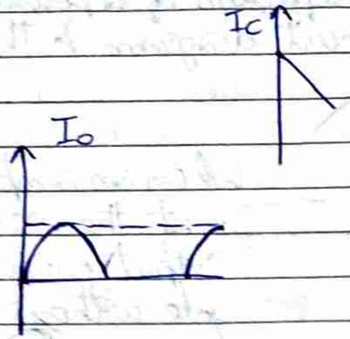


* Class Ampl

Sem-4
Analog Electronics
II

I

* Class Amply

(iv) **Class C Power Amplifier:**
below the cut off point then
lost and o/p current flows only

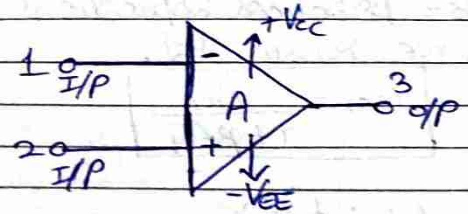
13.1.20

Unit-I

Analog Electronics-II — Books: Shail B. Jain

Linear Integrated Circuits → D Roy Chaudhary

Operational Amplifier (Op-amp):



→ Terminal 1 & 2 are called input terminals where terminal 1 is called inverting input terminal & terminal 2 is called non-inverting input terminal.

→ Terminal 3 is the output terminal.

Characteristics of Ideal Op-Amp: (2.5 marks)

1. Open loop gain should be infinite ($A_{ol} \to \infty$).
2. Input impedance should be infinite ($Z_i \to \infty$).
3. Output impedance should be zero ($Z_o \to 0$).
4. Bandwidth should be infinite.
5. CMRR (Common Mode Rejection Ratio) should be infinite.

Explanations of all above points are on the next page.

Explanation of point ①:

For an ideal op-amp A_{OL} is infinite. It means for practical applications we must have to reduce this gain. Now we will use negative feedback for practical applications except oscillator. We know that,

$$\boxed{A_{CL} = \frac{A_{OL}}{1+\beta A_{OL}}}$$

Explanation of point ②:

There is no any current flowing through terminal 1 & terminal 2 because for an ideal op-amp Z_i is infinite which means the voltage at terminal 1 & terminal 2 are always same & this is called virtual ground or virtual short.

Virtual Short / Virtual Ground:

For an open loop configuration the output voltage can be written as,

$$\boxed{V_o = A_{OL}(V_+ - V_-)}$$

$$\Rightarrow \frac{V_o}{A_{OL}} = V_+ - V_-$$

Since $A_{OL} \to \infty$

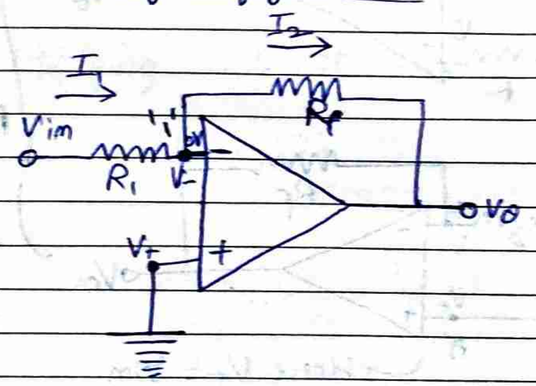
$$\Rightarrow \frac{V_o}{\infty} = V_+ - V_-$$

$$\Rightarrow \boxed{V_+ = V_-}$$

i.e. Voltage at +ve & -ve input terminal are ~~same~~ same which means they are short which is known as virtual short or virtual ground.

14.1.20 # Configuration of a Op-Amp:

1. Inverting Configuration:



Applying KCL at node '1' we get,

$$I_1 = I_2$$

$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_o}{R_f}$$

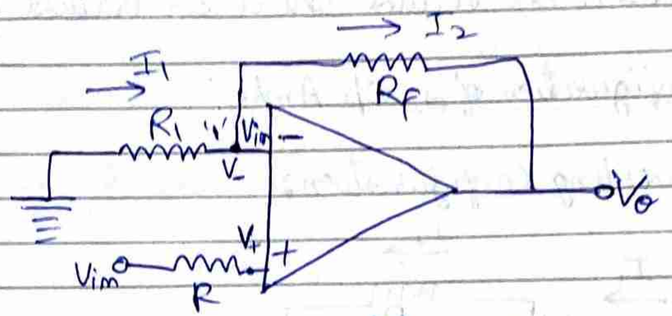
$$\Rightarrow \frac{V_{in}}{R_1} = -\frac{V_o}{R_f} \Rightarrow \boxed{V_o = -\frac{R_f}{R_1} V_{in}}$$

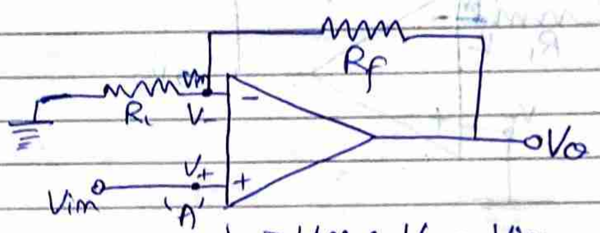
$$\text{or } \boxed{\frac{V_o}{V_{in}} = -\frac{R_f}{R_1}} \to \text{gain}$$

→ The -ve sign in output expression represents 180° phase shift b/w input & output.

→ $\frac{R_f}{R_1}$ is called feedback gain.

