



2. Op-Amp should have a very high gain $(A_d \approx 10^6 \approx \infty)$

$$\boxed{\begin{array}{c} V_+ = V_- \\ I = 0 \end{array}}$$

→ **Non-Inverting Op-Amp.**



Input is applied at non-inverting terminal of Op-Amp.

We have virtual ground present in the Op-Amp.

Applying nodal analysis at inverting terminal.

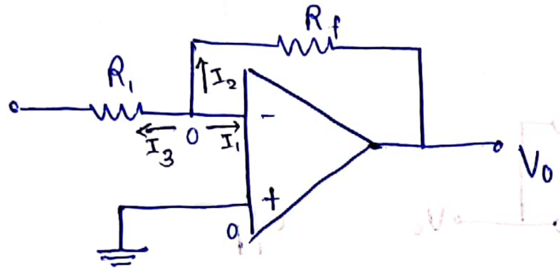
$$I_1 + I_2 + I_3 = 0$$

$$0 + \frac{V_{in} - V_o}{R_f} + \frac{V_{in} - 0}{R_1} = 0 \Rightarrow \boxed{V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}}$$

$$\Rightarrow \frac{V_0}{V_{in}} = \boxed{A_v = \left(1 + \frac{R_f}{R_1}\right)} \rightarrow \text{gain of non-inverting amplifier}$$

30/03/2020

→ Inverting Amplifier, Op-Amp



→ In inverting amplifier, the i/p is applied through the ~~non~~-inverting terminal and non-inverting terminal is grounded.

Applying Nodal Equation at inverting terminal,

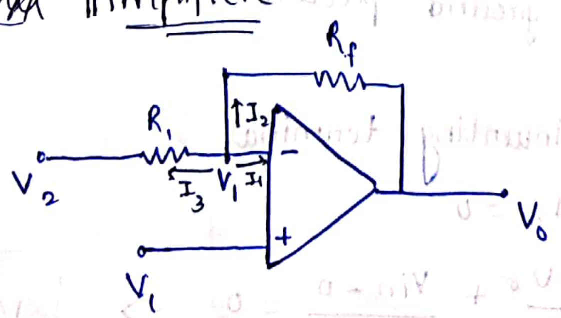
$$I_1 + I_2 + I_3 = 0.$$

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

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

$$\Rightarrow \boxed{\frac{V_0}{V_{in}} = -\frac{R_f}{R_1} = A_d = \text{gain of amplifier}}$$

→ Differential Amplifier



In differential amplifier, the input is applied at both inverting & non inverting terminal.

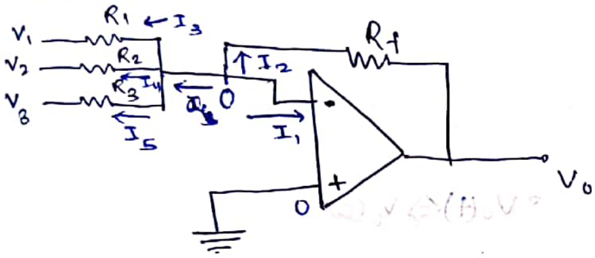
Applying nodal at inverting terminal,

$$I_1 + I_2 + I_3 = 0$$

$$\Rightarrow \quad 0 + \frac{V_1 - V_0}{R_f} + \frac{V_1 - V_2}{R_1} = 0 \quad \Rightarrow \frac{V_0}{R_f} = \frac{V_1 - V_2}{R_1} + \frac{V_1}{R_f}.$$

$$\Rightarrow \quad \boxed{V_0 = R_f\left(\frac{V_1 - V_2}{R_1} + \frac{V_1}{R_f}\right)}$$

Summing Amplifier (Adder / Sumer)



