3. Linear & Non-linear applications of Op-Amp

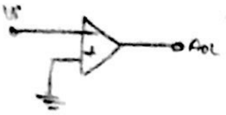
Op-Amp Configuration

- Open loop configuration
  - Inverting
  - Non-inverting
  - Differential Amplifier
- closed loop configuration

Inverting:

$$A_{OL} = \frac{V_o}{V_d} = \frac{V_o}{V_2 - V_1}$$

$$= \frac{V_o}{-V_1} = -\left(\frac{V_o}{V_1}\right)$$



Non-inverting:

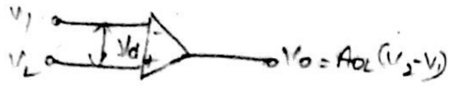
$$A_{OL} = \frac{V_o}{V_d} = \frac{V_o}{V_2 - V_1}$$

$$= \frac{V_o}{V_2 - 0} = \frac{V_o}{V_2}$$

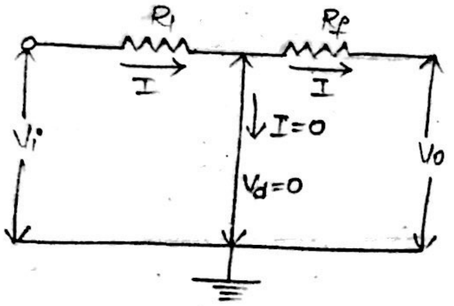
Differential Amplifier:

$$A_{OL} = \frac{V_o}{V_d} = \frac{V_o}{V_2 - V_1}$$

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



Virtual Ground Concept :-



Virtual ground is defined as the differential voltage (V_d) b/w inverting and Non-inverting terminals is zero such concept is called as Virtual ground concept. It is designed as follows by using the open loop gain i.e;

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

If $V_o = 10V$ and $A_{OL} = 10^4$ then

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

$$= \frac{10V}{10^4}$$

$$= 0.001$$

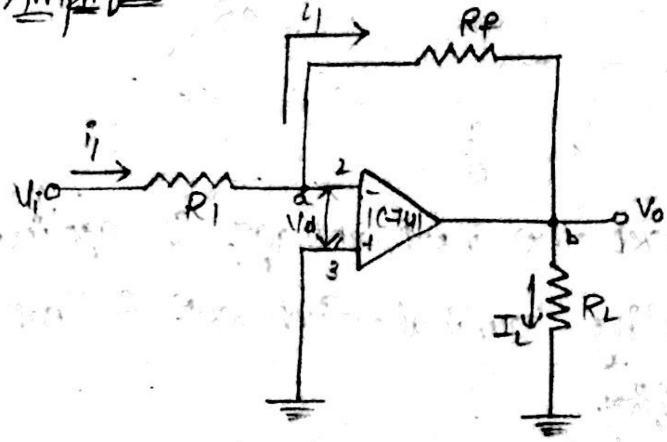
By using practical conditions on Op-Amp A_{OL} is infinity and $V_o = 10V$

$$V_d = \frac{V_o}{A_{OL}} = \frac{10}{\infty} = 0$$

$\therefore V_2 - V_1 = 0$

$$\boxed{V_2 = V_1}$$

Inverting Amplifier:-



From the fig. the flow of current through the resistor R_1 is

$$\boxed{i_1 = \frac{V_i}{R_1}} \text{ ——— } ①$$

The o/p voltage at the o/p terminal with the feed back resistor R_f is

$$\boxed{V_o = -i_1 \cdot R_f} \text{ ——— } ②$$

Sub. eq ① in eq ②

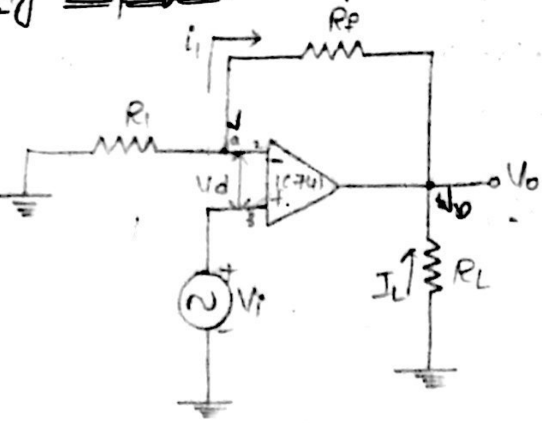
$$V_o = -\left(\frac{V_i}{R_1}\right) \cdot R_f$$

$$\boxed{V_o = -\left(\frac{R_f}{R_1}\right) V_i} \text{ ——— } ③$$

From the eq ③ '-ve' sign indicates the inverting terminal and the o/p voltage both are in 180° out of phase. Then the closed loop gain

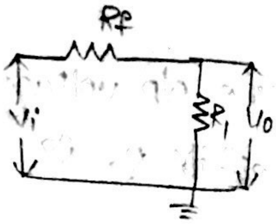
$$\boxed{A_{CL} = \frac{V_o}{V_i} = -\left(\frac{R_f}{R_1}\right)}$$

Non-inverting Amplifier:-



From the ckt the input voltage is applied only from the non-inverting terminal. Such ckt is called as Non-inverting amplifier.

W.K.T the differential voltage at the i/p terminal is zero and at node 'a' the voltage is considered as the input voltage then by using a potential divider rule V_i is



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

$$\frac{V_i}{V_o} = \frac{R_1}{R_1+R_f}$$

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

$$\boxed{A_{CL} = \frac{V_o}{V_i} = \left(1+\frac{R_f}{R_1}\right)}$$

Problem:-

① From the inverting amplifier consider $R_1 = 10K\Omega$, $R_f = 100K\Omega$, $V_i = 1V$ and a load resistor of $R_L = 25K\Omega$ is connected to the o/p terminal. Calculate (i) current i_1 (ii) o/p voltage V_o (iii) load current I_L (iv) total current I_o at the output.

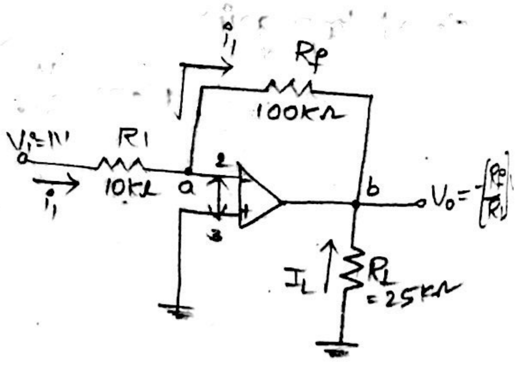
Sol: Given data is

$R_1 = 10K\Omega$

$R_f = 100K\Omega$

$V_i = 1V$

$R_L = 25K\Omega$



(i) $i_1 = \frac{V_i}{R_1} = \frac{1}{10k\Omega} = 0.1mA.$

(ii) $V_0 = -\left(\frac{R_f}{R_1}\right)V_i.$

$= -\left(\frac{100k\Omega}{10k\Omega}\right)1V = -10V$

(iii) $I_L = \frac{V_0}{R_L} = \frac{-10}{25k\Omega} = -0.4mA.$

The load current I_L flows into the circuit then consider

$I_L = 0.4mA.$

(iv) $I_0 = i_1 + i_L = 0.1 + 0.4$

$= 0.5mA.$

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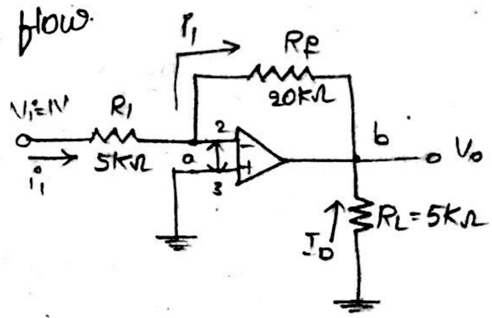
(2) From the non-inverting amplifier consider $R_1 = 5K\Omega$, $R_F = 20K\Omega$, $V_i = 1V$, $R_L = 5K\Omega$ is connected to the o/p voltage. Calculate (i) o/p vol. V_0 (ii) closed loop gain (A_{CL}). (iii) Load current I_L (iv) o/p current I_0 indicating the proper direction of flow.



Sol:- Given data is

$R_1 = 5K\Omega$, $R_f = 20K\Omega$

$V_i = 1V$, $R_L = 5K\Omega$

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

$= \left(1 + \frac{20}{5}\right)1 = 5$

(ii) $A_{CL} = \frac{V_0}{V_i} = \frac{5}{1} = 5.$

(iii) load current $I_L = \frac{V_0}{R_L} = \frac{5}{5K\Omega} = 1mA.$

(iv) $I_0 = I_1 + I_L$

where $I_1 = \frac{V_i}{R_1} = \frac{1}{5K\Omega} = 0.2mA.$

$I_0 = 0.2 + 1$

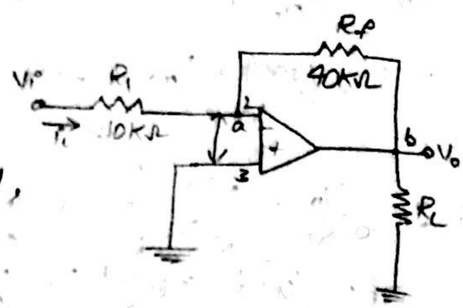
$= 1.2mA.$

from the o/p current $I_0 = 1.2mA$, the direction of current flows to the o/p voltage.

③ Design an amplifier with a gain of +5 using an op-Amp and assume $R_1 = 10K\Omega$. Calculate the feedback resistor R_F.

Sol:- Given $R_1 = 10K\Omega$

gain $A = +5V$



By using non-inverting amplifier,

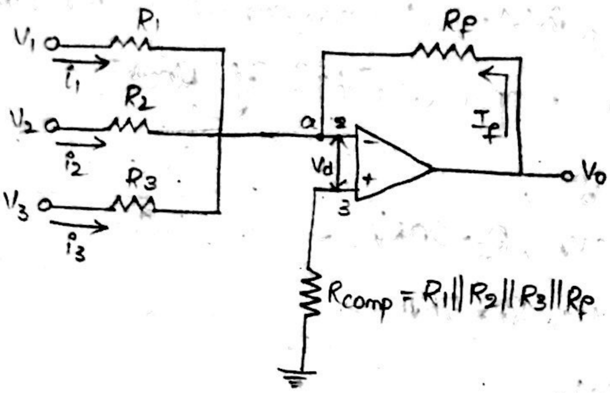
$$A = 1 + \frac{R_F}{R_1}$$

$$5 = 1 + \frac{R_F}{10K\Omega}$$

$$R_F = 40K\Omega$$

Summing Amplifier (or) Adder circuits :-

(i) Inverting Summing Amplifier:-



From the fig. by applying KCL at node 'a'

$$i_1 + i_2 + i_3 + i_f = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_o}{R_f} = 0.$$

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

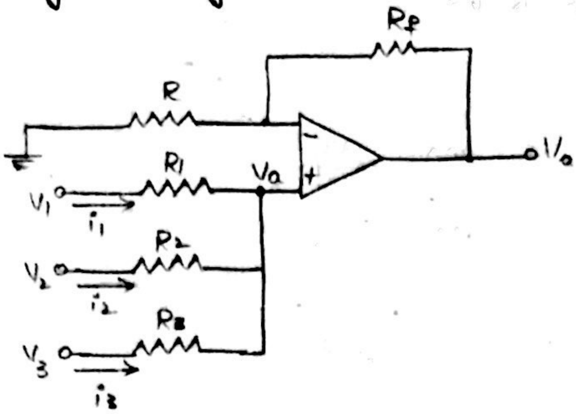
From the inverting terminals of all the resistors are weighted resistors then consider $R_1 = R_2 = R_3 = R_f$ then eq ① becomes.

$$\boxed{V_o = -\left[V_1 + V_2 + V_3\right]}$$

For suppose $R_1 = R_2 = R_3 = 3R_f$.

$$V_0 = -\frac{1}{3}\left[V_1+V_2+V_3\right].$$

(ii) Non-inverting Summing amplifier:-



From the fig. by applying nodal equation at node 'a' then the eq^n can be written as

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

$$\boxed{V_a = \frac{\frac{V_1}{R_1}+\frac{V_2}{R_2}+\frac{V_3}{R_3}}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}}} \text{ ——— } (1).$$

W.K.T from the non-inverting amplifier with resistors R_F and R the o/p voltage V_o is

$$V_o = \left(1+\frac{R_F}{R}\right)V_a \text{ ——— } (2).$$

sub. eq (1) in eq (2).

$$V_o = \left(1+\frac{R_F}{R}\right)\left[\frac{\frac{V_1}{R_1}+\frac{V_2}{R_2}+\frac{V_3}{R_3}}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}}\right] \text{ ——— } (3)$$

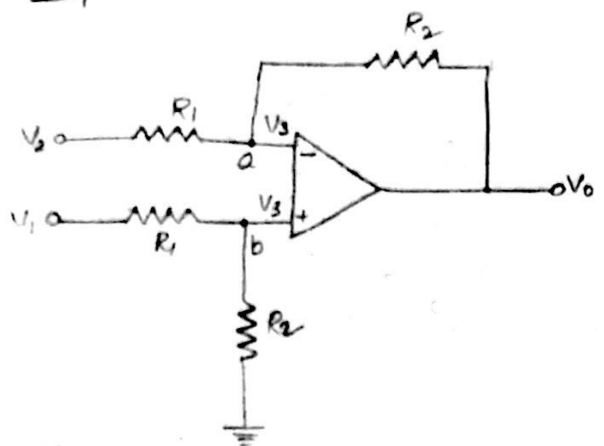
By using non-inverting weighted sum of inputs let us consider

$R_1=R_2=R_3=R=\frac{R_F}{2}$.