2. Non-Inverting Configuration:





→ Here $V_+ = V_{in}$

Both are same because in an ideal op-amp current is 0

KCL at node 1 we get,

$$I_1 = I_2$$

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

$$\Rightarrow -V_{in} R_f = (V_{in} - V_o) R_1$$

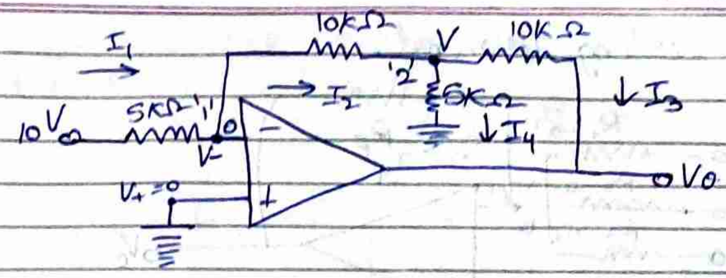
$$\Rightarrow V_o R_1 = V_{in}(R_1 + R_f)$$

$$\Rightarrow \boxed{V_o = \frac{V_{in}(R_1 + R_f)}{R_1}}$$

or $\boxed{V_o = V_{in}\left[1 + \frac{R_f}{R_1}\right]}$

$\Rightarrow \boxed{\frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}}$ → gain

Q1.



Ans. Applying KVL at node '1',

$$I_1 = I_2$$

$$\frac{10 - 0}{5k\Omega} = \frac{0 - V}{10k\Omega}$$

$$V = -\frac{10}{5k\Omega} \times 10k\Omega$$

$$V = -20V$$

Applying KVL at node '2',

$$I_2 = I_3 + I_4$$

$$\frac{20}{10k\Omega} = \frac{V - V_o}{10k\Omega} + \frac{V - 0}{5k\Omega}$$

$$\frac{20}{10k\Omega} = \frac{-20 - V_o}{10k\Omega} + \frac{(-20)}{5k\Omega}$$

$$\Rightarrow 20 = -20 - V_o - 40$$

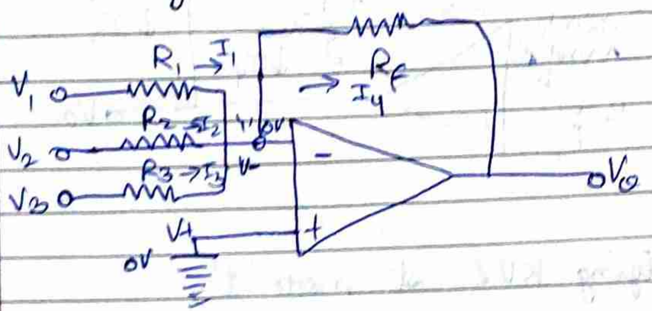
$$\Rightarrow V_o = -60 - 20$$

$$\boxed{V_o = -80V}$$

Adder:

1. Inverting Adder:

In inverting adder we apply input at the inverting terminal.



Applying KCL at node '1' we get,

$$I_1 + I_2 + I_3 = I_4$$

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

$$\Rightarrow \boxed{V_o = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}V_3}$$

If $R_f = R_1 = R_2 = R_3 = R$

then, $\boxed{V_o = -[V_1 + V_2 + V_3]}$

Q2. Design an inverting adder circuit with output $-10V_1 + 5V_2 + 20V_3$.

Ans2. We know $V_o = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}V_3$ (Inverting Adder)

& Given $V_o = -10V_1 + 5V_2 + 20V_3$

On comparing above 2 eq^n we get,

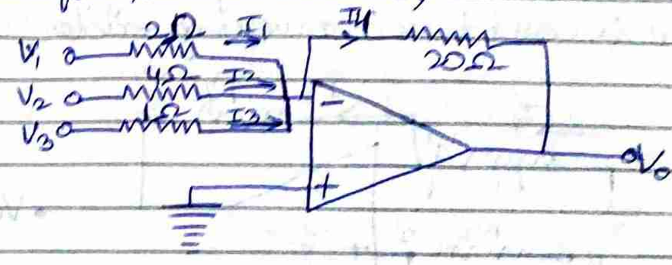
$$-\frac{R_f}{R_1} = -10, \quad -\frac{R_f}{R_2} = 5, \quad -\frac{R_f}{R_3} = 20$$

If we take $R_f = 20\Omega$

then, $R_1 = 2\Omega$, $R_2 = -4\Omega$ & $R_3 = -1\Omega$

or $V_o = -10V_1 + 5V_2 + 20V_3$

therefore, circuit will be,



16/1/20

Q3. Design an op-amp inverting adder circuit having $V_o = -5V_1 - 4V_2 - 10V_3$.

Ans3. We know, $V_o = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}V_3$

& Given $V_o = -5V_1 - 4V_2 - 10V_3$

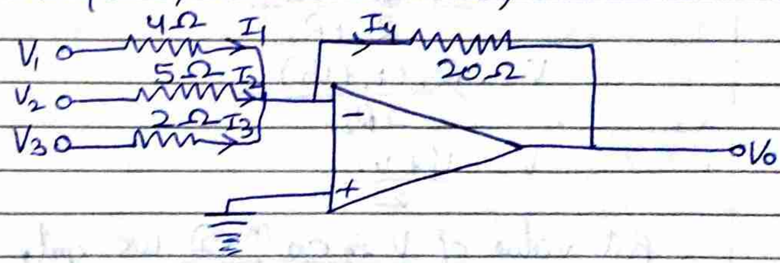
On comparing above 2 eq^n we get,

$$-\frac{R_f}{R_1} = -5, \quad -\frac{R_f}{R_2} = -4, \quad -\frac{R_f}{R_3} = -10$$