Appling Nodal at inverting terminal,

$$I_1 + I_2 + I_3 + I_4 + I_5 = 0$$

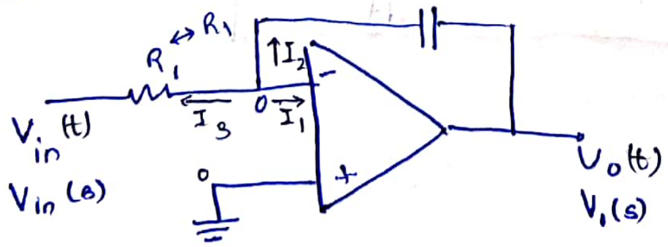
$$\Rightarrow \quad 0 + \frac{0 - V_0}{R_f} + \frac{0 - V_1}{R_1} + \frac{0 - V_2}{R_2} + \frac{0 - V_3}{R_3} = 0$$

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

Considering $R_1 = R_2 = R_3 = R_f$, $\boxed{V_0 = -(V_1 + V_2 + V_3)}$

Integrator

$C \rightarrow \frac{1}{CS}$



$$C \xrightarrow{L.T} \frac{1}{CS} \qquad L \xrightarrow{L.T} LS$$

Note :- $L\{x(t)\} \rightarrow X(s)$

$$L\left\{\frac{d}{dt}x(t)\right\} \leftrightarrow sX(s)$$

$$L\left\{\int x(t)\,dt\right\} \leftrightarrow \frac{X(s)}{s}.$$

Applying nodal at inverting terminal,

$$I_1 + I_2 + I_3 = 0$$

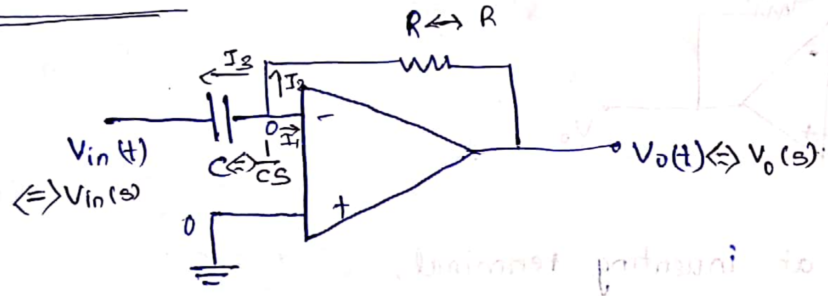
$$\Rightarrow 0 + \frac{0 - V_0(S)}{\frac{1}{CS}} + \frac{0 - V_{in}(s)}{R_1} = 0$$

$\Rightarrow \cancel{V_0(s) \Rightarrow -\frac{CS\,V_{in}(s)}{R}}$ $\Rightarrow$ $\boxed{V_0(s) = \frac{-1}{RC}\frac{V_{in}(s)}{s}}$

By ~~writin~~ converting $V_0(s)$ to t domain,

$$\boxed{V_0(t) = \frac{1}{RC}\int V_{in}(t)\,dt}$$

→ Differentiatore



Applying Nodal analysis to inverting terminal

$$I_1 + I_2 + I_3 = 0$$

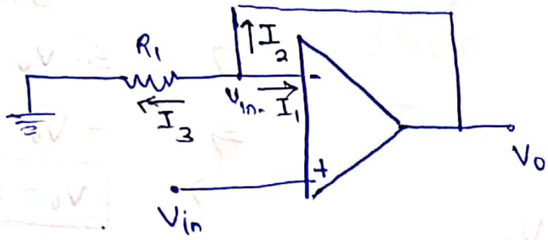
$$\Rightarrow 0 + \frac{0 - V_0(s)}{R} + \frac{0 - V_{in}(s)}{\frac{1}{CS}} = 0$$

$$\Rightarrow V_0(s) = -RC\,(s\,V_{in}(s))$$

Converting the signal to 't' domain

$$\Rightarrow \boxed{V_0(t) = -RC\frac{d\,V_{in}(t)}{dt}}$$

Buffer or Unit Gain Amplifier or Voltage follower.

