Unit-2

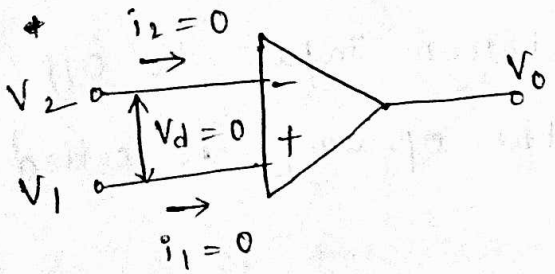
Op-Amp Applications :—

The applications of op-amp are,

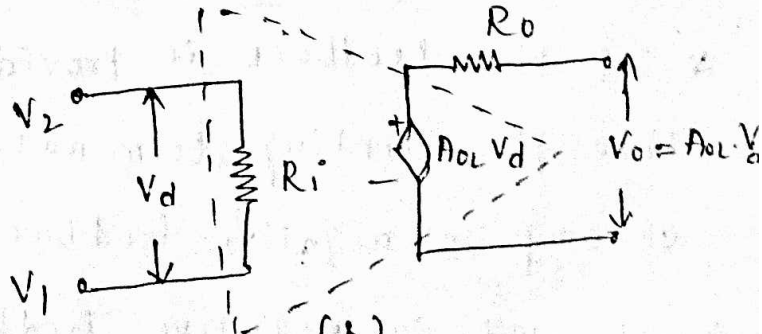
1. Summing Amplifier
2. Difference Amplifier
3. Integrator
4. Differentiator
5. Instrumentation Amplifier.
6. V to I and I to V converter.
7. Comparator
8. Precision Rectifier
9. Log and Antilog Amplifer.
10. Active filters.

Operational Amplifier :—

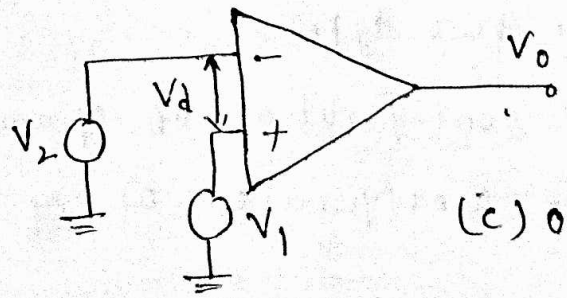
The schematic symbol of an op-amp is shown in below fig.



(a) Ideal op-amp.



(b) equivalent circuit of an op-amp.



(c) open loop circuit.

→ In fig (a) It has two input terminals and one output terminal. other terminals have not shown for simplicity.

→ The − and + symbols at the input refer to inverting and non-inverting input terminals respectively. i.e, if $V_1 = 0$, output V_o is 180° out of phase with input signal V_2.

→ And, when $V_2 = 0$, output V_o will be in phase with input signal applied at V_1.

→ This op-amp is said to be "ideal op-Amp."

→ The o/p voltage of an op-amp fig(b) is given as,

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

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

Op-amp in Negative Feedback :—

* If the feedback is provided between input to o/p through inverting terminal of the op-amp is called op-amp in negative feedback.

* op-amp in negative feedback can be divided into based on the input signal is applied to the terminals of the op-amp, that are two types.

1. Inverting Amplifier configuration of op-amp
2. Non-inverting Amplifier configuration of op-amp.

1. Inverting Amplifier :-

* The input signal is applied to inverting terminal and non-inverting terminal should be grounded. Then the circuit will produce an ouput signal 180° out of phase with the i/p signal.
* Then it is called Inverting amplifier.
* And the figure is shown in below.

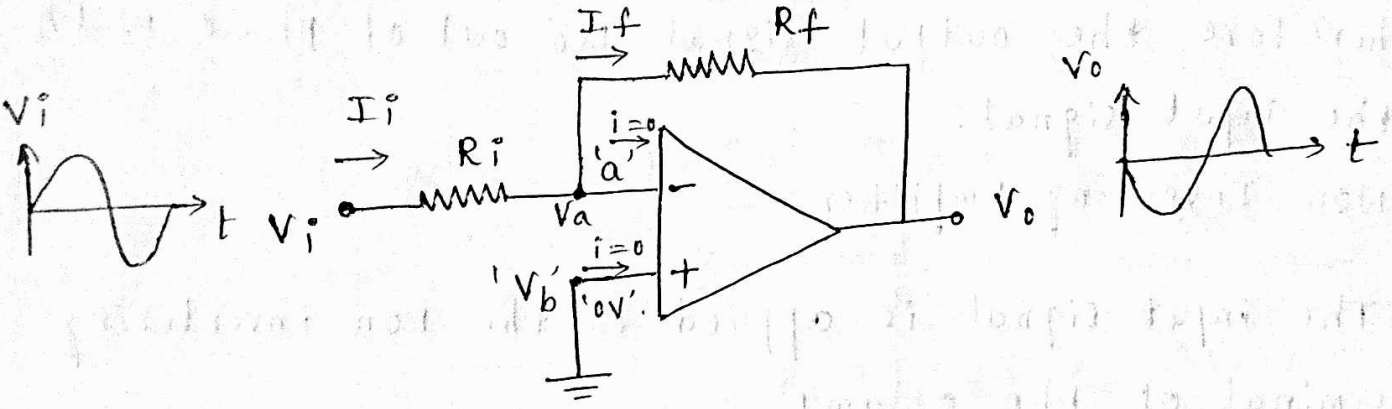


Fig: Inverting Amplifier

Analysis :- Apply KCL at node 'a' from the circuit,

Then the entering current = leaving current.

i.e, $I_i = I_f$.

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

* Based on the concept of virtual Ground, Voltage at inverting terminal 'V_a' is equal to the Voltage at non-inverting terminal. 'V_b' (i.e, 0v)
* Therefore $V_a = 0$.

$$\therefore \frac{V_i - 0}{R_i} = \frac{0 - V_o}{R_f}$$

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

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

The voltage gain, $A_V = \frac{V_o}{V_i} = -\frac{R_f}{R_i}$

$$\therefore A_V = -\frac{R_f}{R_i} \quad \text{(or)}$$

If, $R_f = R_i = 1k\Omega$

$$V_o = -V_i$$

Therefore, the output signal 180° out of phase with the input signal.

2. Non-Inverting Amplifier :—

* The input signal is applied to the non-inverting terminal of the op-amp.
* And the inverting input terminal is grounded. i.e, the output signal will be in phase with the input signal. It is called non-inverting Amplifier.

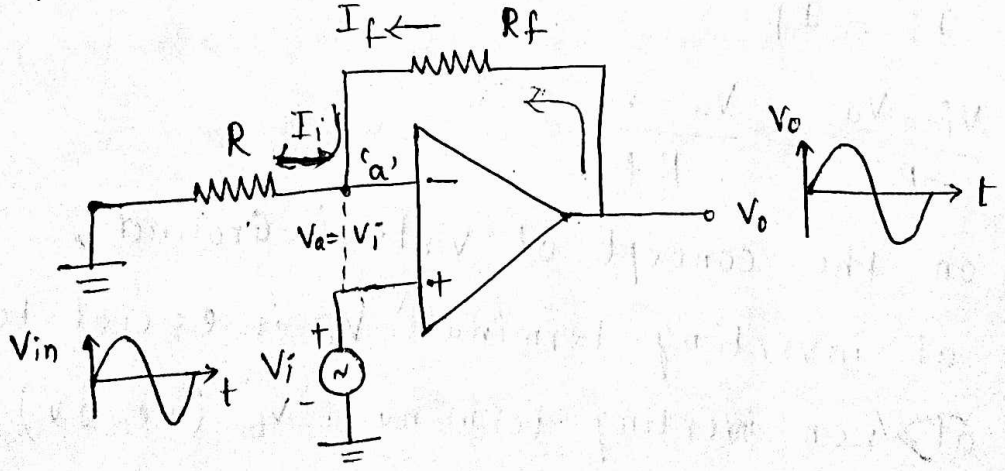


Fig : Non-inverting Amplifier.

Analysis :— Apply KCL at node 'a' from the circuit,

$$I_i + I_f = 0.$$

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

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

∴ Due to the virtual Ground, $\boxed{V_a = V_{in}}$

$$-\frac{V_i}{R} + \frac{V_o}{R_f} - \frac{V_i}{R_f} = 0$$

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

$$= V_i\left[\frac{1}{R_f} + \frac{1}{R}\right]$$

$$V_o = V_i R_f\left[\frac{1}{R_f} + \frac{1}{R}\right]$$

$$= V_i\left[\frac{R_f}{R_f} + \frac{R_f}{R}\right]$$

$$\therefore \boxed{V_o = V_i\left[1 + \frac{R_f}{R}\right]} \quad (\text{or}) \quad \boxed{A_v = \frac{V_o}{V_i} = \left(1 + \frac{R_f}{R}\right)}$$

let, $R_f = R = 1\ k\Omega$

$$\therefore \boxed{V_o = V_i}$$

∴ The o/p signal is in phase with the input signal in non-inverting Amplifier.

Problems :—

1. Design an inverting amplifier with a gain of −10 and input resistance equal to 10 kΩ.

Sol:- The gain of the amplifier, $A_{cl} = -10$.

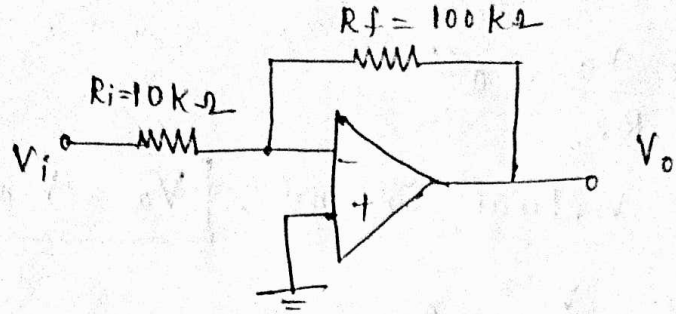
Input Resistance, $R_i = 10\ k\Omega$

since ~~assume~~, ~~$R_f = 10\ k\Omega$~~.

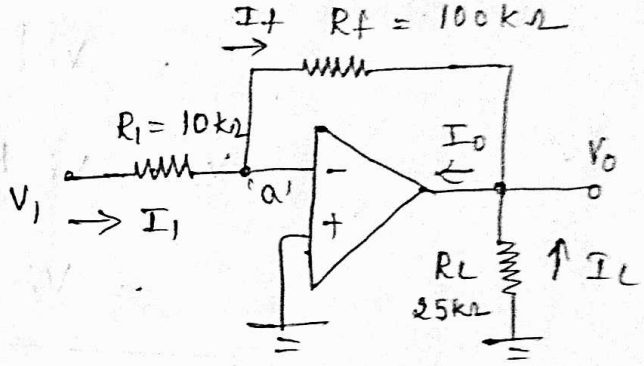
$$\therefore A_{cl} = -\frac{R_f}{R_i} \Rightarrow -10 = \frac{R_f}{10k}$$

$$\therefore R_f = 100\ k\Omega$$

The inverting amplifier circuit as follows.



2. In the figure $R_1 = 10\,k\Omega$, $R_f = 100\,k\Omega$, $V_i = 1V$. A load of $25\,k\Omega$ is connected to the output terminal. Calculate (i) I_1 (ii) V_o (iii) I_L and (iv) Total current I_o into the output pin.



Sol: Given: $R_1 = 10\,k\Omega$

$R_f = 100\,k\Omega$

$V_i = 1V$

$R_L = 25\,k\Omega$.

(i) $I_1 = \frac{V_1}{R_1} = \frac{1V}{10\,k\Omega} = 0.1\,mA$

(ii) $V_o = -\left(\frac{R_f}{R_1}\right) V_i = -\left(\frac{100\,k}{10\,k}\right) 1V = -10V$

(or)

To find 'V_o'. Apply KCL at node 'a'.

$I_1 = I_f$.

$\frac{V_1 - V_a}{R_1} = \frac{V_a - V_o}{R_f}$ [$\because$ Virtual Ground $V_a = 0$]

$\frac{1 - 0}{10\,k} = \frac{0 - V_o}{100\,k}$

$-V_o = \frac{100}{10} = 10$

$\therefore V_o = -10\,V$

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

(iv) $I_1 = 0.1\,mA$.

$I_L = 0.4\,mA$.

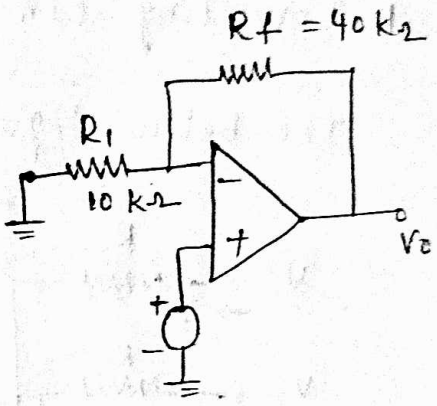
To find the total current, $I_0 = I_L + I_f$

$\therefore I_0 = 0.1\,mA + 0.4\,mA$

$I_0 = 0.5\,mA$

3) Design an Non-inverting Amplifier with a gain of +5 using one op-Amp.

Sol: Since, the gain is positive., $A_{CL} = +5$.



Let, $R_1 = 10\,k\Omega$.

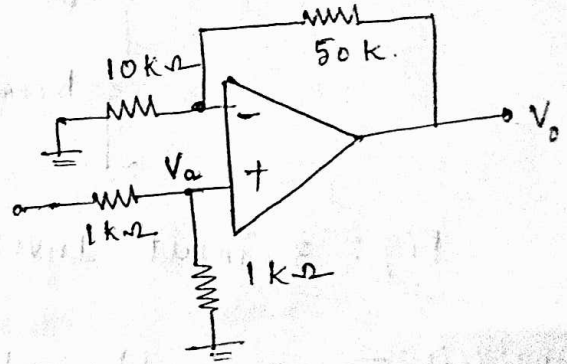
Then, $A_{CL} = 1 + \frac{R_f}{R_1}$

$5 = 1 + \frac{R_f}{10k}$

$\frac{R_f}{10k} = 4 \Rightarrow R_f = 40\,k\Omega$

4) In the figure shown, calculate V_0, if $V_{in} = 1V$.

Sol: The circuit is a non-inverting amplifier.



By using voltage division rule

Then, $V_a = \frac{1k\Omega}{1k\Omega + 1k\Omega} \times V_{in}$

$V_a = \frac{1}{2} \times 1V = 0.5\,V.$

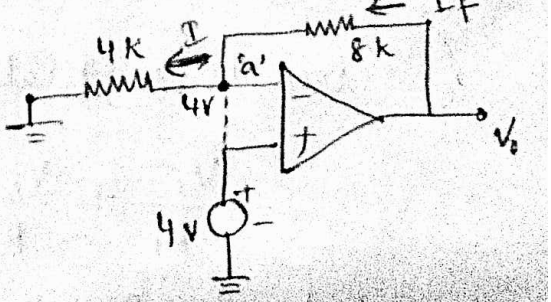
Thus, output voltage $V_0 = \left(1 + \frac{R_f}{R}\right) V_a$

$= \left(1 + \frac{50k}{10k}\right) 0.5$

$\therefore V_0 = 6 \times 0.5 = 3.0\,V$

5) In the CKT shown op-amp ideal. calculate o/p voltage.

Sol: Apply KCL at node 'a',



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

$V_0 = \left(1 + \frac{8}{4}\right) 4 = 3 \times 4 = 12V$

Summing Amplifier :— (or) Adder (or) summer

The summing Amplifier is classified as,

i) Inverting summing Amplifier

2) Non-Inverting summing Amplifier

1. Inverting summing Amplifier :—

The below figure shows the inverting summing Amplifier

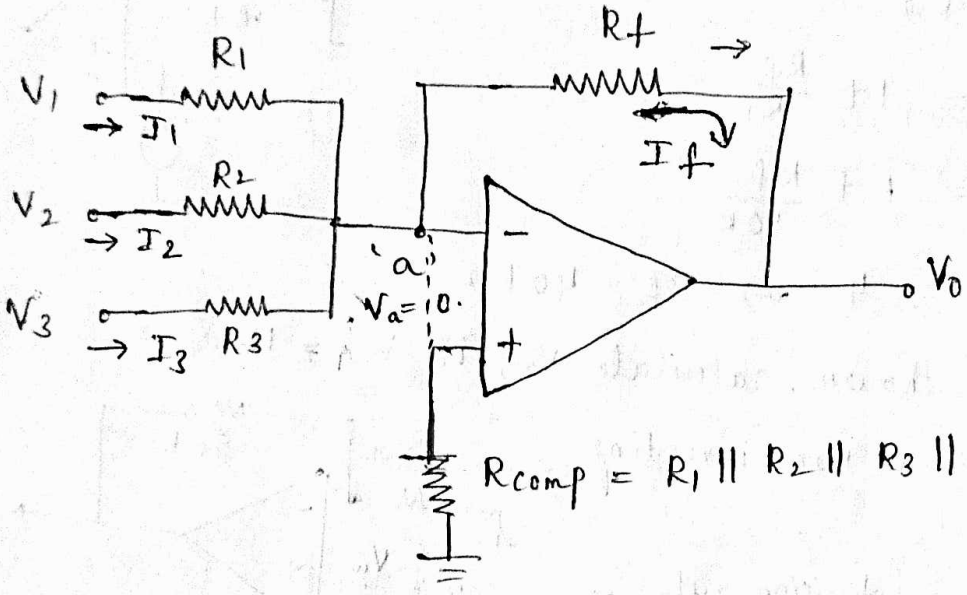


Fig: 3-Input Inverting summing Amplifier.

Analysis :— From the above figure.

Apply KCL at node 'a'.

$$I_1 + I_2 + I_3 + I_f = 0 \quad [I_1 + I_2 + I_3 = I_f]$$

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

Due to virtual Ground $V_a = 0$.

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

Let $R_1 = R_2 = R_3 = R$

$$\frac{V_1}{R} + \frac{V_2}{R} + \frac{V_3}{R} + \frac{V_0}{R_f} = 0$$

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

$$\therefore \boxed{V_0 = -\frac{R_f}{R}\left[V_1 + V_2 + V_3\right]}$$

case(i):- Averaging CKT

If, $R_f = \left(\frac{1}{3}\right) R$.

$$\therefore V_0 = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

(ii) Weight

If $R_f = R = 1k\Omega$

$$\boxed{\therefore V_0 = -\left[V_1 + V_2 + V_3\right]} \text{ (Adder)}$$

2. Non- Inverting summing Amplifier :—

The below figure shows the Non-inverting summing Amplifier.

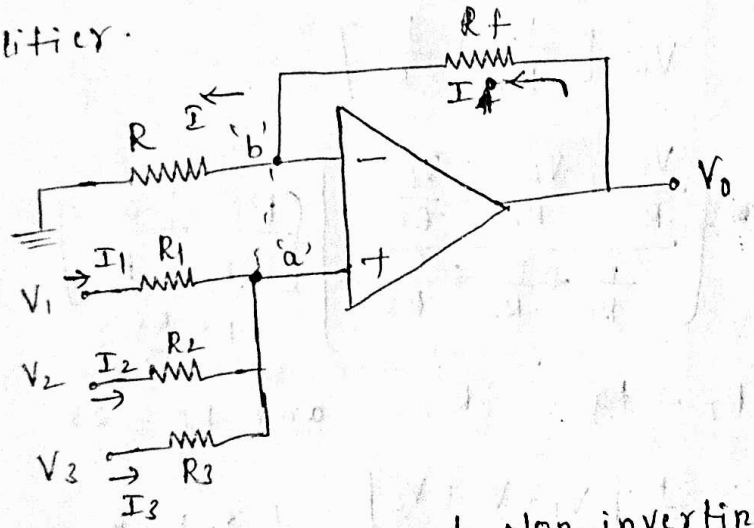


Fig: 3- Input Non-inverting summing Amplifier

Analysis :- From the figure,

Apply KCL at node 'a' in the non-inverting terminal.

$$I_1 + I_2 + I_3 = 0$$

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

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} - V_a\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right] = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = V_a\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right]$$

$$V_a = \quad \rightarrow (1)$$

$$I_f = \frac{V_o - V_b}{R_f} \qquad [\because \text{Virtual Ground } V_a = V_b$$

$$I_f = \frac{V_o - V_a}{R_f} \longrightarrow (2)$$

$$I = \frac{V_b - 0}{R} = \frac{V_a}{R} \longrightarrow (3)$$

$$(2) = (3)$$

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

$$\frac{V_o}{R_f} = V_a \left[\frac{1}{R_f} + \frac{1}{R}\right]$$

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

$$\left[1 + \frac{R_f}{R}\right]$$

Let, $R_1 = R_2 = R_3 = R_f = 'R'$. and $R_f = 2R$.

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

But w. k. T. The o/p of non-inverting amp

$$V_o = \left(1 + \frac{R_f}{R}\right) V_a.$$

$$\therefore V_o = \left[V_1 + V_2 + V_3\right] \quad \text{"Perfect summer"}$$

Ex: Design an adder circuit using an op-amp to get the output expression as, $V_0 = -(0.1V_1 + 0.2V_2 + 0.3V_3)$. where V_1, V_2, and V_3 are the inputs.

Sol: The o/p expression of summing amplifier is,

$$V_0 = -\left[\frac{R_f}{R_1}V_1 + \left(\frac{R_f}{R_2}\right)V_2 + \left(\frac{R_f}{R_3}\right)V_3\right] \longrightarrow (1)$$

Given, $V_0 = -[0.1V_1 + 0.2V_2 + 0.3V_3] \longrightarrow (2)$

compare (1) & (2).

Every i/p signal is amplified with some weightage factor.

choose, $R_f = 10\,k\Omega$.

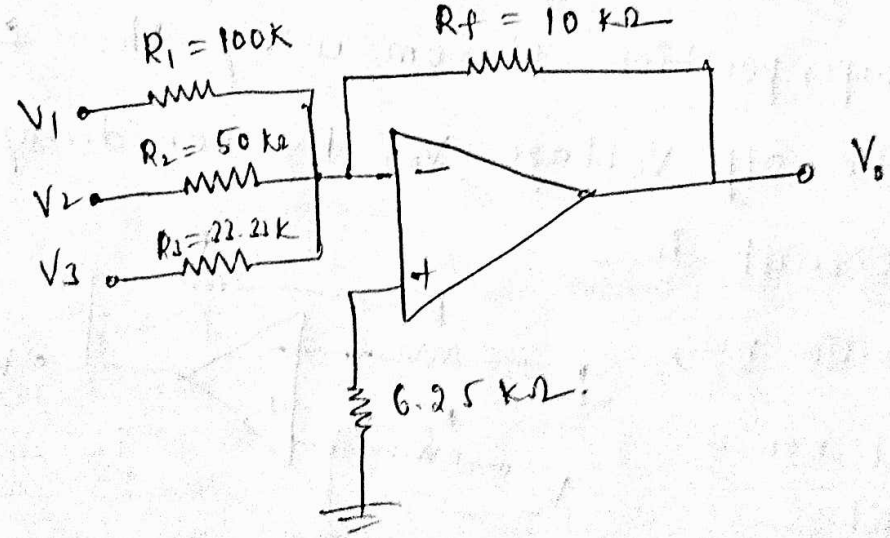
$\therefore \frac{R_f}{R_1} = 0.1$, $\frac{R_f}{R_2} = 0.2$, $\frac{R_f}{R_3} = 0.3$

$\frac{10K}{0.1} = R_1$ $\quad R_2 = \frac{10k}{0.2}$ $\quad R_3 = \frac{10K}{0.3}$

$\therefore R_1 = 100k\Omega$ $\quad R_2 = 50\,k\Omega$ $\quad R_3 = 33.33\,k\Omega$

offset minimizing resistor (R_{om}) $= R_1 \| R_2 \| R_3 \| R_f$.

$\therefore R_{om} = 6.25\,k\Omega$

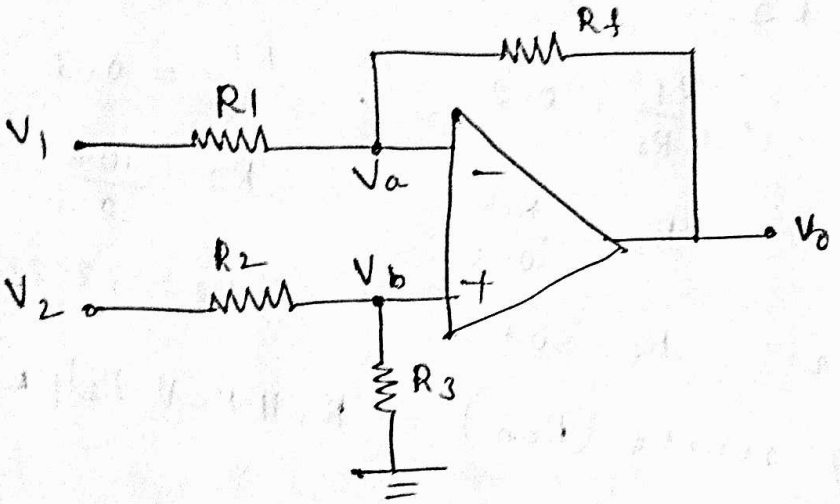


Subtractor: (Difference amplifier)

⇒ An op-amp based subtractor produces an o/p equal to the difference of the i/p voltages applied at its inverting & non-inverting terminals.

⇒ It is also called as difference amplifier, since the o/p is an amplified one.

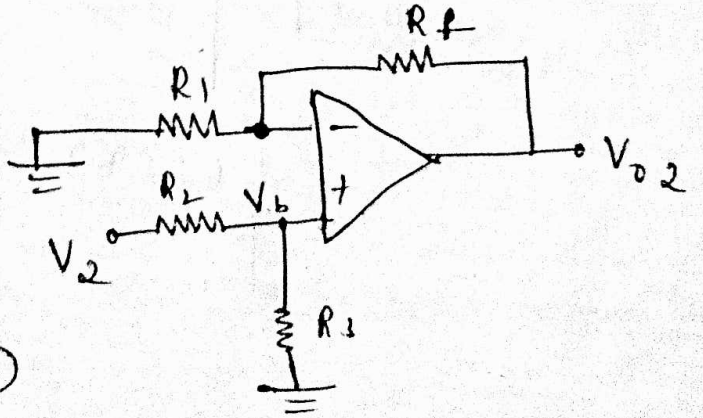
⇒ The circuit diagram of an op-amp based subtractor is shown in the following figure.



⇒ Now, let us find the o/p expression of this circuit 'Vo' is using superposition therom using the following.

Case(i) Lets calculate the o/p voltage V_{o2} by considering only V_2.

⇒ The modified circuit is,



Using voltage division rule,

⇒ The o/p voltage at non-inverting terminal:

$$V_b = V_2\left(\frac{R_3}{R_2+R_3}\right) \longrightarrow (1)$$

$$\therefore V_{o2} = V_b\left(1+\frac{R_f}{R}\right) \longrightarrow (2)$$

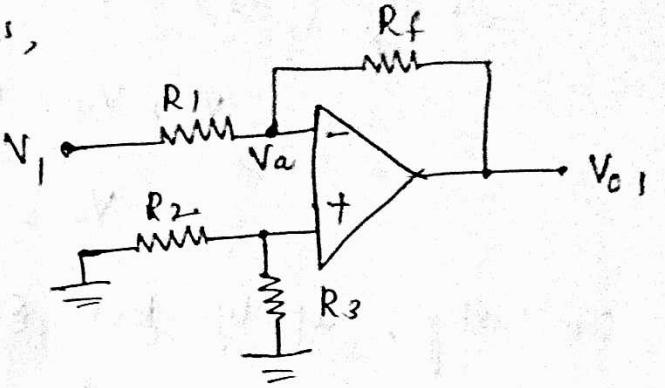
substitute eq ① in ②.

$$\therefore V_{02} = V_2\left(\frac{R_3}{R_2+R_3}\right)\left(1+\frac{R_f}{R_1}\right) \longrightarrow ③$$

Case(ii) :—

Lets find the o/p voltage, V_{01} by considering only 'V_1'.

The modified circuit is becomes,



→ 10, the circuit becomes a inverting op-amp.

