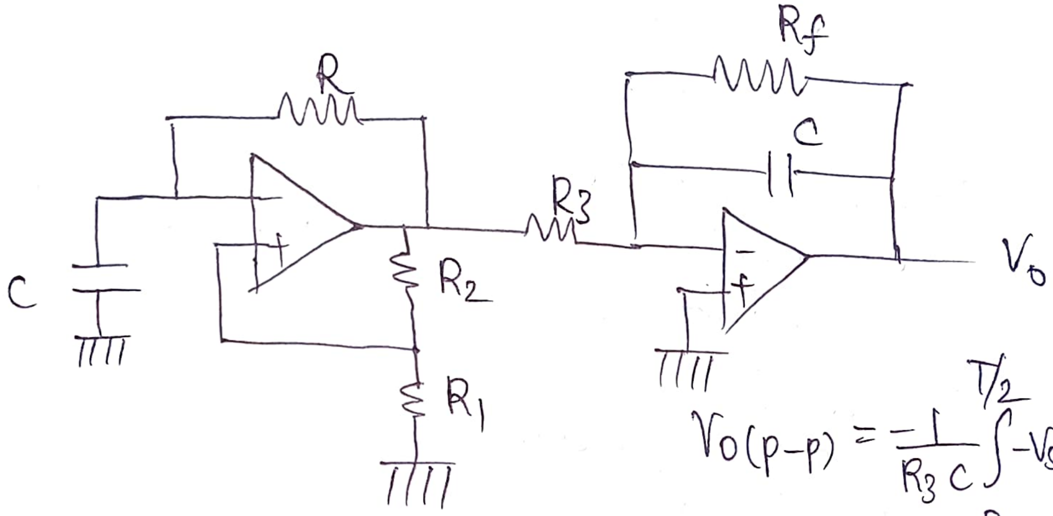
Triangular wave generator using OPAMP:

Astable multivibrator → Integrator → Triangular wave.

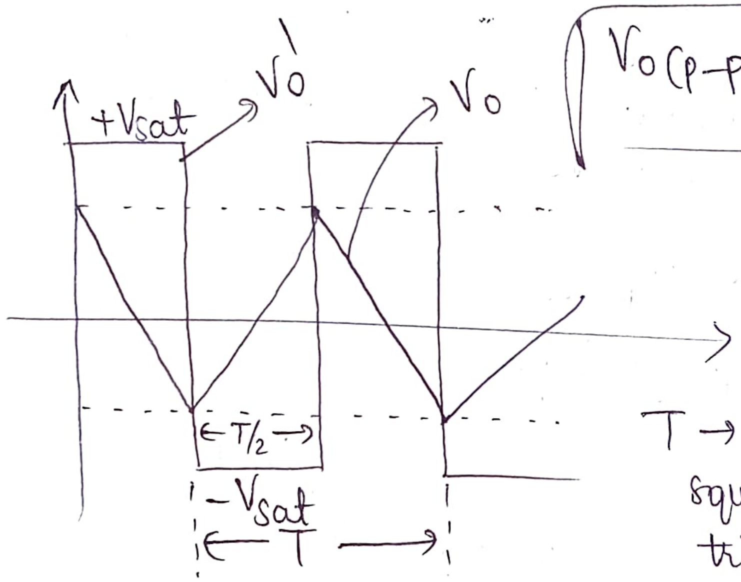


$$V_{o(p-p)} = \frac{-1}{R_3 C}\int_0^{T/2} -V_{sat}\,dt$$

$$\boxed{V_{o(p-p)} = \frac{+V_{sat}\,T}{2R_3 C}}$$

↓

Peak to peak output voltage.



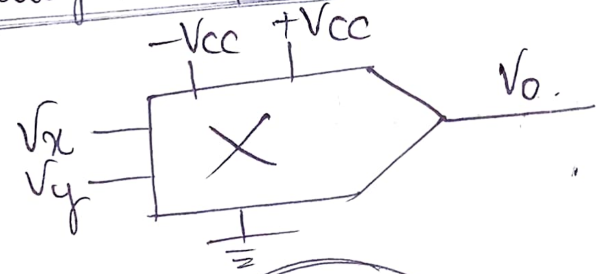
T → time period of square wave and triangular wave.

$$V_o = \frac{-1}{R_3 C}\int V_o'\,dt$$

$$\boxed{\frac{V_{o(p-p)}}{2} = \frac{V_{sat}\,T}{4R_3 C}}$$ → Amplitude of triangular wave.

$$\boxed{T = 2RC\ln\left(\frac{1+\beta}{1-\beta}\right)} \rightarrow \beta = \frac{R_1}{R_1+R_2}$$

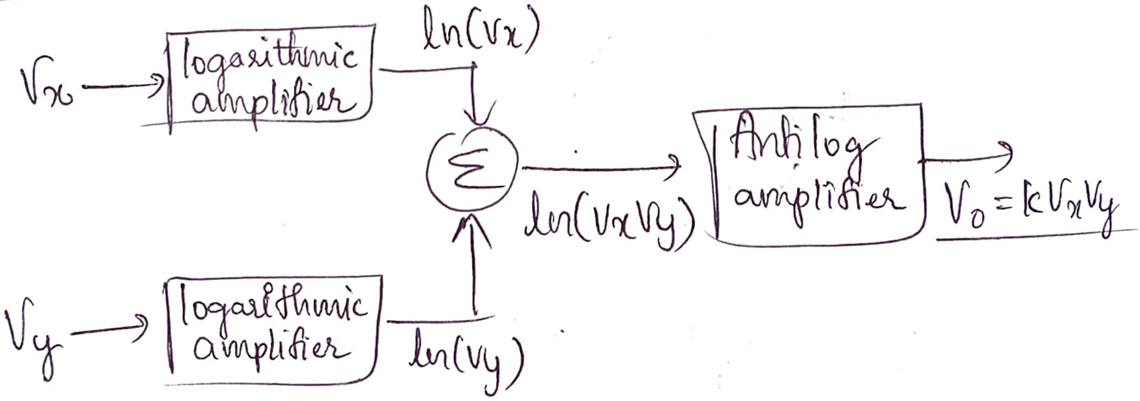
Analog Multiplier :