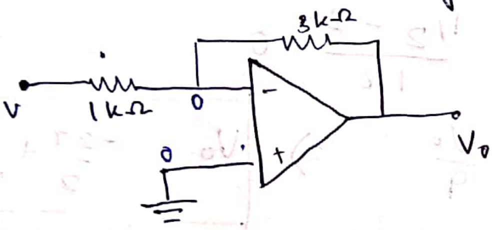


$\Rightarrow \quad V_{in} = V_o \Rightarrow \boxed{V_o = V_{in}}$

$\Rightarrow \quad \boxed{\frac{V_o}{V_{in}} = 1}$

Numerical Problem Solving

1. Determine the output voltage for the following circuits.



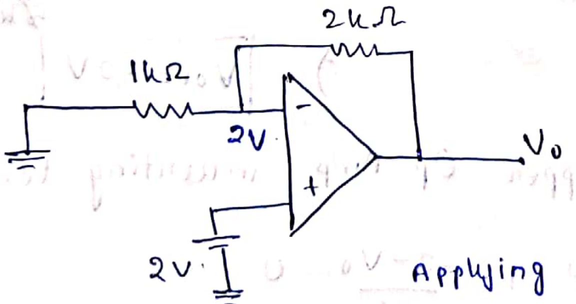
Applying Nodal at inverting terminal.

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

$$\Rightarrow \frac{-V_o}{3k} = \frac{2}{1k}$$

$$\Rightarrow \boxed{V_o = -6V}$$

2.

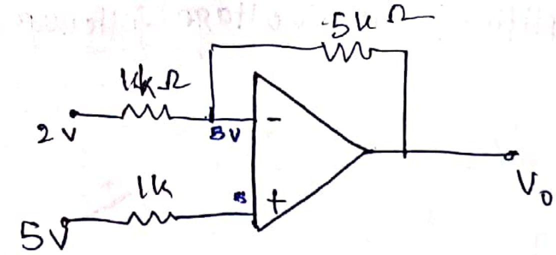


Applying Nodal at inverting terminal

$$0 + \frac{2 - 0}{1k} + \frac{2 - V_o}{2k} = 0$$

$$\Rightarrow 2 - V_o = \frac{-2}{1k} \times 2k \qquad \Rightarrow \boxed{V_o = 6V}$$

Q3



Applying Nodal at inverting terminal.

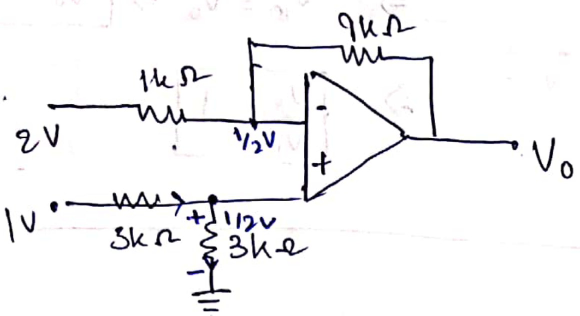
$$0 + \frac{5-V_0}{5k} + \frac{5-2}{1k} = 0$$

$$\Rightarrow 5 - V_0 = -3 \times 5$$

$$\Rightarrow -V_0 = -20$$

$$\Rightarrow \boxed{V_0 = 20V}$$

Q4

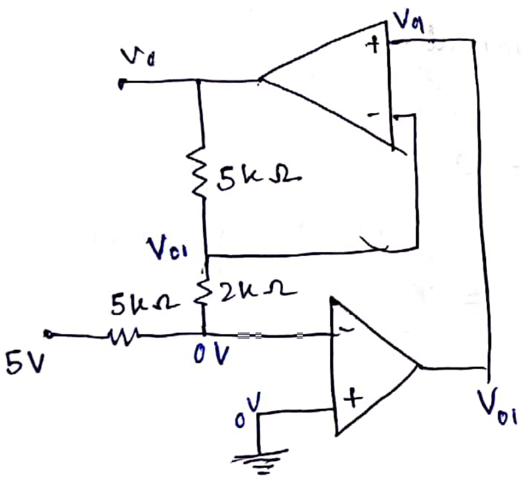


Applying nodal at inverting terminal.