⇒ Therefore the o/p voltage 'V_{01}' of the CKT will be.

$$\therefore V_{01} = -\left(\frac{R_f}{R_1}\right)V_1 \longrightarrow ④.$$

∴ To get the total o/p voltage $V_o = V_{01} + V_{02}$.

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

If $R_1 = R_2 = R_3 = R_f = R$. Then o/p voltage '$V_o$' is,

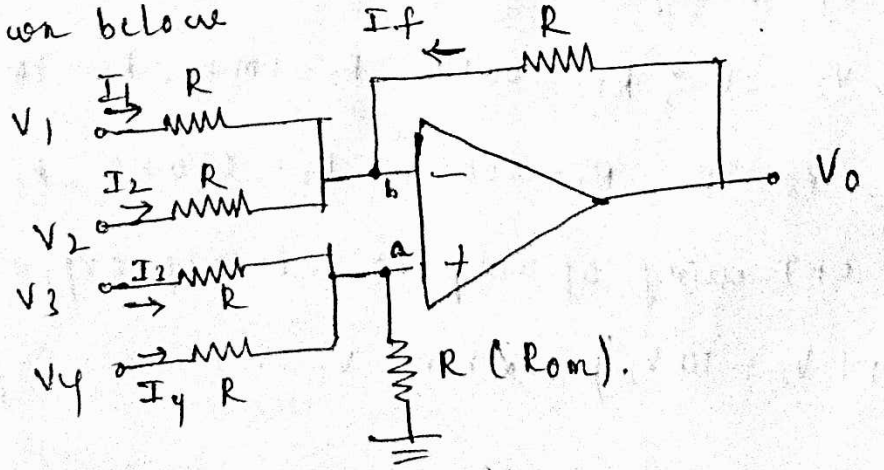
$$V_o = -\left(\frac{R}{R}\right)V_1 + V_2\left(\frac{R}{2R}\right)\left(1+\frac{R}{R}\right)$$

$$= V_2\left(\frac{1}{2}\cdot 2\right) - V_1$$

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

Adder | subtractor :—

⇒ The op-amp is used as adder | subtractor and CKT is shown below



From the above CKT, apply kcl at node 'a'.

$$\frac{V_3 - V_a}{R} + \frac{V_4 - V_a}{R} + \frac{0 - V_a}{R} = 0$$

$$\Rightarrow \frac{1}{R}\left[V_3 + V_4 - 3V_a\right] = 0$$

$$\Rightarrow V_3 + V_4 - 3V_a = 0$$

$$\therefore V_a = \frac{V_3 + V_4}{3} \longrightarrow (1)$$

Similarly, apply kcl @ node 'b'.

$$\frac{V_1 - V_b}{R} + \frac{V_2 - V_b}{R} + \frac{V_o - V_b}{R} = 0$$

$$\frac{1}{R}\left[V_1 + V_2 + V_o - 3V_b\right] = 0$$

$$V_1 + V_2 + V_o - 3V_b = 0$$

$$V_o = 3V_b - V_1 - V_2 \longrightarrow (2)$$

Due to Virtual Ground, $V_a = V_b$. Then eq (2) becomes

$$V_o = 3\left(\frac{V_3 + V_4}{3}\right) - V_1 - V_2$$

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

Problems :-

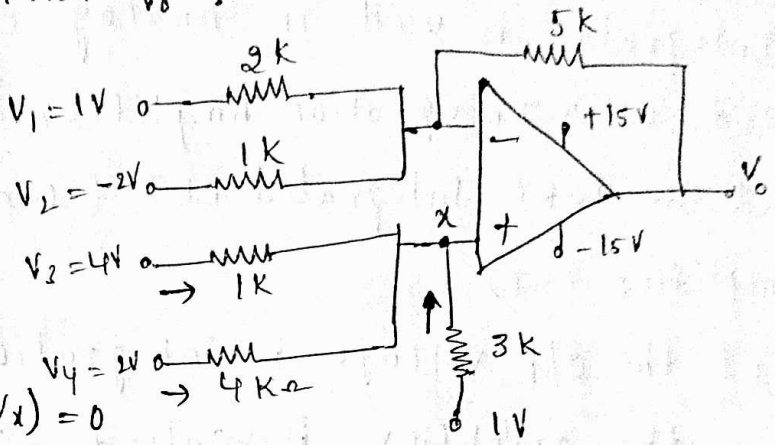
1. Calculate the o/p voltage of an op-amp summing amplifier for the following set of voltages and resistors. Given $R_f = 1\,M\Omega$

a) $V_1 = 1V$, $V_2 = 2V$, $V_3 = 3V$; $R_1 = 500\,k\Omega$, $R_2 = 1\,M\Omega$, $R_3 = 1\,M\Omega$

b) $V_1 = -2V$, $V_2 = 3V$, $V_3 = 1V$; $R_1 = 200\,k\Omega$, $R_2 = 500\,k\Omega$, $R_3 = 1\,M\Omega$

2. Design an adder CKT using op-amp to get o/p expression as, $V_o = -(0.1V_1 + V_2 + 10V_3)$, where V_1, V_2, V_3 are inputs

3. The CKT is shown in below. If $R_f = 5\,k\Omega$, $R_1 = 2\,k\Omega$, $R_2 = 1k$, $R_3 = 1k\Omega$, $R_4 = 4k\Omega$. Find V_o ?



Apply KCL @ node 'x'.

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

$$\frac{12(4-V_x) + 3(2-V_x) + 4(1-V_x) = 0}{12k}$$

$$\Rightarrow 12(4-V_x) + 3(2-V_x) + 4(1-V_x) = 0$$

$$\Rightarrow 48 - 12V_x + 6 - 3V_x + 4 - 4V_x = 0$$

$$\Rightarrow 58 - 19V_x = 0$$

$$V_x = 58/19 = 3.05.$$

Apply KCL @ node 'y'.

$$\frac{1-V_y}{2k} + \frac{(-2-V_y)}{1k} + \frac{V_o - V_y}{5k} = 0.$$

Due to virtual Ground $V_x = V_y \Rightarrow V_y = 3.05.$

$$\frac{1-3.05}{2} + \frac{(-2-3.05)}{1k} + \frac{V_o - 3.05}{5k} = 0.$$

$$-\frac{2.05}{2} - \frac{5.05}{1k} + \frac{V_o - 3.05}{5k} = 0$$

$$-1.025 - 5.05 + \frac{V_o}{5k} - 0.61 = 0$$

$$V_o = 5(6.685)$$

$$\boxed{V_o = 33.425}$$

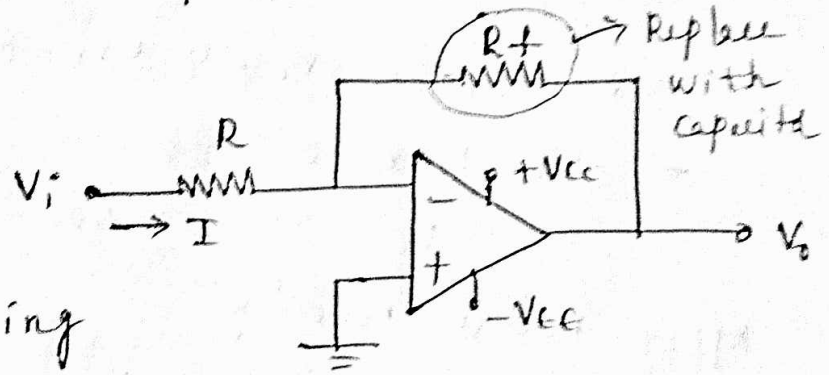
Integrator :— (Integration Amplifier)

⇒ Integrator is used in Analog computer. It is also called as "Integration Amplifier."

→ Let us take Integrator ckt (similar to Inverting Amplifier ckt).

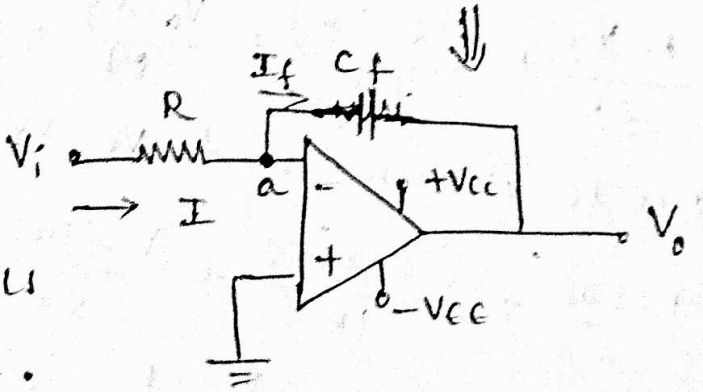
→ If the o/p voltage is integration of i/p voltage then the amplifier is called "Integrator".

→ By replacing of 'R_f' by a capacitor. First, we can take Inverting amplifier.



⇒ From the circuit, the voltage developed across capacitor and charging current relation is,

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



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

⇒ Therefore, the feedback current,

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

Due to Virtual Ground, $V_a = 0$.

$$I_f = -C_f \frac{dV_o}{dt} \longrightarrow (1)$$

→ The i/p current, $I = \frac{V_i - V_a}{R} = \frac{V_i}{R} \longrightarrow (2)$

$① = ②$

$I_f = I$

$$-C_f \cdot \frac{dV_o}{dt} = \frac{V_i}{R}$$

$$\frac{dV_o}{dt} = -\frac{V_i}{RC_f}$$

Apply Integration on both sides.

$$\int \frac{dV_o}{dt} \cdot dt = -\frac{1}{RC_f} \int V_i \, dt + C_1 \quad \rightarrow \text{Integral constant.}$$

let, $C_1 = 0$.

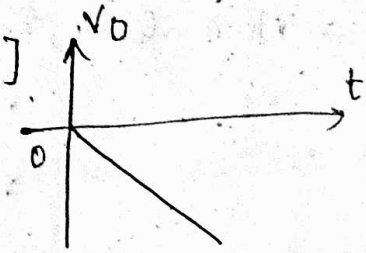
$$\therefore V_o = -\frac{1}{RC_f} \int_0^t V_i \cdot dt$$

⇒ This is the o/p voltage expression of Integration Amplifier

⇒ The o/p is proportional to the integral of i/p voltage.

Case (i) :- (a) If V_i = constant ($V_i = +V$).

⇒ Then, $V_o = -\frac{1}{RC_f} \int_0^t V \cdot dt = -\frac{V}{RC_f} [t]$



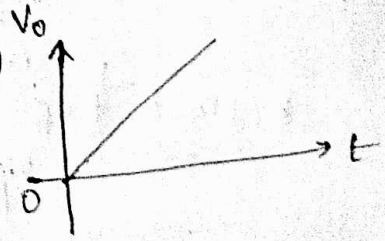
$$V_o = -\frac{Vt}{RC_f}$$

* The o/p will be ramp signal. where $\left(-\frac{V}{RC_f}\right)$ is slope (-ve)

(b) If $V_i = -V$, $\frac{1}{RC_f} \int_0^t (-V) \, dt = \frac{V}{RC_f} (t)$

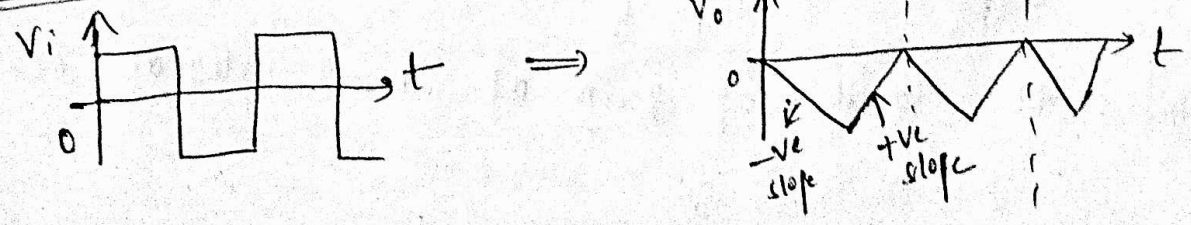
→ Then, $V_o = -$

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



* The slope is positive $\left(\frac{V}{RC_f}\right)$.

case (ii) :- If i/p is a square wave, then the o/p is ramp signal



Case (iii) :— If the i/p is sinusoidal wave,

$\Rightarrow V_i = a_0 \sin wt$, Then $V_o = \frac{-1}{RCf} \int_0^t a_0 \sin wt \, dt$

$$= -\frac{a_0}{RCf} \left[\frac{\cos wt}{w}\right]_0^t$$

$$= \frac{-a_0}{wRCf} \left[\cos w(t) - \cos w(0)\right]$$

$$\boxed{V_o = -\frac{a_0}{wRCf} \cos wt}$$

* The o/p depends on frequency.

Gain of the Integrator :—

* The o/p voltage of inverting Amplifier is,

$$V_o = -\left(\frac{Rf}{R}\right) V_i$$

* Then Gain, $A_{CL} = \frac{V_o}{V_i} = -\frac{Rf}{R} = -\frac{Z_f}{R}$

$X_f = \frac{1}{sCf}$

$$= -\frac{X_f}{R} = -\frac{1}{sRCf}$$

$$\therefore A_{CL} = \frac{-1}{jwRCf}$$

$$A_{CL} = \frac{j}{wRCf}$$, where RC is time constant.

Replace $\frac{1}{RCf}$ by w_a.

$$A_{CL} = \frac{j w_a}{w} = j \frac{2\pi f a}{2\pi f} = j \frac{fa}{f}$$

$$\therefore A_{CL} = j \frac{fa}{f}$$

$$\boxed{|A_{CL}| = \frac{fa}{f}}$$

* This is the closed loop gain of ideal integrator ckt.

* If, $f = 0$; Then $|A_{CL}| = \infty$.

* If, $f = f_a$; Then $|A_{CL}| = 1$. (Unity) i.e, 0 dB.

where, 'f_a' is called unity gain frequency of Integrator

* At which frequency the gain becomes unity. Then that frequency is called unity gain frequency.

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

$$\left\{ \begin{array}{l} \because \omega_a = \frac{1}{RC_f} \\ 2\pi f_a = \frac{1}{RC_f} \\ f_a = \frac{1}{2\pi RC_f} \end{array} \right.$$

* At $f = 0$, [low frequency condition] the o/p is unstable.

* Because the o/p can be non-zero o/p even though V_i is zero. [Because of gain]. That non-zero o/p is called instability of the CKT.

⇒ So, this ideal integrated circuit is not practically used

⇒ To avoid this drawback, at low freq we can make it stable by adding extra resistor.

→ The capacitor is open ckted at low frequencies, so, the gain of the ckt becomes infinite.

→ If the gain is varying, it is not suitable for practical application. Because ckt is unstable at zero frequency.

⇒ To make system stable at low frequency, we need to add one extra resistor 'R_f' is parallel to 'C_f'.

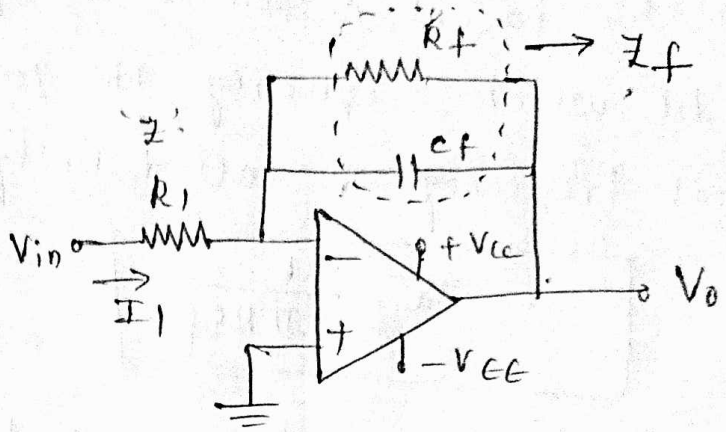
⇒ Because of this 'R_f', we consider another frequency "f_b". (Gain limiting frequency),

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

The practical Integrator :—

* The ideal Integrated CKT is connected with another resistor 'R_f'.

* closed loop gain of the practical Integrated,



$$A_{cl} = -\frac{Z_f}{Z} \longrightarrow (1)$$

$$Z_F = R_f \parallel \frac{1}{sC_f}.$$

$$Z_f = \frac{R_f \cdot \frac{1}{sC_f}}{R_f + \frac{1}{sC_f}} = \frac{R_f}{sC_f R_f + 1}.$$

$$\therefore Z_f = \frac{R_f}{1 + sC_f R_f} \longrightarrow (2)$$

Substitute (2) in (1).

$$(1) \Rightarrow A_{cl} = -\left[\frac{\frac{R_f}{1+sC_f R_f}}{R}\right]$$

$$A_{cl} = -\left(\frac{R_f}{R}\right)\left(\frac{1}{1+sC_f R_f}\right) = -\left(\frac{R_f}{R}\right)\left(\frac{1}{1+j\omega C_f R_f}\right)$$

Here, $\omega_b = \frac{1}{R_f C_f} \Rightarrow R_f C_f = \frac{1}{\omega_b}$.

$$\therefore A_{cl} = \frac{-\left(\frac{R_f}{R}\right)}{1 + j\left(\frac{\omega}{\omega_b}\right)} = \frac{-\left(\frac{R_f}{R}\right)}{1 + j\left(\frac{f}{f_b}\right)}.$$

magnitude of closed loop Gain,

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

⇒ At, $f=0$; The gain $\boxed{|A_{CL}| = \frac{R_f}{R}}$.

⇒ At zero frequency, ideal Integrator is infinite. But practical Integrated is stable. (Finite).

⇒ At $f = f_b$, $\boxed{|A_{CL}| = \frac{R_f/R}{\sqrt{2}}}$

⇒ In dB, $20 \log |A_{CL}| = 20 \log \left(\frac{R_f/R}{\sqrt{2}}\right)$

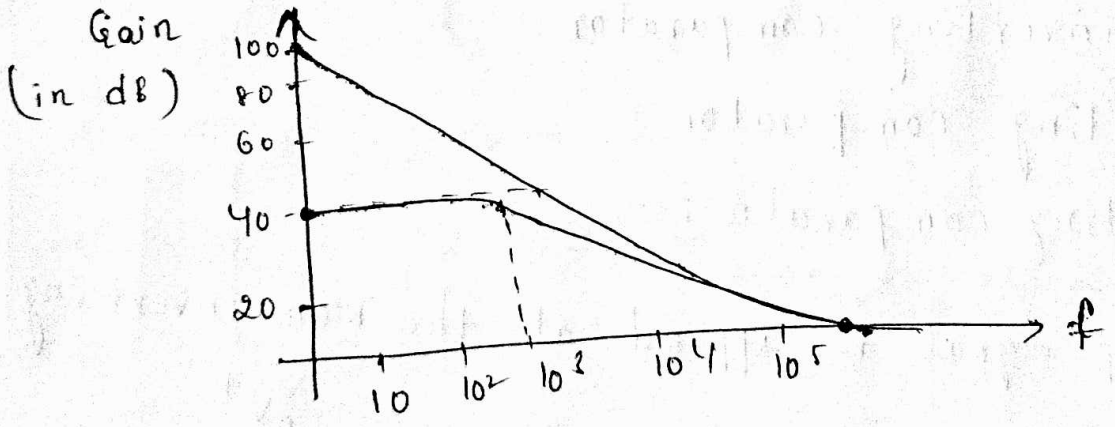
$= 20 \log |R_f/R| - 20 \log \sqrt{2}$

$\therefore 20 \log |A_{CL}| = 20 \log |R_f/R| - 3\,dB$

* f_a – Unity Gain frequency

f_b – cut-off frequency (or) Break frq. (or) Gain limiting frq.

Frequency Response :—



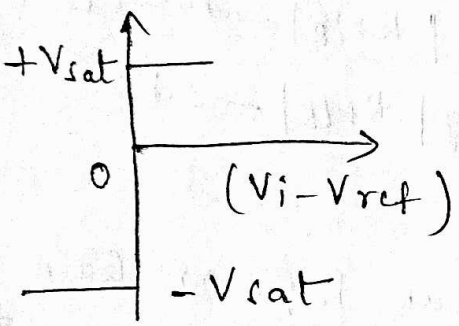
To design a practical Integrator

$\boxed{f_{min} = 10 f_b}$ $\left\{ \because f_b = \frac{f_a}{10} \right\}$

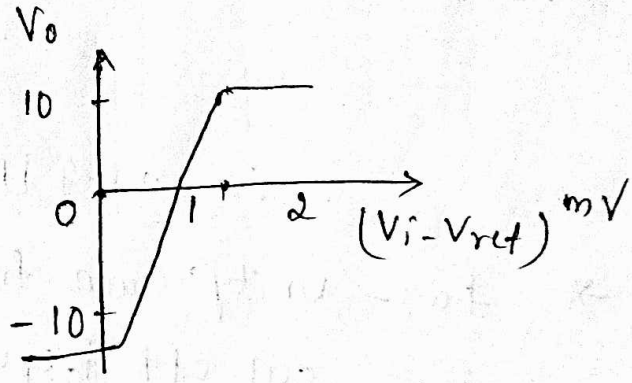
* If $f < f_b$; Integrated behaves like Inverting Amp.
* If $f > f_b$; Then it like a integrator.
* If $f >> f_b$; Then the integrated CKT behaves as Ideal Integrated

comparator :-

* A comparator is a circuit which compares a signal voltage applied at one input of an op-amp with a known reference voltage at the other input.
* The transfer characteristics of a ideal and practical comparator as shown in below



(a) Ideal comparator.



(b) practical comparator.

* There are basically two types of comparators.
  1. Non-inverting comparator
  2. Inverting comparator.

1. Non-Inverting comparata :-

* If, the i/p signal is applied at the Non-inverting terminal and reference signal is applied at inverting terminal.
* Then it is called as non-inverting compalatd.
* Let, i/p signal is sinusoidal and reference voltage is 1V.

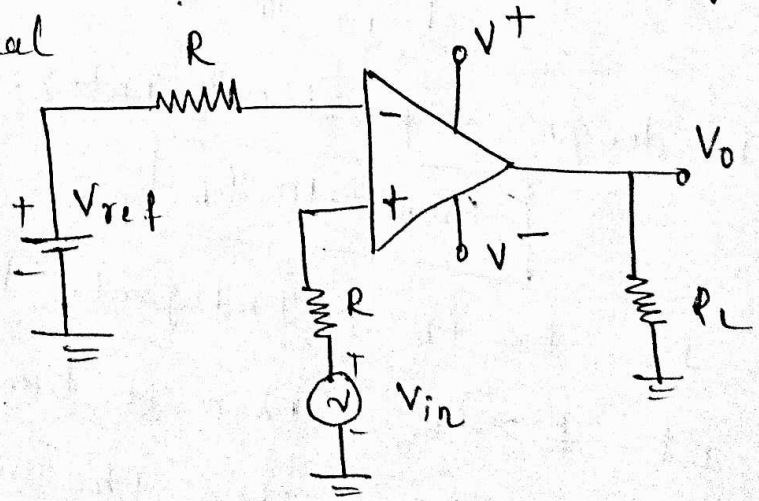


Fig: Non-Inverting comparator

(a) Here, V_{ref} = +ve [i.e, 1V].

The difference voltage, $V_d = V_{in} - V_{ref}$

If, $V_{in} > V_{ref} \Rightarrow V_d$ = +ve

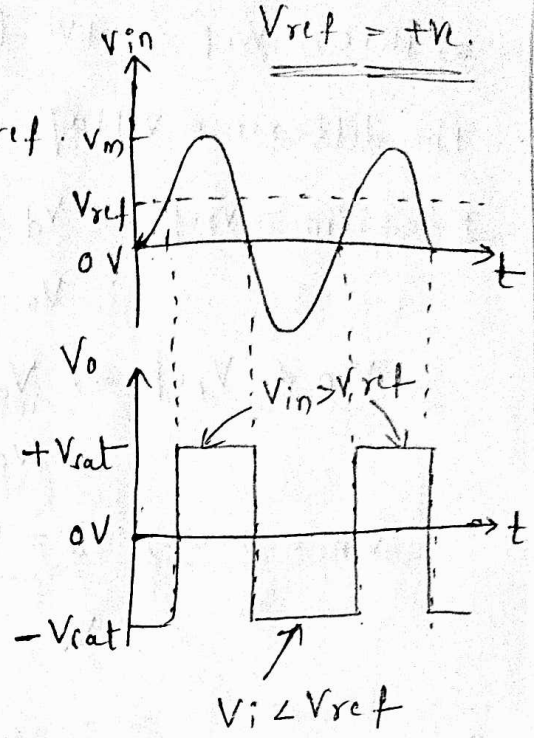
i.e, output voltage, $V_o = +V_{sat}$

If $V_{in} < V_{ref} \Rightarrow V_d$ = −ve

i.e, o/p voltage, $V_o = -V_{sat}$.

If $V_{in} = 0 \Rightarrow V_d = 0 - V_{ref}$

i.e, o/p voltage $V_o = -V_{sat}$.



(b) Here, V_{ref} = −ve [i.e, −1V]

The difference voltage, $V_d = V_{in} - V_{ref}$

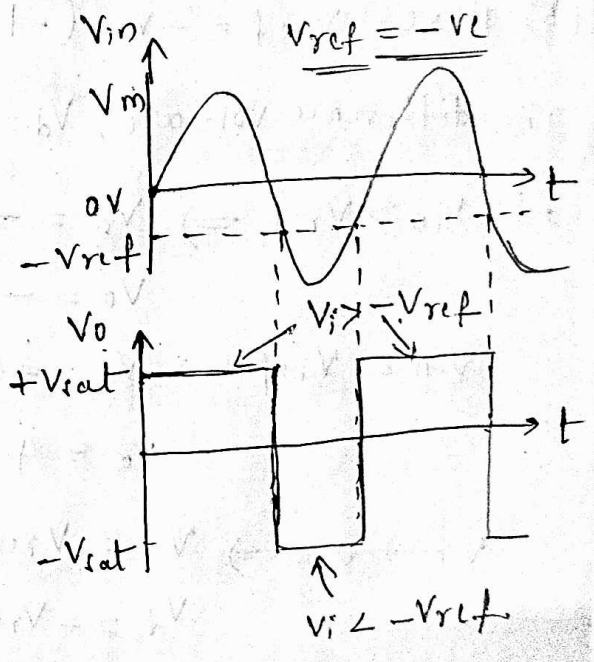
If, $V_{in} > V_{ref} \Rightarrow V_d$ = +ve

$V_o = +V_{sat}$.

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

$V_{in} = 0 \Rightarrow V_d = 0 - (-V_{ref})$

$\therefore V_o = +V_{sat}$.



2. Inverting comparatd :—

* The input signal is applied at inverting terminal & reference signal is applied at non-inverting terminal then it is called inverting comparatd.

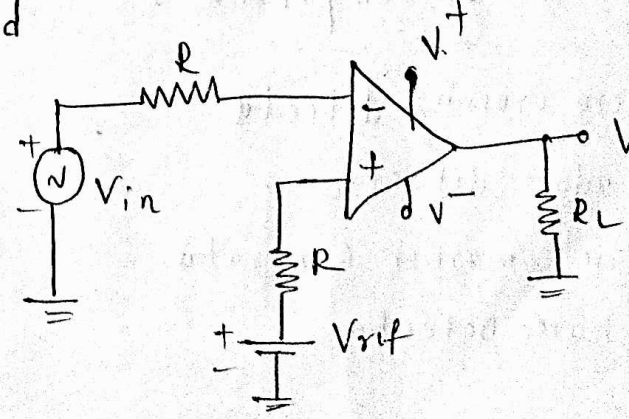


Fig) Inverting comparatd

a) Here, $V_{ref} = +Ve$ (i.e, 1V)

The difference voltage, $V_d = V_{ref} - V_{in}$.

If $V_{in} > V_{ref} \Rightarrow V_d = -V_{sat}$ (-ve).