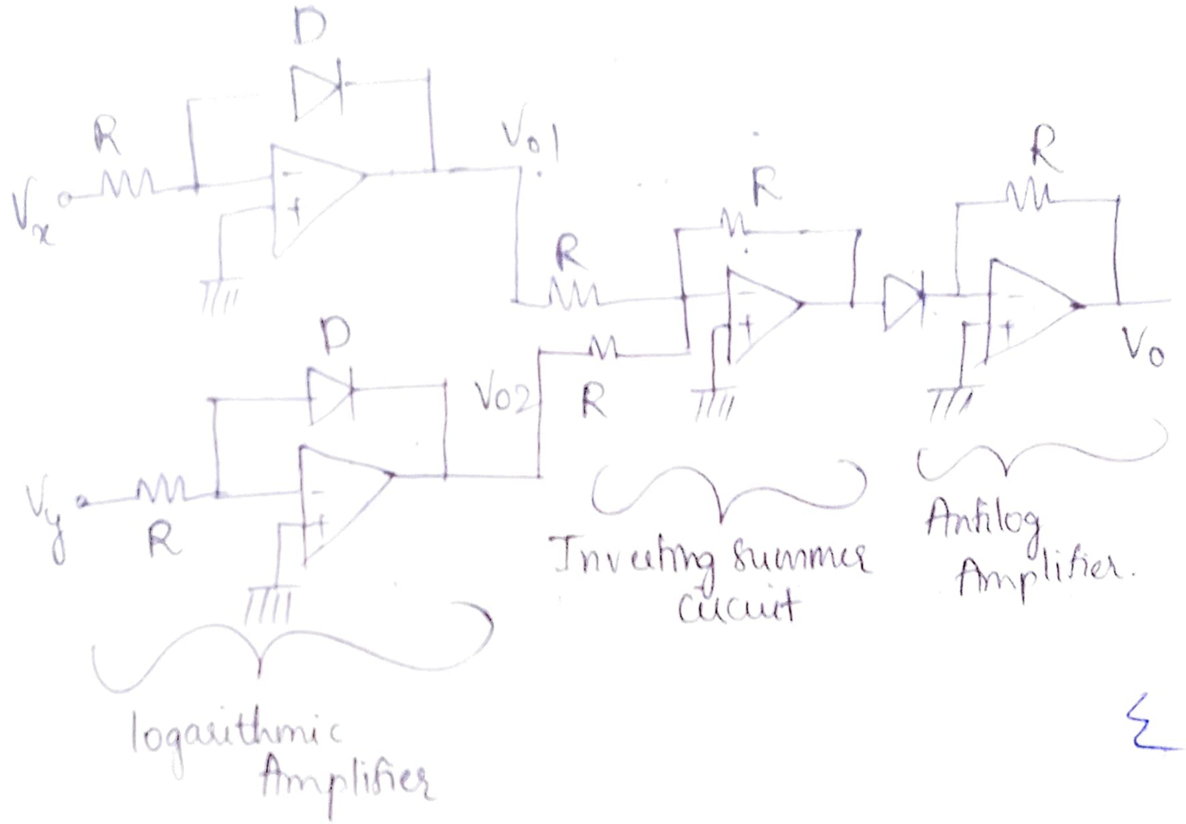


$$V_o = \frac{V_x V_y}{V_{ref}}$$

- Analog multiplier IC which works only when both inputs V_x & V_y are positive and are called First Quadrant IC's.
- In Second Quadrant Analog multiplier will produce correct output only when any of the input is '+ve'.
- In Fourth Quadrant Analog multiplier will produce correct output only when V_x & V_y are either positive or negative.

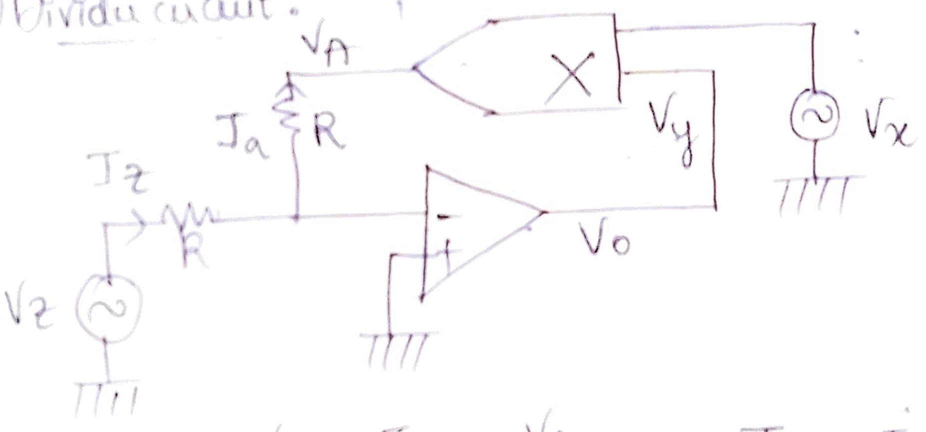
Simple Analog Multiplier :





* Applications of Analog Multiplier:

① Divider circuit:



$I_z = \frac{V_z}{R}$, $I_a = -\frac{V_A}{R}$. $\longrightarrow I_z = I_a$

$\downarrow$

$V_z = -V_A$

$$V_A = \frac{V_x V_y}{V_{ref}} = \frac{V_x V_o}{V_{ref}}$$

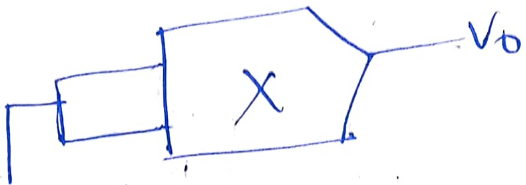
$$-V_z = \frac{V_x V_o}{V_{ref}}$$

$$\boxed{V_o = -V_{ref} \cdot \frac{V_z}{V_x}}$$

dividend

divisor

(2) Frequency doubler using Analog Multiplier:

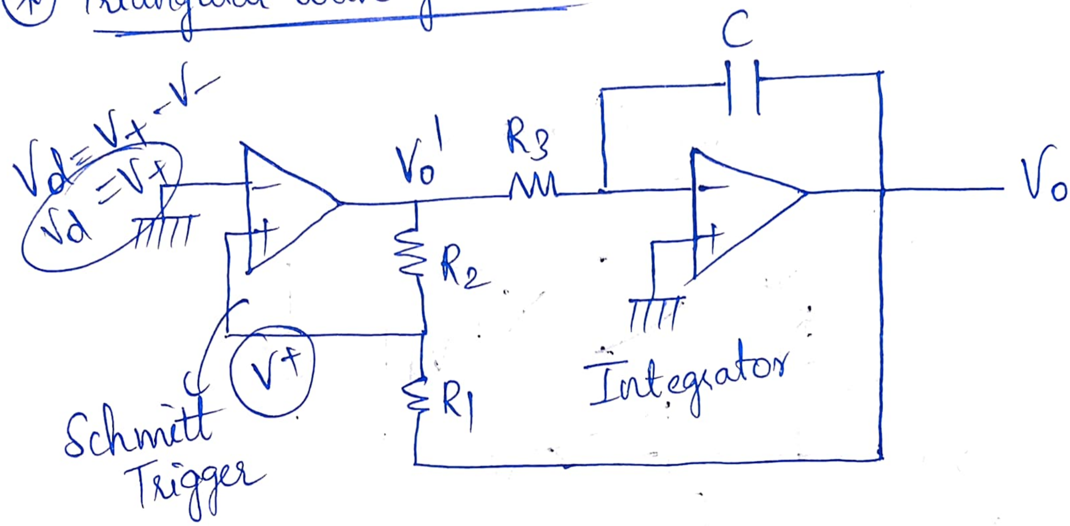


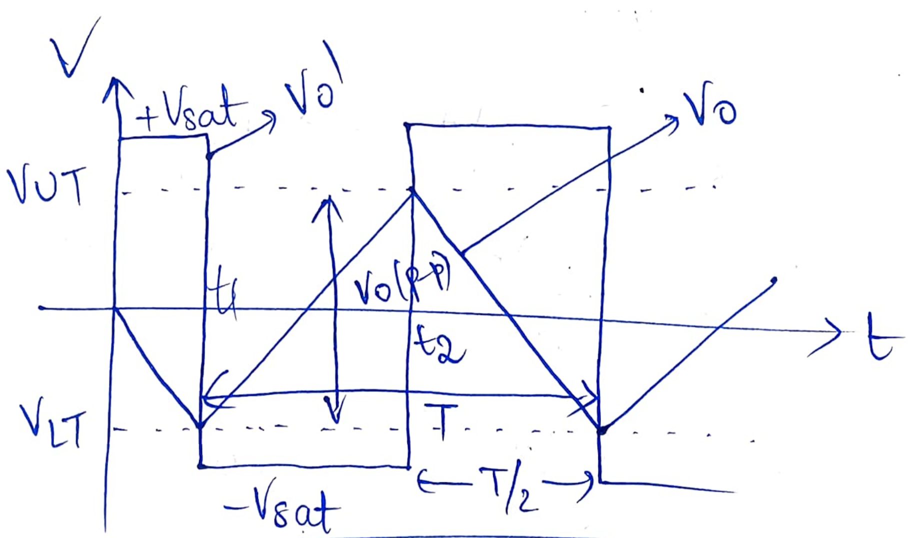
$V_o = A\sin\omega t$

$$V_o = \frac{A^2 \sin^2 \omega t}{V_{ref}} = \frac{A^2}{V_{ref}}\left(\frac{1-\cos 2\omega t}{2}\right)$$

→ Most of the cases, $V_{ref} = 10$

(*) Triangular wave generator:





$$\boxed{V_P = \frac{V_o' R_1}{R_1 + R_2} + \frac{V_o R_2}{R_1 + R_2}}$$

$$V_0 = \frac{-1}{R_3 C} \int_0^t V_{sat}\, dt$$

$$\boxed{V_0 = \frac{-V_{sat} \times t}{R_3 C}}$$

→ When $V_0' = +V_{sat}$,

$$V^+ = \frac{V_{sat} \times R_1}{R_1 + R_2} + \frac{V_0 \times R_2}{R_1 + R_2}$$

→ At instant t_1, $\boxed{V_+ = 0}$

$$0 = \frac{V_{sat} \times R_1}{R_1 + R_2} + \frac{V_0 \times R_2}{R_1 + R_2}$$

$$\boxed{V_0 = -V_{sat} \times \frac{R_1}{R_2} = V_{LT}}$$

→ When $V_0' = -V_{sat}$

$$V_+ = \frac{-V_{sat} \times R_1}{R_1 + R_2} + \frac{V_0 \times R_2}{R_1 + R_2}$$

At time instant, $t = t_2$;

$\boxed{V_+ = 0}$

$$-\frac{V_{sat} \times R_1}{R_1 + R_2} + \frac{V_0 \times R_2}{R_1 + R_2} \rightarrow \boxed{V_0 = \frac{V_{sat} \times R_1}{R_2} = V_{UT}}$$

$$V_{0(p-p)} = V_{UT} - V_{LT}$$

$$\boxed{V_{0(p-p)} = \frac{2V_{sat} \times R_1}{R_2}}$$

$$V_{0(p-p)} = \frac{-1}{R_3 C} \int_0^{T/2} -V_{sat}\, dt$$

$$\frac{2V_{sat} \times R_1}{R_2} = \frac{1}{R_3 C} V_{sat} \times \frac{T}{2} \rightarrow \boxed{T = \frac{4R_3 C R_1}{R_2}}$$

Q: Design a triangular wave generator using OPAMP, with $f = 1kHz$ & $V_{O(p-p)} = 2V$.

Sol:- $V_{O(p-p)} = \frac{2 V_{sat} \times R_1}{R_2}$

if $V_{cc} = \pm 15V$ then assume $V_{sat} \cong 14V$

$\cancel{2} = \frac{\cancel{2} V_{sat} \times R_1}{R_2}$

$\boxed{R_2 = 14 R_1}$

if $R_1 = 10k\Omega$ then $R_2 = 140k\Omega$

$f = \frac{R_2}{4 R_3 C R_1}$

$1 \times 10^3 = \frac{14\cancel{0} \times 10^{\cancel{3}}}{4 \times R_3 \times C \times 1\cancel{0} \times \cancel{10^3}}$