If we take $R_f = 20\Omega$

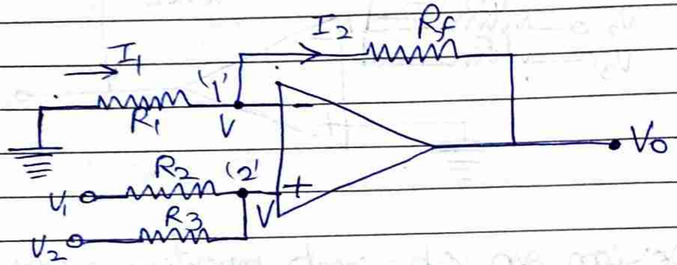
then, $R_1 = 4\Omega$, $R_2 = 5\Omega$ & $R_3 = 2\Omega$

therefore, circuit will be,



2. Non-Inverting Adder:

When more than one input is applied at non-inverting terminal & the inverting terminal is grounded w.r.t non-inverting terminal than it is called non-inverting adder.



$$V = \frac{V_1 R_3 + V_2 R_2}{R_2 + R_3} \rightarrow (1)$$

Applying KCL at node 1 we get,

$$I_1 = I_2$$

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

$$\boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right) V} \rightarrow (2)$$

~~or V_0~~ Let $R_2 = R_3$ then we have,

$$V = \frac{V_1 R_2 + V_2 R_2}{R_2 + R_2}$$

$$V = \frac{\cancel{R_2}(V_1 + V_2)}{2\cancel{R_2}}$$

$$V = \frac{V_1 + V_2}{2}$$

Put value of V in eq^n (2) we get,

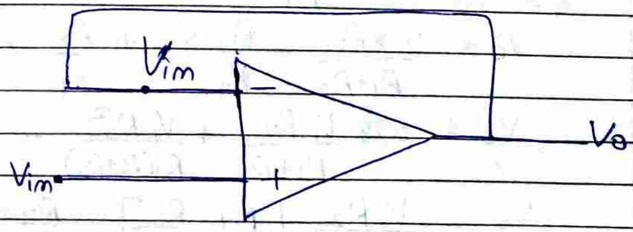
$$\boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right) \frac{V_1 + V_2}{2}}$$

Let $R_f / R_1 = 1$ then we have,

$$\boxed{V_0 = V_1 + V_2}$$

Voltage Follower:

Voltage Follower circuit is used to match impedance between two different circuits or amplifiers.

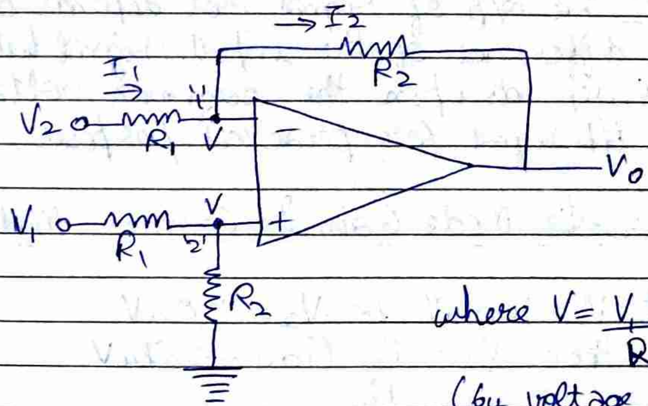


Here, $V_0 = V_{in}$

therefore, $\boxed{A_{CL} = \frac{V_0}{V_{in}} = 1}$

17.1.2020

Difference Amplifier / Subtractor Circuit / Differential Amp:



where $V = \frac{V_1 \times R_2}{R_1 + R_2}$

(by voltage divider)

Applying KCL at node '1'

$$\frac{V_2 - V}{R_1} = \frac{V - V_0}{R_2}$$

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$$\cancel{V_0 = \frac{R_2}{R_1}(V-V_2)}$$

$$V - V_0 = \frac{R_2}{R_1}(V_2 - V)$$

$$V_0 = V - \frac{R_2}{R_1}(V_2 - V)$$

$$V_0 = \frac{V_1 \times R_2}{R_1+R_2} - \frac{R_2 V_2}{R_1} + \frac{R_2}{R_1} \times \frac{V_1 \times R_2}{R_1+R_2}$$

$$V_0 = \frac{V_1 R_2}{R_1+R_2} + \frac{V_1 R_2^2}{R_1(R_1+R_2)} - \frac{R_2 V_2}{R_1}$$

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

$$\Rightarrow \boxed{V_0 = \frac{R_2}{R_1}(V_1 - V_2)}$$

Let $R_2 = R_1$ then $\boxed{V_0 = V_1 - V_2}$

Note: The o/p of signal not depends only on the difference of the input signal but it also depends upon the common voltage of the i/p signal for practical purposes.

Differential Mode Gain & Common Mode Gain:

Let $V_1 = 100\mu V$ & $V_2 = 50\mu V$

then $V_0 = \frac{R_2}{R_1}(100 - 50)\mu V$

Let $R_2 = R_1$ then $V_0 = 50\mu V$

Now consider $V_1 = 1000\mu V$ & $V_2 = 950\mu V$

then $V_0 = 50\mu V$ $[R_2 = R_1]$

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This is true only for an ideal op-amp. However, in practical applications, there is a small response to the common mode component of the input voltages/signals.