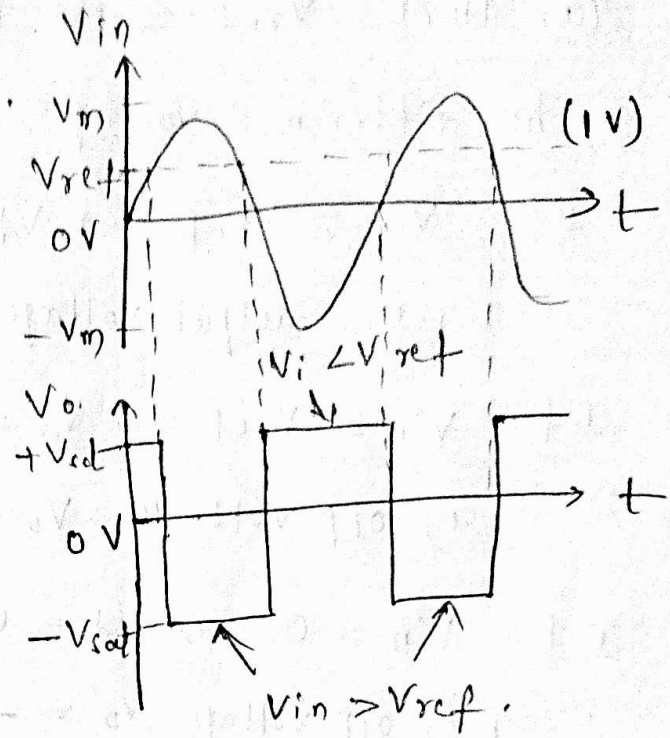
$\therefore V_o = -V_{sat}$

$V_{in} < V_{ref} \Rightarrow V_d = +Ve$

$\therefore V_o = +V_{sat}$.

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

$\therefore V_o = +V_{sat}$.



(b) Here, $V_{ref} = -Ve$ (-1V)

The difference voltage, $V_d = V_{ref} - V_{in}$.

If, $V_{in} > V_{ref} \Rightarrow V_d = -Ve$

$V_o = -V_{sat}$

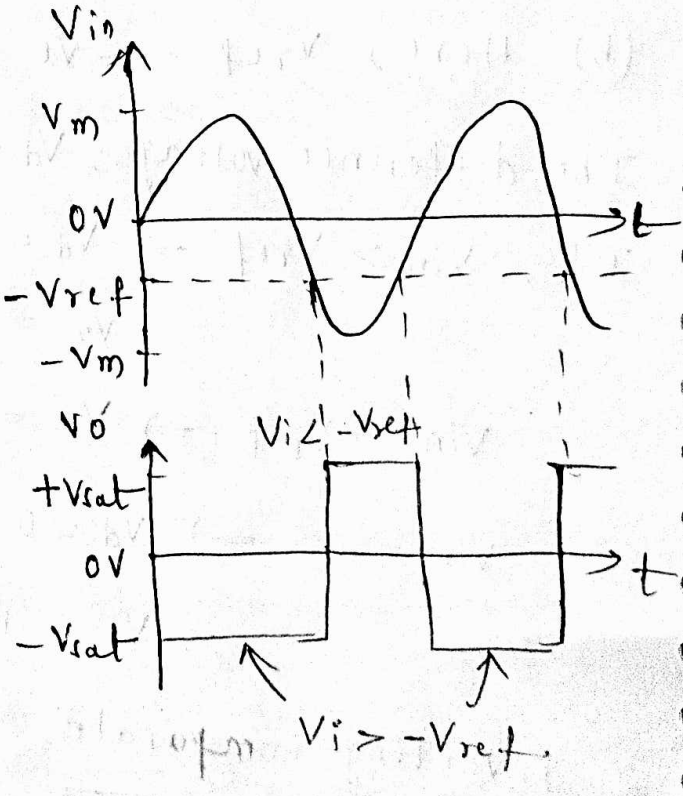
$V_{in} < V_{ref} \Rightarrow V_d = +Ve$

$V_o = +V_{sat}$

$V_{in} = 0, \Rightarrow V_d = V_{ref} - 0$

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

$\therefore V_o = -V_{sat}$.



Applications of comparator :-

1. Zero crossing detector
2. window detector
3. Time marker Generator
4. phase Detector

Precision Rectifiers :-

* The function of ordinary diode is, if input voltage (or) Applied i/p (V_{in}) is greater than or equal to cut-in voltage (V_r).

i.e, $V_{in} \geq V_r$. Then diode becomes conducting or Diode is in forward bias. (ON state).

* If, $V_{in} \leq V_r$. Then diode remains reversed bias (off state). i.e, open circuit

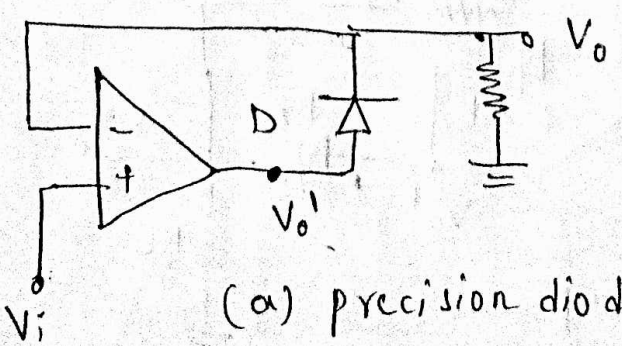
* Diodes used as rectifiers for strong ac signal, which converts ac signal to pulsating dc.

* If ac signal has some 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". This can rectify very weak ac signal.

⇒ These precision Rectifiers are used in bio-medical to rectify the body potential. [like ex: ECG]

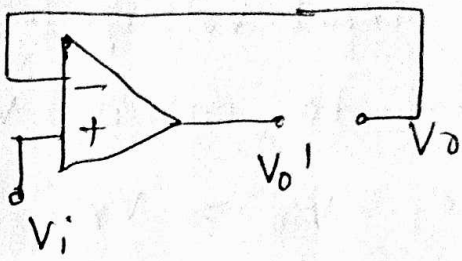
⇒ Precision diode consists of op-amp & ordinary diode. And it is shown in below.



(a) precision diode

⇒ Ordinary diode cannot rectify below cut-in voltage so, to make diode ideal. we need to place in feedback path of op-amp.

⇒ If the diode becomes off, when $V_o' < V_o$. Then op-amp is operated in open-loop condition.



$$\therefore \boxed{V_o' = A_{OL} \cdot V_i} \qquad [\because \text{Practically } A_{OL} = 10^6]$$

$$\Rightarrow \quad V_o' \leq V_r$$

$$A_{OL} \cdot V_i \leq V_r$$

$$V_i \leq \frac{V_r}{A_{OL}}$$

$$V_i \leq \frac{V_r}{10^6} \qquad [\because V_r \text{ has } 0.7\,V].$$

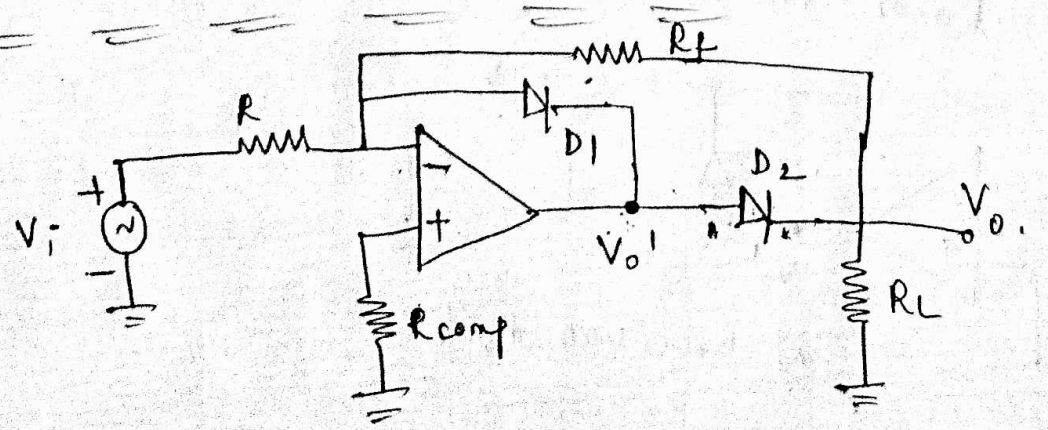
$$V_i \leq 0.7\,\mu V. \quad [\text{Diode is OFF}].$$

⇒ Basically, the precision rectifiers are two types.

(i) Half-wave Precision Rectifier.

(ii) Full-wave Precision Rectifier.

1. Half-wave precision Rectifier :—



⇒ Here V_o' and V_i are in phase with 180° phase shift.

If, i/p is positive ⇒ Then $V_o' = -Ve$

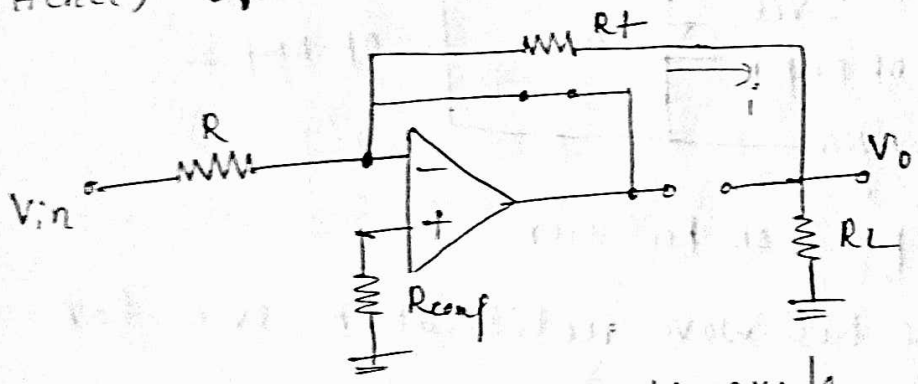
I/p is negative ⇒ Then $V_o' = +Ve$.

⇒ Here we are giving sine wave as input signal.

Case (i) :- For positive Half-cycle

⇒ I/p voltage, $V_i = +VL$, Then o/p $V_o' = -VL$

→) Hence, D_1 is ON and D_2 is OFF.



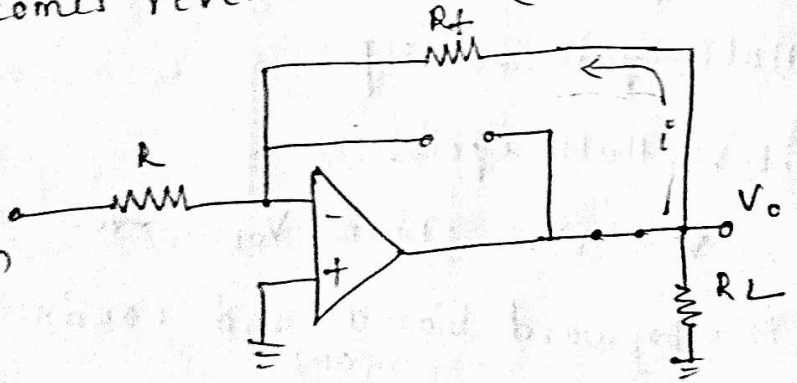
Then, $V_o = 0$.

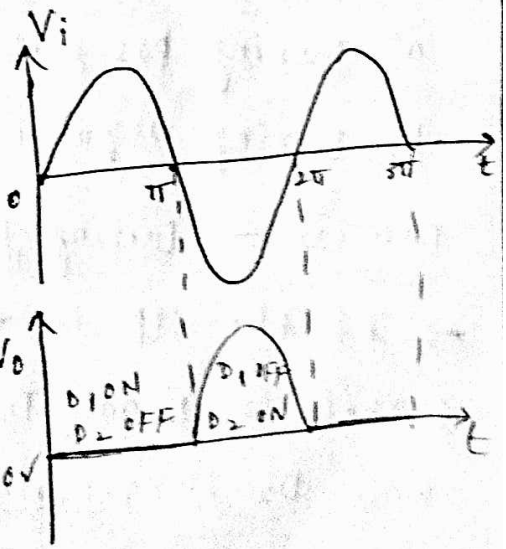
Because, D_2 is in Reverse biased. So no current drop at V_o

Case (ii) :- For negative Half-cycle

⇒ If the i/p voltage, $V_i = -VL$, Then o/p $V_o' = +Ve$

⇒ Hence D_2 is in Forward biased (i.e, ON) and D_1 is becomes reverse biased (i.e, OFF).





Then the CKT becomes inverting amplifier

$$\therefore V_o = -\left(\frac{R_f}{R}\right)V_i.$$

If $R_f = R$

$$V_o = -V_i.$$

(or) $V_{in} = -V_o$ (&) $V_o = -(-V_i)$

$$V_i = +VL$$

Full wave precision Rectifier :-

→ The circuit diagram is shown in below figure

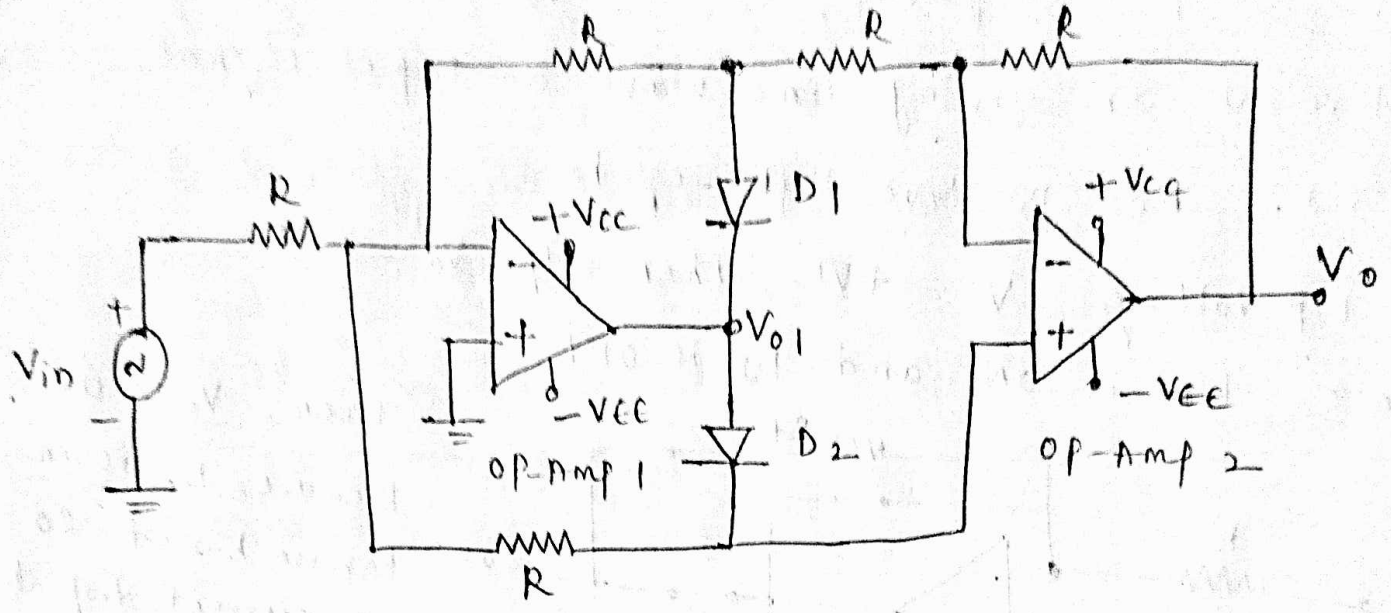


Fig: Full-wave precision Rectifier.

⇒ The CKT provides full-wave rectification even for smaller i/p voltages.

⇒ In order to analyze the working of the CKT, we need to consider following cases.

a) During positive Half-cycle of i/p

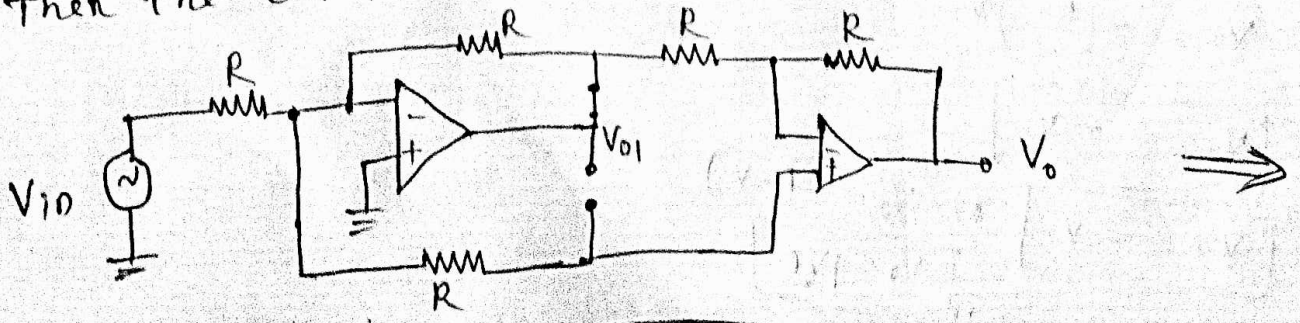
b) During Negative Half-cycle of i/p.

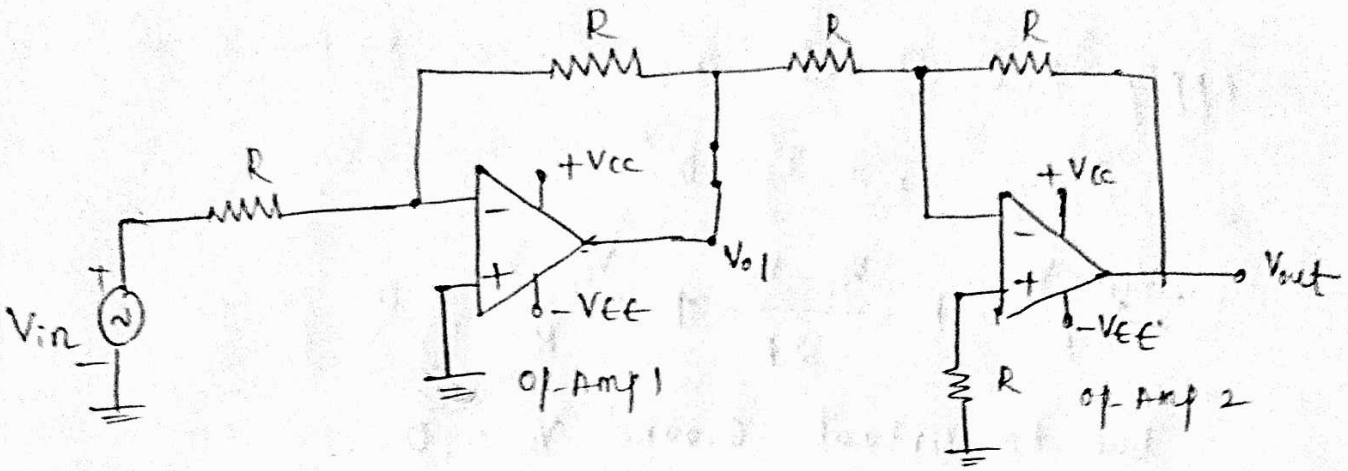
case (i) :- During positive Half-cycle.

→ If the i/p is +ve, V_i = +Ve, Then V_{o1} = -Ve.

→ That is Diode D1 is forward biased (ON) and conducting. and D2 is reverse biased, i.e, OFF, it is open CKT.

⇒ Then the CKT is modified as





i) output ~~of~~ V_{o1} of op-amp-1 is given by,

$$V_{o1} = -\left(\frac{R'}{R'}\right) V_{in}$$

$$V_{o1} = -V_{in}.$$

(ii) output of op-amp-2 is given by.

$$V_o = -\left(\frac{R}{R}\right) V_{o1} = -(-V_{in})$$

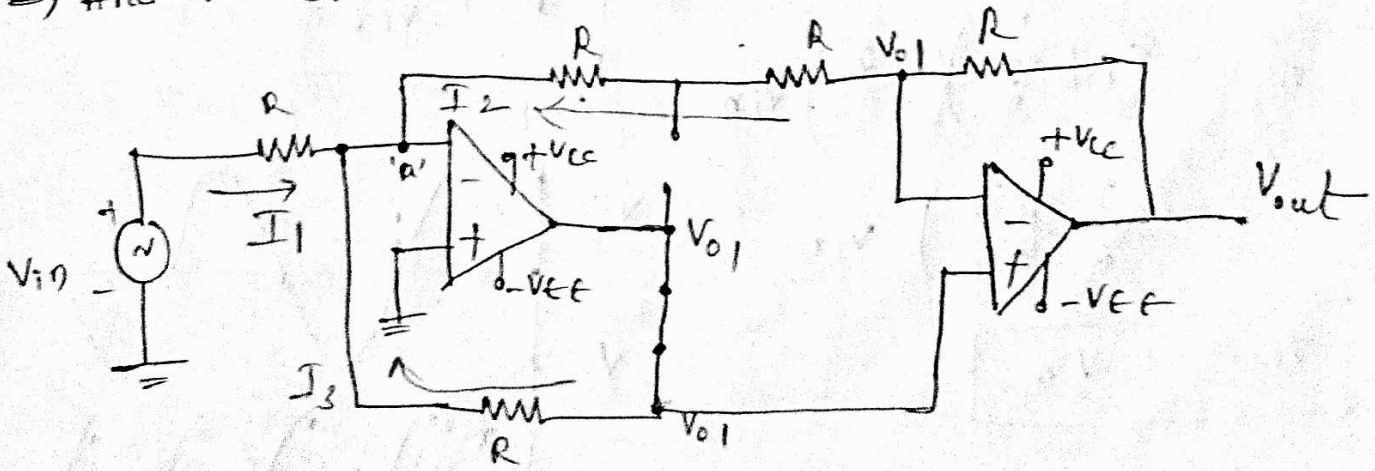
$$\therefore \boxed{V_o = V_{in}}$$

Case (ii):- During Negative Half-cycle

⇒ During negative half-cycle, i/p is -Ve, $V_i = -Ve$,

⇒ Therefore diode D_2 is forward biased i.e, ON state and diode D_1 is reverse biased, i.e, OFF state.

⇒ And the CKT is modified as.



Apply KCL @ node 'a'.

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

$$\frac{V_{in} - V_a}{R} + \frac{V_{o1} - V_a}{2R} + \frac{V_{o1} - V_a}{R} = 0.$$

Due to virtual Ground $V_a = 0$.

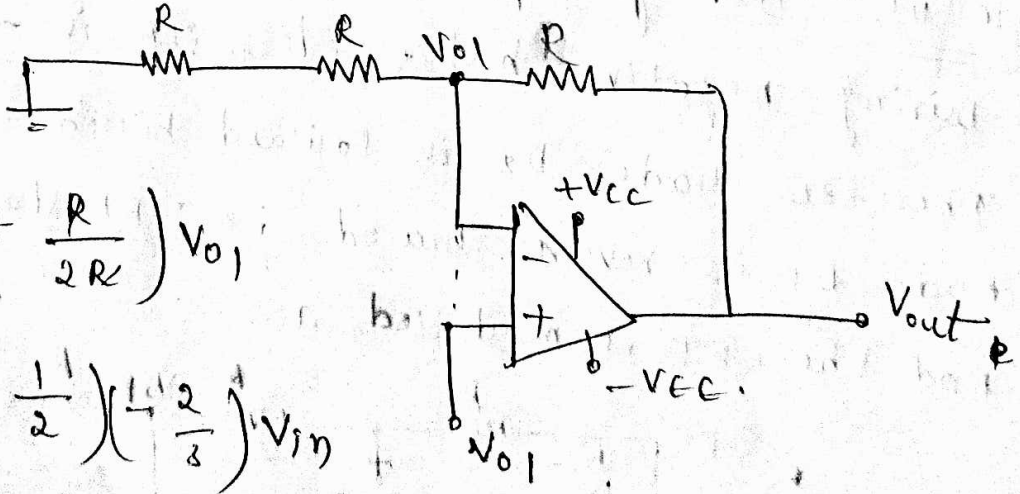
$$\frac{V_{in}}{R} + \frac{V_{o1}}{2R} + \frac{V_{o1}}{R} = 0.$$

$$\frac{V_{in}}{R} + V_{o1}\left[\frac{1}{R} + \frac{1}{2R}\right] = 0$$

$$V_{o1}\left[\frac{3}{2R}\right] = -\frac{V_{in}}{R}.$$

$$\therefore V_{o1} = -\frac{2}{3} V_{in}$$

⇒ The o/p voltage of op-amp 2 is given by.

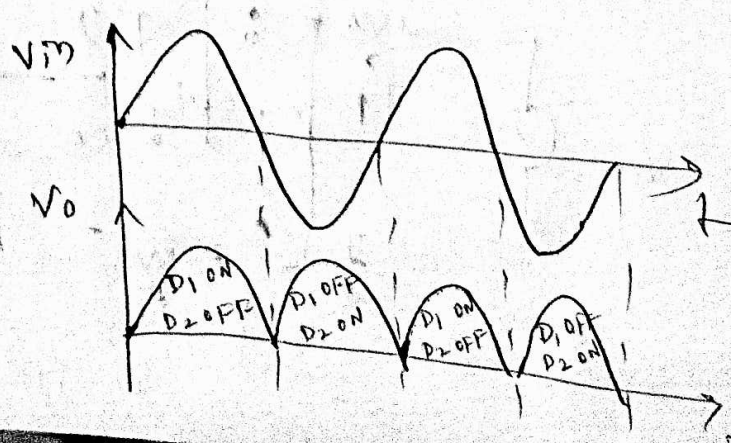


$$\therefore V_{out} = \left(1 + \frac{R}{2R}\right) V_{o1}$$

$$= \left(1 + \frac{1}{2}\right)\left(-\frac{2}{3}\right) V_{in}$$

$$= \frac{3}{2} \cdot \left(\frac{-2}{3}\right) V_{in}$$

$$\boxed{V_{out} = -V_{in}}$$



Instrumentation Amplifier :-

⇒ This is a Difference Amplifier.

⇒ This is a two-stage Amplifier.

⇒ 3-op amp Instrumentation Amplifier is shown in below.

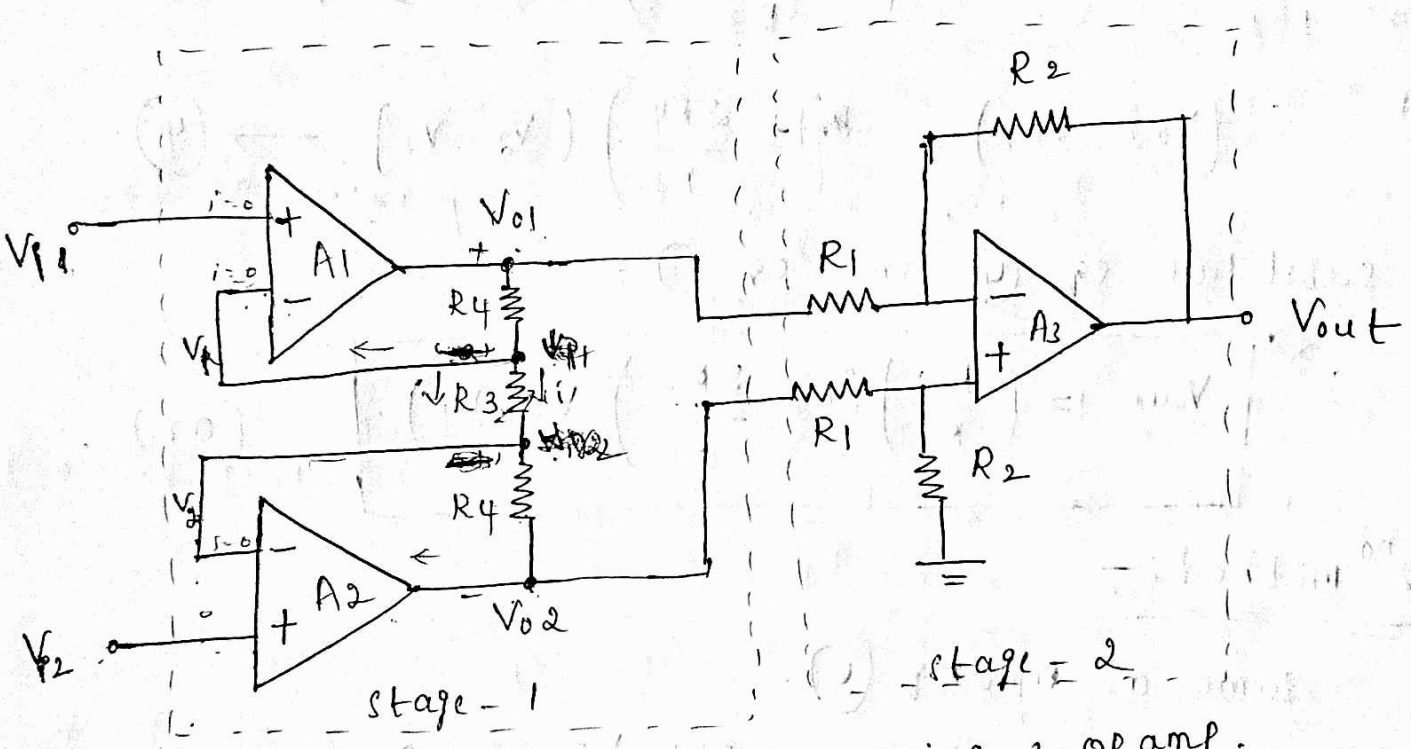


Fig: Instrumentation Amplifier using 3-op amp.