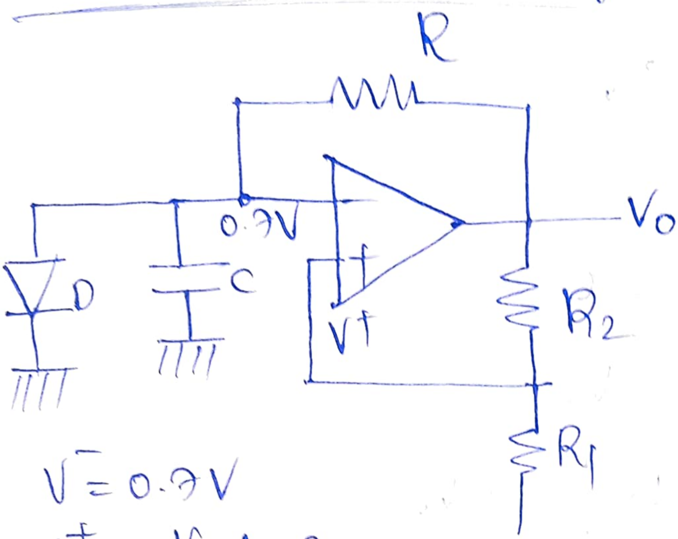
$R_3 C = 3.5 \times 10^{-3}$

$\rightarrow$ Assume $C = 1\mu F$

$R_3 \times 10^{-6} = 3.5 \times 10^{-3}$

$\boxed{R_3 = 3.5 \times 10^3 \Omega}$

⊛ Monostable Vibrator using OPAMP:



if $V_o = +V_{sat}$
then it is stable.

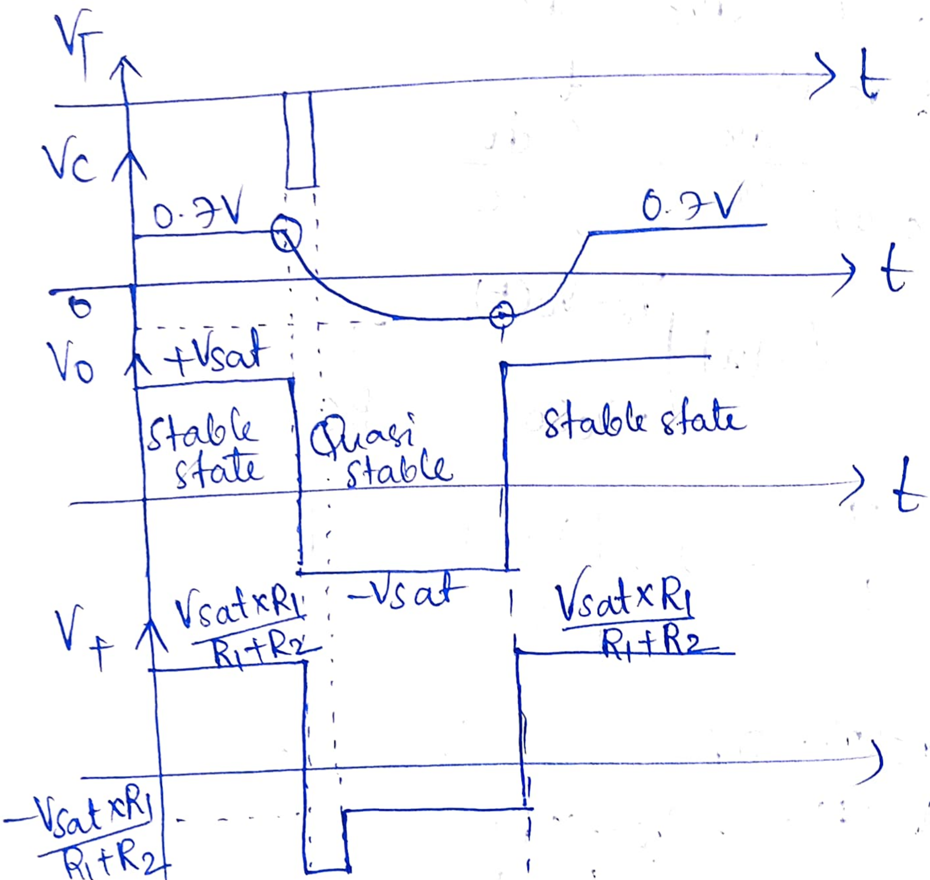
$V^- = 0.7V$

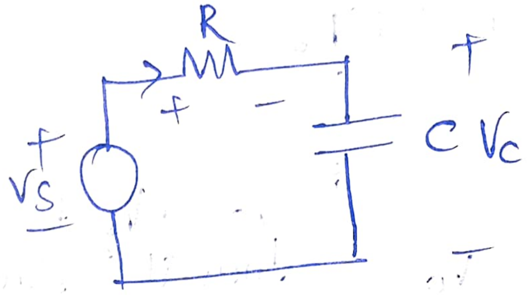
$V^+ = \dfrac{V_{sat} \times R_1}{R_2}$ (if $V_o = +V_{sat}$)

$V_T = 0V$

$V_d = V^+ - V^-$

$V_d = V^+ - 0.7$





$$V_S - iR - V_c = 0$$

$$V_S = iR + V_c$$

$$V_S = RC\frac{dV_c}{dt} + V_c$$

$$\int_{V_c(0)}^{V_c(t)} \frac{dV_c}{V_S - V_c} = \int_0^t \frac{dt}{RC}$$

$$V_S - V_c = x, \quad dV_c = -dx$$

$$\int_{-V_c(0)}^{V_S - V_c(t)} \frac{dx}{x} = \int_0^t \frac{dt}{RC}$$

$$\ln|x| \Big|_{-V_c(0)}^{V_S - V_c(t)} = \frac{t}{RC}$$

$$\frac{t}{Rc} = \ln\left|\frac{V_S - V_c(0)}{V_S - V_c(t)}\right|$$

$V_c(0) = 0V$ $\qquad V_S = -V_{sat}$

$$V_c(t) = -\frac{V_{sat} \times R_1}{R_2 + R_1}$$

$$\boxed{T = RC\ln\left(1 + \frac{R_1}{R_2}\right)}$$

3
4
5
6
7
9

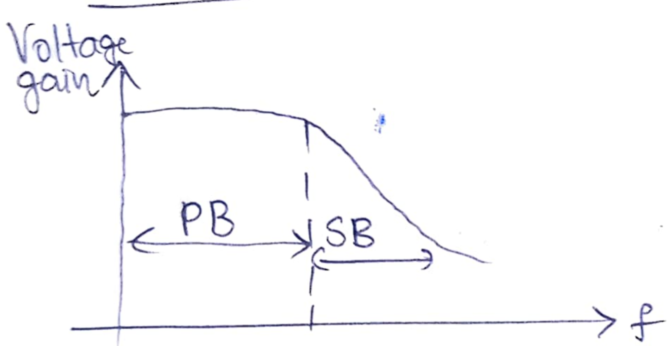
ACTIVE FILTERS

→ A filter is a frequency selective circuit, which allows signals of certain range of frequencies to pass through it and rejecting other frequencies.