The common mode signal is defined as the average of the input signals i.e. $V_{cm} = \frac{V_1 + V_2}{2} \rightarrow (1)$

& $V_d = V_1 - V_2 \rightarrow (2)$

From eq^n (1) & (2)

$$\boxed{V_1 = \frac{2V_{cm} + V_d}{2} \text{ or } V_{cm} + \frac{V_d}{2}} \rightarrow (3)$$

$$\& \boxed{V_2 = \frac{2V_{cm} - V_d}{2} \text{ or } V_{cm} - \frac{V_d}{2}} \rightarrow (4)$$

For the difference amplifier the circuit is symmetric but due to mismatch the gain of the amplifier w.r.t +ve terminal is slightly different in magnitude to that of -ve terminal. So, even with the same voltage applied to both the inputs the output is not 0 & it can be expressed as $\boxed{V_{out} = A_1 V_1 + A_2 V_2} \rightarrow (5)$

where A_1 = Gain when input 1 is applied (+ve)

& A_2 = Gain when input 2 is applied (-ve)

Now putting the value of V_1 & V_2 from eq^n (3) & (4) into (5) we get,

$$V_0 = A_1\left[V_{cm} + \frac{V_d}{2}\right] + A_2\left[V_{cm} - \frac{V_d}{2}\right]$$

$$\boxed{V_0 = V_{cm}[A_1 + A_2] + \frac{V_d}{2}[A_1 - A_2]}$$

$$\Rightarrow \boxed{V_0 = V_{cm}A_{cm} + V_d A_{DM}} \rightarrow (6)$$

$$A_{cm} = A_1 + A_2 \;,\; A_{DM} = \frac{A_1 - A_2}{2}$$

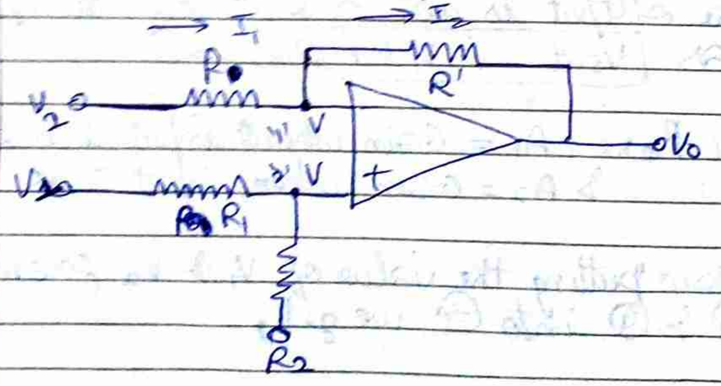
Common Mode Rejection Ratio (CMRR):

It is the ratio of differential mode to common mode gain. It is represenced by ρ.

$$\text{i.e. } \rho = \cancel{\left|\frac{A_{cm}}{A_{DM}}\right|} \left|\frac{A_{DM}}{A_{cm}}\right|$$

$$\boxed{\rho = \frac{(A_1 - A_2)}{2A_1 + A_2}} \text{ (from above eq}^n\text{)}$$

Q. IPU [2016, 2017 1st Term]



(i) Find the o/p voltage V_0.

(ii) Show that the o/p corresponding to CM voltage $V_{cm} = \frac{V_1 + V_2}{2}$ is 0 if $\frac{R'}{R} = \frac{R_2}{R_1}$. Find V_0 in that case.

(iii) Find CMRR of the amplifier if $\frac{R'}{R} \neq \frac{R_2}{R_1}$

Ans (i) Here $V = \frac{V_1 R_2}{R_1 + R_2}$

Applying KCL at node 1,

$$I_1 = I_2$$

$$\frac{V_2 - V}{R} = \frac{V - V_0}{R'}$$

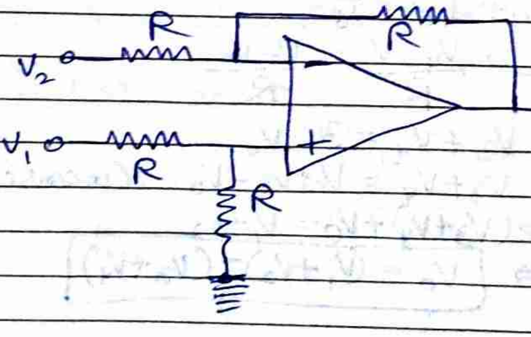
$$V - \frac{R'}{R}[V_2 - V] = V_0$$

$$V_0 = V\left[1 + \frac{R'}{R}\right] - \frac{R'}{R}V_2$$

$V_0 =$

Note: Always the o/p saturates b/w $-V_{EE} \le V_0 \le +V_{CC}$

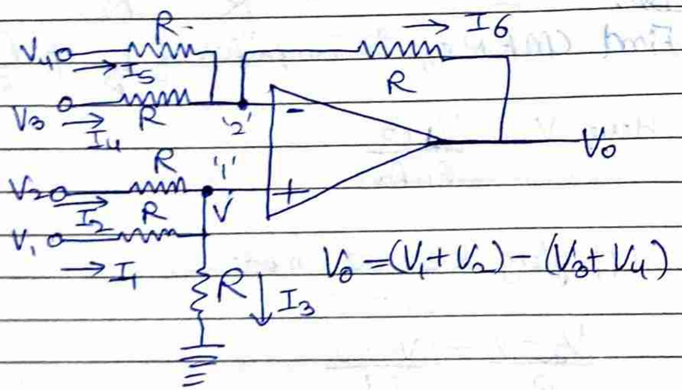
29/1/20 # Subtractor:



$V_0 = V_1 - V_2$

Adder/Subtractor Circuit:

This circuit provides addition & subtraction operation simultaneously



$V_o = (V_1+V_2) - (V_3+V_4)$

KCL at node '1':

$$I_1 + I_2 = I_3$$

$$\frac{V_1-V}{R} + \frac{V_2-V}{R} = \frac{V}{R}$$

$$\Rightarrow V_1 + V_2 = 3V$$

$$\boxed{\therefore V = \frac{V_1+V_2}{3}}$$

KCL at node '2':

$$I_4 + I_5 = I_6$$

$$\frac{V_3-V}{R} + \frac{V_4-V}{R} = \frac{V-V_o}{R}$$

$$\Rightarrow V_3 + V_4 = 3V - V_o$$

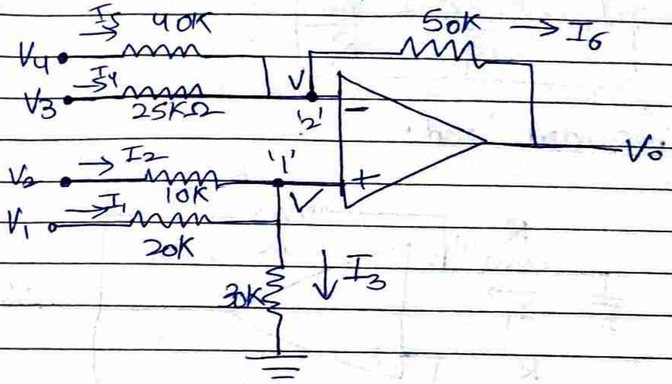
$$\Rightarrow V_3 + V_4 = V_1 + V_2 - V_o \quad \left(\text{because } V = \frac{V_1+V_2}{3}\right)$$

$$\Rightarrow (V_3+V_4) + V_o = V_1 + V_2$$

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

15 + 24
39
11

Q1. For the given figure 1, $V_4 = 2V$, $V_3 = 3V$, $V_2 = 4V$, $V_1 = 5V$, $\boxed{V_o = 6.58V}$



Apply KCL at node '1':

$$I_1 + I_2 = I_3$$

$$\frac{V_1-V}{20k\Omega} + \frac{V_2-V}{10k\Omega} = \frac{V}{30k\Omega}$$

$$\Rightarrow 3V_1 - 3V + 6V_2 - 6V = 2V$$

$$\Rightarrow 3V_1 + 6V_2 = 11V \qquad \Rightarrow V = \frac{3\times5 + 6\times4}{11}$$

$$\boxed{V = 3.54V}$$

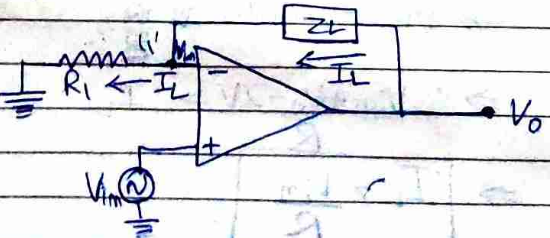
Apply KCL at node '2':

$$\frac{V_4-V}{40k\Omega} + \frac{V_3-V}{25k\Omega} = \frac{V-V_o}{50k}$$

$$\Rightarrow \boxed{V_o = 6.58V}$$

Voltage to Current Converter:

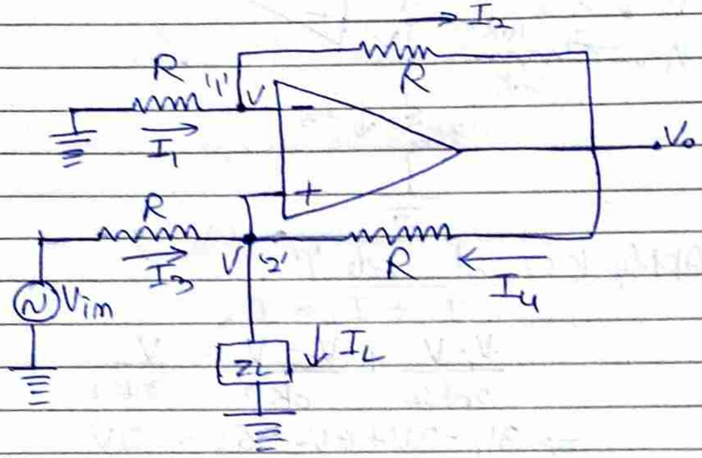
Floating Load:



~~Applying KCL at node 1:~~

$$\boxed{I_L = \frac{V_{in}-0}{R_1} = \frac{V_{in}}{R_1}}$$

*** Grounded Load:



KCL at node 1;

$I_1 = I_2$

$$\frac{0-V}{R} = \frac{V-V_o}{R} \Rightarrow \boxed{V_o = 2V} \text{ or } \boxed{V = \frac{V_o}{2}}$$

KCL at node 2;

$I_3 + I_4 = I_L$

$$\frac{V_{in}-V}{R} + \frac{V_o-V}{R} = I_L$$

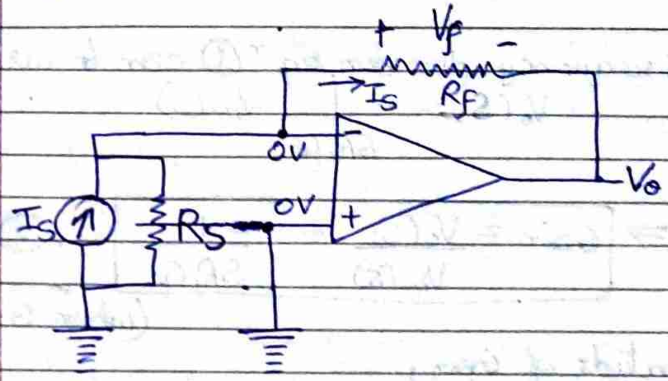
~~⇒ Vin+Vo−2V~~

$$\Rightarrow \frac{V_{in}+V_o-2V}{R} = I_L$$

$$\Rightarrow \boxed{I_L = \frac{V_{in}}{R}}$$

Current to Voltage Convertor: (Trans-Resistance Amplifier)

Photocell, Photodiode and Photo voltaic cell gives an o/p current which is proportional to an incident radiant energy or light. The current through these devices can be converted to voltage by using current to voltage convertor & hence the amount of light incident on these devices can be measured.