From the CKT, The o/p of stage-2 is . ie, difference amplifier o/p.

$$\therefore V_{out} = \left(\frac{R_2}{R_1}\right)(V_{o2} - V_{o1}) \longrightarrow (1).$$

And the current flow through op-amp is zero. ie, i=0.

∴ It can flow only higher potential 'Vo1' to lower potential 'Vo2'.

$$\therefore \text{The current, } i = \frac{V_1 - V_2}{R_3} \longrightarrow (2)$$

$$\text{And} \quad i = \frac{V_{o1} - V_{o2}}{R_4 + R_3 + R_4} \longrightarrow (3)$$

Equate (2) & (3).

$$\therefore \frac{V_1 - V_2}{R_3} = \frac{V_{o1} - V_{o2}}{R_3 + 2R_4}.$$

$$V_{o1} - V_{o2} = \left(\frac{R_3 + 2R_4}{R_3}\right)[V_1 - V_2]$$

$$\therefore (V_{o2} - V_{o1}) = \left(1 + \frac{2R_4}{R_3}\right)(V_2 - V_1) \longrightarrow (4).$$

Substitute eq (4) in eq (1).

$$\therefore \boxed{V_{out} = \left(\frac{R_2}{R_1}\right)\left(1 + \frac{2R_4}{R_3}\right)(V_2 - V_1).} \quad (or).$$

2nd method :-

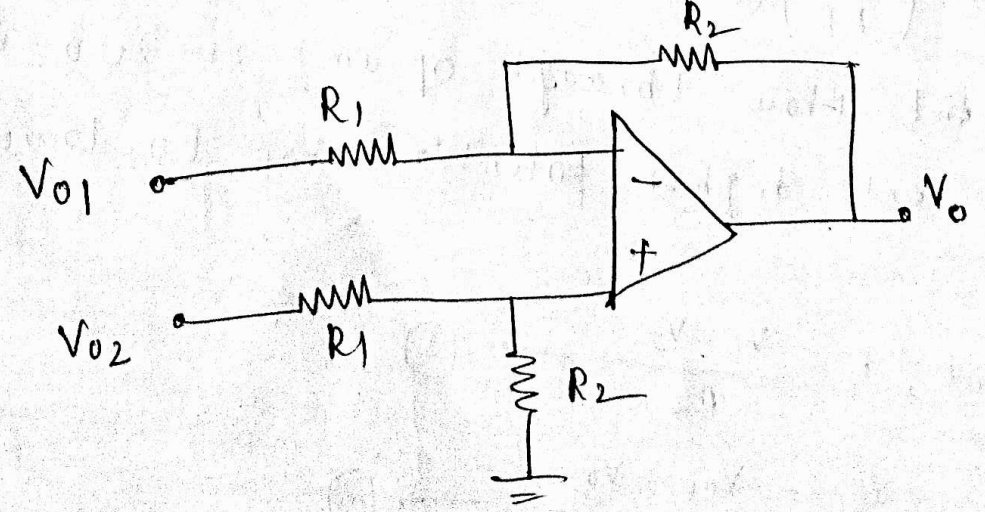
same as upto eq (4).

That is, $(V_{o2} - V_{o1}) = \left(1 + \frac{2R_4}{R_3}\right)(V_2 - V_1)$.

⇒ From the circuit stage-2 is a difference amplifier

⇒ Apply super position theorm,

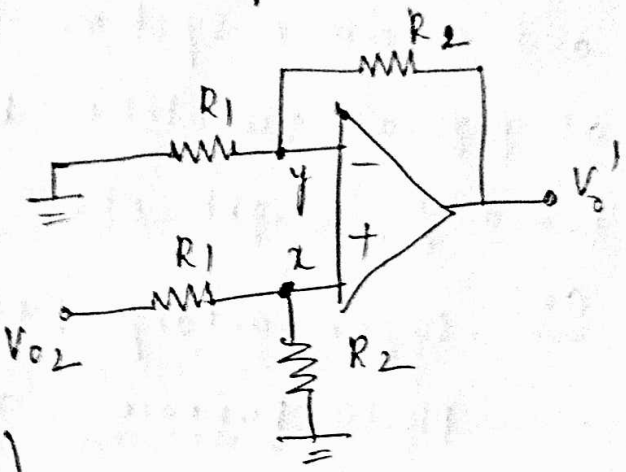
⇒ Then circuit becomes.



Therefore, to get total o/p $V_o = V_o' + V_o''$.

Case(i): By applying superposition theorm,

V_{o1} is Grounded and V_{o2} is acting. And CKT becomes.



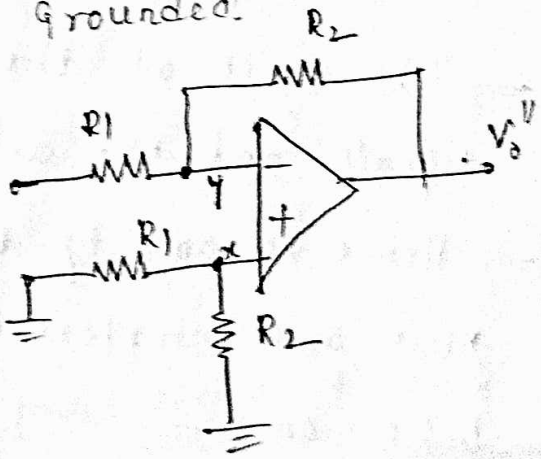
$$V_x = V_{o2}\left(\frac{R_2}{R_1+R_2}\right). \text{ And}$$

$$V_o' = \left(1+\frac{R_2}{R_1}\right)V_x.$$

$$V_o' = \left(1+\frac{R_2}{R_1}\right)V_{o2}\left(\frac{R_2}{R_1+R_2}\right)$$

$$\therefore V_o' = V_{o2}\left(1+\frac{R_2}{R_1}\right)\left(\frac{R_2}{R_1+R_2}\right). \longrightarrow (5)$$

Case(ii) V_{o1} is acting and V_{o2} is Grounded.



Then CKT as a inverting amplifier

$$\therefore V_o'' = -\left(\frac{R_2}{R_1}\right)V_{o1} \longrightarrow (6)$$

∴ The total o/p voltage is,

$$V_o = V_o' + V_o''$$

$$= V_{o2}\left(1+\frac{R_2}{R_1}\right)\left(\frac{R_2}{R_1+R_2}\right) - \left(\frac{R_2}{R_1}\right)V_{o1}$$

$$= V_{o2}\left(\frac{R_1+R_2}{R_1}\right)\left(\frac{R_2}{R_1+R_2}\right) - \left(\frac{R_2}{R_1}\right)V_{o1}$$

$$V_o = \left(\frac{R_2}{R_1}\right)[V_{o2} - V_{o1}] \quad [\because \text{eq } (4)]$$

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

Introduction to Instrumentation Amplifier :-

⇒ many Industrial systems, process control systems and consumer systems require precise measurement of physical quantities like temperature, pressure, humidity, weight, etc.

Ex: Sugar factory : Flow, Level, Temperature of juice
Plastic Furnace : Temp.
Dairy plant : Temp. & Humidity.

⇒ such physical quantities are converted into proportional electrical signal using "transducer."

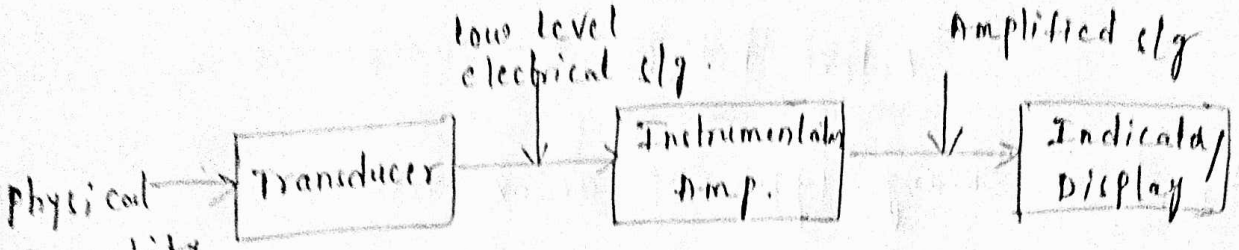
⇒ The most of the transducer o/p's are low level signals and not able to drive next stage of system.

⇒ Hence to amplify the low level signal & reject noise and interference, instrumentation amplifier used

Definition :-

* Instrumentation amplifier is basically a "high gain difference amplifier" with "high i/p impedence" that amplifies the low level o/p signal from transducer by rejecting noise and interference in the signal

* The data acquisition system for Instrumentation Amplifier is shown below



- Temp.
- Humidity
- Pressure, weight, etc.

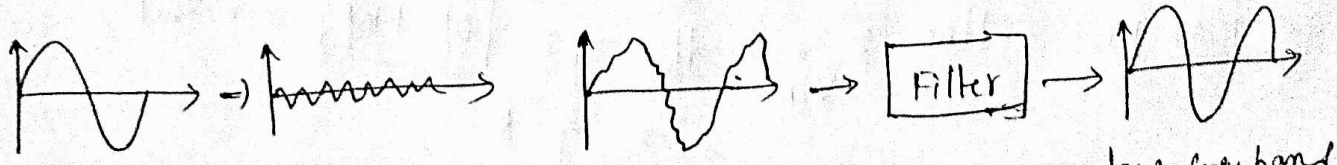
Requirements of good Instrumentation Amp

1. Finite, Accurate and stable gain
2. Easier gain adjustment – Potentiometer, JFET & MOSFET switch
3. High i/p Impedance – To avoid loading of i/p source ($R_i = \infty$)
4. High CMRR – To reject common mode s/g's (∞).
5. Low o/p impedance
6. Low power consumption
7. High slew rate
8. Low Thermal & time drifts.

Active Filters :–

⇒ Filter is a selective circuit. And it passes specific band of frequencies.

⇒ Blocks specific band of frequencies.



Original s/g ⇒ Tx'ion; Noise added

Noisy s/g ↓ Data lost.

Filter can allow freq band and get o/p with out noise.

Active Filters

⇒ There are many type of active filters.

1. low pass Filter
2. High pass Filter
3. Band pass Filter
   - wide Band pass Filter
   - Narrow Band pass Filter
4. Band stop / Band Reject Filter.
   - wide Band Reject Filter
   - Narrow Band Reject Filter. (Notch filter).
5. All pass Filter.

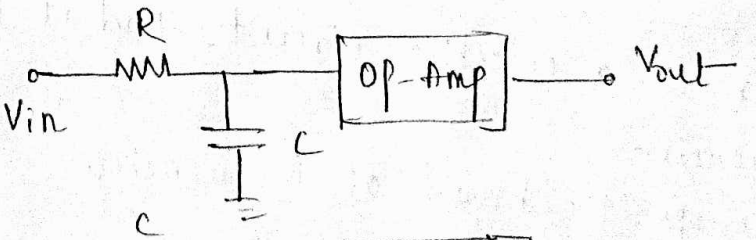
⇒ Active Filters : composed active elements like op-amp, Transistor, diode etc.

⇒ passive Filters : composed passive elements like R, L, C.

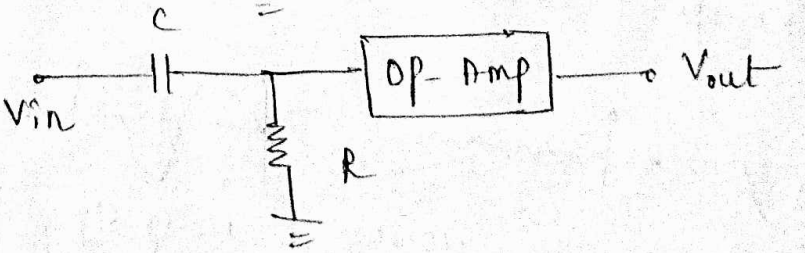
⇒ In that R and C are used in active filters except 'L'. Because inductor has bulky, dissipate more power, emits magnetic fields and costly.

Active RC filters :—

⇒ Low pass Filter :



⇒ High pass Filter :



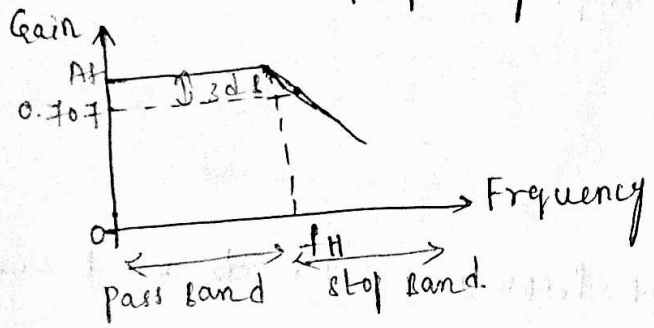
⇒ Advantages :

* Op-Amp provides gain, so i/p signal is not attenuated
* Active Filters are easy to adjust/tune
* No loading problem.
* Cost.

⇒ By all the advantages of active filters, we move on passive filters to active filters

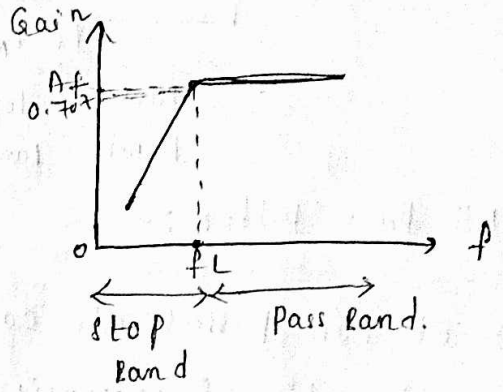
1. Low pass Filter :

⇒ It passes Frequency,
From 0 to f_H.
After f_H → It Rejects / BLOCKS Frequency



2. High pass Filter :—

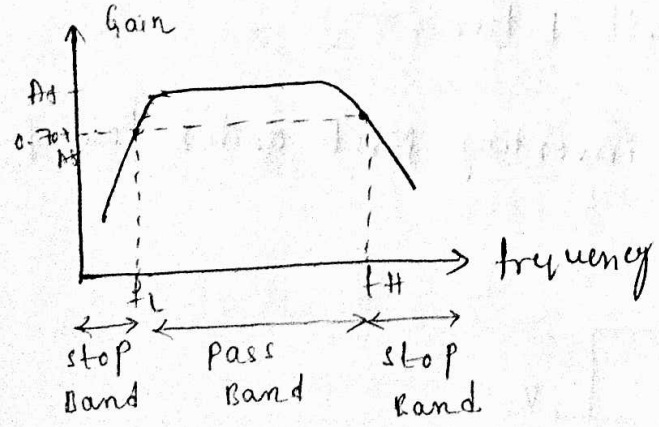
⇒ It Blocks low frequencies. i.e, 0 to f_L.
⇒ And after 'f_L'. it allows the frequencies



3. Band Pass Filter :—

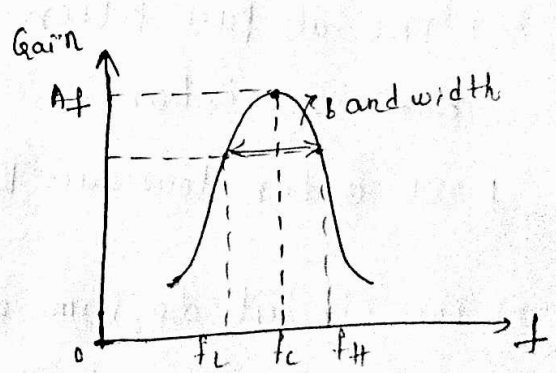
(i) wide Band pass filter

⇒ Frequency passes between, f_L & f_H.
⇒ Quality factd < 10.
i.e, $Q = \frac{f_c}{B.W}$. [center frqency]
⇒ Here Gain is max.



(ii) Narrow Band pass Filter :—

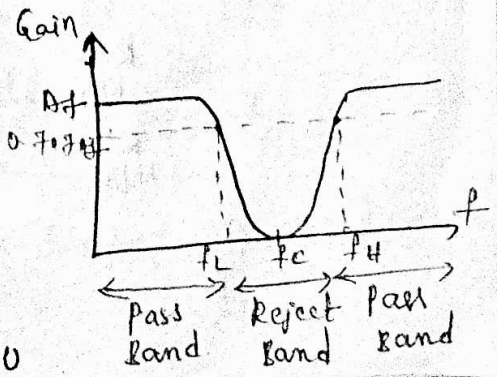
⇒ Frequency passes blw, f_L & f_H
⇒ Quality factd > 10.
⇒ Here, Bandwidth is less.



4. Band Reject Filter :—

(i) wide Band Reject Filter

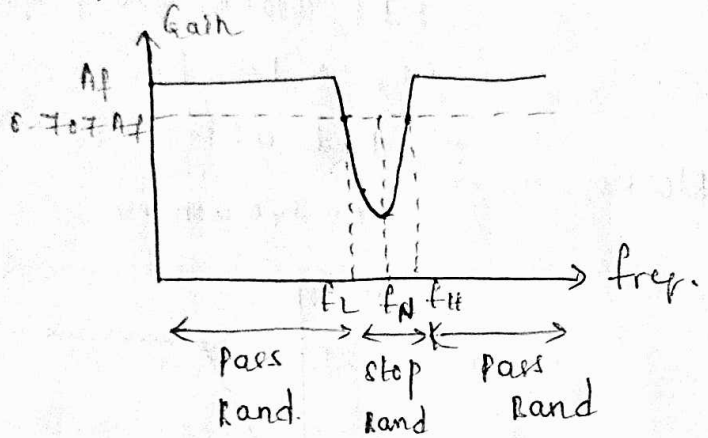
⇒ It blocks / Rejects the frq. blw f_L & f_H.
⇒ Quality factd. < 10



(ii) Narrow Band Reject Filter. (Notch Filter)

⇒ It blocks the frequency blw f_L & f_H.

⇒ Quality factd > 10.



5. All pass Filter :—

⇒ It can passes all category of frequencies. It doesn't block/ rejects the frequencies

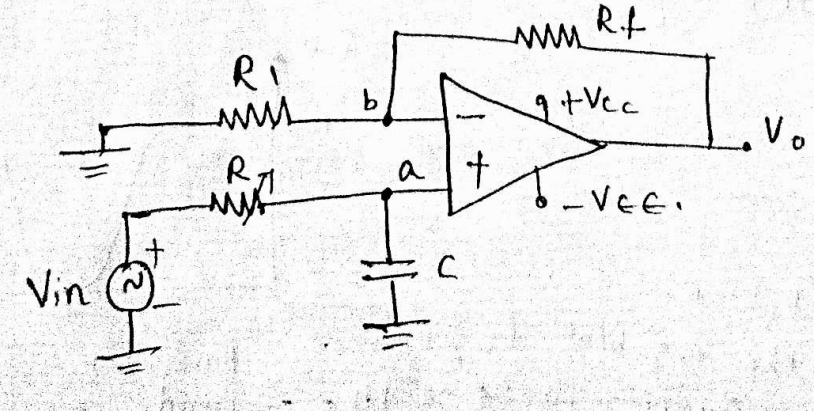
⇒ when signals are transmitted over transmission lines, such as telephone wire. they undergo change in phase.

⇒ To compensate for these phase changes, all pass filters are required.

⇒ The all pass filters are also called delay equalizers or phase correctors.

First order low pass Butterworth Filter :—

⇒ The circuit diagram of Non-inverting first order low pass Butterworth filter is given by.



Analysis of Filter circuit :

From the circuit. $\left[X_C = \frac{1}{j\omega C} \right.$

$$V_a = \left(\frac{X_C}{R + X_C} \right) V_{in}$$

$$V_a = \frac{(1/j\omega C)}{(R + 1/j\omega C)} \cdot V_{in}$$

$$= \frac{(-j/2\pi f C)}{(R - j/2\pi f C)} \cdot V_{in} \quad = \left(\frac{-j/2\pi fC}{\frac{2\pi RCf - j}{2\pi fC}} \right) \cdot V_{in}$$

$$V_a = \left(\frac{-j}{2\pi RCf - j} \right) V_{in}$$

Divide numerator & Denominator by $(-j)$.

$$V_a = \frac{(-j/-j)}{\left(\frac{2\pi RCf - j}{-j}\right)} \cdot V_{in} \quad = \left(\frac{1}{1 + j\,2\pi RCf} \right) \cdot V_{in}.$$

$$\therefore V_a = \left(\frac{1}{1 + j2\pi RCf} \right) V_{in}.$$

And, the o/p voltage of non-inverting Amp.

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

$$V_o = \left(1 + \frac{R_f}{R_1} \right) \left(\frac{1}{1 + j2\pi RCf} \right) V_{in}$$

Here, $A_F = \left(1 + \frac{R_f}{R_1} \right)$ and $f_H = \frac{1}{2\pi RC}$.

$$\therefore V_o = \frac{AF}{1 + j(f/f_H)} \cdot V_{in}$$

$$\frac{V_o}{V_{in}} = \frac{AF}{1 + j(f/f_H)} \Rightarrow \left| \frac{V_o}{V_{in}} \right| = \left| \frac{AF}{1 + j(f/f_H)} \right|$$

$$\therefore \left| \frac{V_o}{V_{in}} \right| = \frac{AF}{\sqrt{1 + (f/f_H)^2}} \quad \& \text{ phase Angle, } \varphi = -\tan^{-1}(f/f_H)$$

1. At very low Frequencies, $f < f_H$.

$$\left|\frac{V_o}{V_{in}}\right| \cong A_F \text{ i.e, constant}$$

2. At $f = f_H$, $\left|\frac{V_o}{V_{in}}\right| \cong \frac{A_F}{\sqrt{2}} = 0.707 A_F$.

i.e, 3 dB down to the level of A_F.

3. At, $f > f_H$, $\left|\frac{V_o}{V_{in}}\right| < A_F$.

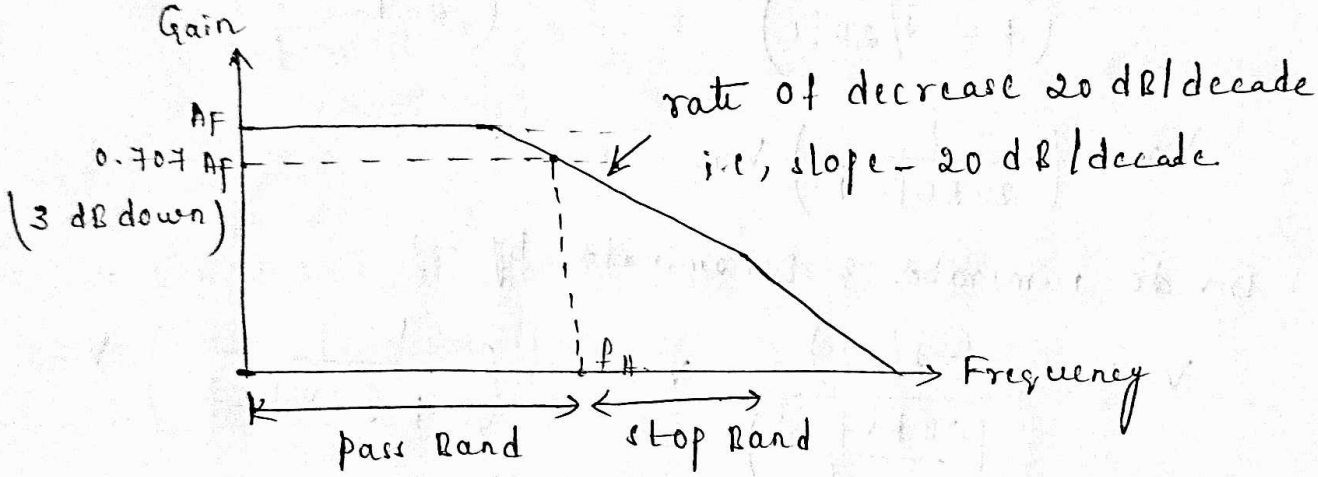


Fig: Frequency Response of Filter.

* For $0 < f < f_H$. the gain is almost constant
* At $f = f_H$, gain reduces to $0.707 A_F$, 3 dB down from A_F.
* At $f > f_H$, the gain decreases at a rate of 20 dB/decade
* 20 dB/decade : decreases of 20 dB in gain per 10 times change in frequency.

Ex: Design a LPF at $f_H = 1$ KHz with a pass band gain of 2

Sol: Given: $f_H = 1$ KHz

$A_F = 2$

Let, $C = 0.01$ μF.

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

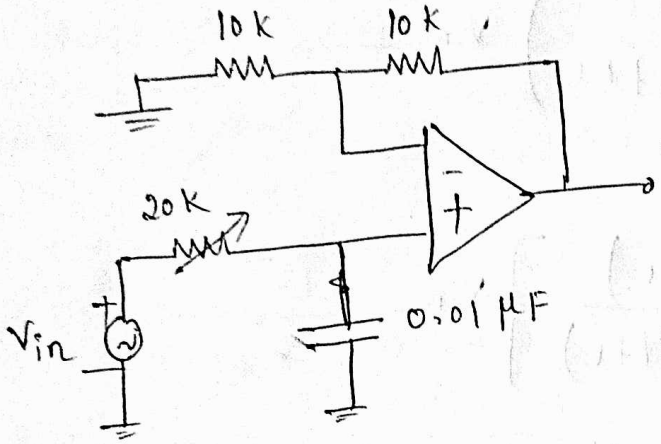
$$R = \frac{1}{2\pi f_H C}$$

$$R = \frac{1}{2\pi \times 1K \times 0.01\mu} = 15.9\ K\Omega$$

$\therefore$ As, $A_f = 2$.

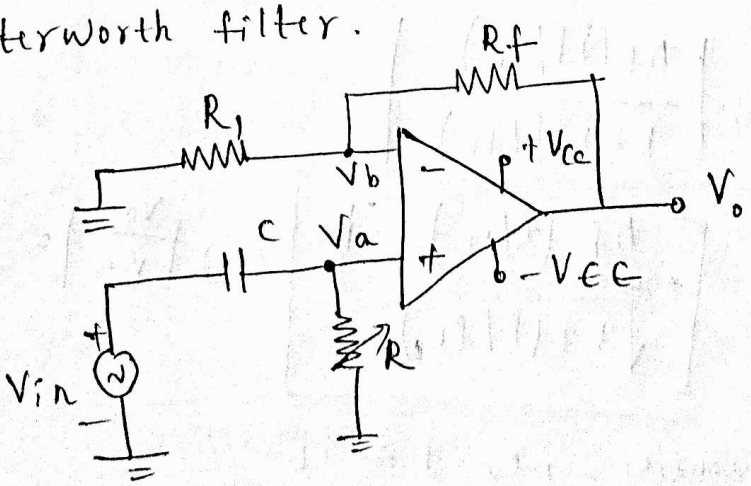
$\therefore A_f = \left(1 + \frac{R_f}{R_1}\right)$; If $R_f = R_1$. Then $A_f = 2$.

$\frac{R_f}{R_1} = 1$; Let $R_f = R_1 = 10\ K\Omega$



First order High pass Butterworth Filter :-

⟹ The circuit diagram of Non-inverting first order High pass butterworth filter.