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

$V_0 = V_1 + V_2 + V_3$

Difference Amplifier (or) Subtractor :-



The difference amplifier is said to be the difference b/w the two i/p voltages. This difference amplifier is used in industrial instrumentation application.

From the fig. nodal eq^n at node 'a' is

$$\frac{V_2 - V_3}{R_1} + \frac{V_3 - V_0}{R_2} = 0 \quad \text{—— (1)}$$

Similarly the nodal eq^n at node 'b' is

~~$(V_3 + V$~~

$$\frac{V_1 - V_3}{R_1} + \frac{V_3}{R_2} = 0 \quad \text{—— (2)}$$

$\frac{V_1}{R_1} - \frac{V_3}{R_1} + \frac{V_3}{R_2}$

$V_3\left[\frac{1}{R_2} - \frac{1}{R_1}\right] + \frac{V_1}{R_1} = 0$

from eq (1)

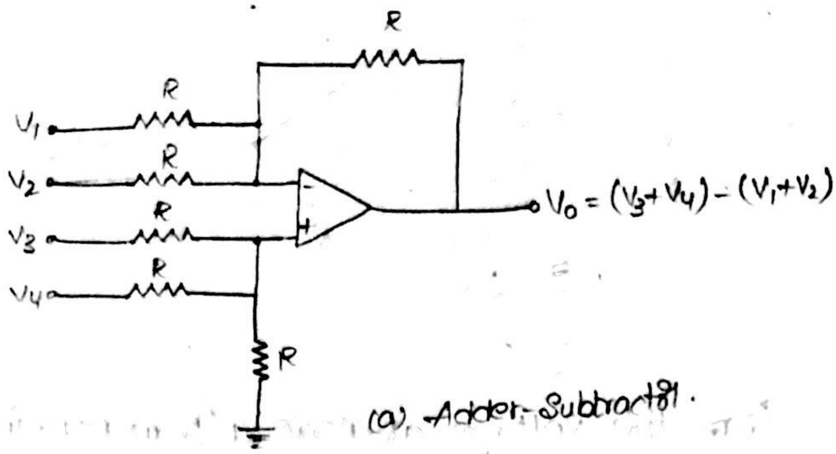
$$\frac{V_0}{R_2} = V_3\left[\frac{1}{R_1} + \frac{1}{R_2}\right] - \frac{V_2}{R_1} \quad \text{—— (3)}$$

from eq (2)

$$V_3\left[\frac{1}{R_2} + \frac{1}{R_1}\right] + \frac{V_1}{R_1} = 0 \quad \text{—— (4)}$$

Sub. eq (4) from eq (3).

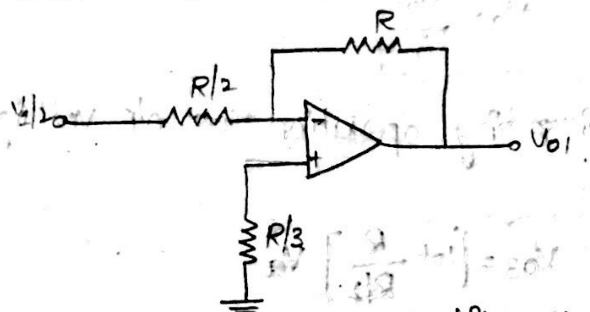
Adder - Subtractor :-



(a) Adder- Subtractor.

The Adder-Subtractor ckt is used for performing both addition and subtraction by using only one Op-Amp.

If we want to find out V_{01} due to V_1 alone is by using the fig (b)



(b) Simplifying circuit for $V_2 = V_3 = V_4 = 0$.

From the fig. the o/p voltage V_{01} is calculated from the inverting operation by making the voltages $V_2 = V_3 = V_4 = 0$ i.e; from fig(b) the o/p voltage

$$V_{01} = -\left(\frac{R}{R/2}\right)\frac{V_1}{2}$$

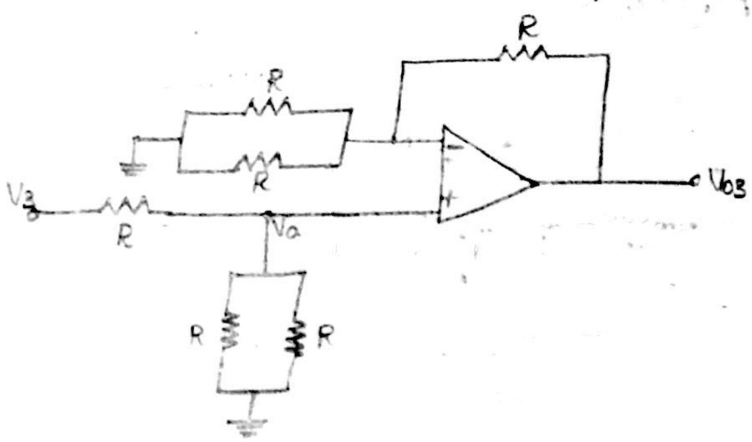
$$\boxed{V_{01} = -V_1}$$

Similarly the o/p voltage V_{02} due to V_2 alone is

$$V_{02} = -\left(\frac{R}{R/2}\right)\cdot\frac{V_2}{2}$$

$$\boxed{V_{02} = -V_2}$$

Now from fig(a) the o/p voltage V_{03} and V_{04} is calculated by using the following fig.



From the voltage at node 'a' from non-inverting terminal V_a is calculated by using a potential divider network

$$V_a = \left[\frac{R/2}{R+\frac{R}{2}}\right] V_3$$

$$\boxed{V_a = \frac{V_3}{3}}$$

From the non-inverting operation the o/p voltage V_{o3} due to V_3 alone is

$$V_{o3} = \left[1+\frac{R}{R/2}\right] V_a$$

$$= \left[1+\frac{R}{R/2}\right] \frac{V_3}{3}$$

$$\boxed{V_{o3} = V_3}$$

Similarly the o/p voltage V_{o4} due to V_4 alone is

$$\boxed{V_{o4} = V_4}$$

Therefore, the total output voltage

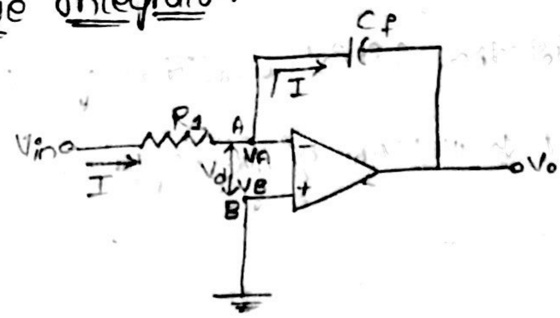
$$V_o = V_{o1} + V_{o2} + V_{o3} + V_{o4}$$

$$= -V_1 - V_2 + V_3 + V_4$$

$$\boxed{V_o = (V_3+V_4) - (V_1+V_2)}$$

Integrator

Ideal Active Integrator:-



the integrator is defined as the active elements are used like an op-Amp such integrator is called as Active Integrator. From the fig. we can observe that node B is grounded then by the virtual ground concept node A is also zero i.e;

$$V_A = V_B = 0$$

Now from the fig. the current flows through the resistor R_1 and capacitor C_f is also zero. Then i/p side the current is written as

$$I = \frac{V_{in} - V_A}{R_1}$$

$$I = \frac{V_{in} - 0}{R_1} \quad (\because V_A = V_B = 0)$$

$$\boxed{I = \frac{V_{in}}{R_1}} \text{ —— } ①$$

Similarly from the o/p side current I can be written as

$$I = C_f \frac{d}{dt}[V_A - V_0]$$

$$\boxed{I = C_f \frac{d}{dt}[-V_0]} \text{ —— } ②$$

Compare eq ① and ② we get

$$\frac{V_{in}}{R_1} = C_f \frac{d}{dt}[-V_0].$$

By applying integration on both sides by limitation 0 to t.

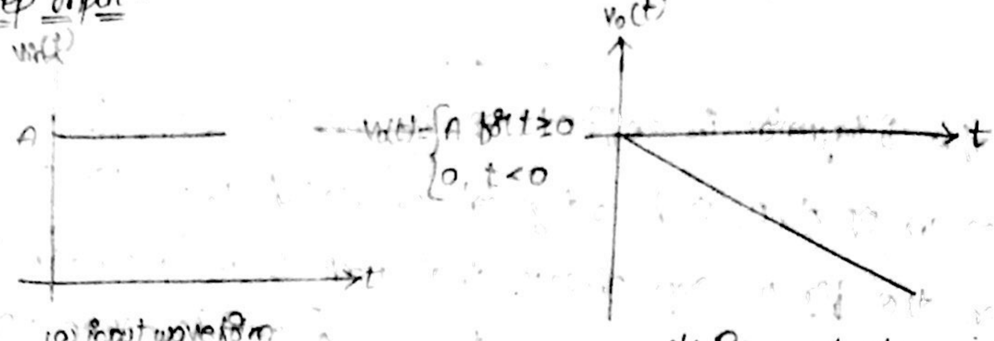
$$\int_0^t \frac{V_{in}}{R_1} = \int_0^t C_f \frac{d}{dt}[-V_0].$$

$$\boxed{V_o(t) = \frac{-1}{R_1 C_f}\int_0^t V_{in}(t) + V_o(0)}$$

where $V_o(0)$ is the initial condition of o/p voltage.

Input and Output Waveforms of Integrator:-

Step Input:-

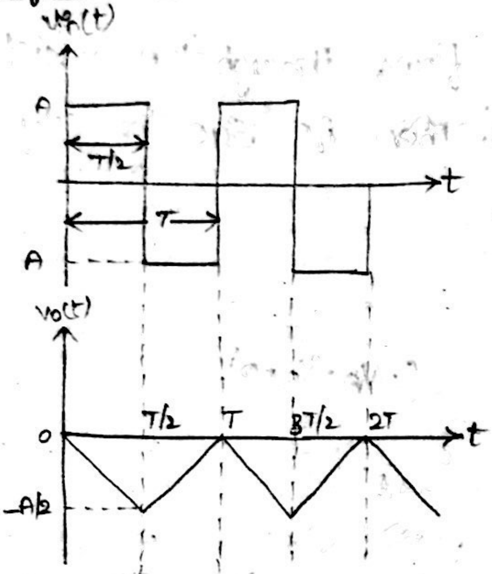


$$v_i(t) = \begin{cases} A & \text{for } t \geq 0 \\ 0, & t < 0 \end{cases}$$

(a) Input waveform

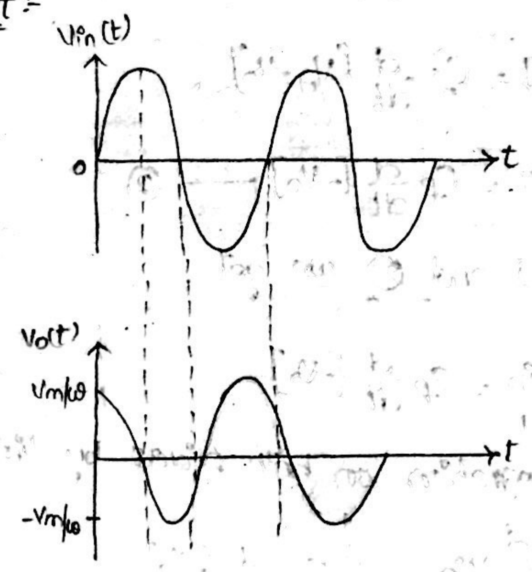
(b) Ramp output

Square wave input:-



$$V_i(t) = \begin{cases} A, & \text{for } 0 < t < T/2 \\ -A, & -\frac{T}{2} < t < T \end{cases}$$