We know from above circuit $V_f = I_S R_f$

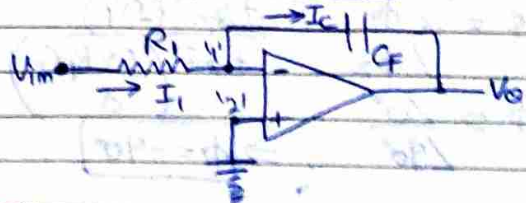
Also $V_f = -V_o \Rightarrow \boxed{V_o = -I_S R_f}$

Integrator:

(i) Basic (2.5 marks)

(ii) Practical (Derivation + numericals) (6.5 marks) [Lossy Integrator]

Basic Integrator circuit:



Apply KCL at node '1':

$$I_1 = I_C$$

$$\frac{V_{in}}{R_1} = -C_F \frac{dV_o}{dt}$$

Integrating both sides we get,

$$\int_0^t dV_o = -\int_0^t \frac{1}{R_1 C_F} V_{in}\, dt$$

$$V_o(t) = \frac{1}{R_1 C_F} \int_0^t V_{in}\, dt + V_C(t) \rightarrow (1)$$

In frequency domain eq^n (1) can be written as,

$$V_o(S) = -\frac{1}{SR_1C_F} V_{in}(S)$$

$$\Rightarrow \boxed{\text{Gain} = \frac{V_o(S)}{V_{in}(S)} = \frac{-1}{SR_1C_F}} \rightarrow (2)$$

(where $S \rightarrow j\omega$)

Magnitude of Gain,

$$|\text{Gain}| = \left| \frac{V_o(S)}{V_{in}(S)} \right|$$

$$|\text{Gain}| = \left| \frac{-1}{j\omega R_1 C_F} \right|$$

$$|\text{Gain}| = \frac{\sqrt{(-1)^2 + (0)^2}}{\sqrt{(0)^2 + (\omega R_1 C_F)^2}}$$

$$\boxed{|\text{Gain}| = \frac{1}{\omega R_1 C_F} = \frac{1}{2\pi f R_1 C_F}}$$

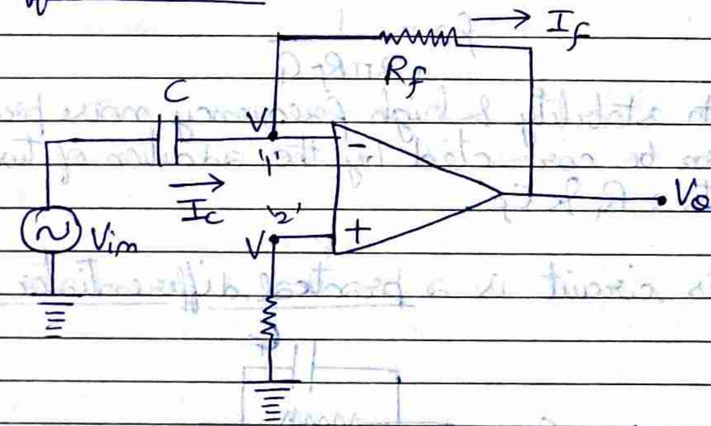
$$\text{Angle } \phi = \frac{\angle \phi_1}{\angle \phi_2} = \frac{\tan^{-1}(0/1)}{\tan^{-1}\left(\frac{\omega R_1 C_F}{0}\right)}$$

$$\phi = \frac{\angle 0°}{\angle 90°} \Rightarrow \boxed{\phi = -90°}$$

→ This circuit provides an output voltage which is proportional to the time integral of the input and R_1C_F.

→ This circuit also works as an integrator, when time constant is very large, that is R_1C_F should be large.

Differentiator:



This circuit performs the mathematic operation of differentiation. The output waveform is the derivative of the input waveform.

Applying KCL at node 1 we get,

$$I_C = I_f$$

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

As $V=0$, because gain (A) is very large,

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

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

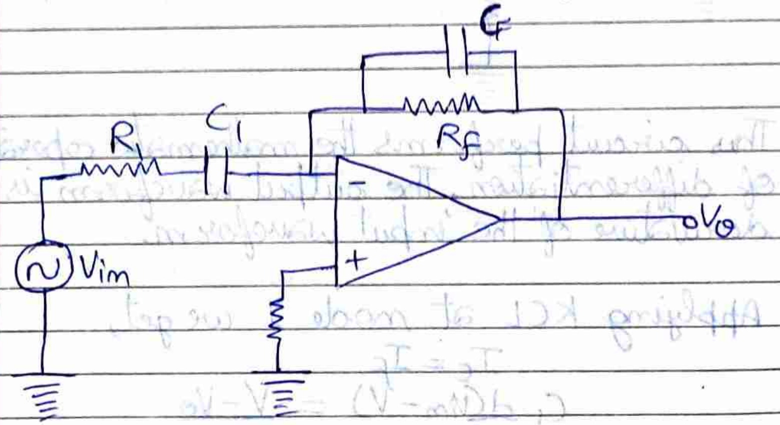
→ Since the differentiator performs the reverse of the integrator's function, a cosine wave input will produce a sine wave output or a triangular input will produce a square wave output.

→ The gain of circuit (R_F/X_{C_1}) increases with increase in frequency at a rate of 20dB/decade. This makes the circuit unstable.

$$f_a = \frac{1}{2\pi R_F C_1}$$

→ Both stability & high frequency noise problems can be corrected by the addition of two components: R_1 & C_F.