Analysis of Filter circuit :-

$$V_a = \left(\frac{R}{R - jX_c}\right) V_{in} = \frac{R}{R - jX_c} \quad \left[\because X_c = \frac{1}{j\omega C},\ X_c = \frac{-j}{\omega C}\right.$$

$\because \omega = 2\pi f$

$$= \left(\frac{R}{R + 1/j\omega C}\right) V_{in} = \left(\frac{R}{R + 1/j2\pi f C}\right) V_{in}$$

$$V_a = \frac{R}{\left(\frac{j2\pi RCf + 1}{j2\pi fC}\right)} \cdot V_{in}$$

$$V_a = \left(\frac{j2\pi RCf}{1 + j2\pi RCf}\right) V_{in}$$

∴ The circuit is in non-inverting amplifier.

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

$$V_o = \left(1 + \frac{R_f}{R_1}\right) \cdot \left(\frac{j2\pi f RC}{1 + j2\pi f RC}\right) V_{in}$$

And, $f_L = \frac{1}{2\pi RC}$

$$\therefore V_o = \left(1 + \frac{R_f}{R_1}\right)\left[\frac{(j f/f_L)}{1 + j(f/f_L)}\right] V_{in}$$

$$\frac{V_o}{V_{in}} = A_f\left[\frac{j(f/f_L)}{1 + j(f/f_L)}\right]$$

Apply magnitude on both sides,

$$\left|\frac{V_o}{V_{in}}\right| = \left|\frac{A_f(jf/f_L)}{1 + j(f/f_L)}\right|$$

$$\therefore \boxed{\left|\frac{V_o}{V_{in}}\right| = \left[\frac{A_f(f/f_L)}{\sqrt{1 + (f/f_L)^2}}\right]} \quad (\text{or}) \quad \left|\frac{V_o}{V_{in}}\right| = \frac{A_f}{\sqrt{1 + (f_L/f)^2}}$$

⇒ 1. At low frequencies, i.e, $f < f_L$.

$$\therefore \left|\frac{V_o}{V_{in}}\right| < A_f.$$

⇒ 2. At $f = f_L$.

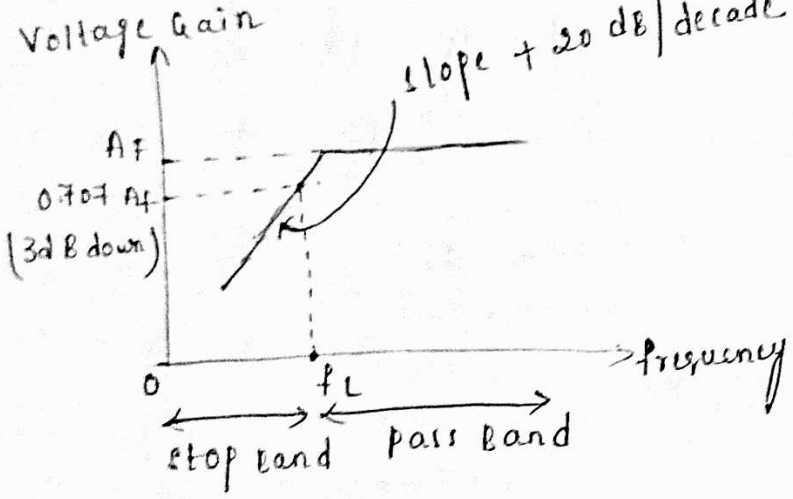
$$\left|\frac{V_o}{V_{in}}\right| = 0.707 A_F$$ i.e, 3dB down from the level of A_f

3. At $f > f_L$. i.e, high frequencies, 1 can be neglected as compared to (f/f_L) from denominator.

$$\therefore \left|\frac{V_o}{V_{in}}\right| \simeq A_F \text{ i.e, constant.}$$

$\{\because \text{Gain} = 20 \log_{10}\left|\frac{V_o}{V_{in}}\right|\}$

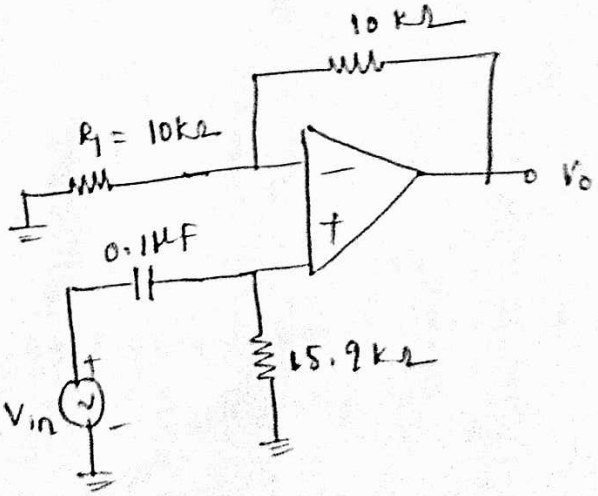
Frequency Response:



* For $0 < f < f_L$, gain increases at a rate of 20 dB/decade
* At $f = f_L$, gain is 0.707 A_F, 3 dB down from A_F.
* At $f > f_L$, the gain is almost constant.

* 20 dB/decade : increase of 20 dB in gain per 10 times change in 'f'.

Ex: Design a HPF at $f_L = 1$ KHz. with pass band gain of 2.



Sol: Given: $f_L = 1$KHz

$A_f = 2$.

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

let, $C = 0.1\mu F$.

$$R = \frac{1}{2\pi (1k)(0.1\mu)}$$

$$R = 15.9\ k\Omega.$$

$$\therefore A_f = 1 + \frac{R_f}{R_1}.$$

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

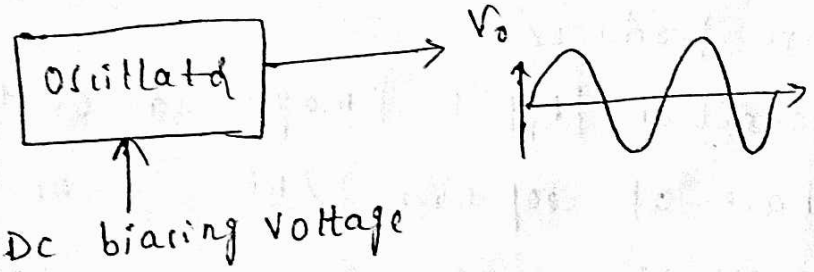
$$\frac{R_f}{R_1} = 1 \implies R_f = R_1 = 10k\Omega.$$

Unit – 3

Wave shaping circuits & oscillators

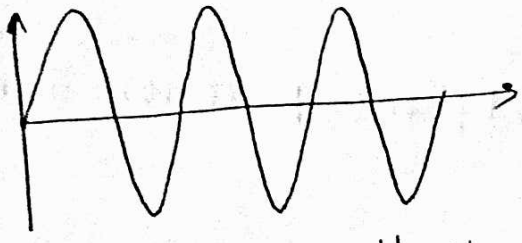
Oscillator :–

* oscillator is an electronic circuit with the help of which alternating waveform (oscillation) is generated.
* It is a amplifier with positive feed back
* No input signal.

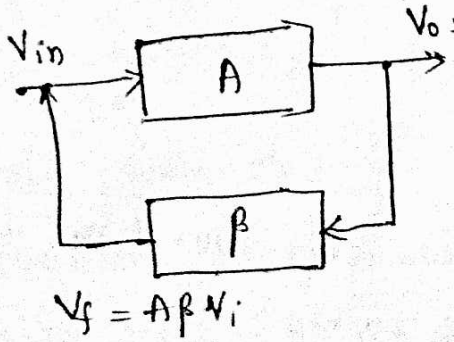


Sustained oscillations :

* If energy equal to loss is externally supplied at every oscillations, there is no decrease in o/p voltage and sustained oscillations are produced.

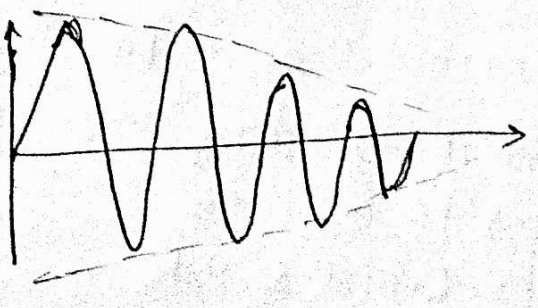


Amplifier with positive feedback ;

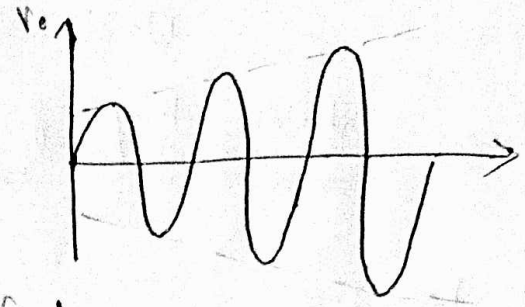


* If Loop Gain, $A\beta < 1$,
  o/p voltage decrease with time as,

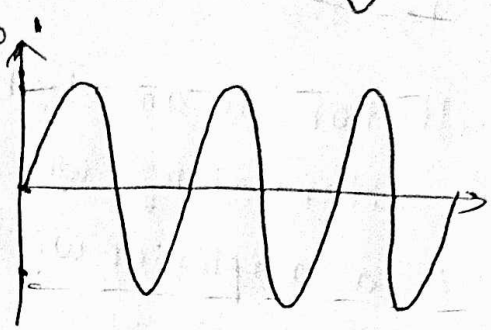
* positive feedback.
  Total Gain, $A_f = \frac{A}{1 - A\beta}$.
  $\therefore A\beta$ = loop Gain.



* If the value of loop Gain, $A\beta > 1$. o/p voltage increased with time



* If, the value of loop Gain, $A\beta = 1$.; $A_f = \frac{A}{0} = \infty$.



→ There is o/p even if there is no input.

⇒ value of o/p voltage remain constant & sustained oscillations are produced

→ If the condition, $|A\beta| = 1$ [magnitude of loop Gain is Unity] and the phase of loop Gain, $\angle A\beta = 0^\circ$ or 360°. to get sustained oscillations. This criteria is called as, "Barkhausen Criteria"

* By using of positive feedback in amplifier it increases the overall gain.

Applications :—

* Used in laptop & smartphone processors for generating the clock signals
* Used in a radio & mobile receivers for generating the local carrier frequency
* signal Generators.

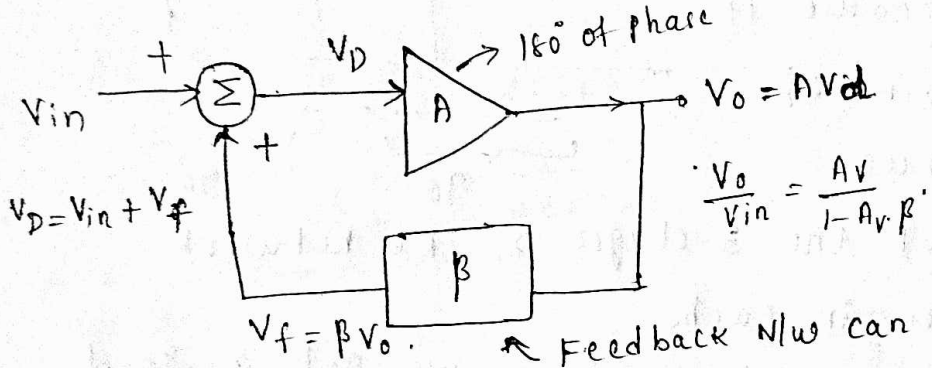
Types of Oscillators :

1. sinusoidal oscillator : It generates pure sine waveform with amplitude & frequency
   - → RC Oscillator
   - → LC Oscillator
   - → Crystal oscillator

2. Non-sinusoidal oscillator (a) Relaxation oscillators: It generates square & triangular wave forms. [Using 555 timer].

* RC phase-shift oscillator :-

* R and C elements to get a feedback network. And This RC oscillators can provides the low frequency, i.e, few Hz to several hundred KHz. (Audio Frequency range - 20 Hz - 20 kHz)



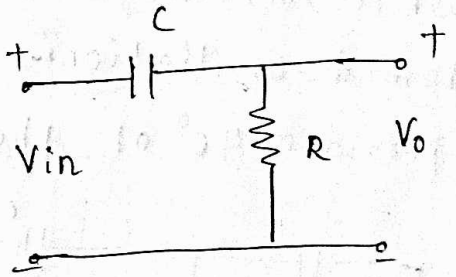
$|A\beta| = 1$

$\angle A\beta = 0°$ & $360°$.

$\frac{V_o}{V_{in}} = \frac{A_V}{1 - A_V \cdot \beta}$

↖ Feedback N/w can provides another 180°

let, take a single RC-circuit.



Transfer function,

$$\left(\frac{V_o}{V_{in}}\right) = \frac{R}{R - jX_c} \quad \left[\because X_c = \frac{1}{\omega c}\right]$$

$$= \frac{R}{R - j(1/\omega c)}$$

$$\frac{V_o}{V_{in}} = \frac{1}{(1 - j/\omega cR)} = \frac{1}{1 - j\left(\frac{X_c}{R}\right)}$$

$\frac{R}{R + X_c} = \frac{R}{R + \frac{1}{j\omega c}}$

$\frac{R}{R - j/\omega c}$

$\frac{R}{R(1 - j/\omega cR)}$

$\frac{1}{1 - j/\omega cR}$

∴ The phase Angle, $\angle\varphi = 0 - \tan^{-1}\left(\frac{1}{\omega CR}\right)$

$$\angle\varphi = \tan^{-1}\left(\frac{1}{\omega cR}\right) = \tan^{-1}\left(\frac{X_c}{R}\right).$$

⇒ The phase shift is depends on the 'R' & X_c.

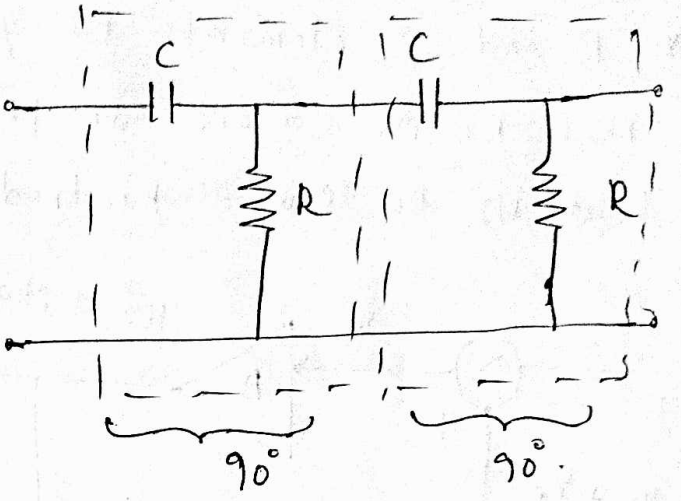
⇒ For very small values of X_c : Then $\angle\varphi = 0$.

⇒ And, $R = 0$. $\angle\varphi = \tan^{-1}\left(\frac{X_c}{0}\right) = \tan^{-1}(\infty) = 90°$

$\therefore \angle\varphi = 90°$.

⇒ Here, the phase is provides 0-90°.

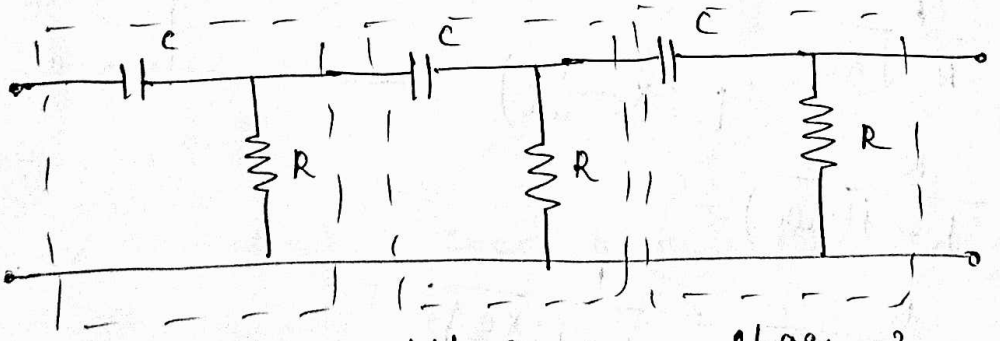
⇒ An single RC-network can provides 90° of phase shift TO get 180° of phase, we can connect another RC-circuit in cascade.



⇒ But practically its not work out by using 2-stages of RC-network. Because it R=0. Then the gain of the CKT becomes zero.

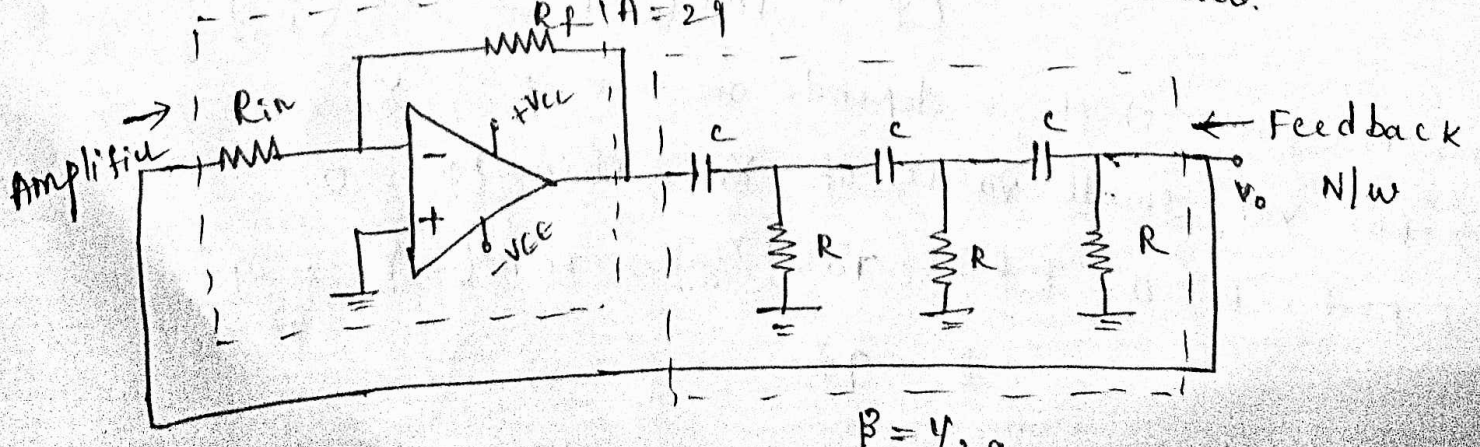
⇒ SO, we can connect the 3-stages of RC network with 60° of phase in each.

⇒ while increase the no. of RC stage, we get a good sustained oscillations. Using of 4-RC network stages, it provides 45° of phase in each RC-stage.



Stage-1 60° | Stage-2 60° | Stage-3 60° | Totally -180° of phase can provided by RC n/w

⇒ The basic RC-phase shift Oscillator is given below.



→ The attenuation for the feedback circuit, $\beta = 1/29$

→ so to get unity loop gain, $A\beta = 1$; $A = 29$.

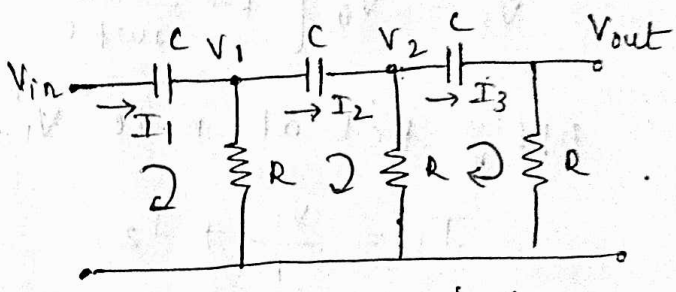
* The circuit provides unity gain at one particular frequency, i.e, resonant frequency (f_r) or operating freq (f_o) oscillator. Then that particular freq. overall gain becomes zero.

* For N-stages are used, $f_r = \frac{1}{2\pi RC\sqrt{N}}$

If, $N = 3$, $f_r = \frac{1}{2\pi RC\sqrt{6}}$

$N = 4$, $f_r = \frac{1}{2\pi RC\sqrt{8}}$.

Analysis :—



At node 'V_2'.

Let Assume voltages V_1, V_2 and currents I_1, I_2 and I_3.

Find out V_1, V_2 and I_1, I_2 and I_3 interms of 'V_o'.

Case (i) : At node V_2.

$$V_2 = V_o + I_3(-jX_c)$$

$$V_2 = V_o - jI_3X_c.$$

Now. $V_o = I_3 \cdot R \Rightarrow I_3 = \frac{V_o}{R}$ and $X_c = \frac{1}{\omega C}$.

$$\therefore V_2 = V_o - j\left(\frac{V_o}{R}\right)\left(\frac{1}{\omega C}\right) = V_o + \left(\frac{V_o}{j\omega CR}\right)$$

$$V_2 = V_o\left[1 + \frac{1}{j\omega CR}\right] \longrightarrow (1)$$

Apply KCL at node 'V_2'. Then Find I_2 interms of V_o.

$$I_2 = \left(\frac{V_2}{R}\right) + I_3.$$

$$\therefore I_2 = \frac{V_o}{R}\left[1 + \frac{1}{j\omega CR}\right] + \left(\frac{V_o}{R}\right)$$

$$I_2 = \frac{V_o}{R}\left[1 + \frac{1}{j\omega CR} + 1\right] = \frac{V_o}{R}\left[2 + \frac{1}{j\omega CR}\right] \longrightarrow (2)$$

Case (ii) :- At node 'V_1'. Apply KVL @ node V_1.

$$V_1 = V_2 + I_2(-jX_c) \qquad \left\{ X_c = \frac{1}{\omega C} \right.$$

$$V_1 = V_2 + \frac{I_2}{j\omega C} \qquad \left. \frac{1}{j} = -j \right.$$

Substitute eq ① & ② in the above equation.

$$V_1 = V_0\left[1 + \frac{1}{j\omega CR}\right] + \frac{V_0}{R}\left[2 + \frac{1}{j\omega CR}\right]\cdot\frac{1}{j\omega C}$$

$$= V_0\left[1 + \frac{1}{j\omega CR} + \frac{2}{j\omega RC} + \frac{1}{j^2\omega^2R^2C^2}\right]$$

$$V_1 = V_0\left[1 + \frac{3}{j\omega RC} - \frac{1}{\omega^2R^2C^2}\right] \longrightarrow ③.$$

Apply KCL at node 'V_1'. Then Find I_1 interms of 'V_0'.

$$I_1 = \frac{V_1}{R} + I_2.$$

$$I_1 = \frac{V_0}{R}\left[1 + \frac{3}{j\omega RC} - \frac{1}{\omega^2R^2C^2}\right] + \frac{V_0}{R}\left[2 + \frac{1}{j\omega CR}\right]$$

$$I_1 = \frac{V_0}{R}\left[1 + \frac{3}{j\omega RC} - \frac{1}{\omega^2R^2C^2} + 2 + \frac{1}{j\omega CR}\right]$$

$$\therefore I_1 = \frac{V_0}{R}\left[3 + \frac{4}{j\omega RC} - \frac{1}{\omega^2R^2C^2}\right]$$

→ Now to get the relationship blw Input & Output Voltag

$$V_{in} = V_1 + I_1(-jX_c)$$

$$= V_1 + \frac{I_1}{j\omega C}$$

$$= V_0\left[1 + \frac{3}{j\omega RC} - \frac{1}{\omega^2R^2C^2}\right] + \frac{V_0}{R}\left[3 + \frac{4}{j\omega RC} - \frac{1}{\omega^2R^2C^2}\right]\frac{1}{j\omega C}$$

$$V_{in} = V_0\left[1 + \frac{3}{j\omega RC} - \frac{1}{\omega^2R^2C^2} + \frac{3}{j\omega RC} + \frac{4}{j^2\omega^2R^2C^2} - \frac{1}{j\omega^3R^3C^3}\right]$$

$$\therefore \boxed{V_{in} = V_o\left[1 + \frac{6}{j\omega RC} - \frac{5}{\omega^2 R^2 C^2} - \frac{1}{j\omega^3 R^3 C^3}\right]}$$

* Now, the o/p voltage will only have a real part.

That means the imaginary part of this expression is zero

$$\therefore \frac{6}{\omega RC} - \frac{1}{\omega^3 R^3 C^3} = 0.$$

$$\Rightarrow \frac{6}{\omega RC} = \frac{1}{\omega^3 R^3 C^3}$$

$$\Rightarrow \omega^2 R^2 C^2 = \frac{1}{6}.$$

$$\Rightarrow \omega^2 = \frac{1}{6.R^2.C^2}$$

$$\omega = \frac{1}{RC\sqrt{6}} \qquad [\because \omega = 2\pi f]$$

$$\therefore *** \boxed{f = \frac{1}{2\pi RC\sqrt{6}}}$$

$\Rightarrow$ So, Lets find the gain of the circuit at this frequency once the imaginary part is zero. Then the expression is becomes.

$$V_{in} = V_o\left[1 - \frac{5}{\omega^2 C^2 R^2}\right]$$

Let, $\omega = \frac{1}{RC\sqrt{6}}$; $V_{in} = V_o\left[1 - \frac{5}{\left(\frac{1}{RC\sqrt{6}}\right)^2 R^2 C^2}\right]$

$$= V_o\left[1 - \frac{5}{\left(\frac{1}{6^2 . R^2 C^2}\right) R^2 C^2}\right]$$

$$= V_o\left[1 - 30\right]$$

$$V_{in} = V_o[-29]$$

$$\therefore \beta = \boxed{\frac{V_o}{V_{in}} = -\frac{1}{29}}$$

$|A| \geq 29$

And. $A\beta = 1$

$A\frac{1}{29} = 1$

$\boxed{\therefore A = -29}$

* This is the attenuation of feedback RC N/w. where '-' is that, the phase shift 180° which provides by RC-N/w.

Problems :-

1. Design RC phase shift oscillator at frequency 10kHz.

Sol: we know that, $f = \frac{1}{2\pi RC\sqrt{6}}$ and $\frac{R_f}{R_1} = 29$.

Assumed data, $C = 0.1\mu F$.

$$\therefore 10\times10^3 = \frac{1}{2\pi R\, 0.1\times10^{-6}\sqrt{6}}$$

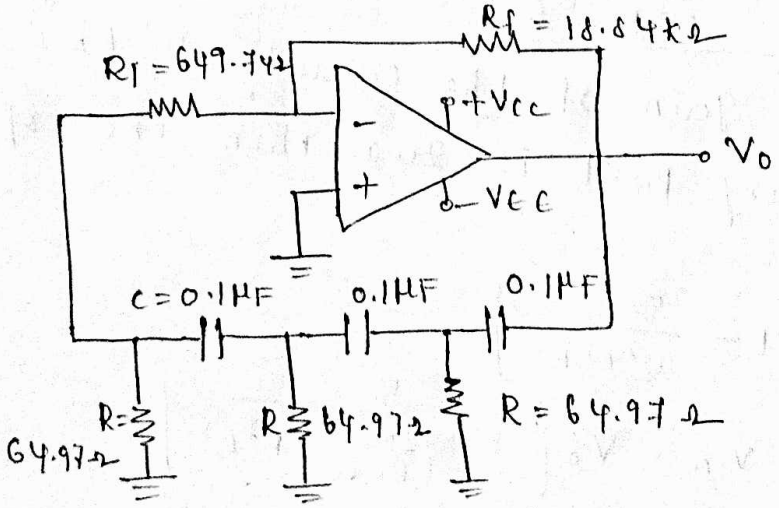
$$\therefore R = 64.97\,\Omega$$

$\therefore$ If $R_1 >> R$, $R_1 = 649.74\,\Omega$. [10 times of R]

And, $\frac{R_f}{R_1} = 29$.

$$R_f = 29.R_1 = 29\times649.74$$

$$\therefore R_f = 18842\,\Omega = 18.84\,k\Omega$$



2. Design RC phase shift oscillator using op.amp. at frequency 1kHz

Sol: Given : $f_o = 1\,kHz$.

choose $C = 0.1\mu F$.