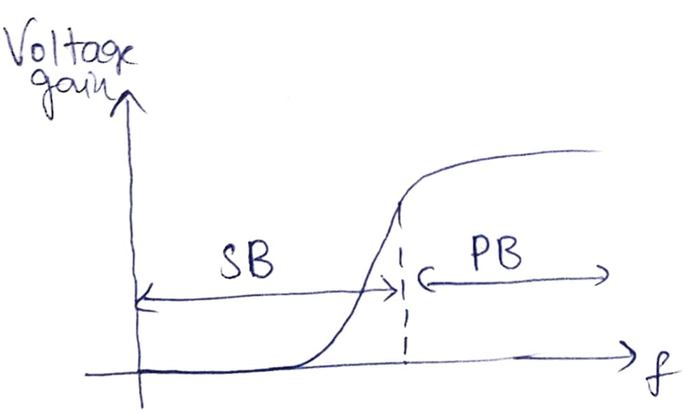
→ There are two kinds of filters
   ① Active filters – {made of passive + active elements}
   ② Passive filters – {made of only passive elements}

→ Types of Active filters
   ① Low pass filters
   ② High pass filters
   ③ Band pass filters
   ④ Band reject filter (or) Band stop filter.

→ frequency responses of active filters:

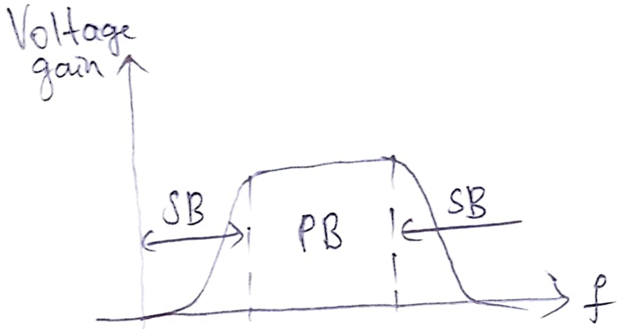


Low pass filter

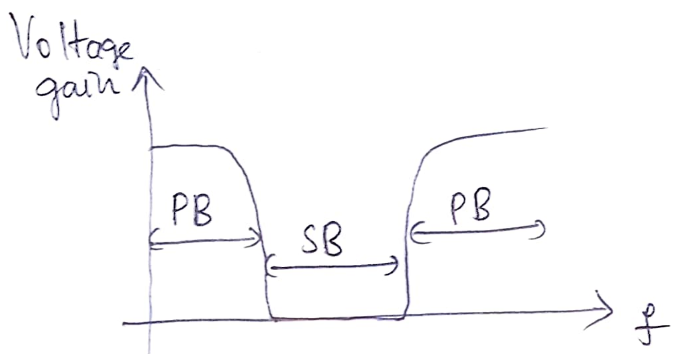


High pass filter

SB – stop Band
PB – pass Band



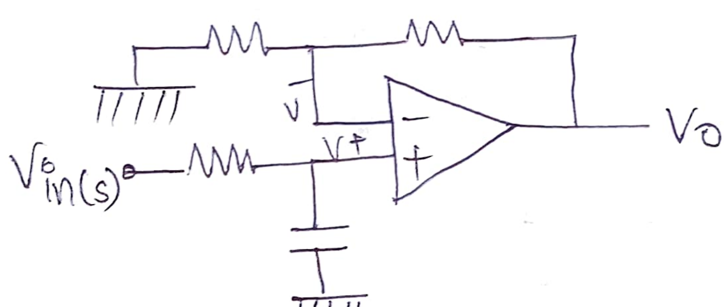
Band Pass filter



Band Reject filter

① Low pass filter :

(i) First order Low pass filter :



→ It is first order because $A_v(s) = \dfrac{1+\frac{R_f}{R_1}}{1+sRC}$

↳ s has only 1 degree.

$$V^+(s) = \frac{V_{in}(s)}{R+\frac{1}{sC}} \times \frac{1}{sC}$$

$$V^+(s) = \frac{V_{in}(s)}{1+sRC}$$

$$V_o(s) = \left(1+\frac{R_f}{R_1}\right)V^+(s)$$

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

$$A_{vf}(s) = \frac{V_o(s)}{V_{in}(s)} = \left(1+\frac{R_f}{R_1}\right) \times \frac{1}{1+sRC}$$

$s = j\omega$

$$A_{vf}(j\omega) = \left(1+\frac{R_f}{R_1}\right) \times \frac{1}{1+j\omega RC}$$

$$|A_{vf}(j\omega)| = \frac{\left(1+\frac{R_f}{R_1}\right)}{\sqrt{1+\omega^2R^2C^2}}$$

$|A_{vf}(j\omega)|_{max}$ when $\omega = 0$

$$|A_{vf}(j\omega)|_{max} = 1+\frac{R_f}{R_1}$$

$$|A_{vf}(j\omega)| = \frac{|A_{vf}(j\omega)|_{max}}{\sqrt{1+\omega^2R^2C^2}}$$

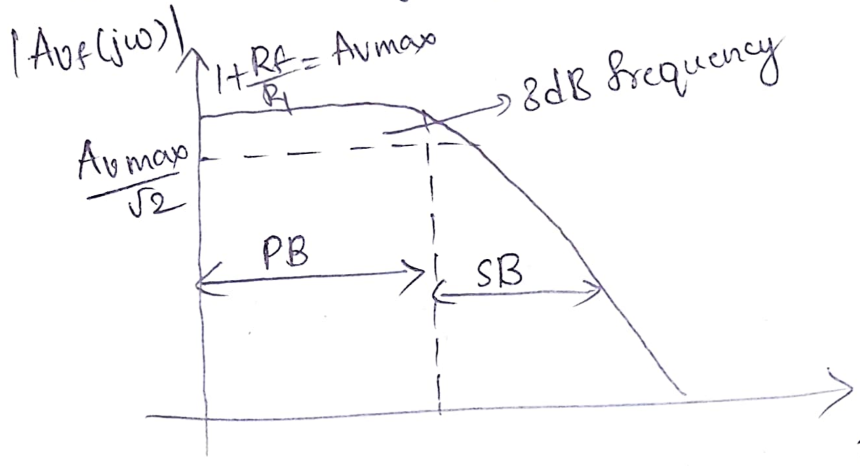
ω_0 $f_0 \rightarrow$ frequency at which gain is $\frac{1}{\sqrt{2}}$ times maximum gain.

$$\frac{\cancel{|A_{vf}|_{max}}}{\sqrt{2}} = \frac{\cancel{|A_{vf}|_{max}}}{\sqrt{1+\omega^2R^2C^2}}$$

Cutoff frequency.