$$0 + \frac{1/2 - V_0}{9k} + \frac{1/2 - 2}{1k} = 0$$

$$\Rightarrow -\frac{3}{2} + \frac{1}{18} = \frac{V_0}{9} \Rightarrow \boxed{V_0 = -\frac{27}{2} + \frac{1}{2} = -13V}$$

Q5.



Applying Nodal at lower Op-Amp inverting terminal.

$$0 + \frac{0 - V_{01}}{2k} + \frac{0-5}{5k} = 0$$

$$\Rightarrow -V_{01} = \frac{\cancel{5}}{\cancel{5k}} \times 2\cancel{k}$$

$$\Rightarrow \boxed{V_{01} = -2V}$$

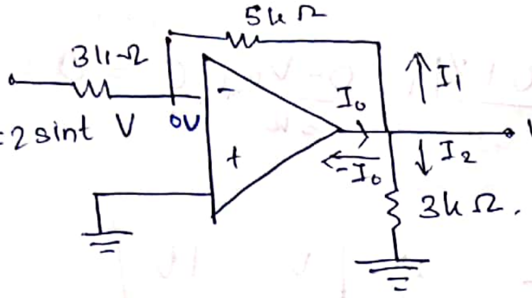
Applying Nodal at upper Op-Amp inverting terminal,

$$0 + \frac{-2-0}{2k} + \frac{-2-V_0}{5k} = 0$$

$$\Rightarrow -2 - V_0 = 5$$

$$\Rightarrow \boxed{V_0 = -7V}$$

6. Determine V_o & I_o for circuit shown.



Applying Nodal at inverting terminal,

$$0 + \frac{0 - V_o}{5k} + \frac{0 - 2\sin t}{3k} = 0.$$

$$\Rightarrow V_o = -\frac{10}{3}\sin t \text{ V}.$$

~~Now, $I_o = \frac{V_o}{3k\Omega} = -\frac{10}{9}\sin t$ mA.~~

Applying Nodal,

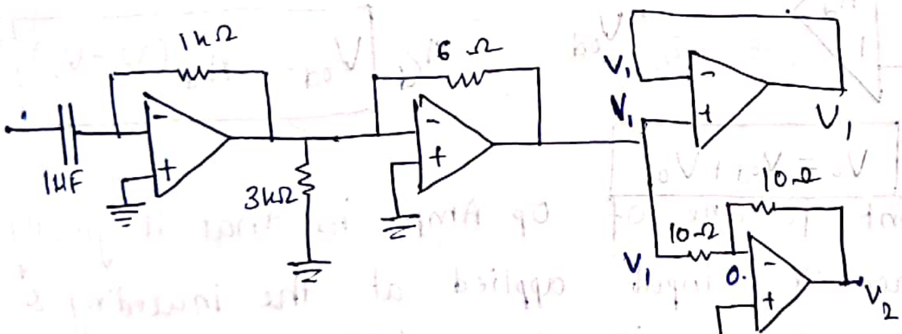
$$-I_o + I_1 + I_2 = 0$$

$$\Rightarrow I_o = I_1 + I_2$$

$$= \frac{V_o - 0}{5k} + \frac{V_o - 0}{3k}.$$

$$= \frac{8V_o}{15k} = -\frac{8 \times 10^2}{15 \times 3_3} = -\frac{16}{9}\sin t \text{ mA}.$$

Q7. Determine the relation between V_1 & V_2.