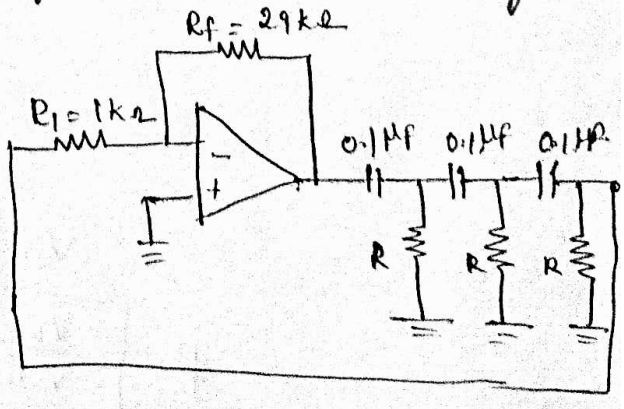
$$f_o = \frac{1}{2\pi RC\sqrt{6}}$$

$$R = \frac{1}{2\times3.14\times0.1\times10^{-6}\times1\times10^{3}\sqrt{6}}$$

$$R = 649.7\,\Omega \simeq 650\,\Omega.$$

Gain, $|A| > 29 \Rightarrow \frac{R_f}{R_1} > 29$

Choose $R_1 = 1k\Omega$, $\therefore R_f = 29k\Omega$



Wien Bridge Oscillator :-

* Another commonly used audio frequency oscillator is a wien bridge oscillator. And the CKT is shown in below figure.
* It may be noted that the feedback signal in this CKT is connected to the non-inverting input terminal, so that the op-amp is working as a non-inverting amplifier.
* Therefore, feedback network need not provide any phase shift
* The circuit can be viewed as a wien bridge with a series RC network in one arm and a parallel RC network in the adjoining arm.
* Resistors R_3 and R_4 are connected in the remaing two arms.
* The condition of 0° phase shift around the CKT is achieved by balancing the bridge.

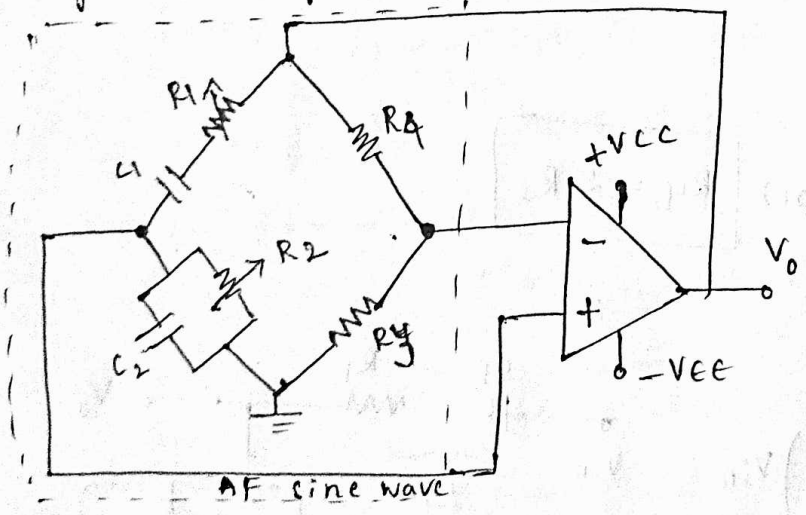
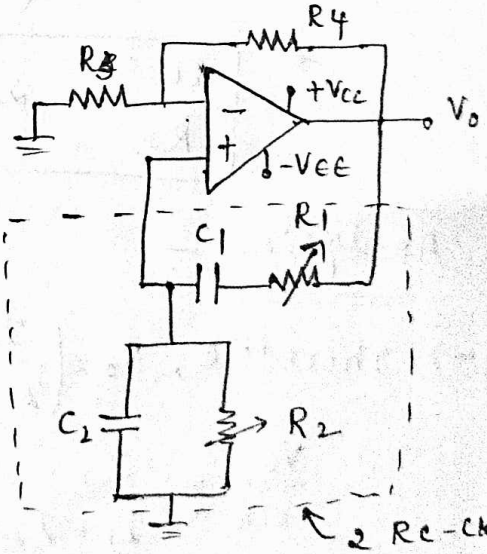


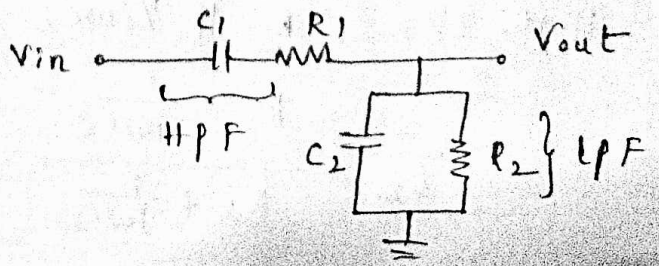
Fig: Wien Bridge Oscillator

⟹ To Re-arrangement of the CKT becomes.



⟹ op-Amp is the non-inverting CKT.

⟹ HPF doesn't passes the low frequency signals.



⇒ Then, LPF passes or allows the low frequency signals.
For low frequency signals, C_2 is becomes open circuit.
i.e, $V_{in} = V_{out}$.

⇒ when $V_{in} = 0$, for high frequency clg it has a low impedance.

⇒ But one particular freq., the output is maximum i.e, resonant frequency (f_r) or frequency of oscillation (f_o).

⇒ If, $R_1 = R_2$, $C_1 = C_2$ } Then ** $f_r = \frac{1}{2\pi RC}$. And $\beta = \frac{1}{3}$.

$A = 3$.

⇒ If $R_1 \neq R_2$, $C_1 \neq C_2$ } Then *** $f_r = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$. Then $A\beta = 1$.

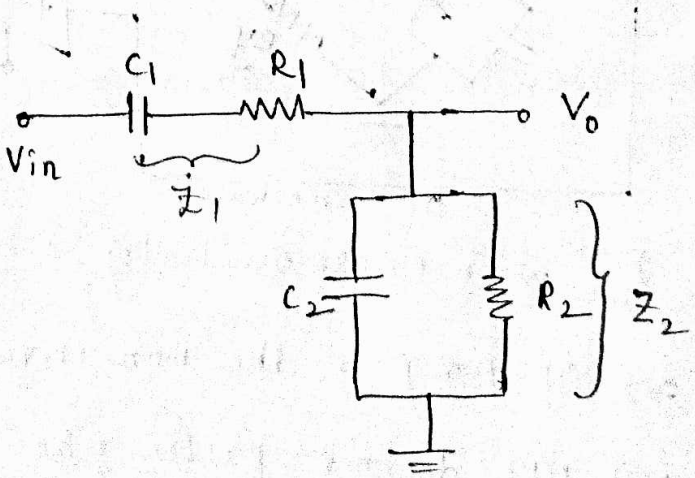
⇒ Here, the op-amp is non-inverting configuration.

$$A = 1 + \left(\frac{R_4}{R_3}\right)$$

$$3 = 1 + \left(\frac{R_4}{R_3}\right)$$

** $\frac{R_4}{R_3} = 2$ (or) $R_4 = 2 \cdot R_3$

Analysis :-



⇒ Therefore, $V_o = \left(\frac{Z_2}{Z_1 + Z_2}\right) V_{in}$

$$\frac{V_o}{V_{in}} = \frac{Z_2}{Z_1 + Z_2} \longrightarrow (1)$$

Here, $Z_2 = R_2 \parallel 1/j\omega C_2$

$$Z_2 = \frac{R_2 \times \frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}} = \frac{R_2}{j\omega R_2 C_2 + 1}, \quad Z_1 = R_1 + \frac{1}{j\omega C_1}$$

∴ substitute 'Z_1' and 'Z_2' in eq ①

$$\frac{V_o}{V_{in}} = \frac{\left(\frac{R_2}{1+j\omega R_2 C_2}\right)}{\left(R_1 + 1/j\omega C_1\right) + \left(\frac{R_2}{1+j\omega R_2 C_2}\right)}$$

$$= \frac{R_2/(1+j\omega R_2 C_2)}{\left(\frac{j\omega R_1 C_1 + 1}{j\omega C_1}\right) + \left(\frac{R_2}{1+j\omega R_2 C_2}\right)}$$

$$= \frac{R_2/(1+j\omega R_2 C_2)}{\frac{(1+j\omega R_1 C_1)(1+j\omega R_2 C_2) + j\omega R_2 C_1}{(j\omega C_1)[1+j\omega R_2 C_2]}}$$

$$= \frac{j\omega C_1 R_2}{[1 + j\omega R_2 C_2 + j\omega R_1 C_1 + j^2\omega^2 R_1 C_1 R_2 C_2 + j\omega R_2 C_1]}$$

$$\left(\frac{V_o}{V_{in}}\right) = \frac{j\omega R_2 C_1}{(1 - \omega^2 R_1 R_2 C_1 C_2) + j\omega[R_1 C_1 + R_2 C_2 + R_2 C_1]}$$

By taking Real part as zero.

$$1 - \omega^2 R_1 R_2 C_1 C_2 = 0$$

$$\Rightarrow \omega^2 R_1 R_2 C_1 C_2 = 1$$

$$\omega^2 = \frac{1}{R_1 R_2 C_1 C_2}$$

$$\omega = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$2\pi f = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$\boxed{\therefore f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}} \quad ; \text{ If } R_1 \neq R_2, \; C_1 \neq C_2.$$

If, $R_1 = R_2$, $C_1 = C_2$ $\quad \boxed{f = \frac{1}{2\pi RC}}$.

To get attenuation of feedback circuit, taking imaginary term.

$$\frac{V_o}{V_{in}} = \frac{R_2 C_1}{R_1 C_1 + R_2 C_2 + R_2 C_1}$$ } 'β' feedback fraction.

But, $A\beta = 1$

$$A = \frac{1}{\beta} = \frac{R_1 C_1 + R_2 C_2 + R_2 C_1}{R_2 C_1}$$

$$A = \frac{R_1 C_1}{R_2 C_1} + \frac{R_2 C_2}{R_2 C_1} + \frac{R_2 C_1}{R_2 C_1}$$

$$\therefore A = \frac{R_1}{R_2} + \frac{C_2}{C_1} + 1 \implies |A\beta| \geq 1$$ to sustained oscillations

$|A| \geq 3$.

We know that, $A = 1 + \left(\frac{R_4}{R_3}\right)$

$\therefore \beta = 1/3$.

Equate both, $1 + \frac{R_4}{R_3} = \frac{R_1}{R_2} + \frac{C_2}{C_1} + 1$

$A = 3$.

Let, $R_1 = R_2 = R$, $C_1 = C_2 = C$.

$$\therefore \frac{R_4}{R_3} = 2 \quad \text{(or)} \quad R_4 = 2R_3.$$

Problem: Design wien bridge oscillated using op-amp. for the Frequency of oscillation $f_o = 10\,KHz$

Sol: $f_o = 10\,KHz$.

If $R_1 = R_2$, $C_1 = C_2$.

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

let $C = 0.01\,\mu F$

$$R = \frac{1}{2\pi(10 \times 10^3)(0.01\,\mu)}$$

$R = 1.59\,K\Omega$

$C_1 = C_2 = 0.01\,\mu F$

$R_1 = R_2 = 1.59\,K\Omega$.

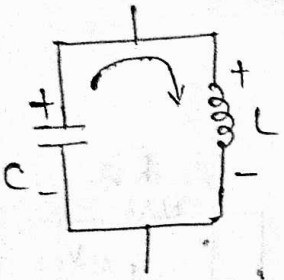
let $R_3 = 10\,K\Omega$, $R_4 = 20\,K\Omega$

LC oscillators :—

⇒ In the oscillator, the feedback circuit is a combination of 'L' and 'C'. Then it is a LC oscillators or tank circuit.

⇒ Inductor, L → stores the energy in magnetic field.

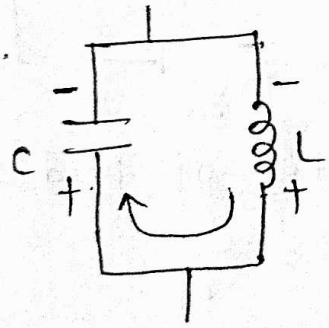
⇒ capacitor, C → stores the energy in electrostatic field.

1. 

⇒ In this L and C are connected in parallel. such type of circuit is called as LC-Tank circuit (or) Resonant CKT.

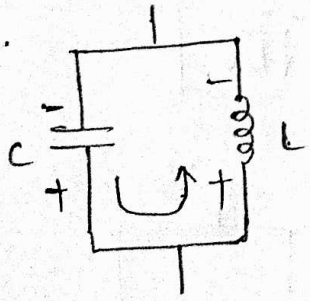
⇒ when i/p is received by the capacitd, the capacitd is fully charged its starts discharging & inductor starts charging

⇒ Then energy in inductor is increased then, energy in capacitor is decreases.

2. 

⇒ Inductor produces back emf. And the polarity is also changed. Then inductor starts discharging.

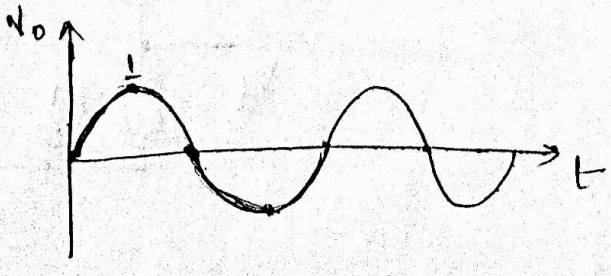
⇒ capacitor is starts to charging.

3. 

⇒ Once the capacitor is fully charged, again capacitd is starts to discharging.

⇒ Inductor starts to charged.

⇒ And it is shown in below.



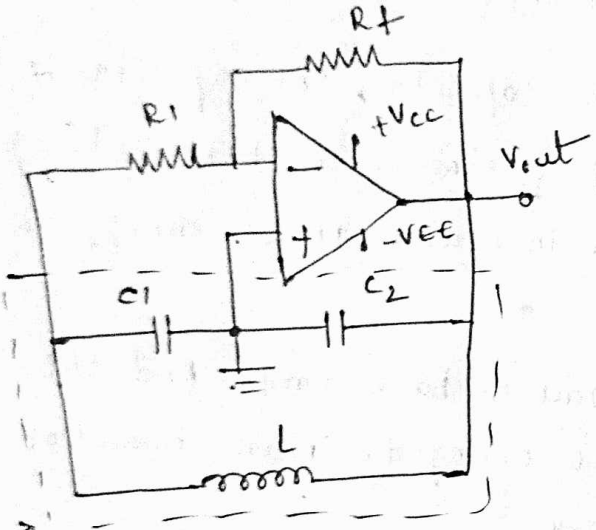
⇒ Types of LC-oscillators.

1. Colpitts oscillator
2. Hartley oscillator.

⇒ These LC-oscillators are High frequency oscillator.
It is suitable for high frequencies upto hundreads of MHz

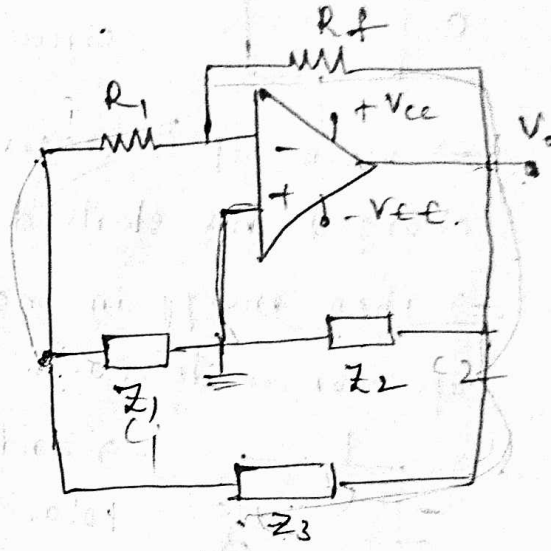
1. Colpitt's oscillator :—

The below figure shows the colpitt's oscillator.



Feedback circuit.
i.e, provides 180° phase

⇒



⇒ The ratio of feedback faction 'β' = $\frac{C_2}{C_1}$.

$$\therefore f = \frac{1}{2\pi\sqrt{LC}}$$

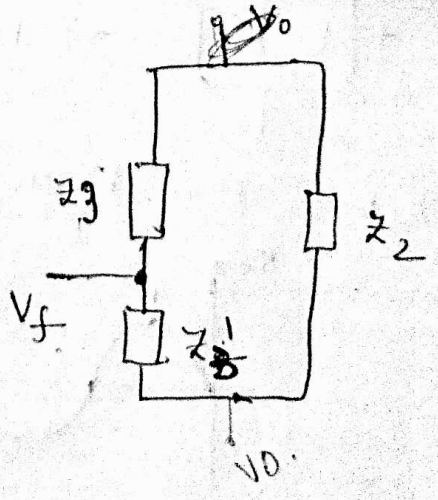
Analysis :—

let C_1, C_2 as Z_1 and Z_2.
L as Z_3.

From this ckt,

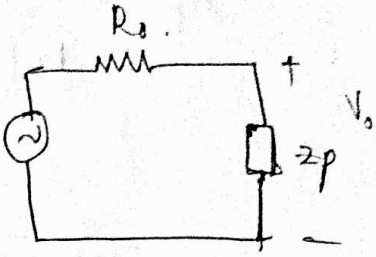
$$V_f = V_0\left(\frac{Z_1}{Z_1+Z_3}\right)$$

$$\beta = \frac{V_f}{V_0} = \frac{Z_1}{Z_1+Z_3}.$$



∴ The equivalent resonant impedance of feedback network,

$$Z_p = Z_2 \,||\, (Z_1 + Z_3)$$



$$V_o = \frac{Z_p}{Z_p + R_o} \cdot (-A_V \cdot V_i)$$

$$\frac{V_o}{V_i} = -A_V \left(\frac{Z_p}{Z_p + R_o} \right)$$

$$A = -A_V \left(\frac{Z_p}{Z_p + R_o} \right)$$

(Overall Gain)

$$A = -A_V \left[\frac{Z_2(Z_1+Z_3) / Z_1+Z_2+Z_3}{\left(\frac{Z_2(Z_1+Z_3)}{Z_1+Z_2+Z_3} \right) + R_o} \right]$$

$$\therefore A = -A_V \left[\frac{Z_2(Z_1+Z_3)}{Z_2(Z_1+Z_3) + R_o(Z_1+Z_2+Z_3)} \right]$$

$$\therefore \text{Loop Gain, } A\beta = \left[\frac{-A_V \cdot Z_2(Z_1+Z_3)}{Z_2(Z_1+Z_3) + R_o(Z_1+Z_2+Z_3)} \right] \left(\frac{Z_1}{Z_1+Z_3} \right)$$

$$A\beta = \left[\frac{-A_V \cdot Z_1 Z_2}{R_o(Z_1+Z_2+Z_3) + Z_2(Z_1+Z_3)} \right]$$

∴ Here, $Z_1 = \frac{1}{j\omega C_1}$, $Z_2 = \frac{1}{j\omega C_2}$ and $Z_3 = j\omega L$

$$\therefore \text{Loop Gain, } A\beta = \frac{-A_V \cdot \left(\frac{1}{j\omega C_1}\right)\left(\frac{1}{j\omega C_2}\right)}{R_o\left[\left(\frac{1}{j\omega C_1}\right) + \left(\frac{1}{j\omega C_2}\right) + j\omega L\right] + \frac{1}{j\omega C_2}\left[\frac{1}{j\omega C_1} + j\omega L\right]}$$

$$= \frac{-A_V \cdot \frac{1}{(j\omega C_1)(j\omega C_2)}}{R_o\left[\frac{j\omega C_2 + j\omega C_1 + j\omega L(j\omega C_1)(j\omega C_2) + \left[1 + j\omega L \cdot j\omega C_1\right]}{j\omega C_1 \, j\omega C_2}\right]}$$

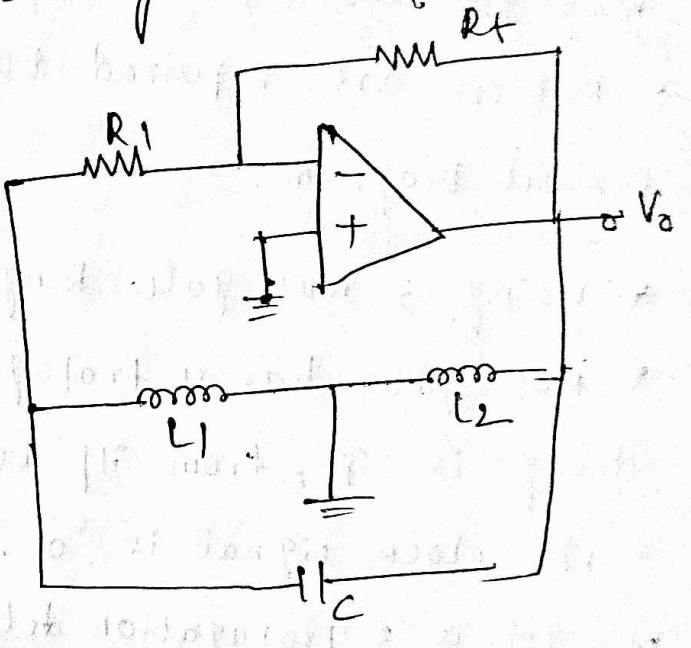
$\therefore$ The gain $A \simeq Av$ $\quad |Av| \geq \frac{C_1}{C_2}$.

$|A| \geq \frac{X_2}{X_1}$ $\quad A\beta = 1$

$\Rightarrow A = \frac{C_1}{C_2}$, $\beta = \frac{C_2}{C_1}$

Hartely oscillator:

The below figure shows the hartely oscillator



we know that,

$X_1 + X_2 + X_3 = 0$

$X_1 = j\omega L_1$, $X_2 = j\omega L_2$

$X_3 = \frac{1}{j\omega C}$

$j\omega L_1 + j\omega L_2 + \frac{1}{j\omega C} = 0$

$j\omega [L_1 + L_2] - \frac{j}{\omega C} = 0$

$j\left[\omega(L_1+L_2) - \frac{1}{\omega C}\right] = 0$

$\omega [L_1 + L_2] = \frac{1}{\omega C}$

$\omega^2 = \frac{1}{C[L_1+L_2]}$

$\omega = \frac{1}{\sqrt{C(L_1+L_2)}}$

$2\pi f = \frac{1}{\sqrt{C(L_1+L_2)}}$

$f = \frac{1}{2\pi\sqrt{C \cdot L_{eq}}}$.

For sustained o/p

$|A| > \frac{X_2}{X_1}$

$|A| > \frac{\omega L_2}{\omega L_1}$

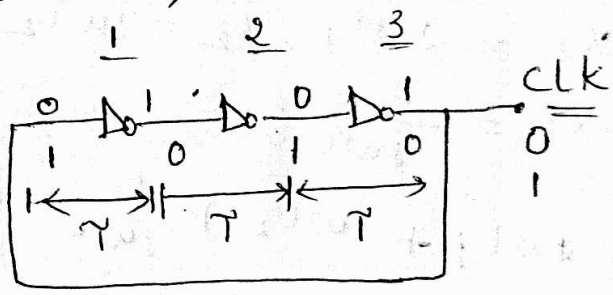
$|A| > \frac{L_2}{L_1}$.

Ring oscillator :—

* In Ring oscillator we connect NOT gates in a ring.
* Based on the feedback signal, it generates clock o/p.
* No. of NOT gates in ring should be odd.
* Here, clock signal is process dependent, so clock signal may get unstable.
* Buffers are required to drive the load.

Circuit Diagram :—

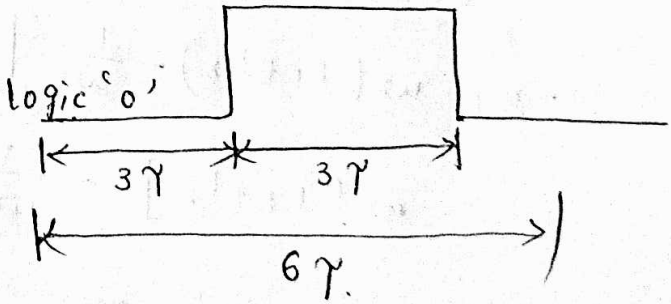
* Using 3-NOT gates Ring oscillator is,
* NOT gate has a propagation delay is τ, from i/p to o/p.
* The clock signal is '0'. it will get a 3 propagation delays.



* Frequency, $f = \frac{1}{T}$

$$f = \frac{1}{6\tau}$$

$$\therefore f = \frac{1}{2NT}$$



Crystal oscillator :— Applications :

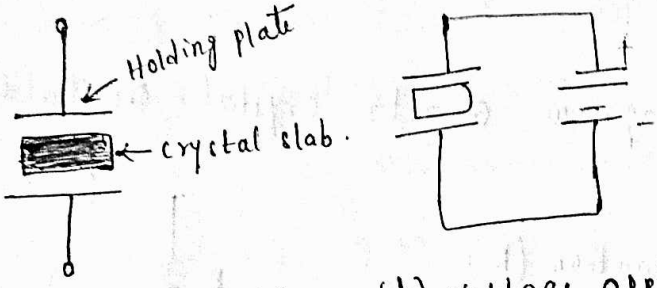
* measure the effect of voltage & temp. on IC.
* During wafer testing
* Frequency synthesizers
* Data Recovery in serial data communications

Crystal oscillator :-

⇒ An electronic oscillator circuit that uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a precise frequency.

⇒ Each crystals has its own unique frequency. Implies greater stability in holding the constant frequency.

⇒ Prefered for greater frequency stability.



a) crystal oscillator symbol.

(b) voltage applied

Piezo electric Effect :-

⇒ Under the influence of mechanical pressure, voltage gets generated across the opposite faces of the crystal.

⇒ On application of mechanical force to make the crystals vibrate the A.C voltage gets generated across it.

⇒ Conversely, if the crystal is subjected to A.C voltage, it vibrates causing mechanical distortion in the crystal shape.

Crystal Types :-

1. Naturally occurring :

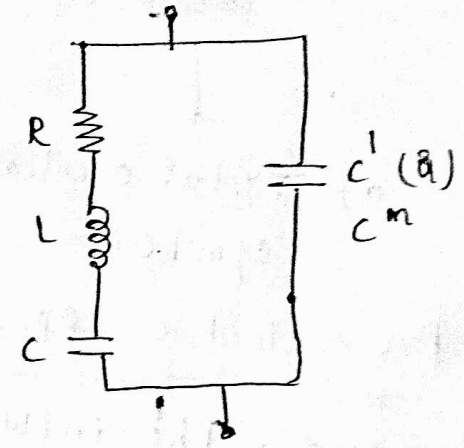
* Rochelle salt : Greatest piezoelectric activity.
  But mechanically weakest.
  Used in microphones.
* Tourmaline : Least piezoelectric effect.
  But mechanically strongest.
  Most expensive.

* Quartz : compromise between properties of Rochelle salt and Tourmaline.
Easily Available.
Very commonly used oscillator.
Used in watches

2. Synthetically occuring
Ex: Lithium tentalite, Gallium phosphate, langasite.

⇒ Construction :-

The equivalent circuit diagram quartz crystal Oscillator is,



⇒ On Vibration,
1. Internal Frictional Vibration (R)
2. Mass if crystal Indicating inertia (L)
3. some stiffness represented by a capacitor (C).
4. Mounting capacitance, C_m & C'.

⇒ RLC forms a resonating CKT. For finding resonant frequency 'fr'.

$$\therefore f_r = \frac{1}{2\pi\sqrt{LC}} \times \sqrt{\frac{Q^2}{1+Q^2}}$$

where, 'Q' is the Quality factor of crystal, $Q = \frac{\omega L}{R}$.

⇒ Q of the crystal is very high. (20,000 typically) & upto 10^6. Hence, $\sqrt{\frac{Q^2}{1+Q^2}}$ factor approaches unity and we get.

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

⇒ f_r is infact inversely propotional to the thickness of the crystal. i.e, $\boxed{f_r \propto \frac{1}{t}}$, where t = Thickness.

⇒ so, at high frequencies, the crystal thickness is small. But it makes mechanically weak.

⇒ Hence, the limiting range of such oscillations to 200 & 300KHz

Series Resonance :-

⇒ One resonant condition occurs when the reactance of series RLC circuit is equal. i.e, $X_L = X_C$.

⇒ Impedance in this condition minimum, which is resistance 'R'.