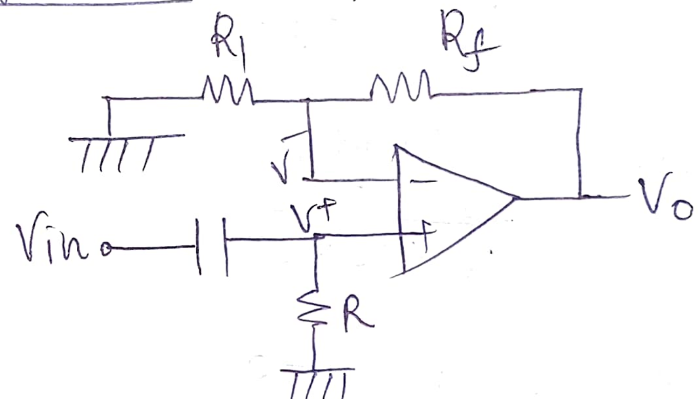
$$\omega_0 = \frac{1}{RC} \rightarrow \boxed{f_0 = \frac{1}{2\pi RC}}$$

→ When ω_0 is very large, then $|A_{vf}|_{max} = 0$



→ This is also called as Butterworth 1st order LPF.

② High pass filter:



→ This is first order HPF, also called as Butterworth 1st order HPF.

$$V^+(s) = \frac{V_{in}(s) \times R}{\frac{1}{SC} + R}$$

$$V^+(s) = \frac{V_{in}(s) \times SCR}{1+SCR}$$

For non-inverting OP-AMP,

$$V_o(s) = V^+(s)\left(1+\frac{R_f}{R_1}\right)$$

$$\boxed{V_o(s) = \frac{V_{in}(s) \times SCR}{1+SCR}\left(1+\frac{R_f}{R_1}\right)}$$

$$A_{vf}(s) = \frac{V_o(s)}{V_{in}(s)} = \frac{sRC\left(1+\frac{R_f}{R_1}\right)}{1+sRC}$$

$s = j\omega$

$$A_{vf}(j\omega) = \frac{j\omega RC\left(1+\frac{R_f}{R_1}\right)}{1+j\omega RC}$$

$$|A_{vf}(j\omega)| = \frac{\omega RC\left(1+\frac{R_f}{R_1}\right)}{\sqrt{1+\omega^2R^2C^2}}$$

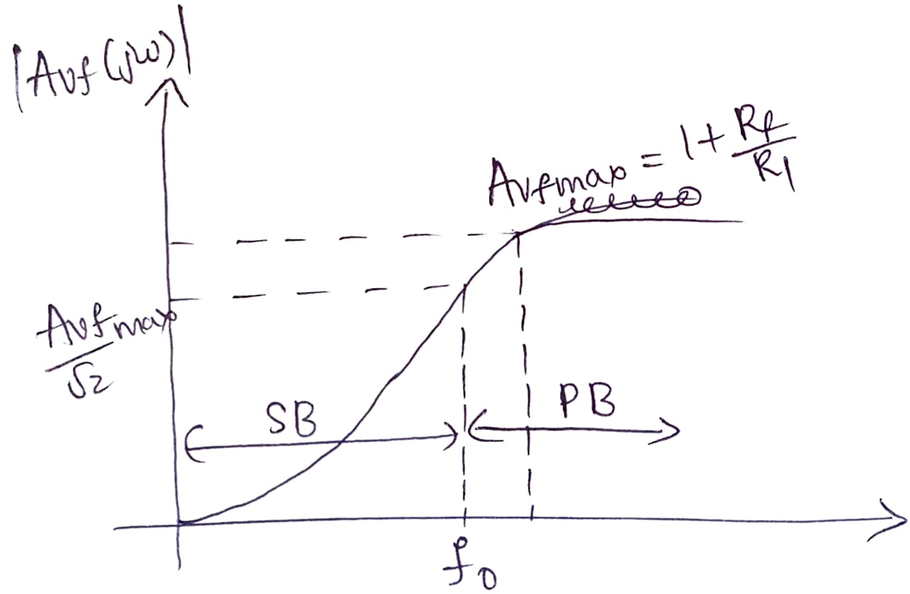
$$|A_{vf}(j\omega)| = \frac{\left(1+\frac{R_f}{R_1}\right)}{\sqrt{1+\frac{1}{\omega^2R^2C^2}}}$$

→ Maximum voltage gain occurs at $\omega = \infty$

$$|A_{vf}|_{max} = \left(1+\frac{R_f}{R_1}\right)$$

→ Minimum voltage gain occurs at $\omega = 0$

$$|A_{vf}|_{min} = 0$$



At $f = f_0$ (cut off frequency),
gain is $\frac{1}{\sqrt{2}}$ times the maximum gain.

$$|A_{vf}(2\pi f_0)| = \frac{A_{vf\,max}}{\sqrt{2}}$$

$$\frac{\cancel{A_{vf}}\,max}{\sqrt{2}} = \frac{\cancel{A_{vf}\,max}}{\sqrt{1+\frac{1}{\omega_0^2 R^2 C^2}}}$$