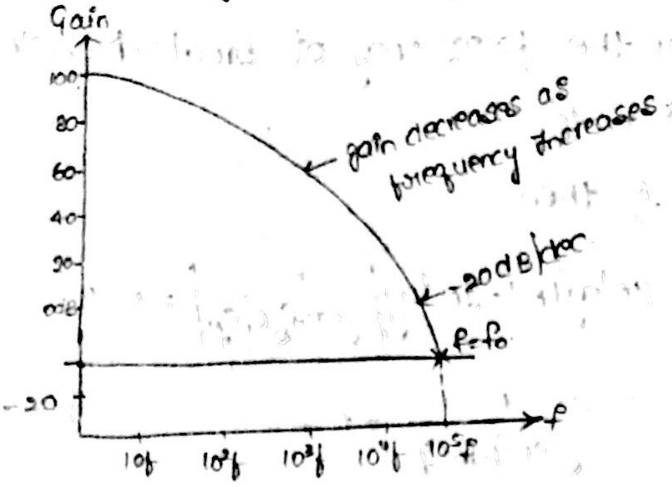
Sine wave input:-



$V_{in}(t) = V_m \sin\omega t$

$$V_o(t) = \frac{-1}{R_1 C_f}\int_0^t V_{in}(t) + V_o(0)$$

Frequency Response of ideal integrator:-



W.K.T for an ideal active integrator the output equation is

$$V_o(t) = \frac{-1}{R_1 C_f} \int_0^t V_{in}(t) + V_o(0)$$

where $V_o(0)$ is the initial conditions i.e, $V_o(0) = 0$.

$$\therefore V_o(t) = \frac{-1}{R_1 C_f} \int_0^t V_{in}(t) \text{ ——— } ①$$

Taking the Laplace transform on b.s then eq ① becomes

$$V_o(s) = \frac{-1}{R_1 C_f}\left[\frac{1}{s}\right] \cdot V_{in}(s) \quad \left[\because \int_0^t dt = \frac{1}{s}\right].$$

$$\frac{V_o(s)}{V_{in}(s)} = \frac{-1}{s R_1 C_f} \quad [\because s = j\omega].$$

Replace ~~s/jω~~ ~~then~~ s by jω then

$$\frac{V_o(j\omega)}{V_{in}(j\omega)} = \frac{-1}{j\omega R_1 C_f} = \frac{-1}{j 2\pi f R_1 C_f}$$

$$\boxed{|A| = \left|\frac{V_o(j\omega)}{V_{in}(j\omega)}\right| = \frac{1}{j 2\pi f R_1 C_f}}$$

At very low frequencies the gain becomes infinity this is because of the capacitive reactance is very high for low frequencies i.e,

$f=0$

and consider the frequency at break down the gain becom unity i.e; at 0dB.

Let $f=f_b$ then

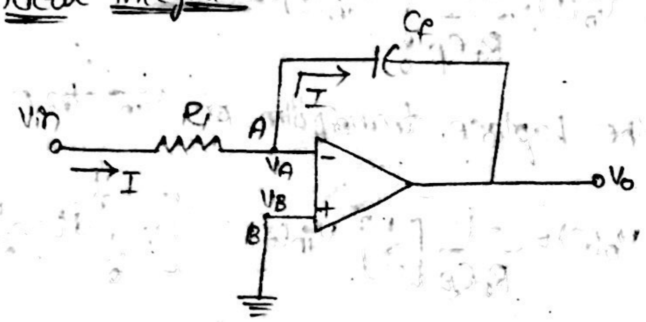
$$20\log|A| = 20\log\left|\frac{1}{j2\pi f_b R_1 C_f}\right| = 0dB$$

$$\frac{1}{j2\pi f_b R_1 C_f} = 1.$$

$$\boxed{f_b = \frac{1}{j2\pi R_1 C_f}}$$

From this break down frequency the gain drops to 0dB at frequency $f=f_b$ the gain rolls of at a rate of every 20dB/dec.

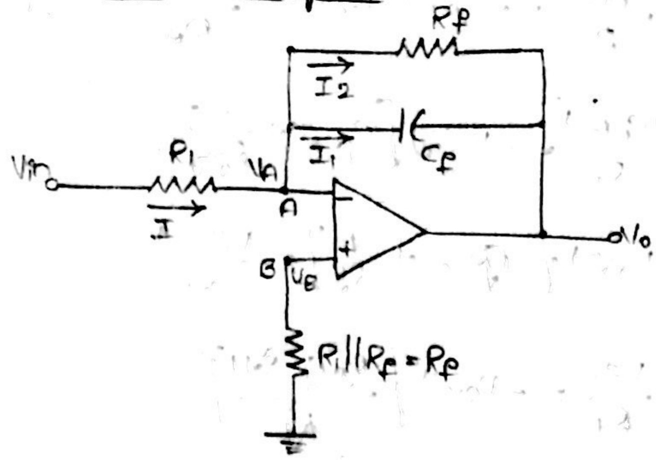
Errors in Ideal Integrator :-



By observing the ideal active integrator there are two errors will be produced, first error is produced in the presence of input signal. Those components are i/p offset voltage error and bias current error. By using these two errors the original integration is not possible due to that output waveforms may be destroyed by the i/p offset voltage error.

The limitation of ideal integrator is the B.W is very small due to this the ideal integrator cannot be used in practically.

Analysis of Practical Integrator



The practical integrator was used to overcome the drawbacks of ideal integrator. From the fig. by using the virtual ground concept at node 'B' the voltage is '0'. Similarly at node 'A' is also zero i.e;

$$V_A = V_B = 0.$$

From the fig.

$$I = \frac{V_{in} - V_A}{R_1} = \frac{V_{in}}{R_1} \quad (\because V_A = 0) \text{ ——— } (1)$$

Similarly,

$$I_1 = C_f \cdot \frac{d}{dt}\left[V_A - V_o\right].$$

$$I_1 = C_f \cdot \frac{d}{dt}\left[-V_o\right] \text{ ——— } (2)$$

and $I_2 = \dfrac{V_A - V_o}{R_f}$

$$I_2 = \frac{-V_o}{R_f} \text{ ——— } (3)$$

By applying KCL at node 'A'

$$I = I_1 + I_2.$$

$$\boxed{\frac{V_{in}}{R_1} = C_f \cdot \frac{d}{dt}\left[-V_o\right] - \frac{V_o}{R_f}} \text{ ——— } (4)$$

By applying laplace transform on b.s for eq (4) becomes

$$\frac{V_{in}(S)}{R_1} = -C_f \cdot S \cdot V_o(S) - \frac{V_o(S)}{R_f} \qquad \left[\because \frac{d}{dt} = S\right]$$

$$\frac{V_{in}(S)}{R_1} = -V_o(S)\left[C_f \cdot S + \frac{1}{R_f}\right]$$

$$V_o(S)\left[C_f \cdot S + \frac{1}{R_f}\right] = \frac{V_{in}(S)}{R_1}$$

$$\frac{V_{in}}{R_1} = -V_o(S)\left[\frac{R_f C_f \cdot S+1}{R_f}\right]$$

$$V_o(S) = \frac{-V_{in}}{R_1\left[\frac{R_f C_f S+1}{R_f}\right]}$$

$$V_o(S) = \frac{-V_{in}(S) \cdot R_f}{R_1\left[R_f C_f \cdot S+1\right]} \quad \text{—— } (5)$$

From eq (5)

$$V_o(S) = \frac{-V_{in}(S)}{R_1}\left[\frac{1}{C_f S + \frac{1}{R_f}}\right]$$

$$V_o(S) = \frac{-V_{in}(S)}{R_1 C_f \cdot S + \frac{R_1}{R_f}}$$

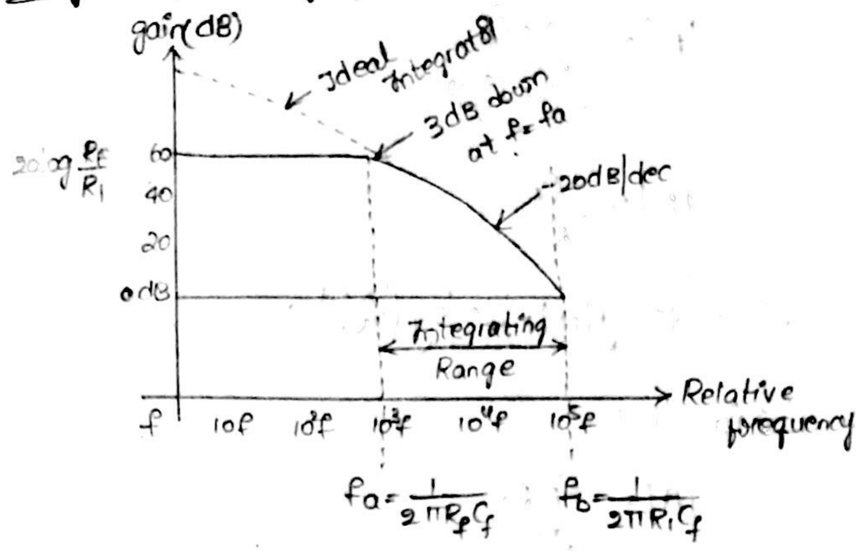
By considering the above eq^n R_f is very large compare the $\frac{R_1}{R_f}$ then neglecting $\frac{R_1}{R_f}$ then the eq^n becomes.

$$\boxed{V_o(S) = \frac{-V_{in}(S)}{R_1 C_f \cdot S}}$$

Then the o/p voltage becomes in time domain

$$\boxed{V_o(t) = \frac{-1}{R_1 C_f}\int_0^t V_{in}(t)} \qquad \left[\because \int dt = \frac{1}{S}\right]$$

Frequency response of Practical Integrator:-



W.K.T from the eq^n of practical Integrator

$$\frac{V_0(s)}{V_{in}(s)} = \frac{-R_F/R_1}{1+s \cdot R_f C_f} \quad (\text{from eq } 5)$$

Replace s by jω.

$$\frac{V_0(j\omega)}{V_i(j\omega)} = \frac{-R_F/R_1}{1+j\omega \cdot R_f \cdot C_f}$$

$$= \frac{-R_F/R_1}{1+j2\pi f R_f \cdot C_f}$$

$$\boxed{A = \frac{V_0(j\omega)}{V_{in}(j\omega)} = \frac{-R_F/R_1}{1+j(f/f_a)}} \quad \text{——— ①} \quad \left[\because f_a = \frac{1}{2\pi R_f C_f}\right].$$

This f_a is the break down frequency (or) corner frequency of practical integrator. thus the frequency response remains constant for all frequencies less than f_a and from the frequency f_a onwards the frequency increases then the gain decreases at a rate of 20dB/dec.

By using eq ① the magnitude response is

$$|A| = \frac{R_F/R_1}{\sqrt{1+\left(\frac{f}{f_a}\right)^2}} \quad \text{——— ②}$$

→ As $f \to 0$ then magnitude of A is.

$$|A| = \frac{R_F/R_1}{\sqrt{1+\left(\frac{0}{f_a}\right)^2}}$$

$$|A| = \frac{R_F}{R_1}$$

i.e; $20\log|A| = 20\log\left(\frac{R_F}{R_1}\right)$.

→ As $f \Rightarrow f_a$ then

$$|A| = \frac{R_F/R_1}{\sqrt{2}}$$

$$= 0.707\left(\frac{R_F}{R_1}\right)$$

i.e; $20\log|A| = 20\log(0.707) + 20\log\left(\frac{R_F}{R_1}\right)$.

$$= -3\,dB + 20\log\left(\frac{R_F}{R_1}\right).$$

Thus the magnitude of gain drops by 3dB at frequency $f = f_a$ which is the break down frequency. For the integration the frequency response must be st. line of slope 20dB/dec which is possible for frequencies greater than f_a and less than f_b.

Thus in b/w f_a and f_b the practical integrator acts as an integrator. Below f_a the integration doesn't takes place.