⇒ Therefore, the series resonance frequency is same as the resonating frequency, given by.

$$\boxed{f_s = \frac{1}{2\pi\sqrt{LC}}}$$

Parallel Resonance :-

⇒ other reactance condition occurs when reactance of series resonate is equals the reactance of the mounting capacitor. C_M

⇒ Thus, the impedance offered by the crystal to the external circuit is maximum.

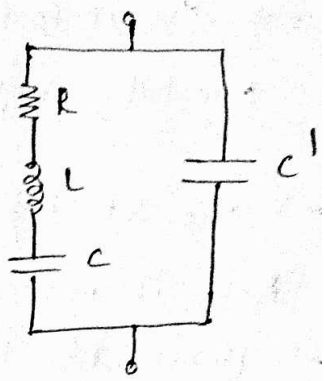
⇒ Under parallel Resonance, the equivalent capacitance is,

$$C_{eq} = \frac{C_M \times C}{C_M + C}$$

⇒ Hence, parallel Resonating frequency is given by.

$$\boxed{f_p = \frac{1}{2\pi\sqrt{L\,C_{eq}}}}$$

Impedance of Quartz crystal :-



The impedance of Quartz crystal is,

$$Z = \left[r + j\omega L + \frac{1}{j\omega C} \right] \| \left(\frac{1}{j\omega C'} \right)$$

since, the internal resistance is very small.

$$\therefore Z = \left[j\omega L + \frac{1}{j\omega C} \right] \| \left(\frac{1}{j\omega C'} \right)$$

$$= \frac{\left(j\omega L + \frac{1}{j\omega C} \right)\left(\frac{1}{j\omega C'} \right)}{\left[j\omega L + \frac{1}{j\omega C} + \frac{1}{j\omega C'} \right]}$$

$$= \frac{j\omega L \left[1 + \frac{1}{(j\omega C)(j\omega L)} \right] \left(\frac{1}{j\omega C'} \right)}{j\omega L \left[1 + \frac{1}{(j\omega C)(j\omega L)} + \frac{1}{(j\omega C')(j\omega L)} \right]}$$

$$= \frac{\left[1 - \frac{1}{\omega^2 LC} \right] \left(\frac{1}{j\omega C'} \right)}{\left[1 - \frac{1}{\omega^2 LC} - \frac{1}{\omega^2 LC'} \right]}$$

$$Z = \frac{\left[1 - \frac{1}{\omega^2 LC} \right]}{1 - \frac{1}{\omega^2 L \left[\frac{1}{C} + \frac{1}{C'} \right]}} \cdot \left(\frac{-j}{\omega C'} \right)$$

Here, $\omega_s^2 = \frac{1}{LC}$ and $\omega_p^2 = \frac{1}{L}\left[\frac{1}{C} + \frac{1}{C'} \right]$

$$\therefore Z = \frac{\left(1 - \frac{\omega_s^2}{\omega^2} \right)}{\left(1 - \frac{\omega_p^2}{\omega^2} \right)} \cdot \left(\frac{-j}{\omega C'} \right) = \left(\frac{\omega^2 - \omega_s^2}{\omega^2 - \omega_p^2} \right) \left(\frac{-j}{\omega C'} \right)$$

$$\boxed{\therefore Z = \frac{f^2 - f_s^2}{f^2 - f_p^2} \cdot \left(\frac{-j}{\omega C'} \right)}$$: This is the impedance of Quartz crystal.

where, ω_s = series Resonant frequency

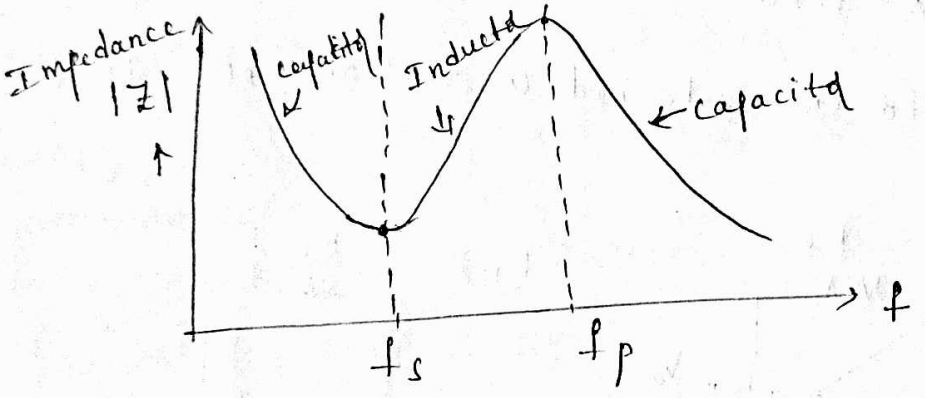
ω_p = parallel Resonant frequency.

* If, $f = f_s$. Then impedance $Z = 0$.

Then Quartz crystal undergoes series resonance.

* If, $f = f_p$. Then impedance $Z = \infty$.

Then Quartz crystal undergoes parallel resonance.



* over all crystal has good frequency stability.
* Quartz crystal cannot be effected by temp. and aging
* Hence it is used in computers, counters, basic timing devices in the electronic wrist watches, microprocessors etc.

Ex: A crystal has $L = 2H$, $C = 0.01\ pF$, and $R = 2\ k\Omega$. Its mounting capacitance is 2pF. calculate its series & parallel resonating frequency

Sol: Given: $L = 2H$

$C = 0.01\ pF$

$R = 2\ k\Omega$.

C' & $C_m = 2pF$.

$f_s = ?$

$f_p = ?$

$$\therefore C_{eq} = \frac{C' \times C}{C' + C} = \frac{2 \times 10^{-12} \times 0.01 \times 10^{-12}}{2 \times 10^{-12} + 0.01 \times 10^{-12}} = 9.95 \times 10^{-15}\ F$$

$$\therefore f_s = \frac{1}{2\pi\sqrt{LC}}$$

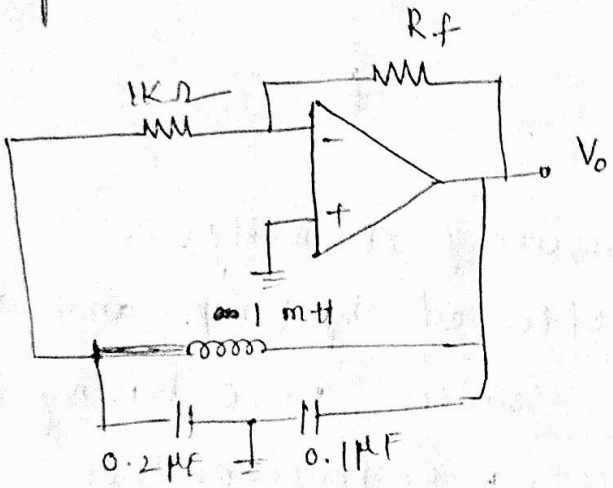
$$f_s = \frac{1}{2\pi\sqrt{2\times 0.01\times 10^{-11}}} = 1.125 \text{ MHz}$$

$$f_p = \frac{1}{2\pi\sqrt{LC_{eq}}}$$

$$\therefore f_p = \frac{1}{2\pi\sqrt{2\times 9.95\times 10^{-15}}} = 1.126 \text{ MHz}$$

2. Find 'Rf' Value, fd the sustained oscillations in colpitt's & Hartely oscillators

(i)



Find R_f.

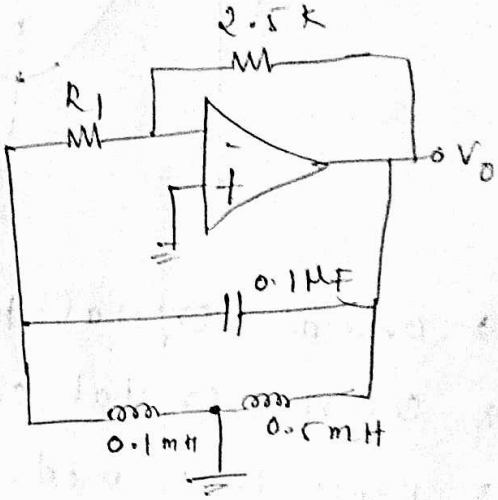
$$A = \frac{C_1}{C_2}$$

$$\left(\frac{R_f}{R_1}\right) = \frac{C_1}{C_2}$$

$$R_f = (1K)\left(\frac{0.2\mu}{0.1\mu}\right)$$

R_f =

(ii)



Find 'R_1'.

$$A \geq \frac{L_2}{L_1}$$

$$\frac{R_f}{R_1} = \frac{L_2}{L_1}$$

$$R_f = R_1\left(\frac{L_2}{L_1}\right)$$

$$R_1 = \frac{0.5m}{0.1m \times 2.5K}$$

R_1 =

Schmitt Trigger :— [Regenerative Comparatd]

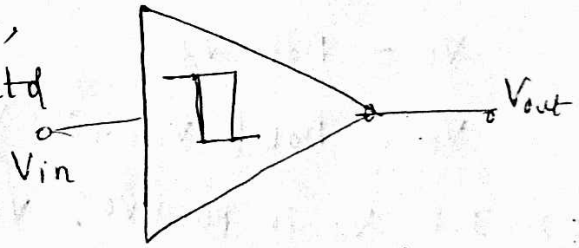
⇒ A schmitt Trigger is a comparatd CKT that incorporatu positive feedback producing two distinct switching threshold.

⇒ It was invented in 1934 by American scientict otto schmit to reduce problems arising due to small i/p signal variations thresholding digital circuits.

⇒ The main factors of a schmitt trigger include;

1. Hysteresis : It exhibits two different switching threshold voltages for the rising and falling signal edges due to positive feedback.
2. Noise elimination :- The hysteresis eliminates minor noise and fluctuations in the i/p signal
3. Square wave output : A schmitt Trigger converts analog signals like sine waves into clean digital square waves.

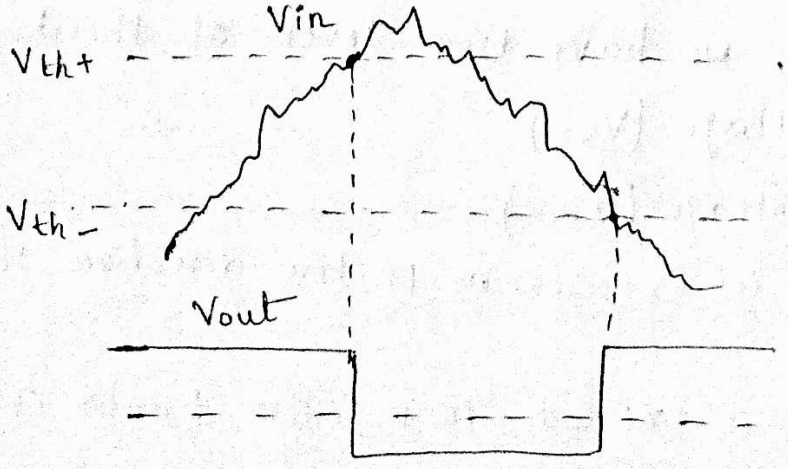
⇒ This is the symbol of schmitt triggu,



It is also called as, Bistable multivibratd circuit.

⇒ That remains in either of its two stable output states untill a threshold triggering i/p forces a state change.

⇒ schimitt trigger is also called as Regenerative Comparatd.



⇒ The definition of schmitt Trigger is, the o/p voltage changes its states when ever input voltage exceeds certain voltage level, upper threshold voltage V_{UT} and lower threshold voltage V_{LT}.

⇒ Types of schmitt Trigger.

1. Inverting schmitt Trigger
2. Non-inverting schmitt Trigger.

1. Inverting Schmitt Trigger :-

⇒ The below figure shows the Inverting schmitt Trigger.

⇒ In the inverting op-amp,

$$V_o = -A_{OL} \cdot V_{in}$$

⇒ In inverting schmitt Trigger,

$$V_o = A_{OL}(V_f - V_{in})$$

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

$$V_o = A_{OL}(-V_{in} + V_f)$$

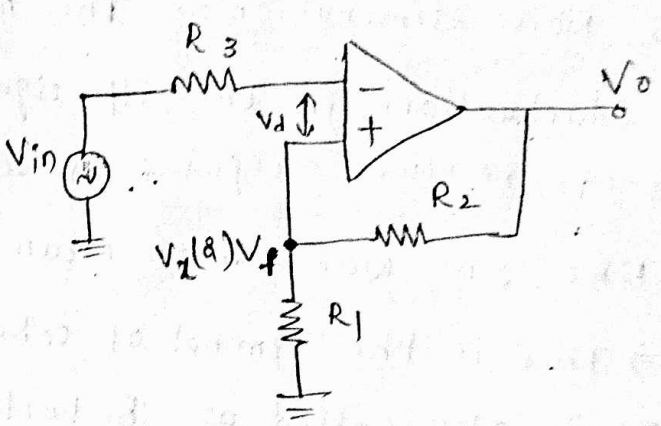


fig: Inverting schmitt Trigger

⇒ If V_d is positive, V_o is positive

If V_d is negative, V_o is negative.

⇒ The voltage across R_1 is feedback voltage V_f.

$$\therefore V_f = \left(\frac{R_1}{R_1 + R_2}\right) V_o$$

⇒ In schmitt trigger, we have two levels of threshold voltage

(i) Upper Threshold voltage (V_{UT})

(ii) Lower Threshold voltage (V_{LT})

⇒ If the i/p voltage is exceeds in positive direction it is V_{UT}.

⇒ If the i/p voltage is exceeds in negative direction it is V_{LT}

⇒ The value of V_{in} that forces the o/p to make the transition from $+V_{sat}$ to $-V_{sat}$.

⇒ when, $V_{out} = +V_{sat}$.

$$V_f = V_{UT}$$

$$\therefore V_f = \left(\frac{R_1}{R_1+R_2}\right) V_o$$

$$V_{UT} = \left(\frac{R_1}{R_1+R_2}\right) + V_{sat}.$$

⇒ The value of V_{in} that forces the o/p to make the transition from $-V_{sat}$ to $+V_{sat}$.

⇒ when, $V_{out} = -V_{sat}$

$$V_f = V_{LT}$$

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

Working: Let initially $V_{out} = +V_{sat}$.

$$\therefore V_f = V_{UT} = +V_{sat}\left(\frac{R_1}{R_1+R_2}\right) = +\beta V_{sat}.$$

⇒ If, $V_{in} > V_{UT}$ ⇒ V_d is negative. Then $V_o = -V_{sat}$.

⇒ Now, $V_{out} = -V_{sat}$.

$$\therefore V_f = V_{LT} = -V_{sat}\left(\frac{R_1}{R_1+R_2}\right) = -\beta V_{sat}$$

⇒ If $V_{in} > V_{LT}$ ⇒ V_d is negative. Then $V_o = -V_{sat}$.

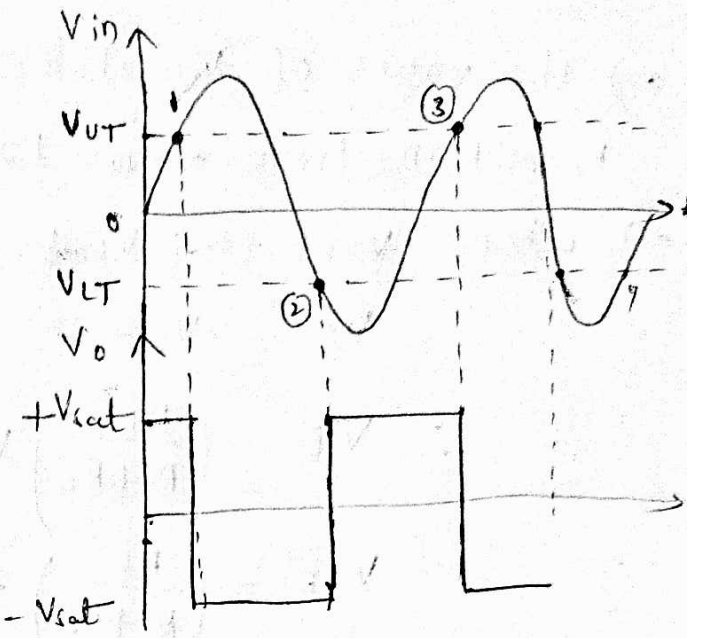
⇒ Now, $V_{out} = -V_{sat}$.

$$V_f = V_{LT}.$$

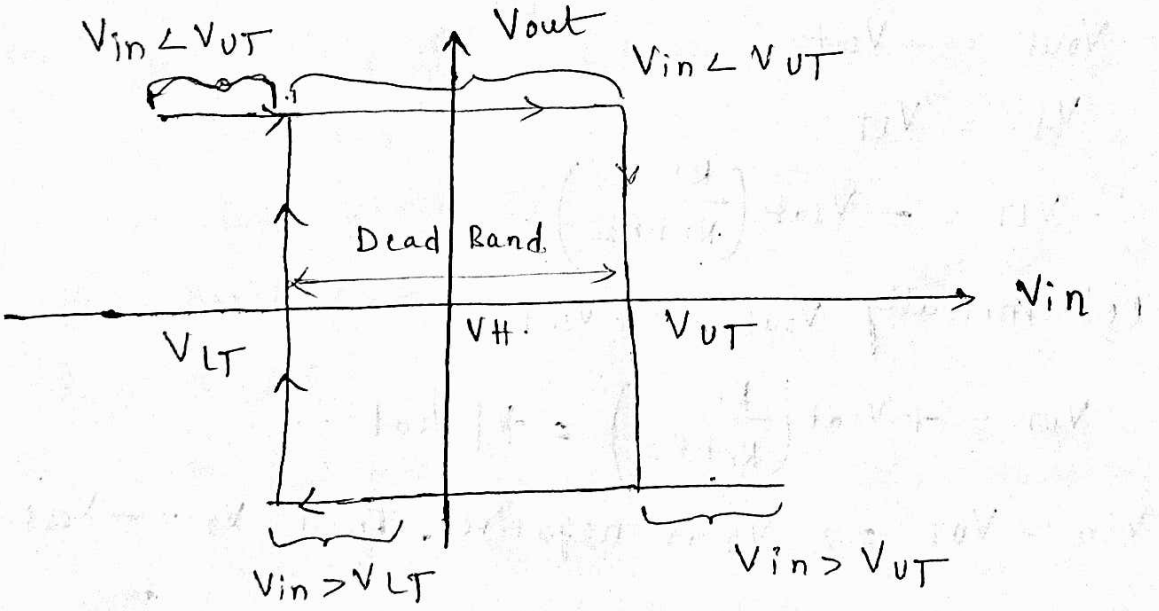
If, $V_{in} < V_{LT}$ ⇒ V_d is positive, Then $V_o = +V_{sat}$.

⇒ The input & o/p waveforms are shown in below figure

Condition	Differential I/p voltage	o/p voltage
1. If $V_{in} < V_{UT}$	V_d positive	$V_{out} = +V_{sat}$
2. $V_{in} > V_{UT}$	V_d negative	$V_{out} = -V_{sat}$
3. $V_{in} > V_{LT}$	V_d negative	$V_o = -V_{sat}$
4. $V_{in} < V_{LT}$	V_d positive	$V_o = +V_{sat}$



Transfer characteristics of Inverting schmitt Trigger:-

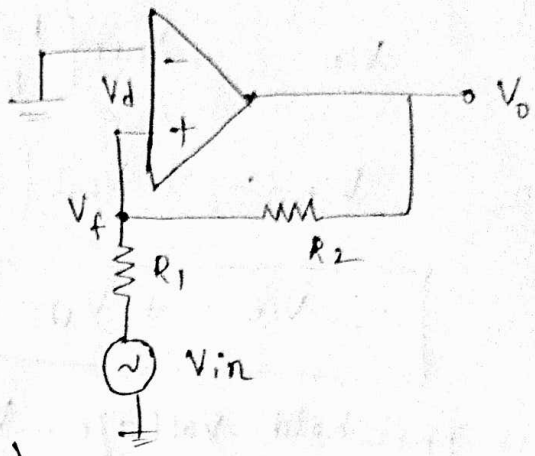


⇒ This dead band zone is called Hysteresis curve and the voltage is called Hysteresis voltage V_H.

$$\therefore V_H = V_{UT} - V_{LT}$$

$$\therefore V_H = +2 V_{sat}\left(\frac{R_1}{R_1 + R_2}\right)$$

2. Non-Inverting Schmitt Trigger:



⇒ The o/p voltage of an op-amp.

$V_o = A_{OL}(V_f - 0)$

$V_o = A_{OL} \cdot V_f$

⇒ The o/p voltage depends on 'V_f'.

⇒ From the CKT,

$$V_f = V_{out}\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right).$$

By superposition theorem,

when V_o is shorted & V_{in} is acting.

$$V_f = V_{in}\cdot\left(\frac{R_2}{R_1+R_2}\right)$$

when V_{in} is shorted & V_o is acting.

$$V_f = V_o\cdot\left(\frac{R_1}{R_1+R_2}\right)$$

∴ Total voltage, $V_f = V_{in}\left(\frac{R_2}{R_1+R_2}\right) + V_o\left(\frac{R_1}{R_1+R_2}\right)$.

Upper Threshold voltage – V_{UT}.

⇒ The value of V_{in} which makes the $V_f = 0$ and forces the o/p to make the transition from $-V_{sat}$ to $+V_{sat}$.

⇒ For V_o to switch from $-V_{sat}$ to $+V_{sat}$.

⇒ V_{in} crosses V_{UT}

⇒ V_{in} crosses 0V ($V_f > 0$).

$V_{in} = V_{UT}$ ⇒ $V_f = V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right)$

$V_f = 0$.

$$0 = V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{UT}\left(\frac{R_2}{R_1+R_2}\right)$$

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

$$V_{in} = -V_{out}\left(\frac{R_1}{R_2}\right) \qquad [\because V_{out} = -V_{sat}]$$

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

$$\boxed{\therefore V_{in} = +V_{UT}}$$

Lower Threshold Voltage - V_{LT}

⇒ The value of V_{in} which makes $V_f = 0$ and forces the o/p to makes the transition from $+V_{sat}$ to $-V_{sat}$.

⇒ Then V_{in} crosses V_{LT}.

⇒ V_{in} crosses 0V. [$V_f < 0$]

$\therefore V_{in} = V_{LT}$

$V_f = 0$.

$$\Rightarrow V_f = V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_1}{R_1+R_2}\right)$$

$$\Rightarrow 0 = V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_1}{R_1+R_2}\right)$$

$$V_{in} = -V_{out}\left(\frac{R_1}{R_2}\right) \qquad [\because V_{out} = +V_{sat}]$$

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

$$\boxed{V_{in} = V_{LT}}$$

Working:

⇒ If $V_f > 0 \Rightarrow V_{out} = +V_{sat}$

⇒ If $V_f < 0 \Rightarrow V_{out} = -V_{sat}$.

$$\therefore V_f = V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right)$$

⇒ when $V_f > 0$. Then $V_{out} = +V_{sat}$.

$$\Rightarrow V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right) > 0$$

$$\Rightarrow V_{sat}\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right) > 0.$$

$$\Rightarrow V_{in}\left(\frac{R_2}{R_1+R_2}\right) > -V_{sat}\left(\frac{R_1}{R_1+R_2}\right)$$

$$\Rightarrow \boxed{V_{in} > -V_{sat}\left(\frac{R_1}{R_2}\right)}$$

Therefore, $V_{in} > V_{LT}$. ⇒ Then $V_{out} = +V_{sat}$

$V_{in} < V_{LT}$ ⇒ Then $V_{out} = -V_{sat}$.

⇒ when $V_f < 0$. Then $V_{out} = -V_{sat}$.

$$\Rightarrow V_o\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right) < 0.$$

$$\Rightarrow -V_{sat}\left(\frac{R_1}{R_1+R_2}\right) + V_{in}\left(\frac{R_2}{R_1+R_2}\right) < 0$$

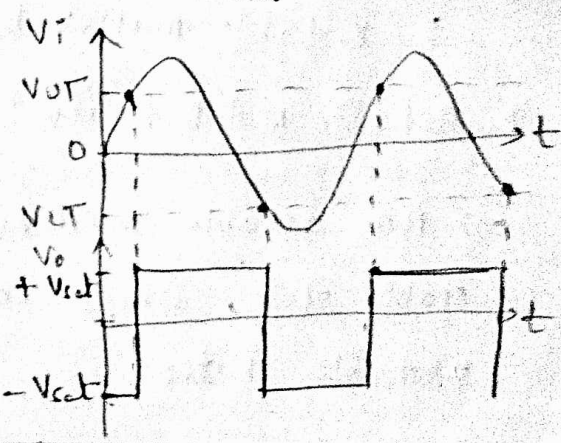
$$\Rightarrow V_{in}\left(\frac{R_2}{R_1+R_2}\right) < V_{sat}\left(\frac{R_1}{R_1+R_2}\right)$$

$$\boxed{\therefore V_{in} < V_{sat}\left(\frac{R_1}{R_2}\right)}$$

Therefore, $V_{in} < V_{UT}$. ⇒ Then $V_{out} = +V_{sat}$.

$V_{in} > V_{UT}$ ⇒ Then $V_{out} = +V_{sat}$.

	Condition	Differential i/p voltage	o/p voltage
1.	$V_{in} < V_{UT}$	V_d negative	$V_o = -V_{sat}$
2.	$V_{in} > V_{UT}$	V_d positive	$V_o = +V_{sat}$
3.	$V_{in} < V_{LT}$	V_d positive	$V_o = +V_{sat}$
4.	$V_{in} > V_{LT}$	V_d negative	$V_o = -V_{sat}$.



Applications :—

1. speed of response is high
2. No Relay chattering
3. Adjustable duty cycle
4. Used in signal conditioning applications to remove noise from signals.
5. Used in digital circuits.

Multivibrators :—

⇒ A multivibrator is an electronic circuit, used to implement a variety of simple two-state devices such as relaxation oscillators, timers, latches and flip flops

→ It can generates many oscillations.

→ Used in microprocessors

⇒ Used in audio signal processing

⇒ According to the working state and o/p waveform, multivibrator circuits are generally divided into three main types.

1. Astable multivibrator
2. monostable multivibrator.
3. Bistable multivibrator.

1. Astable multivibrator :—

⇒ An astable multivibrator is a circuit without a stable state, which constantly switches between two unstable states.

⇒ The circuit continuously generates a square wave signal through the process of charging and discharging.

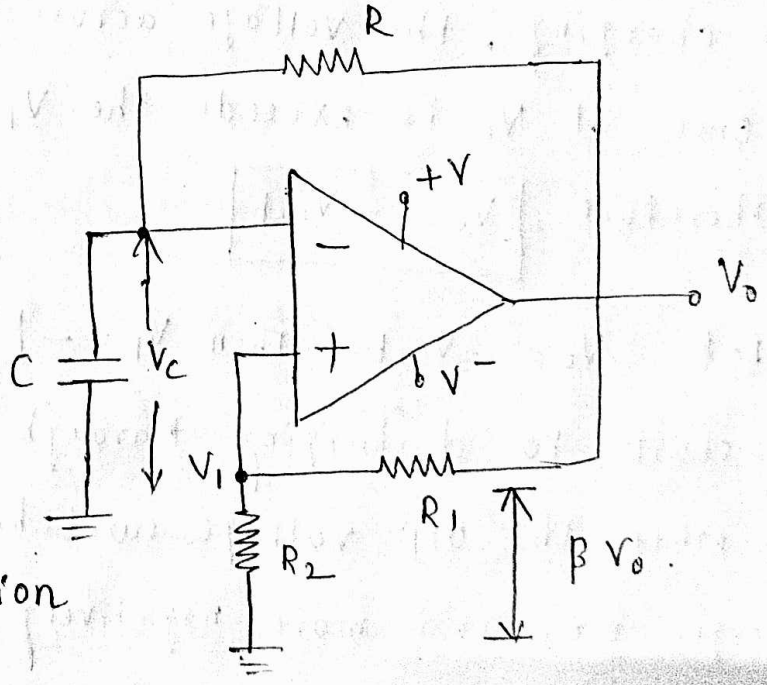
⇒ The o/p waveform has a fixed frequency and duty cycle and the frequency is determined by the capacitance & resistance values in the circuit.

⇒ There is no stable state and the circuit oscillates continuously.