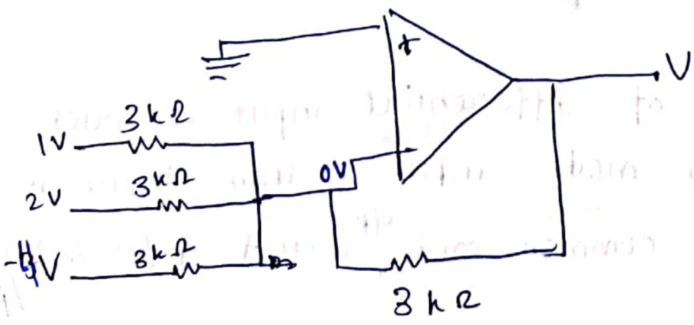


Applying Nodal,

$$\frac{0 - V_1}{10} + \frac{0 - V_2}{10} + 0 = 0$$

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

Q8



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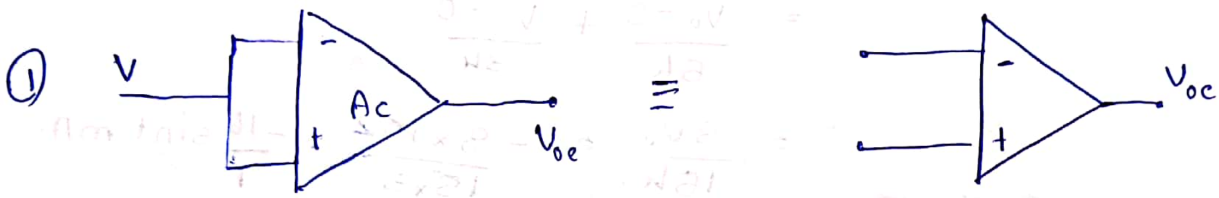
Applying Nodal,

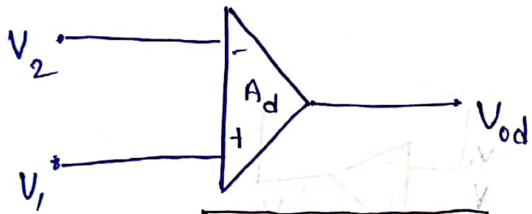
$$\frac{0-1}{3k} + \frac{0-2}{3k} + \frac{0+4}{3k} + \frac{0-V_o}{3k} + 0 = 0$$

$$\Rightarrow \frac{V_o}{3k} = \frac{1}{3k} \Rightarrow \boxed{V_o = 1V}$$

Common Mode Rejection Ratio (CMRR)

① 

$$\boxed{V_{oc} = A_c \times V}$$

② 

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

$$\boxed{V_o = V_{od} + V_{oc}}$$

• One of the important feature of Op-Amp is that it greatly amplifies the differential input applied at the inverting & non-inverting terminal and it also slightly amplifies the signal that are both common to both inverting & non inverting terminal.

So, the total output in Op-Amp is due to both differential as well as common mode output.

→ since the amplification of differential input is much greatere than common mode input, then there is a chance of rejection of common mode o/p w.r.t differential o/p.

This rejection is described by a numerical factore which is called CMRR.

CMRR is defined as the ratio of differential gain to the common mode gain.

$$\boxed{CMRR \triangleq \frac{A_d}{A_c}}$$

A_d: Differential Gain

A_c = Common mode gain

* Power Gain in Absolute Scale.

$$\boxed{A_p = \frac{P_o}{P_{in}}}$$

* Power Gain in Logarithmic scale. (dB)

$$\boxed{A_p\Big|_{dB} = 10 \log_{10} \frac{P_o}{P_{in}}}$$

* Voltage Gain.

$A_v = \frac{V_o}{V_{in}}$ → Absolute scale

$A_v\Big|_{dB} = 20 \log_{10}\left(\frac{V_o}{V_{in}}\right) dB$ → dB scale

$A_I = \frac{I_o}{I_{in}}$. → Absolute Scale

$A_I\Big|_{dB} = 20 \log_{10}\left(\frac{I_o}{I_n}\right) dB$ → dB scale.