For the proper integration the time period 'T' of the input signal has to be larger than (or) equal to $R_f \cdot C_f$ i.e; $\underline{T \geq R_f \cdot C_f}$

where $R_f C_f = \frac{1}{2\pi f_a}$. i.e;

$$\boxed{T \geq \frac{1}{2\pi f_a}}$$

<u>Applications:-</u>

* Practical Integrator ckts mostly used in

1. Analog computers.

2. Solving differential equations.

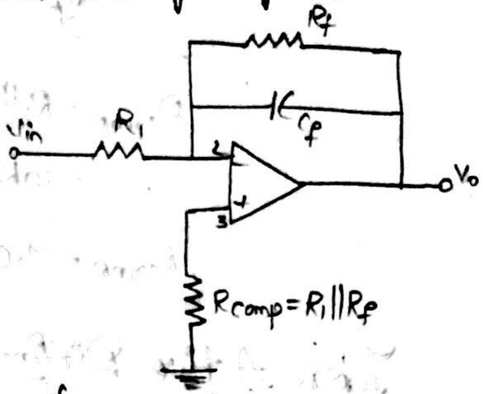
3. In analog to digital convertors.

4. In ramp wave generators.

5. In various signal wave shaping circuits.

Problem:-

1) Design a practical Integrator circuit with a dc gain of 10, to integrate a square wave 10KHz.



A: Given data is

$$\text{gain } A = 10V.$$

$$\text{frequency } f = 10KHz.$$

for the dc gain the practical Inverter $|A|$ is

$$|A| = \frac{R_F}{R_1}$$

$$\cancel{|A|} = \boxed{10 = \frac{R_F}{R_1}} \quad \text{——— } 1$$

for the practical integrator the proper integration must be produced.

$$f \geq 10 f_a.$$

$$f = 10 f_a$$

$$f_a = \frac{f}{10}.$$

$$f_a = \frac{\cancel{10}KHz}{\cancel{10}}$$

$$\boxed{f_a = 1KHz.}$$

Now for practical integrator $f_a = \frac{1}{2\pi R_f C_f}$.

$$1KHz = \frac{1}{2\pi R_f C_f}.$$

$$R_f C_f = \frac{1}{2\pi \cdot 1KHz}.$$

$$\boxed{R_f C_f = 0.159 \times 10^{-3} \text{ms}} \quad \text{——— } 2$$

from eq ①, assume $R_1 = 10K\Omega$ then R_F is

$$\boxed{R_F = 100K\Omega}$$

$$100K\Omega \cdot C_f = 0.159\times10^{-3}.$$

$$C_f = \frac{0.159\times10^{-3}}{100K\Omega}$$

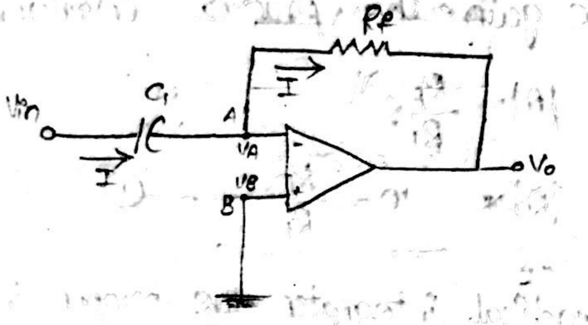
$$\boxed{C_f = 1.59\,nF.}$$

$$R_{comp} = R_1 \| R_f$$

$$= 10K\Omega \| 100K\Omega.$$

$$\boxed{R_{comp} = 9.09\Omega}$$

Ideal Active Differentiator :-



from the fig. by using virtual ground concept at node 'B' the voltage is zero. Then automatically at node 'A' the voltage is zero. i.e;

$$V_A = V_B = 0.$$

Now from the fig. input side current I is

$$I = C_1 \cdot \frac{d}{dt}\left[V_{in} - V_A\right].$$

$$\boxed{I = C_1 \cdot \frac{d}{dt} V_{in}} \text{ ——— ① } (\because V_A = 0)$$

from the o/p side current I is

$$I = \frac{V_A - V_o}{R_f}$$

$$\boxed{I = \frac{-V_o}{R_f}} \text{ ——— ②}$$

By equating eq ① and ②

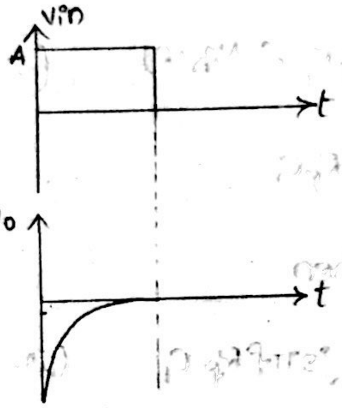
$$\frac{-V_o}{R_f} = C_1 \cdot \frac{dV_{in}}{dt}$$

$$\boxed{V_o = -R_f C_1 \cdot \frac{dV_{in}}{dt}}$$

From the above eq^n $R_f \cdot C_1$ is a time constant which is considered as a unity for better calculations of i/p and o/p waveforms.

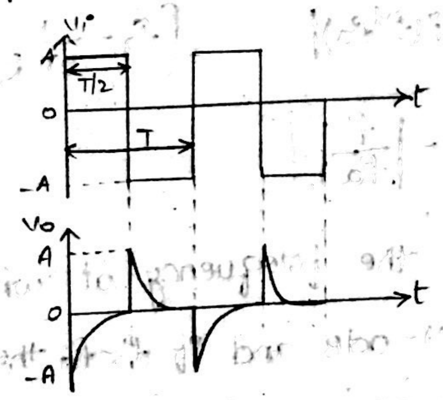
Input and Output Waveforms:-

Step input:-



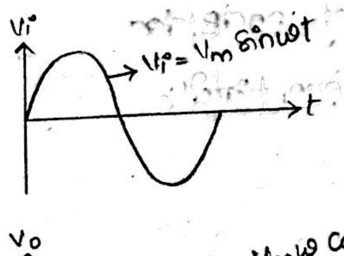
$$V_i(t) = \begin{cases} A, & \text{for } t \geq 0 \\ 0, & \text{for } t < 0 \end{cases}$$

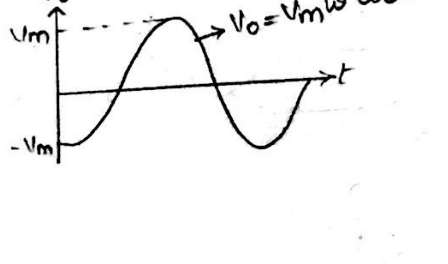
Square wave:-



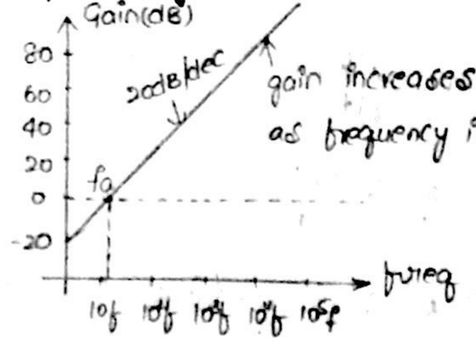
$$V_i(t) = \begin{cases} A, & \text{for } 0 < t < T/2 \\ -A, & \text{for } T/2 < t < T \end{cases}$$

Sine wave:-





Frequency response of ideal differentiator:-



W.K.T the differential eq^n

$$V_o(t) = -R_f C_1 \frac{d}{dt} V_{in}(t) \quad \text{——} \ (1)$$

Applying laplace transforms on both sides.

$$V_o(s) = -R_f C_1 \cdot s \cdot V_{in}(s) \qquad \left(\because \frac{d}{dt} = s\right).$$

$$\frac{V_o(s)}{V_{in}(s)} = -s R_f C_1.$$

Replace s by $j\omega$ then

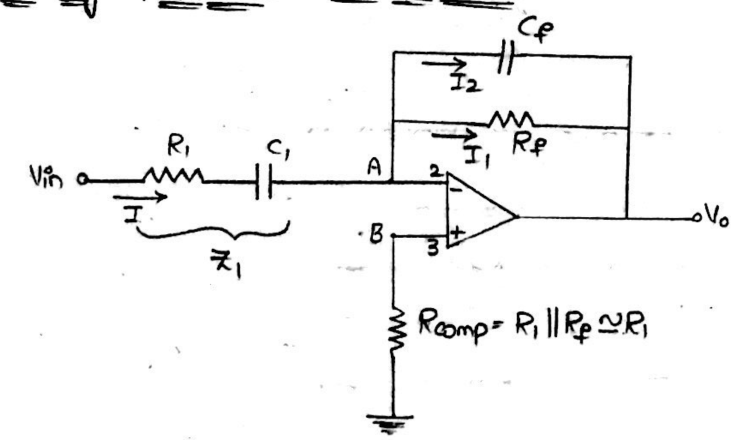
$$\frac{V_o(j\omega)}{V_{in}(j\omega)} = -j 2\pi f R_f \cdot C_1 \qquad (\omega = 2\pi f).$$

$$= |j(f/f_a)| \qquad \left[f_a = \frac{1}{2\pi R_f C_1}\right].$$

$$\boxed{|A| = \frac{V_o(j\omega)}{V_{in}(j\omega)} = \left|\frac{f}{f_a}\right|}$$

The frequency f_a is the frequency at which the gain becomes unity i.e; $20 \log(1) = 0dB$ and if $f < f_a$ the response is -ve, if $f \geq f_a$, the gain response increases as frequency increases with a roll rate of 20dB/dec.

Analysis of Practical differentiator:-



From the fig. by using virtual ground concept at node B. voltage is zero then automatically at node A voltage is also zero i.e, $V_A = V_B = 0$.

From the fig, the current I is

$$I = \frac{V_{in} - V_A}{Z_1} = \frac{V_{in} - V_A}{R_1 + \frac{1}{SC_1}} = \frac{V_{in}}{\frac{SR_1C_1+1}{SC_1}} \qquad (\because Z_1 = R_1 + 1/SC_1)$$

$$\boxed{I = \frac{SC_1 V_{in}}{1+SR_1C_1}} \text{ ——— (1)}$$

$$\text{Current } I_1 = \frac{V_A - V_0}{R_f} = \frac{-V_0}{R_f} \text{ ——— (2)}$$

Similarly current $I_2 = C_f \frac{d}{dt}(V_A - V_0)$

$$= -C_f \frac{d}{dt}(V_0) \text{ ——— (3)}$$

From the fig. by applying KCL at node A

$$I = I_1 + I_2$$

$$\frac{SC_1 V_{in}}{1+SR_1C_1} = \frac{-V_0}{R_f} - C_f \cdot \frac{d}{dt}(V_0) \text{ ——— (4)}$$

By applying laplace transform for eq (4)

$$\frac{SC_1 V_{in}(S)}{1+SR_1C_1} = \frac{-V_0(S)}{R_f} - C_f S \cdot V_0 S \qquad \left(\because \frac{d}{dt} = S\right)$$

$$\frac{SC_1 V_{in}(S)}{1+SR_1C_1} = -V_0(S)\left[\frac{1}{R_f} + C_f S\right]$$

$$\frac{SC_1 V_{in}(S)}{1+SR_1C_1} = -V_0(S) \frac{1+R_fC_fS}{R_f}$$

$$\boxed{V_0(S) = -\frac{SR_fC_1 V_{in}(S)}{(1+SR_1C_1)(1+SR_fC_f)}}$$

If $R_fC_f = R_1C_1$ then $V_0(S)$ is

$$\boxed{V_0(S) = \frac{-SR_fC_1 V_{in}(S)}{(1+SR_1C_1)^2}} \text{ ——— (5)}$$

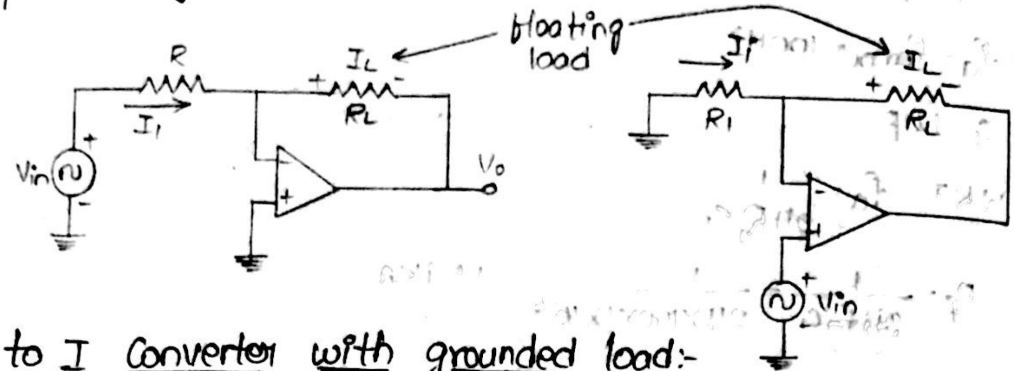
Here $R_fC_f >> R_1C_1$ then neglecting R_1C_1 from above eq^n then

$$\boxed{I_L \propto V_i}$$

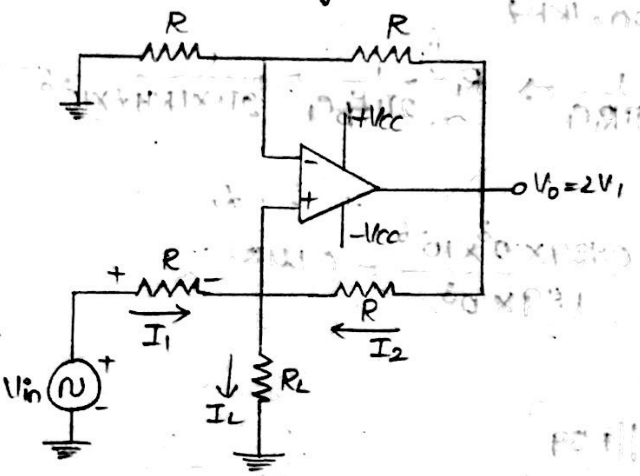
from the fig. as the input current I_i of an Op-Amp is zero then the load current

$$\boxed{I_L = I_i = \frac{V_i}{R_L}}$$

Then the load current is always proportional to the input voltage and works as V to I converter.