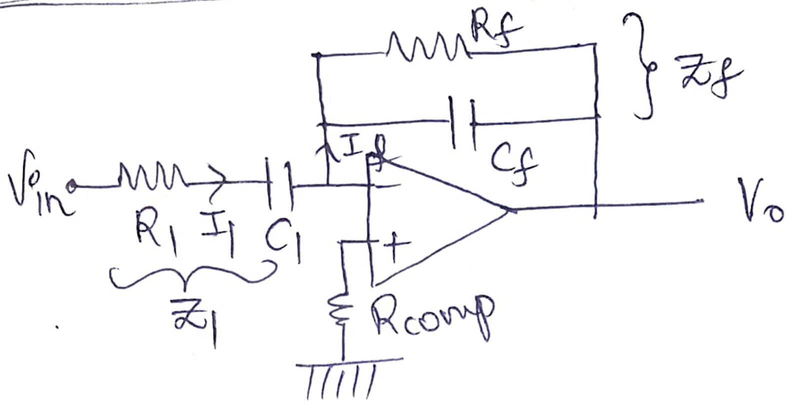
$$\frac{1}{\omega^2 R^2 C^2} = 2-1$$

$$\omega^2 R^2 C^2 = 1$$

$$\boxed{\omega_0 = \frac{1}{RC}}$$

$$\boxed{f_0 = \frac{1}{2\pi RC}}$$

- Practical Differentiator using OPAMP:



$$Z_1(S) = R_1 + \frac{1}{SC_1} = \frac{SC_1R_1 + 1}{SC_1}$$

$$Z_f(S) = R_f \parallel C_f = \frac{R_f \times \frac{1}{SC_f}}{R_f + \frac{1}{SC_f}} = \frac{R_f}{1 + SC_fR_f}$$

$$I_1(S) = \frac{V_{in}(S) - 0}{Z_1(S)} \qquad I_2(S) = \frac{0 - V_o(S)}{Z_2(S)}$$

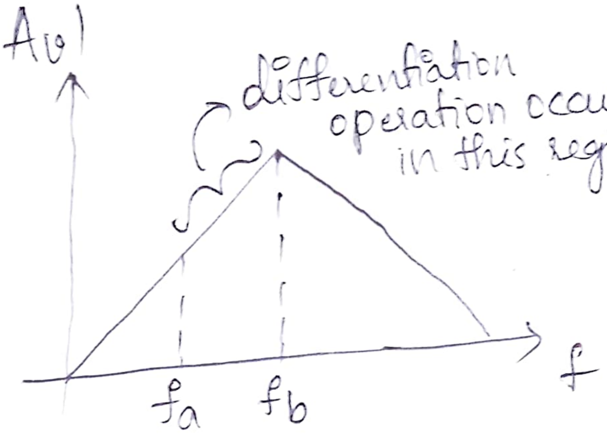
$$I_1(S) = I_2(S) \quad (\text{Virtual ground})$$

$$\frac{V_{in}(S)}{Z_1(S)} = \frac{-V_o(S)}{Z_2(S)}$$

$$\frac{V_{in}(S)}{\frac{1+SC_1R_1}{SC_1}} = \frac{-V_o(S)}{\frac{R_f}{1+SC_fR_f}}$$

$$\frac{V_o(S)}{V_{in}(S)} = \frac{-R_f}{(1+SC_fR_f)} \times \frac{SC_1}{(1+SC_1R_1)}$$

$$\boxed{|A_v(S)| = \frac{SR_fC_1}{(1+SC_fR_f)(1+SR_1C_1)}}$$



$f_a \rightarrow$ frequency at which gain = 1.

$$\left(f_a = \frac{1}{2\pi R_f C_1} \qquad f_b = \frac{1}{2\pi R_1 C_1} \right)$$

For proper differentiation,

If $R_f C_1 >> R_f C_f$

$R_f C_1 >> R_1 C_1$ then

$$A_v(s) = -sR_f C_1$$

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

$$V_o(s) = -sV_{in}(s) R_f C_1$$

$$\boxed{V_o(t) = -R_f C_1 \frac{d}{dt} V_{in}(t)}$$

If $R_1 C_1 = R_f C_f$

$$|A_v(s)| = \frac{sR_f C_1}{(1+sC_1R_1)^2}$$

$$|A_v(s)| = \frac{j\omega R_f C_1}{(1+j\omega C_1 R_1)^2}$$

$$|A_v(s)| = \frac{f/f_a}{1+(f/f_b)^2}$$

Q: Design a differentiator using op-amp to differentiate an input signal with $f_{\cancel{max}\,min} = 200\,Hz$. Draw output waveform for sine wave with 1V peak at 200 Hz.

Sol:- $f_{\cancel{max}\,min} = f_a = 200\,Hz$

$$\frac{1}{2\pi R_f C_1} = 200$$

$\rightarrow$ (let $C_1 = 0.1\,\mu F$)

$$R_f = \frac{1}{2\pi \times 0.1 \times 10^{-6} \times 200} = \underline{7.962\,k\Omega}$$

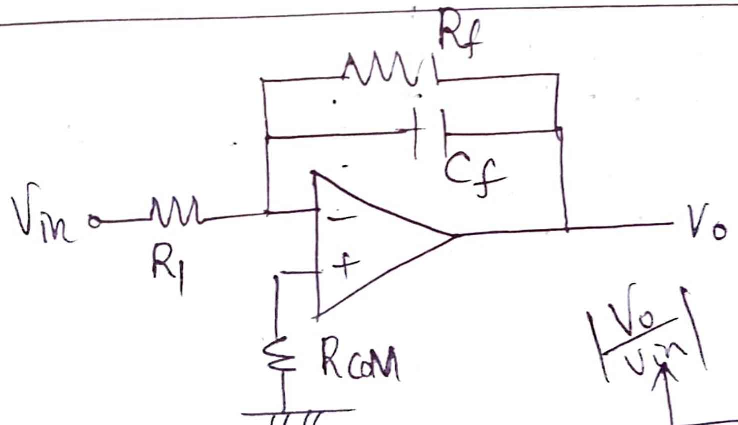
$$f_b = 10 f_a$$

$$\frac{1}{2\pi R_1 C_1} = 10 \times 200$$

$$R_1 = \frac{1}{2\pi \times 2000 \times 0.1 \times 10^{-6}} = \underline{0.796\,k\Omega}$$

$$R_1 C_1 = R_f C_f$$

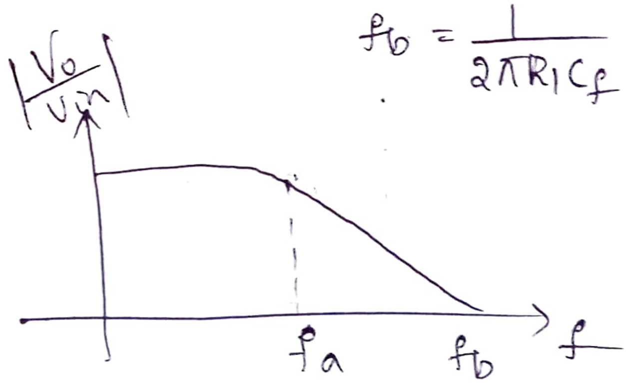
$$C_f = \frac{R_1 C_1}{R_f} = \underline{0.01\,\mu F}$$



$$f_b = 10 f_a$$

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

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



Q: Design a practical integrator with lower limit of frequency is 160 Hz.