- $CMRR = \frac{A_d}{A_c}$ → Absolute scale.
- $CMRR = 20 \log_{10}\left(\frac{A_d}{A_c}\right) dB$ → dB scale.

Q In an Op-Amp with ~~V_{od}~~ $A_d = 10^6$ & CMRR is 20dB, what is the ~~com~~ ~~V~~ A_c?

Ans: ~~$20 \quad 20 \log_{10}\left(\frac{10^6}{A_c}\right) dB$~~.

$CMRR = \frac{A_d}{A_c} \Rightarrow CMRR = \frac{10^6}{A_c}$

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

$\Rightarrow \cancel{20} = \cancel{20} \log_{10} CMRR$

$\Rightarrow \boxed{10^1 = CMRR}$

$\Rightarrow 10 = \dfrac{10^6}{A_c} \Rightarrow \boxed{A_c = 10^5}$

Q Repeat the above question with $A_d = 20dB$ and determine the value of A_c.

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

$\Rightarrow 1\cancel{20} = \cancel{20}\log 20 - \log A_c$

$\Rightarrow 1 - \log 20 = -\log A_c$

$\Rightarrow \cancel{\log}\ \log 2 = \log A_c \Rightarrow \boxed{A_c = 2}$

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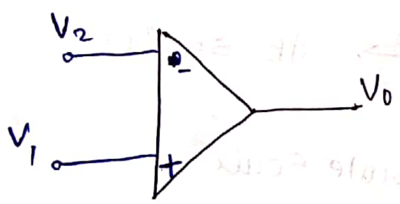
Continuation of CMRR



$$V_o = V_{oc} + V_{od}$$
$$= \underbrace{A_c}_{\text{common mode gain}} \cdot V_c + \underbrace{A_d}_{\text{Diff. mode gain}} \cdot V_d$$

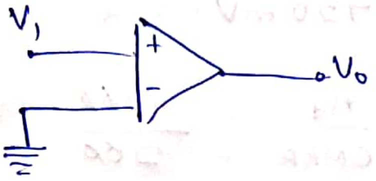
$V_c =$ common mode i/p $= V_1 + V_2 / 2$

$V_d =$ Diff. mode i/p $= V_1 - V_2$

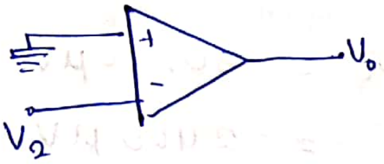
$$V_o = A_c\left(\frac{V_1+V_2}{2}\right) + A_d(V_1 - V_2)$$
$$= \left(\frac{A_c}{2} + A_d\right)V_1 + \left(\frac{A_c}{2} - A_d\right)V_2$$
$$= A_1V_1 + A_2V_2$$

where $A_1 = \frac{A_d + A_c}{2}$ $A_2 = \frac{A_c - A_d}{2}$.

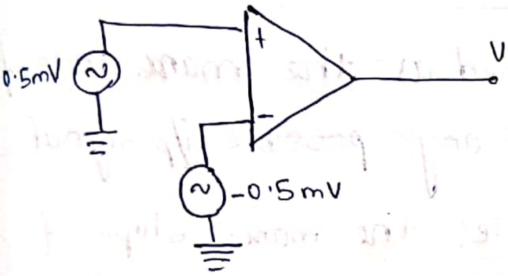
$A_1 = \frac{V_o}{V_1}\Big|_{V_2=0}$

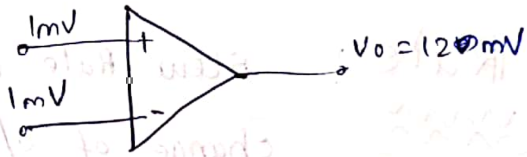


$A_2 = \frac{V_o}{V_2}\Big|_{V_1=0}$



Calculate CMRR for the setup shown below.