V to I Converter with grounded load:-



From the fig. by applying KCL at node V_1 is

$$I_L = I_1 + I_2$$

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

$$= \frac{V_i + V_o}{R} - \frac{2V_1}{R}$$

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

$$\boxed{V_1 = \frac{V_i + V_o - I_L R}{2}} \longleftarrow (1)$$

W.K.T from the non-inverting amplifier gain A is

$$\frac{V_o}{V_1} = 1 + \frac{R}{R} = 2$$

$$\boxed{V_0 = 2V_1} \quad \text{——— (2)}$$

Sub. eq (1) in eq (2)

$$V_0 = 2\left(\frac{V_i + V_0 - I_L R}{2}\right)$$

$$V_0 = V_i + V_0 - I_L R$$

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

Applications of V-I Converter:-

V-I converter is used in

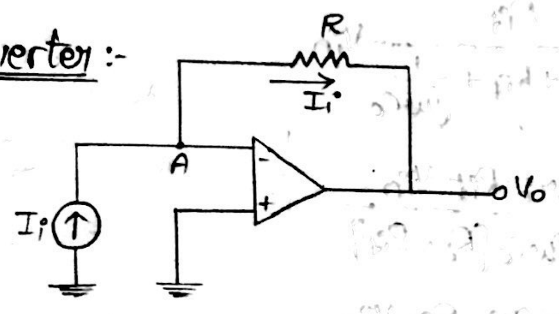
(1) Low voltage dc voltmeters.

(2) Low voltage AC voltmeters.

(3) Diode tester.

(4) Zener diode tester.

I-V Converter:-



From the fig. by using virtual ground concept

$$V_A = V_B = 0$$

from the fig.

$$I_i = \frac{V_A - V_0}{R} = \frac{-V_0}{R} \qquad (\because V_A = 0).$$

i.e; the input current is directly proportional to o/p voltage V_0

This circuit is also called as current control voltage source (or) trans resistance amplifiers.

Applications of I-V Converter:-

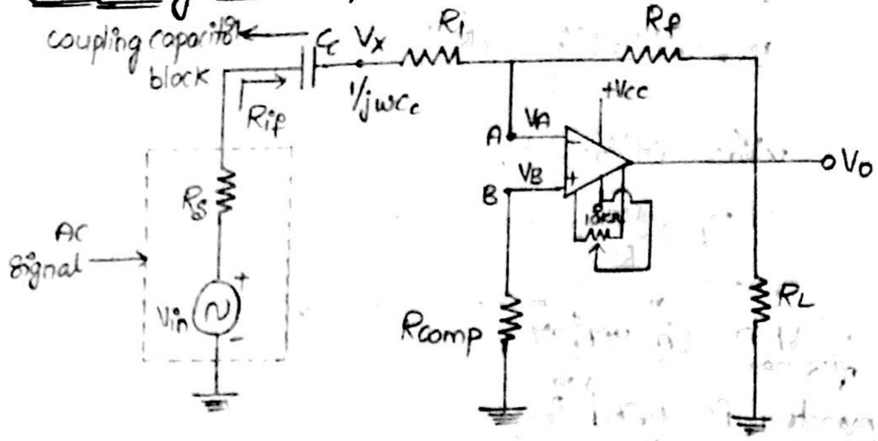
I-V Converters are used in

(1) Photo diode tester.

(2) Photo FET Detector.

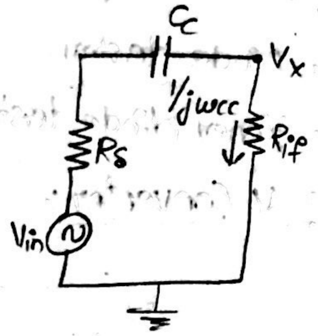
AC Amplifiers :-

Inverting AC amplifier :-



From the circuit consider the i/p of inverting AC amplifier is the AC signal is applied. By using the voltage divider network circuit.

Using Potential divider rule



$$V_X = \frac{R_{if}}{R_s + R_{if} + \frac{1}{j\omega C_c}} V_{in}$$

$$= \frac{j\omega C_c \cdot R_{if} \cdot V_{in}}{1 + j\omega C_c [R_s + R_{if}]}$$

$$= \frac{j2\pi f C_c \cdot R_{if} \cdot V_{in}}{1 + j2\pi f C_c [R_s + R_{if}]}$$

$$\boxed{V_X = \frac{j2\pi f C_c \cdot R_{if} \cdot V_{in}}{1 + j(f/f_L)}} \text{ ——— (1)} \qquad \left[\because f_L = \frac{1}{2\pi C_c (R_s + R_{if})}\right]$$

W.K.T from the inverting amplifier o/p voltage.

$$V_o = \frac{-R_F}{R_1} V_X \text{ ——— (2)}$$

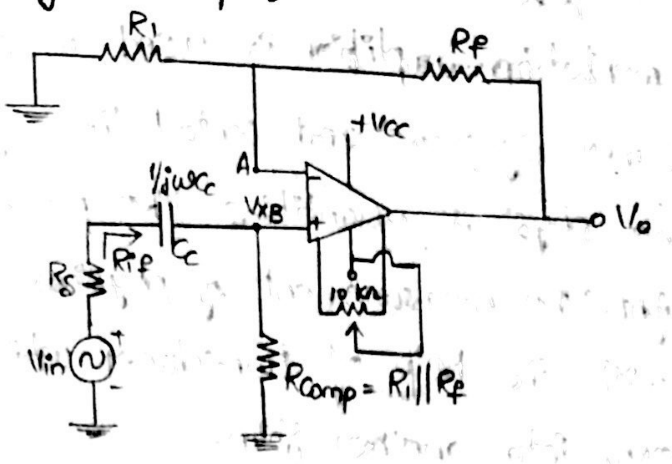
sub. eq (1) in (2)

$$\boxed{V_o = \frac{-R_F}{R_1} \left[\frac{j2\pi f C_c R_{if} \cdot V_{in}}{1 + j(f/f_L)} \right]}$$

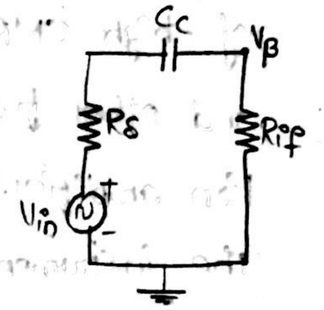
The coupling capacitor C_c controls the lower frequency limits and from the above eq^n if $f < f_L$ the gain response is increases and if $f > f_L$ the constant response was produced

R_1

Non-inverting AC amplifier:-



From the circuit consider the i/P of non-inverting AC amplifier is the AC signal is applied. By using the voltage divider network circuit.



Using Potential divider rule.

$$V_{XB} = \frac{R_{if}}{R_s + R_{if} + \frac{1}{j\omega C_c}} \cdot V_{in}$$

$$= \frac{V_{in} \cdot R_{if} \cdot j\omega C_c}{1 + j\omega C_c [R_s + R_{if}]}$$

$$V_{XB} = \frac{j 2\pi f C_c \cdot R_{if} \cdot V_{in}}{1 + j 2\pi f C_c [R_s + R_{if}]}$$

$$V_{XB} = \frac{j 2\pi f C_c \cdot R_{if} \cdot V_{in}}{1 + j(f/f_L)} \quad \text{——} (1) \qquad \left[\because f_L = \frac{1}{2\pi C_c (R_s + R_{if})}\right]$$

W.K.T from the non-inverting amplifier o/P voltage

$$V_o = 1 + \frac{R_F}{R_1} V_x \quad \text{——} (2)$$

Sub. eq (1) in eq (2)

$$V_o = 1 + \frac{R_F}{R_1} \left[\frac{j 2\pi f C_c \cdot R_{if} \cdot V_{in}}{1 + j(f/f_L)}\right]$$

The coupling capacitor C_c controls the lower frequency limits and from the above eq.n if $f < f_L$ the gain response is increases and if $f > f_L$ the constant response was produced due to the capacitor control frequency then gain is

$$\boxed{A \simeq 1+\frac{R_F}{R_1}}$$

Instrumentation Amplifier:-

Instrumentation amplifier is used in industrial applications, consumer systems and control the system which is measured the physical quantities like pressure, temperature, humidity and weight. The measurement of physical quantities can be measured with the help of transducer which converts one form of energy into another form.

"A specific amplifier which satisfying the requirements of high CMRR, high i/p impedance and low power consumption and other features such an amplifier is called as instrumentation amplifier. This amplifier was used in low level amplification. The instrumentation Amplifier is also called as Data Amplifier whose gain is

$$A=\frac{V_0}{V_2-V_1}$$

where V_0 is the o/p voltage of instrumentation amplifier.

V_2-V_1 is the differential i/p of the o/p stage.

Requirements of Instrumentation Amplifier:-

The instrumentation amplifier requires following specification

(1) Finite and stable gain.

(2) Easier gain adjustment.

(3) High CMRR.

(4) High i/p impedance.

(5) Low o/p impedance.

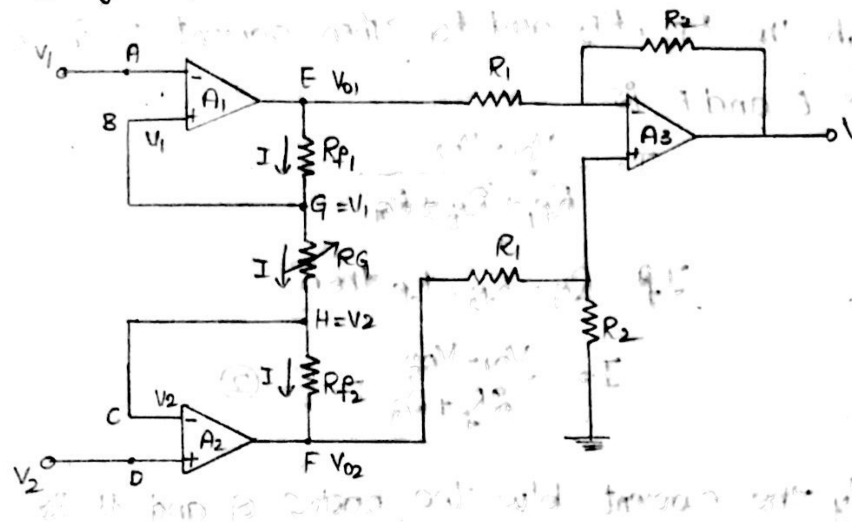
(6) High slew rate.

(7) High thermal drift.

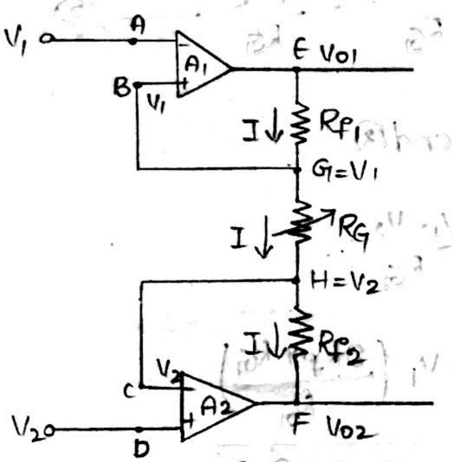
(8) Differential amplifier must be involved.

(9) Low power consumption.