⇒ The o/p is a periodic square wave signal.

⇒ The frequency of the o/p signal is controlled by the capacitor and the resistor.

⇒ The below figure shows the Astable multivibrator circuit.



⇒ This is also called as, Free Running Oscillator.

⇒ The principle of generation of square wave o/p is to force an op-amp to operate in the saturation region.

⇒ From the figure, $\beta = \frac{R_2}{R_1 + R_2}$.

And, $V_1 = V_o\left(\frac{R_2}{R_1 + R_2}\right) = \beta V_o$.

⇒ Due to the positive feedback, the o/p voltage saturated from $+V_{sat}$ and $-V_{sat}$.

$\therefore V_o = \pm V_{sat}$.

⇒ Therefore, $V_1 = \pm \beta V_{sat}$.

⇒ Here, the circuit compares with these voltages i.e, V_1 and V_c. Therefore $\boxed{V_d = V_1 - V_c}$

⇒ If $V_1 < V_c$. Then $V_d = -Ve \Rightarrow V_o = -V_{sat}$

If $V_1 > V_c$. Then $V_d = +Ve \Rightarrow V_o = +V_{sat}$.

⇒ Hence the o/p changes from $+V_{sat}$ to $-V_{sat}$ and $-V_{sat}$ to $+V_{sat}$.

Operation:

⇒ Let, $V_o = +V_{sat}$. Then $V_1 = +\beta V_{sat}$. Hence the capacitor is charging, the voltage across the capacitor (V_c) is increases

⇒ Once, it V_c is exceeds the V_1. Then V_d is negative.

Therefore, $\boxed{V_o = -V_{sat}}$.

2. Let, $V_o = -V_{sat}$. Then $V_1 = -\beta V_{sat}$. Hence the capacitor is start to discharging through R.

⇒ when the o/p voltage switches to $-V_{sat}$, the capacitor charges more and more negatively untill its voltage just exceeds $-\beta V_{sat}$.

⇒ The o/p switches back to to $+V_{sat}$.

$\boxed{\therefore \quad V_o = +V_{sat}}$

⇒ The output wave fdm is shown in below.

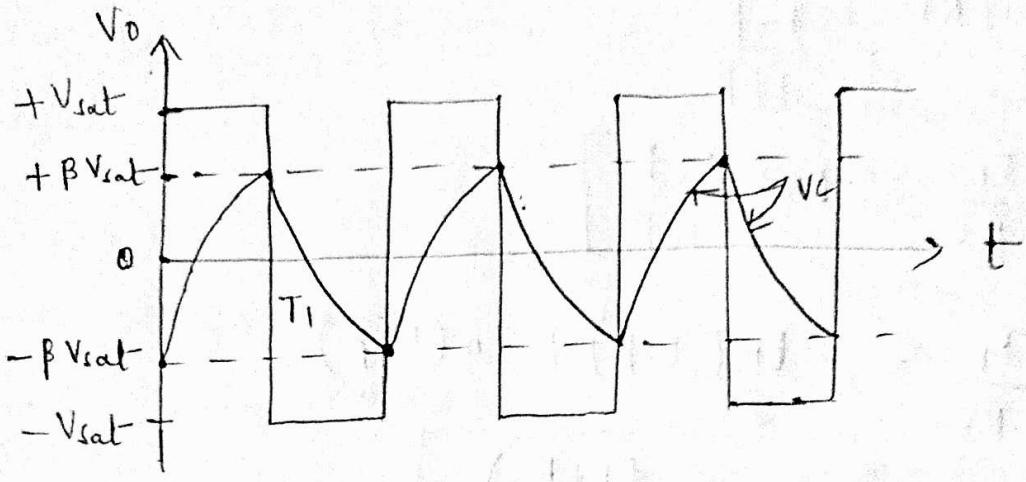


fig: waveform.

⇒ The frequency is determined by the time it takes the capacitor to charge from $-\beta V_{sat}$ to $+\beta V_{sat}$ and vice versa.

⇒ The voltage across the capacitor as a function of time is given by.

$$V_c(t) = V_{final} + (V_{initial} - V_{final})\, e^{-t/RC}$$

∴ where, the final value, $V_f = +V_{sat}$

Initial value, $V_i = -\beta V_{sat}$.

Therefore, $V_c(t) = +V_{sat} + [-\beta V_{sat} - V_{sat}]\, e^{-t/RC}$

$$V_c(t) = V_{sat} - V_{sat}[1+\beta]\, e^{-t/RC}.$$

At, $t = T_1$. voltage across the capacitor reaches $+\beta V_{sat}$. and switching takes place.

Therefore, $V_c(T_1) = +\beta V_{sat} = V_{sat} - V_{sat}[1+\beta]\, e^{-T_1/RC}$.

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

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

let, ~~The t~~

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

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

$$\frac{T_1}{RC} = -\ln(1-\beta) + \ln(1+\beta)$$

$$\therefore T_1 = RC \ln\left(\frac{1+\beta}{1-\beta}\right)$$

This give only one half of the period.

The total time period is,

$$T = 2T_1 = 2RC\ln\left(\frac{1+\beta}{1-\beta}\right)$$

$\Rightarrow$ Here, $\beta = \frac{R_2}{R_1+R_2}$. If $R_1 = R_2$.

$$\beta = \frac{R_2}{2R_2} = 0.5$$

$$\therefore T = 2RC \ln\left(\frac{1+0.5}{1-0.5}\right)$$

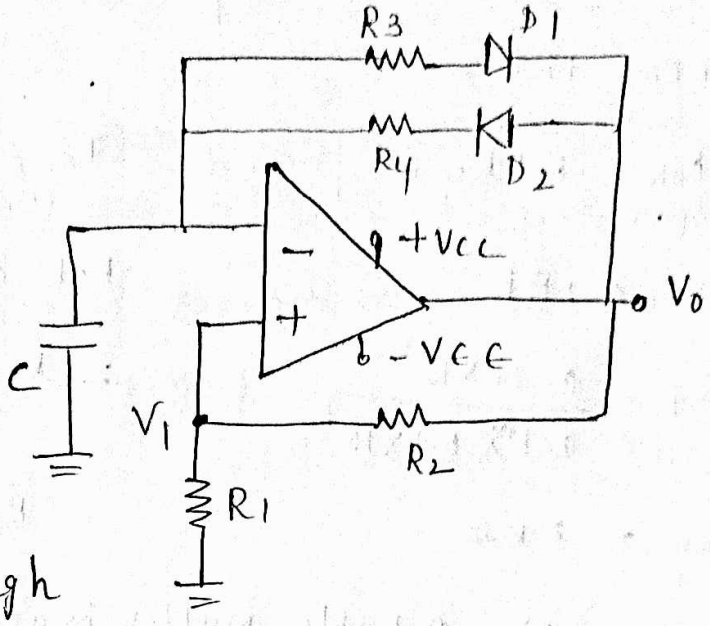
$$T = 2.2RC \cong 2RC$$

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

NOTE: * This is applicable for 50% of duration Time i.e, [Duty cycle].

Duty cycle, $D = \frac{T_{ON}}{T_{ON}+T_{OFF}}$ (a) $\frac{\text{Active Time of the clk s/g}}{\text{Total Time of cycle}}$

⇒ For an the Asymmetric Astable multivibratd, we can use diodes in the circuit, to get other than the 50% of duty cycle.



⇒ If, $V_o = +V_{sat}$, Then capacitd charge through R_4. Diode D_2 is Forwald biased.

⇒ If, $V_o = -V_{sat}$. Then capacitor discharges through 'R_3'. Diode D_1 is Reversed biased.

⇒ Therefore, the charging time, $T_c = 1.1\ R_4C$

The. Discharging time, $T_{D1} = 1.1\ R_3.C$

∴ Total Time period, $\boxed{T = T_c + T_D.}$

Problem:

1. Design a Astable multivibratd circuit with frequency of 1KHz with the duty cycle 1/3.

Sol) Given: $D = \frac{1}{3}$, w.k.t, $D = \frac{T_{ON}}{T_{ON} + T_{OFF}}$ → (1)

$f = 1\ KHz$

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

∴ $T = 1\ msec.$

Total Time period, $T = T_{ON} + T_{OFF}$

$T_{ON} + T_{OFF} = 1\ msec$ → (2)

(1) ⇒ $\frac{1}{3} = \frac{T_{ON}}{T_{ON} + T_{OFF}}$

$T_{ON} = \frac{1 \times 10^{-3}}{3} = 0.33\ msec.$

∴ (2) ⇒ $T_{OFF} = 1 \times 10^{-3} - 0.33 = 0.67\ msec.$

If, $V_o = +V_{sat}$. Then capacitor is charged through R_4.

$V_o = -V_{sat}$. Then capacitor is discharged through R_3.

We know that,

$T_{ON} = 1.1 R_4 C$ (c) and $T_{OFF} = 1.1 R_3 C$ (Dis)

Let $C = 0.1\mu F$.

$$R_4 = \frac{0.33 \times 10^{-3}}{1.1 \times 0.1 \times 10^{-6}}$$

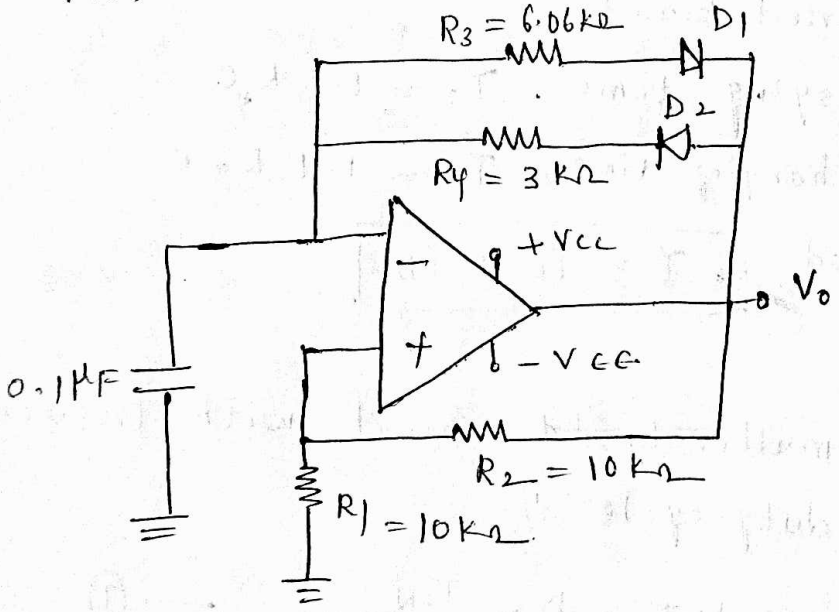
$$R_4 = 3\ k\Omega$$

Let $C = 0.1\mu F$

$$\therefore R_3 = \frac{0.67 \times 10^{-3}}{1.1 \times 0.1 \times 10^{-6}}$$

$$R_3 = 6.06\ k\Omega$$

Therefore, the Astable multivibrator is given as follows



EX: 2) To design and setup the astable multivibrator using op-amp with frequency of oscillation is 1kHz. Consider 50% duty cycle.

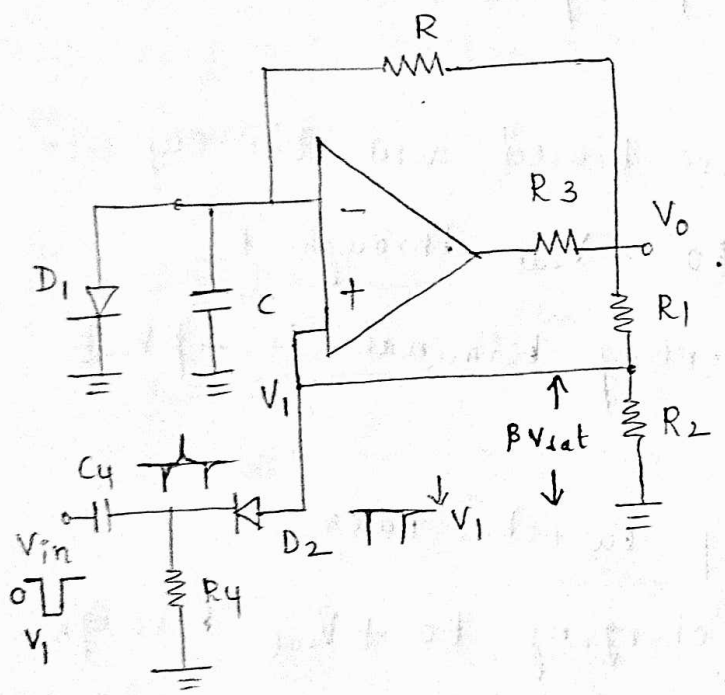
Monostable multivibrator :-

⇒ Monostable multivibrator has one stable state and the other is quasi stable state.

⇒ The circuit is useful for generating single o/p pulse of adjustable time duration in response to a triggering signal.

⇒ The width of the o/p pulse depends only on external components connected to the op-amp.

⇒ The below circuit shows the modified form of the Astable multivibrator.



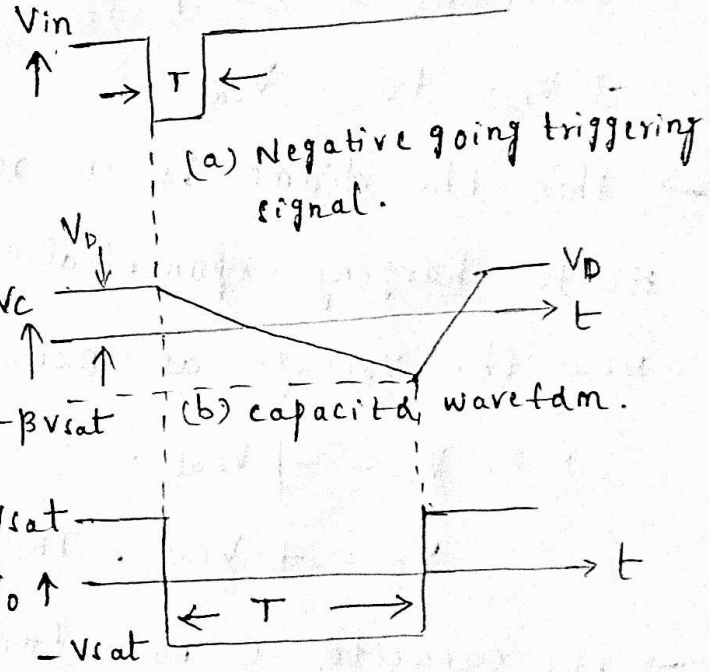


Fig: Monostable Multivibrator (c) output wave form.

⇒ Working :-

→ A diode D_1 clamps the capacitor voltage to 0.7V. when, $V_o = +V_{sat}$.

→ A negative voltage going pulse signal of magnitude V_1 passing through the differentiator R_4C_4 and diode D_2 produces a negative going triggering impulse, and is applied to the non-inverting terminal.

⇒ Let us assume, $V_o = +V_{sat}$. It is in stable state. Then diode D_1 conducts and V_c the voltage across the capacitor C gets clamped to +0.7V

→ The voltage at the non-inverting terminal is $+\beta V_{sat}$

⇒ Now, if the negative trigger of magnitude V_i is applied to the non-inverting terminal. So that the effective signal at this terminal is less than 0.7 V.

→ Therefore the o/p of the op-amp will switch from $+V_{sat}$ to $-V_{sat}$.

⇒ Then the diode is in reverse biased and the capacitor starts charging exponentially to $-V_{sat}$ through R.

Now the voltage at non-inverting terminal is $-\beta V_{sat}$.

i.e, $V_c = -\beta V_{sat}$.

$V_o = +V_{sat}$. The o/p switches back.

→ The capacitor C now starts charging to $+V_{sat}$ through R until V_c is 0.7V as capacitor C gets clamped to the voltage

⇒ simply we can say that,

If, no triggering. V_o remains stable state.

Then $V_o = +V_{sat}$

Then capacitor is charging, Diode D_1 is F.B.

$V_c = V_{DF}$

⇒ When Trigger is applied (i.e, negative spike). It causes decreases the 'V_1'.

when, $V_1 < V_c \Rightarrow V_d = V_1 - V_c = -Ve$

Then $\boxed{V_o = -V_{sat}}$.

Due to -ve output, capacitd 'c' is discharged through 'R'

Then V_c decreases.

when, $V_1 > V_c \Rightarrow V_d = +Ve$.

Then $\boxed{V_o = +V_{sat}}$

⇒ Here o/p changes from $-V_{sat}$ state to $+V_{sat}$ state without triggering.

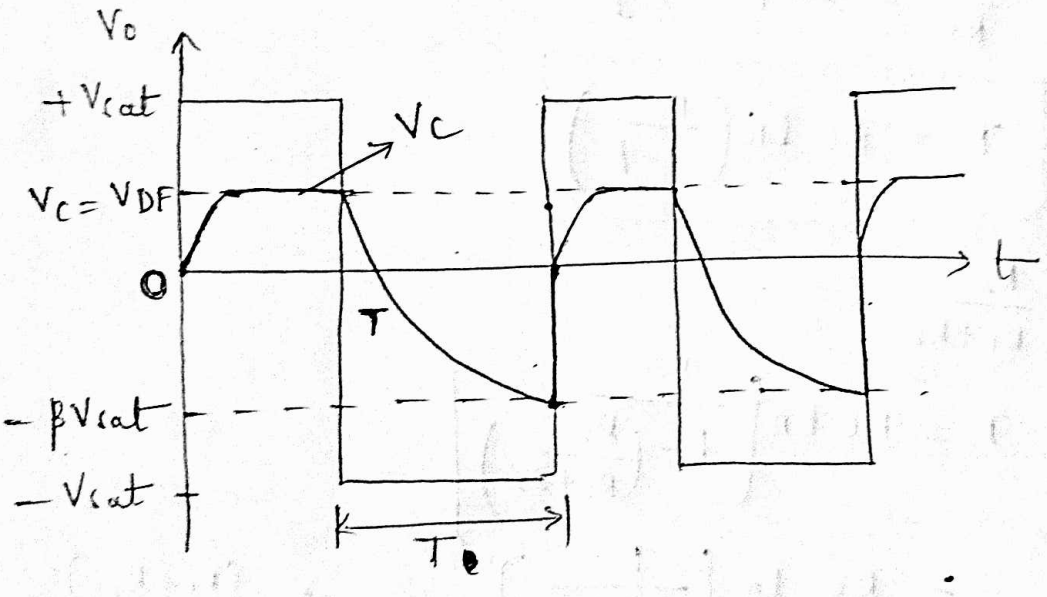


fig: output wave fdm.

Finding 'T':

The pulse width T of monostable multivibratd is calculated as follows.

⇒ The capacitd voltage with time is given by,

$$V_c(t) = V_f + [V_{ini} - V_{final}]\, e^{-t/RC}.$$

⇒ At $t=0$, The initial value, $V_{initial} = 0$.

At $t>0$, the final value. $V_{final} = -V_{sat}$.

$$V_c = -\beta V_{sat}.$$

$$\therefore V_c(T) = V_f + (V_{in} - V_{fi})\, e^{-T/RC}$$

$$-\beta V_{sat} = -V_{sat} + [0 - (-V_{sat})]\, e^{-T/RC}$$

$$+\beta V_{sat} = +V_{sat}\left[1 - e^{-T/RC}\right]. \qquad [\because t = T]$$

$$1-\beta = e^{-T/RC}.$$

$$-\frac{T}{RC} = \ln[1-\beta]$$

$$\therefore \boxed{T = RC.\ln\left(\frac{1}{1-\beta}\right)}$$

Here, $\beta = \frac{R_2}{R_1+R_2}$.

$$\therefore T = RC \ln\left[\frac{1}{1-\left(\frac{R_2}{R_1+R_2}\right)}\right]$$

$$= RC \ln\left[\frac{1}{\left(\frac{R_1}{R_1+R_2}\right)}\right] = RC \ln\left[\frac{R_1+R_2}{R_1}\right]$$

$$T = RC \ln\left[1 + \frac{R_2}{R_1}\right]$$

$\therefore$ If $R_1 = R_2 \Rightarrow T = RC \ln(2)$

$$\therefore \boxed{T = 0.69\, RC}$$

$$\therefore \boxed{f = \frac{1}{0.69\, RC}}$$

Triangular wave generator

A triangular wave generator is an electronic circuit that produces a triangular waveform, which is a type of wave form that has a triangular shape. It has linear increase and decrease in amplitude.

→ characterstics of waveform :-

* Frequency : The number of cycles per second, measured in hertz (HZ).
* Amplitude : The maximum value of the waveform, measured in volts (V).
* period : The time taken for one complete cycle, measured in seconds (s).
* Integrator : An integrator that have to converts a square wave into a triangular wave form.
* Comparator : A comparator circuit that compares the output of the ~~tri~~ integrator with reference voltage.
* switch : A switch that switches the output of the integrator between two states, depending on the output of the comparator.

working principle :-

1. The Integrator circuit integrates the square wave input producing a triangular waveform.
2. The comparator circuit ~~waveform~~ compares the output of the integrator with a reference voltage.

3. when the output of integrator exceeds the reference voltage, the comparator switches the output of the integrator to a lower state.

4. when the output of integrator falls below the reference voltage, the comparator switches the output of the ~~voltage~~, ~~the~~ integrator to a high state.

5. The switch circuit switches the output of the integrator between the two states, producing a triangular waveform.

Applications :-

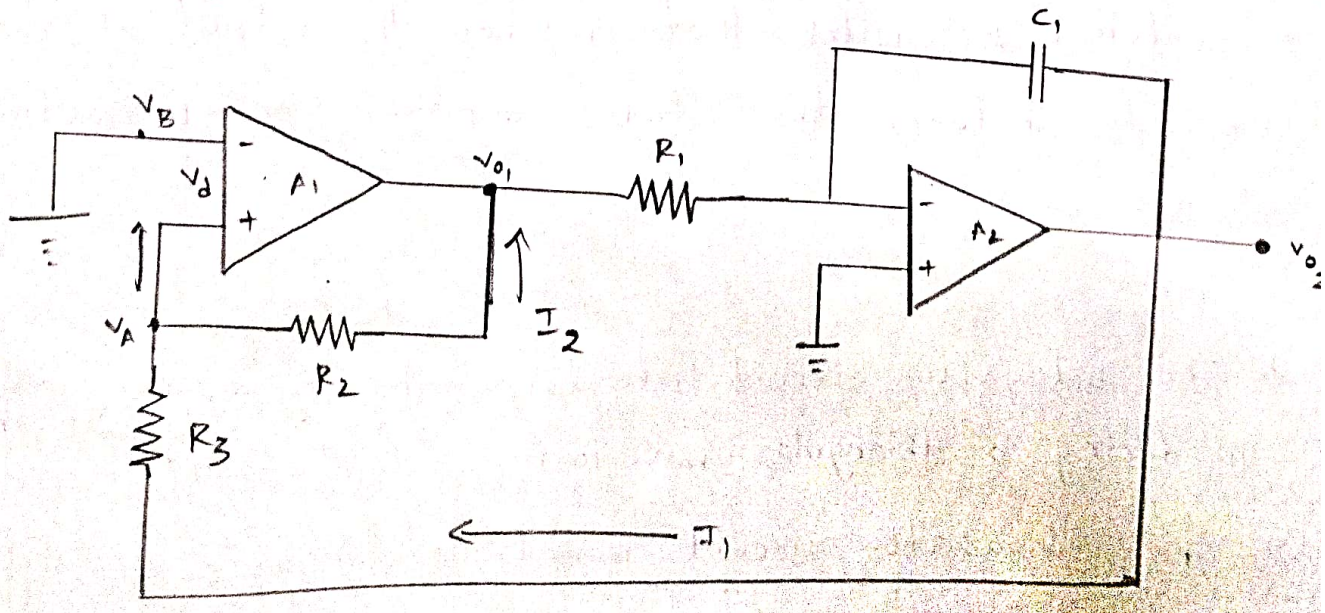
→ In Analog to Digital conversion (ADC)

→ pulse width modulation (PWM) circuits

→ switch mode power supply (SMPS)

→ Motor driver control circuit.

circuit diagram :-



$A_1 \longrightarrow$ Non-inverting schmit trigger

$A_2 \longrightarrow$ Integrator ckt.

$$V_d = V_A - V_B$$

when

$V_A > V_B$

$\hookrightarrow V_d = +Ve$

$V_{o_1} = +V_{sat}$

$V_A < V_B$,

$\hookrightarrow V_d = -Ve$

$V_{o_1} = -V_{sat}$

$V_{o_1} = \pm V_{sat}$ (square wave)

$$V_{o_2} = -\frac{1}{R_1 C_f} \int_0^t V_{o_1}\, dt$$

apply kcl at node A

$I_1 = I_2$

$$\frac{V_{o_2} - V_A}{R_3} = \frac{V_A - V_{o_1}}{R_2}$$

V_{o_1} will swing b/w $+V_{sat}$ & $-V_{sat}$

$V_A = 0$

let $V_{o_1} = +V_{sat}$

$$\frac{V_{o_2}}{R_3} = \frac{-V_{o_1}}{R_2} = \frac{-V_{sat}}{R_2}$$

$$V_{o_2} = -\frac{R_3}{R_2} V_{sat}$$

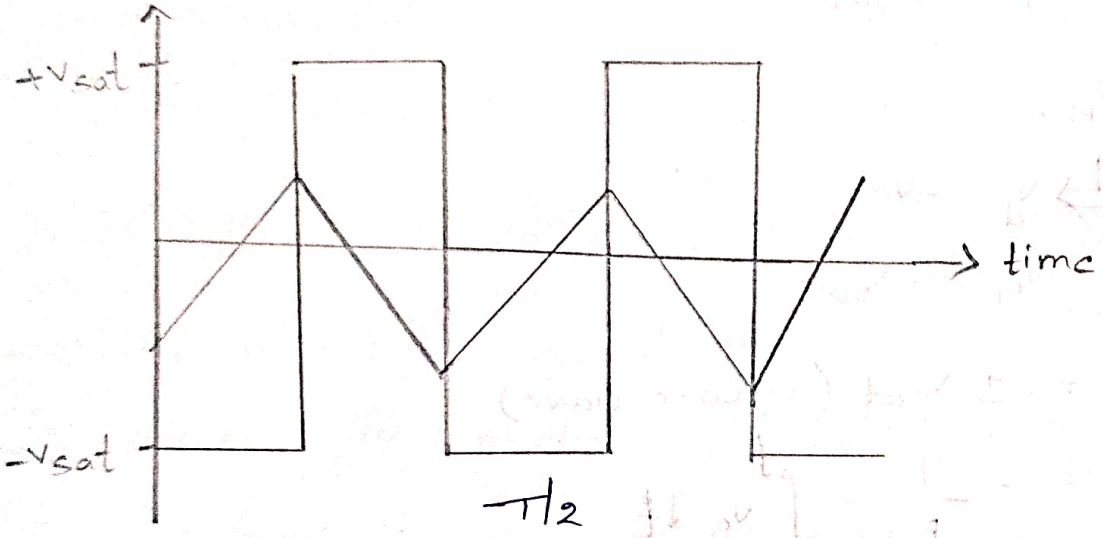
Assume $V_{o_1} = -V_{sat}$

$$\frac{V_{o_2}}{R_3} = \frac{+V_{sat}}{R_2} \Rightarrow V_{o_2} = V_{sat} \cdot \frac{R_3}{R_2}$$

$$V_{o_2}(p\text{-}p) = 2\frac{R_3}{R_2} V_{sat} \longrightarrow (1)$$

$$V_{o_2} = -\frac{1}{R_1 C_f} \int_0^t V_{o_1}\, dt$$

WAVEFORM :-



$$= -\frac{1}{R_1 C_f} \int_0^{T/2} (-V_{sat})\, dt$$

$$= \frac{V_{sat}\, T}{2 R_1 C_f} \longrightarrow (2)$$

from (1) & (2)

$$V_{o_2}(p\text{-}p) = V_{o_2}$$

$$\frac{2R_3}{R_2} V_{sat} = \frac{T}{2R_1 C_f} V_{sat}$$

$$T = \frac{4 R_3 R_1 C_f}{R_2}$$

$$f = \frac{R_2}{4R_1 R_3 C_f}$$