$V_{od} = 8V$ $V_{od} = 12mV$

$V_o = V_{oc} + V_{od} = \cancel{20V}\ 8V + 12mV$

$V_{oc} = A_c V_c = A_c \times \frac{V_1 + V_2}{2}$ $\Rightarrow$ $12\ mV = A_c \times 1mV$

$\Rightarrow \boxed{A_c = 12}$

$V_{od} = A_d V_d = A_d(V_1 - V_2) = A_d(0.5 - (-0.5))\ mV$

$\Rightarrow 8 = A_d\ 1mV \Rightarrow \boxed{A_d = 8000}$

$\boxed{CMRR = \frac{A_d}{A_c} = \frac{8000}{12}}$ $\Rightarrow$ Absolute scale

$CMRR\Big|_{dB} = 20\log_{10}\left(\frac{8000}{12}\right) dB$ $\Rightarrow$ Logarithmic scale.

Ex $V_{i_1} = 20\mu V$ $V_{i_2} = 140\ \mu V$ $A_d = 6000$ $CMRR = 200$

Determine the output voltage.

Sol: $V_o = V_{oc} + V_{od}$

$= A_d \cdot V_d + A_c V_c$

$\Rightarrow V_d = -120\ \mu V$ $V_c = 80\ \mu V$

$V_{od} = A_d \cdot V_d = -120\ \mu V \times 6000$
$= -720\ mV.$

$A_c = \dfrac{A_d}{CMRR} = \dfrac{6000}{200} = 30$

Now, $V_{oc} = A_c \cdot V_c = 30 \cdot 80\ \mu V$
$= 2400\ \mu V = 2.4\ mV$

So, $\boxed{V_o = (-720 + 2.4)\ mV = -717.6\ mV}$

* **Slew Rate:** Slew Rate is defined as the max. rate of change of o/p for any possible i/p signal of an Op-Amp. i.e. the max. slope of o/p of Op-Amp.

$$\text{Slew Rate} = \left.\frac{dV_o}{dt}\right|_{max.} \qquad \boxed{V/\mu s \ \text{Unit}}$$

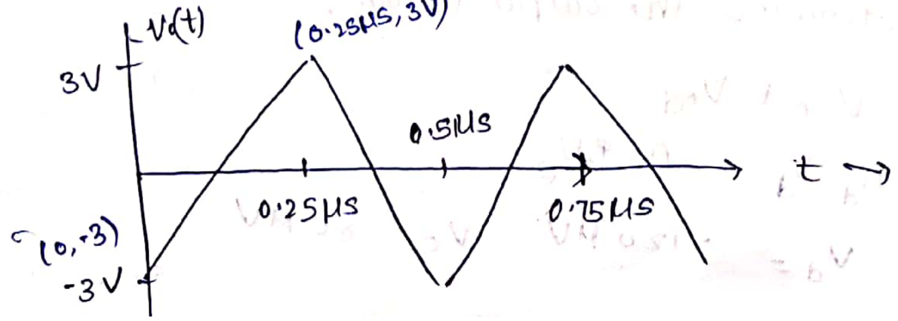
Q For an Op-Amp, $V_o = V_m \sin 2\pi f_m t$. Determine the slew rate of the Op-Amp.

$$\text{Slew rate} = \left.\frac{dV_o}{dt}\right|_{max} = V_m \frac{d \sin 2\pi f_m t}{dt}$$

$$= 2\pi V_m f_m \cos 2\pi f_m t \,\Big|_{max}$$

$$\boxed{S.R = 2\pi f_m V_m,\ V/\mu s}$$

Q Determine the slew Rate of the given o/p of the Op-Amp which is shown below.



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$$S.R = \left.\frac{dV_o}{dt}\right|_{max} = \frac{[3-(-3)]\,V}{0.25\ \mu s} = \frac{6\ V}{0.25\ \mu s} = 24\ V/\mu s$$

Block Diagram of Op-Amp