Three stage Op-Amp Instrumentation Amplifier:-



Analysis of Instrumentation Amplifier:-



From the three stage Op-Amp instrumentation amplifier the o/p stage is the standard basic differential amplifier. So if the o/p of op-Amp A_1 is V_{01} and Op-Amp A_2 is V_{02}. Then the differential eq^n of o/p stage of an op-Amp A_3 is

$$\boxed{V_0 = \frac{R_2}{R_1}\left[V_{02}-V_{01}\right]} \quad \text{—— (1)}$$

From the fig. the node A potential of an Op-Amp A_1 is V_1 and the potential of node B is also V_1 hence the potential of node G is also V_1. Similarly the node D potential of Op-Amp A_2 is V_2 and the potential at node C is also

V_2 then potential of H is also V_2.

Now from the fig. the i/p current of an Op-Amp A_1 and A_2 are zero and hence the current remains same through the R_{F_1}, R_{F_2} and R_G. Then current I in between nodes E and F is

$$I = \frac{V_{01} - V_{02}}{R_{f_1} + R_{f_2} + R_G}$$

If $R_{f_1} = R_{f_2} = R_f$ then

$$\boxed{I = \frac{V_{01} - V_{02}}{2R_f + R_G}} \text{———} (2)$$

Similarly the current b/w the nodes G and H is

$$\boxed{I = \frac{V_G - V_H}{R_G} = \frac{V_1 - V_2}{R_G}} \text{———} (3)$$

By equating (2) and (3)

$$\frac{V_{01} - V_{02}}{2R_f + R_G} = \frac{V_1 - V_2}{R_G}$$

$$V_{02} - V_{01} = V_2 - V_1 \cdot \left(\frac{2R_f + R_G}{R_G}\right)$$

$$\boxed{V_{02} - V_{01} = V_2 - V_1 \left[1 + \frac{2R_f}{R_G}\right]} \text{———} (4)$$

Sub. eq (4) in (1)

$$V_0 = \frac{R_2}{R_1}\left[1 + \frac{2R_f}{R_G}\right] V_2 - V_1$$

This eq.^{n} gives the overall gain of instrumentation Amplifier.

<u>Advantages</u>:-

Instrumentation amplifiers are used

i) For variable gain resistance (R_G).

The gain can be easily adjusted without disturbing the circuit.

2. The gain depends on external resistance and hence it can be adjusted accurately by selecting high quality resistances.

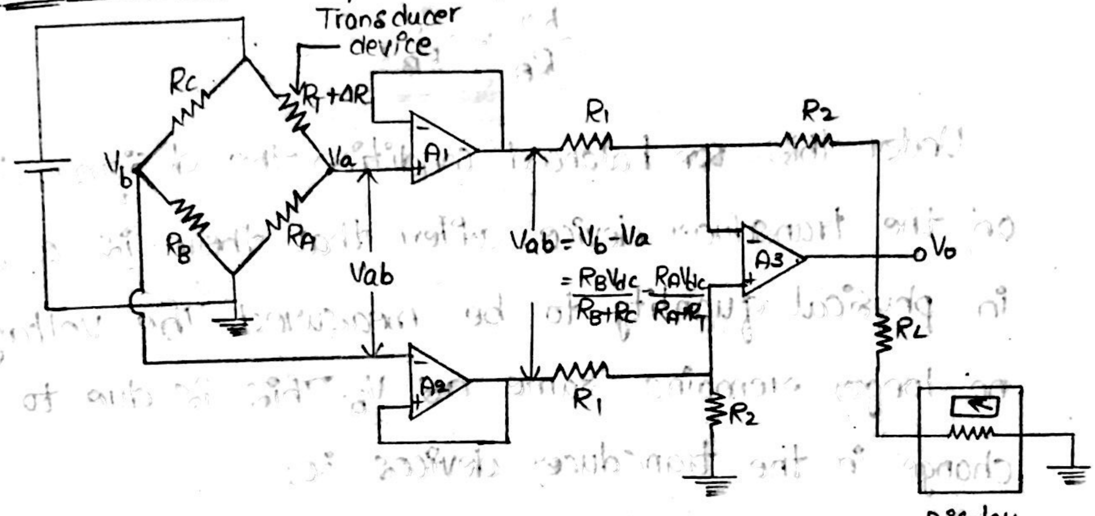
3. The i/p impedance depends on the non-inverting amplifier with extremely high.

4. The o/p impedance on the Op-Amp A_3 which is very low.

5. The CMRR of the o/p Op-Amp A_3 is very high.

6. By trimming any one of the resistances at the o/p stage the CMRR can be made extremely high.

Instrumentation Amplifier with transducer bridge:-



From the circuit the transducer devices using the transducer bridge whose resistance (R_T) varies due to the change in physical condition. The examples of such resistive transducer devices are temperature, photo resistor whose resistance can be changed with change in the light sensitivity. From the fig, R_T is the transducer device which is one side of resistive bridge while ΔR is the change in resistance R_T i.e; $R_T \pm \Delta R$. At some reference condition of physical energy the bridge is balanced at $V_a = V_b$. i.e;

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

From the circuit the differential voltage amplifies the voltage is $V_d = V_{ab} = V_b - V_a = 0$.

$$= \frac{R_B V_{dc}}{R_B + R_C} - \frac{R_A V_{dc}}{R_A + R_T} = 0$$

$$= \frac{R_B V_{dc}(R_A + R_T) - R_A V_{dc}(R_B + R_C)}{(R_B + R_C)(R_A + R_T)} = 0.$$

$$R_B V_{dc}(R_A + R_T) - R_A V_{dc}(R_B + R_C) = 0$$

$$R_B V_{dc} R_A + R_B V_{dc} R_T - R_A V_{dc} R_B - R_A V_{dc} R_C = 0$$

$$R_B R_T = R_A R_C$$

$$\boxed{\frac{R_T}{R_A} = \frac{R_C}{R_B}}$$

Under this ~~son~~ balanced condition the designer depends on the transducer device, after that there is a change in physical quantity to be measured. The voltage no longer remains same as V_b. This is due to that change in the transducer devices i.e;

$$R_T \pm \Delta R$$

The resistances R_B and R_C constant and V_B also remains same but V_A changed its denominator by $R_T + \Delta R$ i.e;

$$V_a = \frac{R_A V_{dc}}{R_A + R_T + \Delta R}, \quad V_b = \frac{R_B V_{dc}}{R_B + R_C}.$$

Then the voltage $V_{ab} = V_b - V_a$.

$$= \frac{R_B V_{dc}}{R_B + R_C} - \frac{R_A V_{dc}}{R_A + R_T + \Delta R}.$$

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

$$= \frac{RV_{dc}}{R+R} - \frac{RV_{dc}}{R+R+\Delta R}$$

$$= \frac{RV_{dc}(2R+\Delta R) - RV_{dc}(2R)}{2R(2R+\Delta R)} = \frac{RV_{dc}\,\Delta R}{2R(2R+\Delta R)} = \frac{V_{dc}\,\Delta R}{4R+2\Delta R}$$

Now, the gain of the first stage of Op-Amp A_1 is unity and it is a voltage follower circuit while the gain of the second stage Op-Amp A_2 is $A = \frac{-R_F}{R_1}$. Then the total o/p voltage $V_o = V_{ab} \cdot A$

$$\boxed{V_o = \frac{-R_2}{R_1} \cdot \frac{V_{dc}\,\Delta R}{2(2R+\Delta R)}}$$

As the change in resistance $\Delta R \ll 2R$ then neglecting ΔR term then

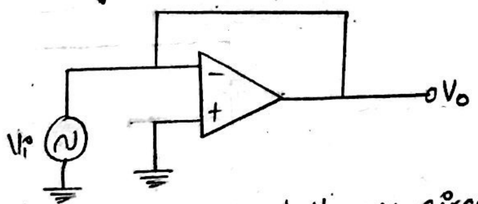
$$\boxed{V_o = \frac{-R_2}{R_1} \cdot \frac{V_{dc}\,\Delta R}{4R}}$$

Applications of Instrumentation Amplifiers :-

Instrumentation Amplifiers are used

(1) for temperature controller.
(2) for temperature indicator.
(3) light intensity meter.
(4) for analog weight scale.

Buffers (or) Voltage follower circuit :-



(a) Voltage follower circuit

Voltage follower circuit is defined as o/p follows the i/p i.e; the exact i/p voltage for the o/p i.e;

$$V_o = V_i$$

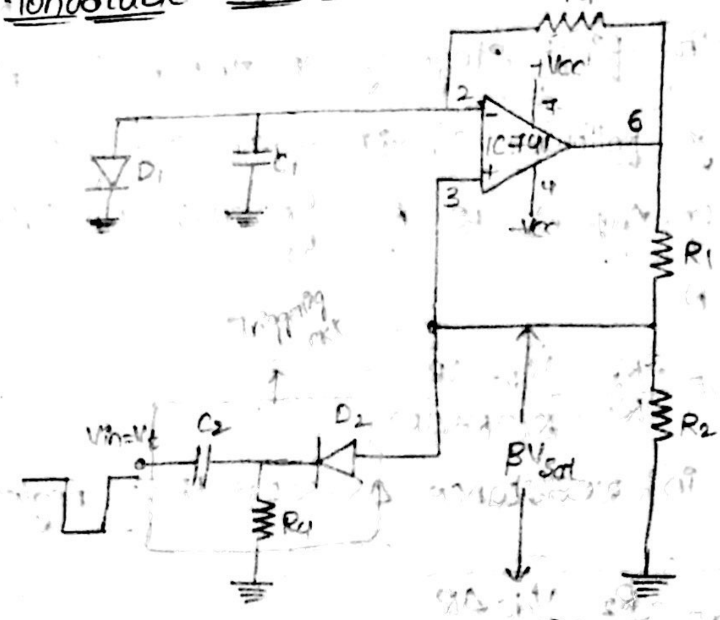
for the voltage follower the gain is unity i.e; $V_o = V_i$

$$\boxed{A = \frac{V_o}{V_i} = 1}$$

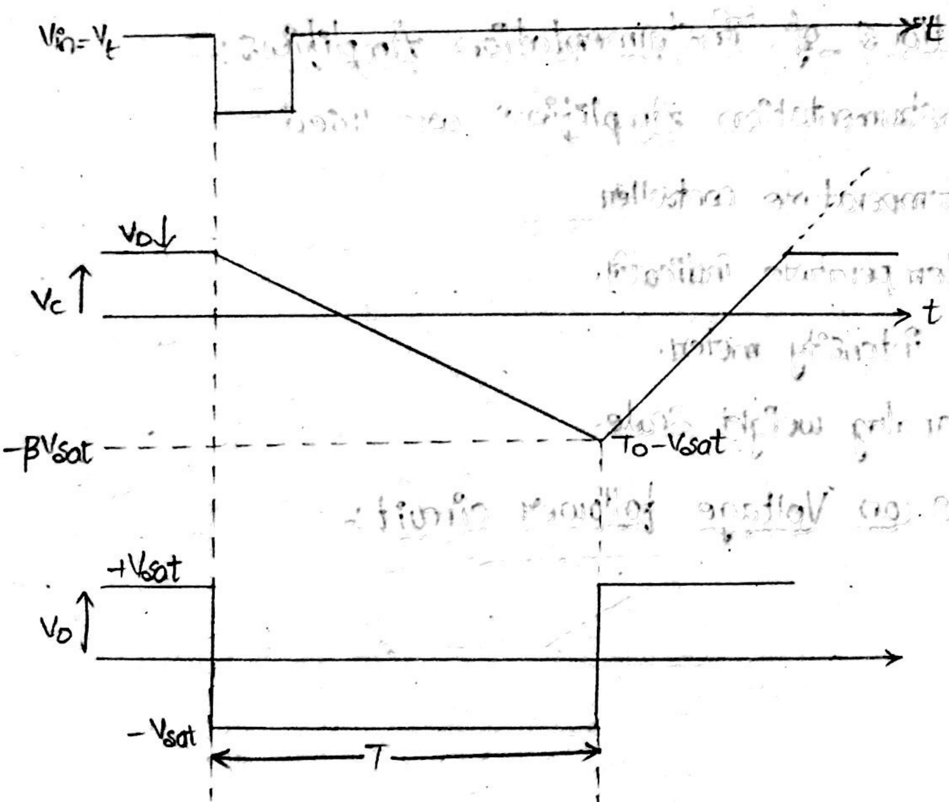
Non-linear function generator :-

Multivibrators :-

Monostable Multivibrator :- (Single shot Multivibrator).