Sol: $f_a = 160\,Hz$

$$\frac{1}{2\pi R_f C_f} = 160 \qquad \text{Assume, } C_f = 0.01\,nF$$

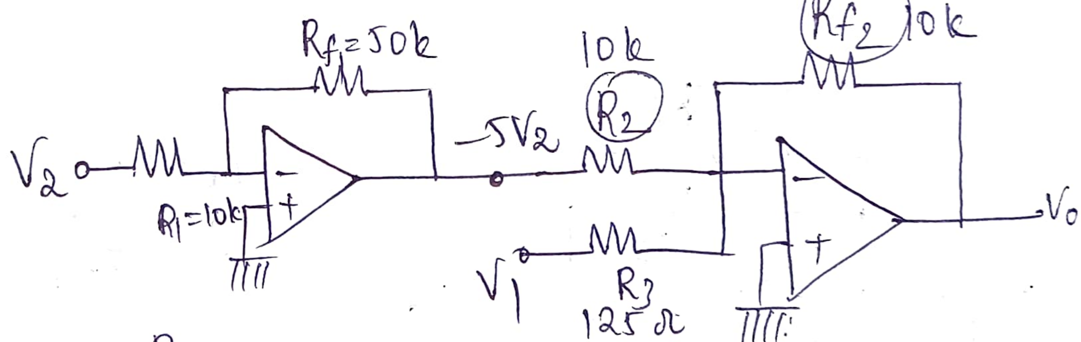
$$R_f = \frac{1}{2\pi \times 160 \times 0.01 \times 10^{-9}}$$

$f_b = 10 f_a = 1600\,Hz$

$$\frac{1}{2\pi R_1 C_f} = 1600 \rightarrow R_1 = \frac{1}{2\pi \times 1600 \times 0.01 \times 10^{-9}}$$

Q: Design a circuit using OPAMP, which gives output $V_o = 5V_2 - 8V_1$ where V_2 & V_1 are inputs.

Sol:



$$\frac{R_{f1}}{R_1} = 5$$

$R_{f1} = 50k$

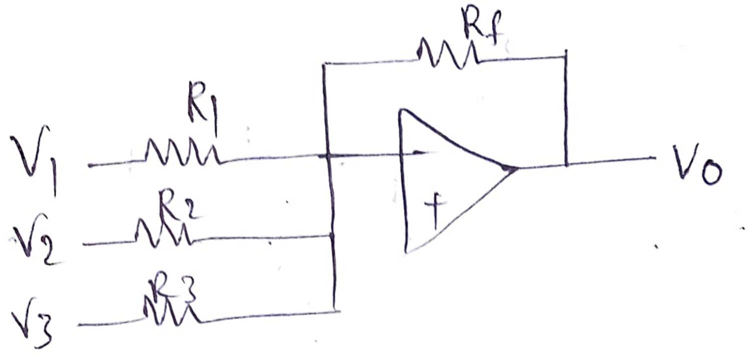
$$\frac{R_{f2}}{R_2} = 1 \rightarrow R_{f2} = R_2 = 10k$$

$$\frac{R_{f2}}{R_3} = 8 \rightarrow R_3 = \frac{10k}{8} = 125\,\Omega$$

Q: Design an OPAMP circuit which performs following operation

$$V_0 = -V_1 - 2V_2 - 3V_3$$

Sol:



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

$$\frac{R_f}{R_1} = 1 \qquad \frac{R_f}{R_2} = 2 \qquad \frac{R_f}{R_3} = 3$$

Let $R_f = 100k$,

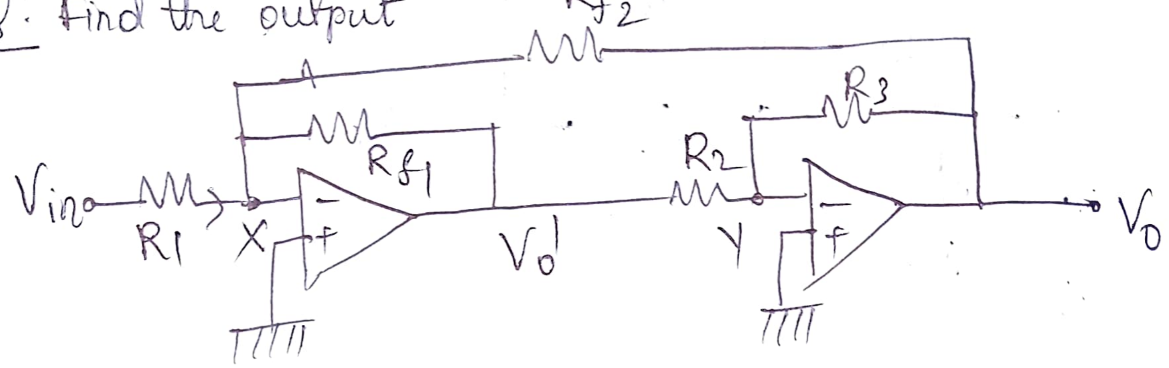
$R_1 = 100k$

$R_2 = 50k$

$R_3 = \frac{100k}{3}$

Q: Design a practical integrator ... a signal having max freq 200Hz.

Q: Find the output



Sol:-

Apply KCL at Node X,

$$\frac{V_{in}}{R_1} = \frac{-V_o'}{R_{f1}} - \frac{V_o}{R_{f2}}$$

Apply KCL at Node Y,

$$\frac{V_o'}{R_2} = \frac{-V_o}{R_3}$$

$$\boxed{V_o' = -\frac{R_2}{R_3} \times V_o}$$

$$\frac{V_{in}}{R_1} = \frac{+R_2}{R_3 R_{f1}} V_o - \frac{V_o}{R_{f2}}$$

$$= -V_o \left(\frac{-R_2 R_{f2} + R_3 R_{f1}}{R_3 R_{f1} R_{f2}} \right)$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{-R_3 R_{f1} R_{f2}}{R_1 (-R_2 R_{f2} + R_3 R_{f1})}}$$