(a) Monostable Multivibrator



(b) Input and Output waveforms

Circuit Operation:-

Let us consider in the stable state the o/p voltage V_0 is at $+V_{sat}$ then i.e;

$$V_0 = +V_{sat}$$

Then the diode D_1 conducts and the capacitor voltage V_C gets clamped to 0.7V then the voltage at the +ve i/p terminal through the resistors R_1 and R_2 is $+\beta V_{sat}$ i.e;

$$\beta = \frac{R_2}{R_1 + R_2}$$

Now, if a -ve trigger of i/p voltage is applied to the +ve input terminal which is less than 0.7V then the o/p of an Op-Amp switches to $+V_{sat}$ to $-V_{sat}$. Then the diodes gets reverse biased and the capacitor starts discharges exponentially to $-V_{sat}$ till to the o/p voltage $-\beta V_{sat}$.

The general solution for a single time constant RC circuit with initial voltage (V_i) and final voltage (V_f) using the expression.

$$V_0 = V_f + [V_{in} - V_f]e^{-t/RC} \quad (1)$$

From the o/p wave form.

$$V_f = -V_{sat}$$

$$V_i = V_D.$$

Sub. in eq (1)

$$V_0 = -V_{sat} + [V_D - (-V_{sat})]e^{-t/RC} \quad (2)$$

At time constant t=T the capacitor voltage is equal to o/p voltage i.e;

$$V_C = V_0 = -\beta V_{sat}$$

Sub. in eq (2)

$$-\beta V_{sat} = -V_{sat} + [V_D + V_{sat}]e^{-T/RC}$$

$$[-\beta V_{sat} + V_{sat}] = [V_D + V_{sat}]e^{-T/RC}$$

$$-V_{sat}[\beta+1] = [V_D + V_{sat}]\, e^{-T/RC}$$

$$e^{-T/RC} = \frac{V_{sat}(1-\beta)}{V_D + V_{sat}}$$

$$-T/RC = \ln\left[\frac{(1-\beta)V_{sat}}{V_D + V_{sat}}\right]$$

$$T = -RC \ln\left[\frac{(1-\beta)V_{sat}}{V_D + V_{sat}}\right]$$

$$T = -RC \ln\left[\frac{(1-\beta)}{1+\frac{V_D}{V_{sat}}}\right]$$

$$\boxed{T = RC \ln\left[\frac{1+\frac{V_D}{V_{sat}}}{1-\beta}\right]} \longrightarrow (3)$$

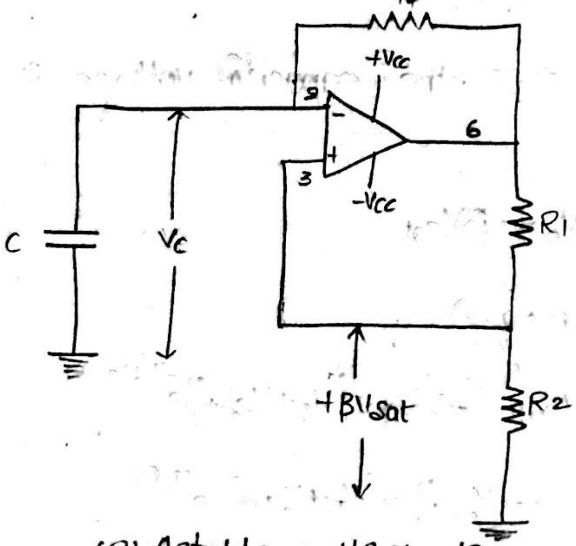
where $\beta = \frac{R_2}{R_1+R_2}$ and consider if $R_1 = R_2$ then $\beta = \frac{1}{2}$ and also if $V_{sat} >> V_D$ then eq (3) can be written as.

$$T = RC \ln\left[\frac{1}{1-\frac{1}{2}}\right]$$

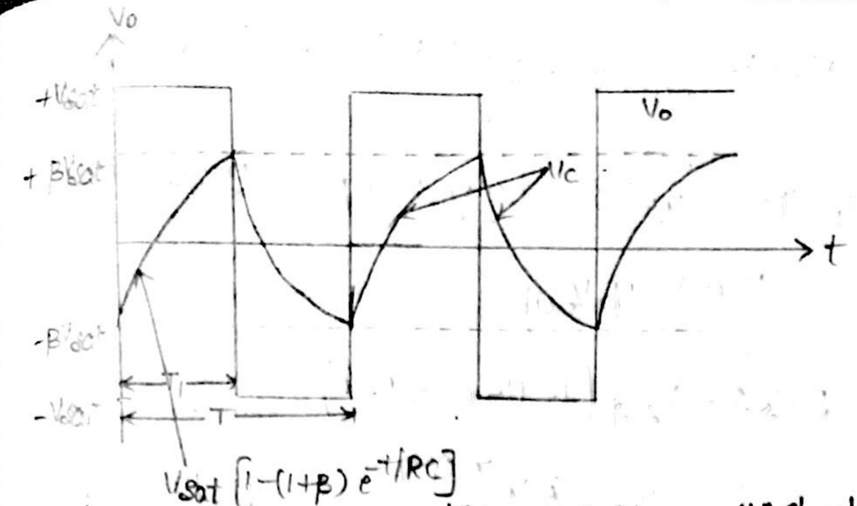
$$T = RC \ln[2]$$

$$\boxed{T = 0.693RC}$$

Astable Multivibrator :- Free running (or) Square wave generator:-



(a) Astable multivibrator



The another name for Astable multivibrator is free running multivibrator. It is having both states are the Quasi stable states.

Let us consider an instant time the o/p is at $+V_{sat}$ the capacitor starts charging towards $+V_{sat}$ by using the resistors R_f, the voltage at +ve i/p terminal is held at βV_{sat} by using the resistors R_1 and R_2. This condition continues the charging capacitor rises until exceeds $+\beta V_{sat}$.

When the voltage is at -ve i/p terminal then the o/p is driven to $-V_{sat}$ at this instant the capacitor voltage begins to discharge to the $-V_{sat}$. In this Astable multivibrator the frequency is determined by the time it starts the capacitor to charge from $-\beta V_{sat}$ to $+\beta V_{sat}$. The voltage across the capacitor as a function of time is given the expression

$$V_C(t) = V_f + \left[V_{in} - V_f\right] e^{-t/RC} \quad \text{——— (1)}$$

where $V_f = +V_{sat}$ and $V_{in} = -\beta V_{sat}$.

$$V_C(t) = V_{sat} + \left[-\beta V_{sat} - V_{sat}\right] e^{-t/RC}.$$

$$V_C(t) = V_{sat}\left[1 - \beta - 1\right] e^{-t/RC}.$$

$$\boxed{V_c(t) = V_{sat}\left[1-(1+\beta)e^{-t/RC}\right].} \text{ --- } (2)$$

At time $t=T_1$ the capacitor charges upto βV_{sat} i.e;

$$V_c(t) = +\beta V_{sat}.$$

$$\beta \cancel{V_{sat}} = \cancel{V_{sat}}\left[1-(1+\beta)e^{-T_1/RC}\right]$$

$$\beta = \left[1-(1+\beta)e^{-T_1/RC}\right] \qquad \left[\because \beta = \frac{R_2}{R_1+R_2} = \frac{1}{2}\right]. \quad \because R_1 = R_2$$

$$\frac{1}{2} = \left[1-(1+\frac{1}{2})e^{-T_1/RC}\right].$$

$$1-\frac{1}{2} = (1+\frac{1}{2})e^{-T_1/RC}$$

$$1-\beta = (1+\beta)e^{-T_1/RC}.$$

$$e^{-T_1/RC} = \frac{1-\beta}{1+\beta}.$$

$$-T_1/RC = \ln\left[\frac{1-\beta}{1+\beta}\right]$$

$$\boxed{T_1 = RC \ln\left[\frac{1+\beta}{1-\beta}\right].}$$

W.K.T $\beta = \frac{R_2}{R_1+R_2}$ if $R_1 = R_2$ then $\beta = \frac{1}{2}$.

$$T_1 = RC \ln\left[\frac{1+\frac{1}{2}}{1-\frac{1}{2}}\right]$$

$$T_1 = RC \ln[3]$$

$$\boxed{T_1 = 1.09\,RC.}$$

Using the time period $T_1 = 1.09\,RC$ the completion of one clock cycle it takes total time period is equal to $2T_1$ i.e;

$$T = 2T_1$$

$$= 2 \times 1.09\,RC$$

$$\boxed{T = 2.18\,RC.}$$

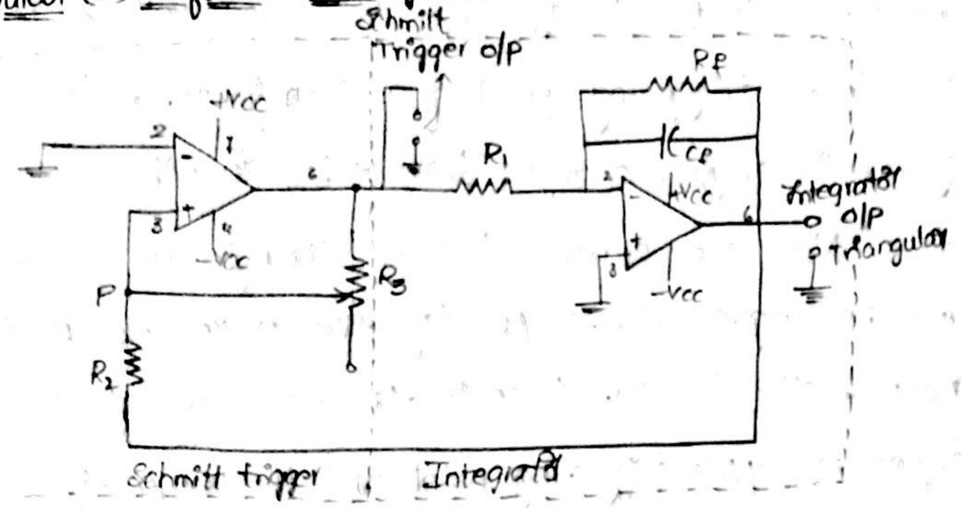
The frequency of oscillation for Astable multivibrator is

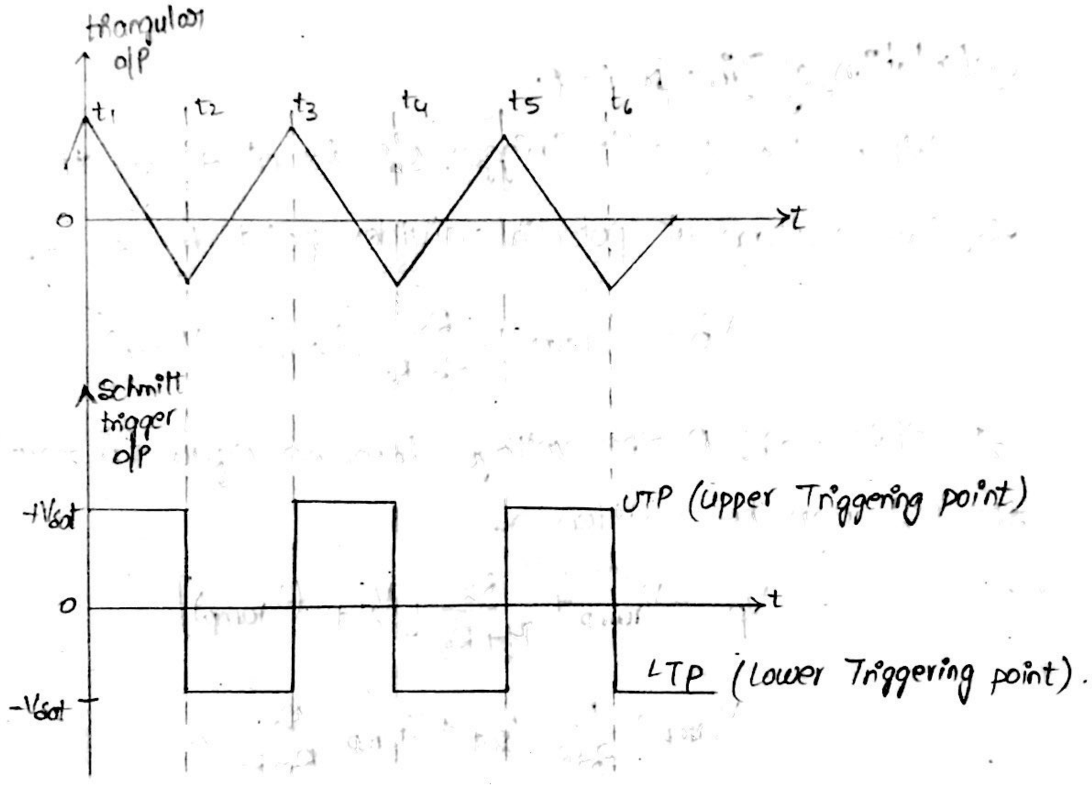
$$f = \frac{1}{T}$$

$$f = \frac{1}{2.18RC}$$

$$\boxed{f = \frac{0.45}{RC}}$$

Triangular (or) Square wave generator:-





From the triangular and square wave generator the o/p of the integrator is triangular o/p. If its i/p is square wave it is coming from the Schmitt trigger o/p.

Circuit Operation:-

The o/p of the Schmitt trigger is $+V_{sat}$. This voltage forces current I through the capacitor charging +ve polarity and this produces a -ve going ramp at its o/p for the time interval t_1 to t_2. At t_2 when the ramp voltage is equal to the lower triggering point of a Schmitt trigger then the o/p of Schmitt trigger changes from $+V_{sat}$ to $-V_{sat}$.

Now the current direction through the capacitor discharging and recharges with a polarity +ve to -ve and produces a +ve ramp in the interval t_2 to t_3. At t_3 the o/p of the Schmitt trigger is upper triggering point and it changes from $-V_{sat}$ to $+V_{sat}$.

Calculation of Time period:-

When the Schmitt Trigger o/p is at $+V_{sat}$ the effective voltage at potential divider point P is given by

$$V_P = -V_{ramp} + \frac{R_2}{R_2+R_3}\left[V_{sat} - (-V_{ramp})\right]$$

At this point P the voltage becomes equal to zero. Then the eq^n can be written as

$$V_P = -V_{ramp} + \frac{R_2}{R_2+R_3}\left[V_{sat} - (-V_{ramp})\right].$$

$$-V_{ramp} + \frac{R_2}{R_2+R_3}V_{sat} + V_{ramp}\cdot\frac{R_2}{R_2+R_3} = 0$$

$$-V_{ramp}\left[1 - \frac{R_2}{R_2+R_3}\right] + \frac{R_2}{R_2+R_3}\cdot V_{sat} = 0.$$

$$-V_{ramp}\left[\frac{\cancel{R_2}+R_3-\cancel{R_2}}{\cancel{R_2+R_3}}\right] = \frac{-R_2\cdot V_{sat}}{\cancel{R_2+R_3}}.$$

$$\boxed{\therefore -V_{ramp} = \frac{-R_2}{R_3}\left[+V_{sat}\right].}$$

Illy when the schmitt trigger o/p is at $-V_{sat}$ then V_{ramp} is

$$\boxed{V_{ramp} = \frac{-R_2}{R_3}(-V_{sat})}$$

Then the total peak to peak amplitude (or) voltage of triangular wave can be given as

$$V_{p-p} = V_{ramp} - (-V_{ramp})$$

$$= \frac{-R_2}{R_3}(-V_{sat}) - \left[\frac{-R_2}{R_3}(+V_{sat})\right]$$

$$= \frac{2R_2}{R_3}(V_{sat})$$

Now the time taken by the o/p voltage to swing from -ve ramp to +ve ramp is equal to the half of the time period i.e; T/2 then the time will be calculated from the integrator o/p using the eqn

$$V_o(t) = \frac{-1}{R_1 C_f}\int_0^t V_{in}(t) + V_o(0)$$

$$\boxed{V_{p-p} = \frac{-1}{R_1 C_1}\int_0^t V_{in}(t)}$$

The capacitor i/p voltage is at $-V_{sat}$ and $t = T/2$ then V_{p-p} is

$$V_{p-p} = \frac{-1}{R_1 C_1}\int_0^{T/2}(+V_{sat})$$

$$\frac{2R_2}{R_3}(\cancel{V_{sat}}) = \frac{\cancel{V_{sat}}}{R_1 C_1}\int_0^{T/2} dt$$

$$\boxed{T = \frac{4R_1 C_1 R_2}{R_3}}$$

Then the frequency of oscillation is calculated by using

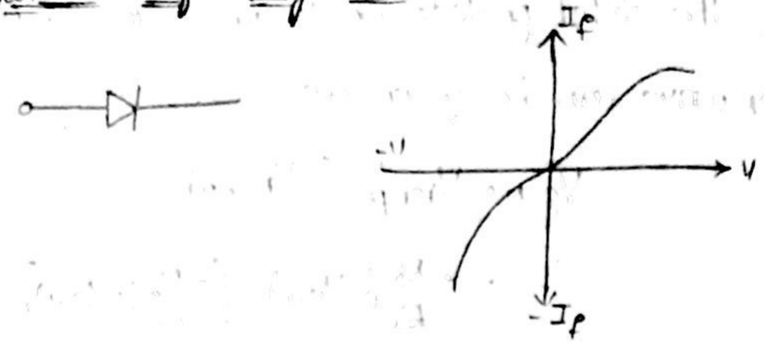
$$f = \frac{1}{T}$$

$$\boxed{f = \frac{R_3}{4R_1 R_2 C_1}}$$

Log and Antilog Amplifiers

Log Amplifiers:-

Basic Logarithmic eq^n using diode:-



W.K.T the basic eq^n for current to voltage relationship for the diode is given as

$$I_f = I_o[e^{-V/\eta V_T} - 1] \quad \text{——— ①}$$

where I_f is the diode current

I_o is the reverse saturation current

V is the voltage of the diode.

η is the one of germanium, 2 for silicon [$\eta=1$ for ge, $\eta=2$ for si]

V_T is voltage equivalent temperature i.e;

$$V_T = K \times T$$

where K is Boltzman constant i.e; $K = 8.62 \times 10^{-15} V$.

T is standard temperature

from the above eq ① $e^{-V/\eta V_T} >> 1$ then

$$I_f = I_o[e^{-V/\eta V_T}]$$

By applying natural logarithm on b.s and neglect the -ve value of voltage V then

$$\ln[I_f] = \ln[I_o(e^{V/\eta V_T})].$$

$$= \ln[I_o] + \ln[e^{V/\eta V_T}]$$

$$\ln[I_f] - \ln[I_o] = V/\eta V_T$$

$$\boxed{V = \eta V_T \ln\left[\frac{I_f}{I_0}\right]}$$

Basic eq^n for logarithm using transistor:-

W.K.T the current to voltage relation for BJT transistor is

$$I_C = \alpha I_S\left[e^{V_{BE}/V_T} - 1\right] \quad \text{——} (1)$$

where $I_C \rightarrow$ collector current

$I_S \rightarrow$ emitter saturation current

If $\alpha \cong 1$ then from eq (1) $e^{V_{BE}/V_T} >> 1$ then

$$I_C = I_S\left[e^{V_{BE}/V_T}\right].$$

By applying natural logarithm on b.s.

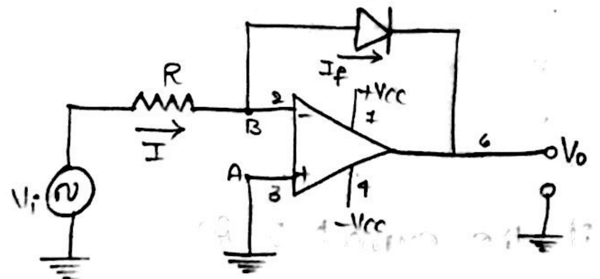
$$\ln[I_C] = \ln\left[I_S\left(e^{V_{BE}/V_T}\right)\right]$$

$$\ln[I_C] = \ln[I_S] + \ln\left(e^{V_{BE}/V_T}\right).$$

$$\ln[I_C] - \ln[I_S] = V_{BE}/V_T.$$

$$\boxed{V_{BE} = V_T \ln\left[\frac{I_C}{I_S}\right]}$$

Logarithm using diode:-



From the fig. by using virtual ground concept at nodes A and B are zero i.e;

$$V_A = V_B = 0$$

Now current $I = \frac{V_{in} - V_B}{R} = \frac{V_{in}}{R}$ $(\because V_B = 0)$

$$\boxed{I = \frac{V_{in}}{R}} \quad \text{——— (1)}$$

The Op-Amp current is zero then at node B the current $I = I_f$ then the current through the diode and the voltage across the diode is

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

$$\boxed{V_D = -V_0} \quad \text{——— (2)}$$

W.K.T the current to voltage relation of diode is given as

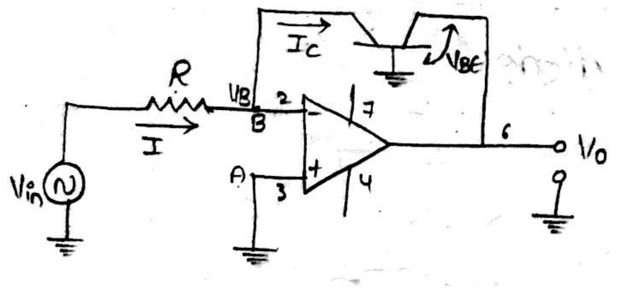
$$V_D = \eta V_T \ln\left[\frac{I_f}{I_0}\right].$$

$$-V_0 = 1\, V_T \cdot \ln\left[\frac{I_f}{I_0}\right]. \qquad (\because \eta = 1)$$

$$-V_0 = 1 \cdot V_T \cdot \ln\left[\frac{V_{in}}{I_0 \cdot R}\right]. \qquad \left[\because I = I_f,\ I = \frac{V_{in}}{R}\right].$$

$$\boxed{V_0 = -V_T \cdot \ln\left[\frac{V_{in}}{I_0 \cdot R}\right]}$$

Log Amplifier using transistor:-



From the circuit the current I is

$$I = I_C = \frac{V_{in} - V_B}{R}$$

$$\boxed{I = I_C = \frac{V_{in}}{R}} \quad \text{——— (1)}$$

from the o/p side, $V_{BE} = V_B - V_0$

$$\boxed{V_{BE} = -V_0} \text{ --- } (2)$$

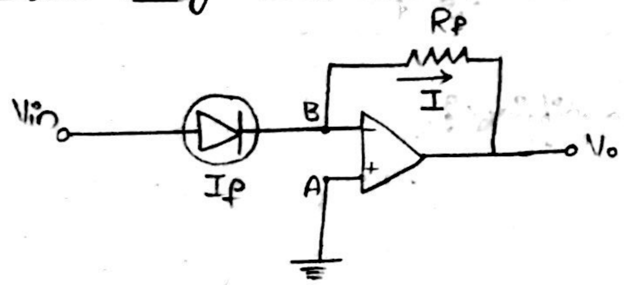
W.K.T the relation b/w collector current to base to emitter voltage is

$$V_{BE} = V_T \ln\left[\frac{I_c}{I_s}\right].$$

$$-V_0 = V_T \ln\left[\frac{V_{in}}{R \cdot I_s}\right]$$

$$\boxed{V_0 = -V_T \ln\left[\frac{V_{in}}{R \cdot I_s}\right]}$$

Anti-log Amplifier using diode:-



From the circuit the current I must be same as I_f i.e;

$$I = I_f = -\frac{V_0}{R_f} \text{ --- } (1) \qquad \frac{V_B - V_0}{R_f} = \frac{-V_0}{R_f}$$

W.K.T the basic eq^n for log amplifier using diode is

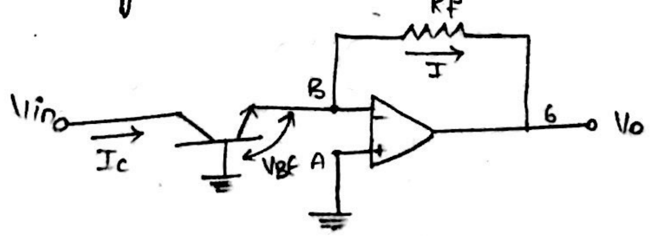
$$V = \eta V_T \cdot \ln\left[\frac{I_f}{I_0}\right].$$

$$V = V_T \cdot \ln\left[\frac{-V_0/R_f}{I_0}\right].$$

$$V = V_T \cdot \ln\left[\frac{-V_0}{R_f}\right] - \ln[I_0]. \qquad [\because \eta = 1].$$

$$\boxed{V_0 = -I_0 R_f e^{V/V_T}}$$

Anti-log Amplifier using Transistor:-



from the circuit,

$$I = I_C = \frac{V_B - V_0}{R_f}$$

$$\boxed{I = I_C = \frac{-V_0}{R_f}} \quad (1)$$

W.K.T the basic eq^n for log amplifier using Transistor is

$$V_{BE} = V_T \ln\left[\frac{I_C}{I_S}\right]$$

$$V_{BE} = V_T \cdot \ln\left[\frac{-V_0}{R_f \cdot I_S}\right]$$

$$\boxed{V_0 = -I_S \cdot R_f\, e^{V_{BE}/V_T}}$$