This circuit is a practical differentiator.



then, $f_b = \frac{1}{2\pi R_1 C_1}$

Thus R_1C_1 & R_FC_F helps to reduce significantly the effect of high frequency input, amplifier noise, and offsets.

→ The differentiator is most commonly used in wave shaping circuits to detect high frequency components in an input signal and also as a rate of change of detector in FM modulators.

Q1. (i) Design an op-amp differentiator that will differentiate input signal. $f_{max} = 100Hz$.
(ii) Draw the output waveform for sine wave of 1V peak of 100Hz applied to the differentiator.
(iii) Repeat part (ii) for square wave input.

Ans:- (i) To design a good differentiator, take the value of f_a, which is equal to highest frequency of the input signal.

Consider a value of C_1 (less than $1\mu F$) & find the value of R_F. Let $C_1 = 0.1\mu F$ (always)

Let $f_b = 10 f_a$.
Now calculate the value of R_1 & C_F from the relation $R_F C_F = R_1 C_1$.

We have from the basic differentiator circuit,

$$f_a = \frac{1}{2\pi R_F C_1}$$

$$\Rightarrow R_F = \frac{1}{2\pi f_a C_1}$$

$$= \frac{1}{2\times 3.14\times 100\times 0.1\times 10^{-6}}$$

$$\boxed{R_F = 15.9k\Omega}$$

Also we have $f_b = 10 f_a$

$f_b = 10 \times 100\,Hz$

$\boxed{f_b = 1000Hz \text{ or } 1kH}$

We know that, $f_b = \dfrac{1}{2\pi R_1 C_1}$

$\Rightarrow R_1 = \dfrac{1}{2\pi f_b C_1}$

$\Rightarrow R_1 = \dfrac{1}{2\times 3.14\times 1000\times 0.1\times 10^{-6}}$

$\Rightarrow \boxed{R_1 = 1.59k\Omega}$

From the condition of practical differentiator i.e. $R_f C_f = R_1 C_1$ we have,

$C_f = \dfrac{R_1 C_1}{R_f}$

$C_f = \dfrac{1.59k\Omega \times 0.1\times 10^{-6}}{15.9k\Omega}$

$\boxed{C_f = 0.01\mu F}$

(ii) Also we have, $V_o = -R_f C_1 \dfrac{dV_{in}}{dt}$

Where $V_{in} = V_o' \sin\omega t$

$= 1 \sin\omega t$ (because 1V peak)

$= \sin 2\pi f t$

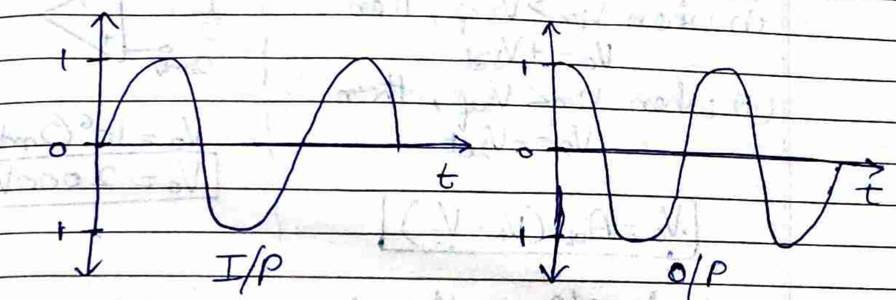
$= \sin 200\pi t$

$V_o = -R_f C_1 \dfrac{d(\sin 200\pi t)}{dt}$

$\Rightarrow V_o = -R_f C_1 (\cos 200\pi t)(200\pi)$

$\Rightarrow \boxed{V_o = -200\pi R_f C_1 \cos(200\pi t)}$

Output waveform:



Comparator:

1. In an open loop configuration, op-amp behaves as analog comparator.
2. It compares one time varying signal with the fixed reference voltage.
3. The output of comparator saturates b/w $\pm V_{sat}$.

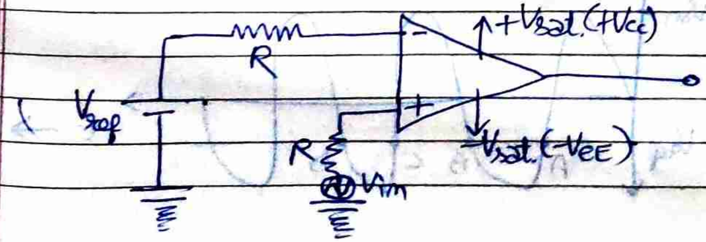
$+V_{CC} \rightarrow +V_{sat}$

$-V_{EE} \rightarrow -V_{sat}$

Types of Comparator:

1. Non-Inverting Comparator
2. Inverting Comparator

Non-Inverting Comparator:

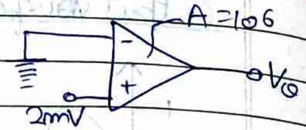


Rules:

(i) when $V_{in} > V_{ref}$, then
$V_o = +V_{sat}$

(ii) when $V_{in} < V_{ref}$, then
$V_o = -V_{sat}$

$$\boxed{V_o = A_{OL}(V_+ - V_-)}$$

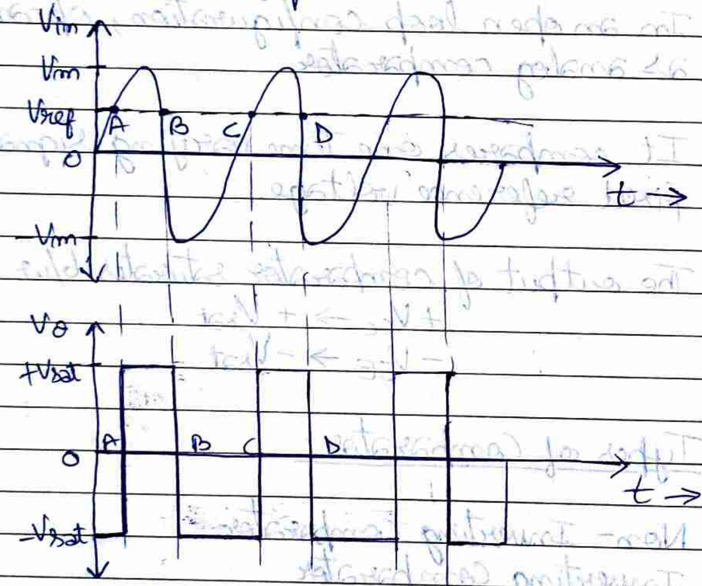


$V_o = 10^6(2mV - V_o)$

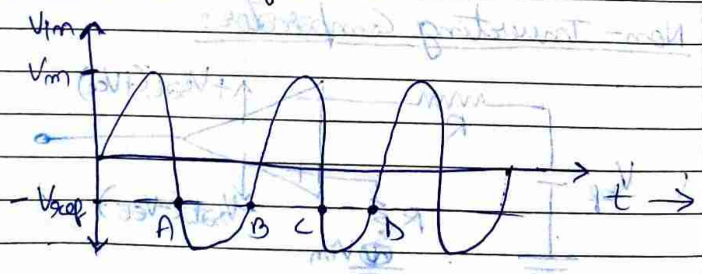
$\boxed{V_o = 2000V}$

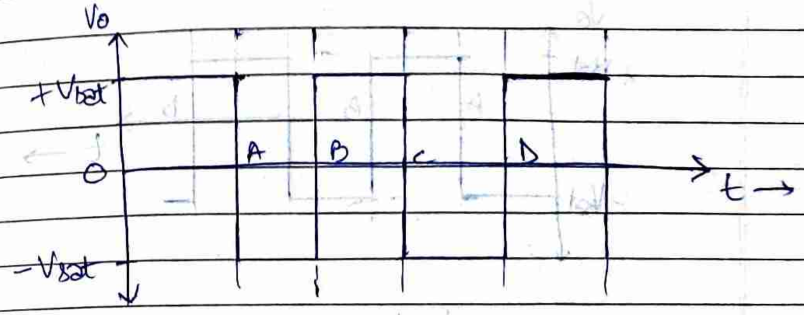
I/P & O/P Waveforms:

Case 1: When V_{ref} is +ve

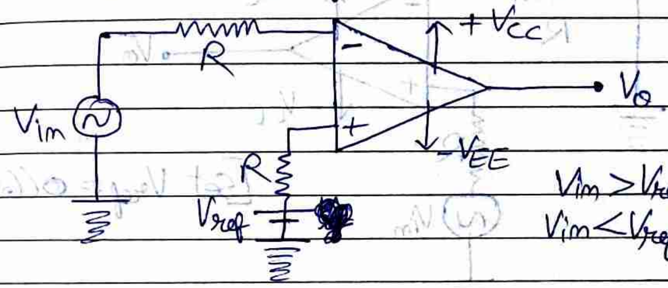


Case-2: When V_{ref} is -ve



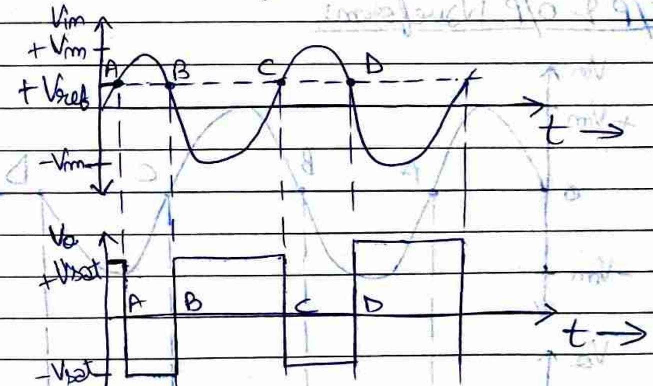


~~Voltage~~ Inverting Comparator:

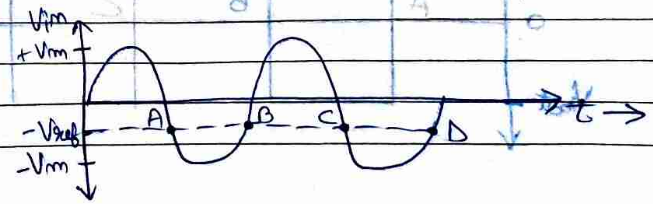


$V_{in} > V_{ref}$; $V_o = +V_{sat}$
$V_{in} < V_{ref}$; $V_o = -V_{sat}$

Case-1: When V_{ref} is +ve



Case-2: When V_{ref} is -ve



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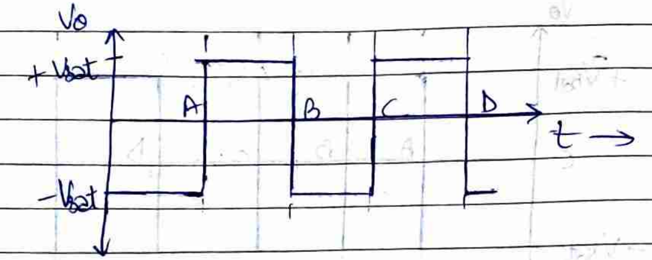
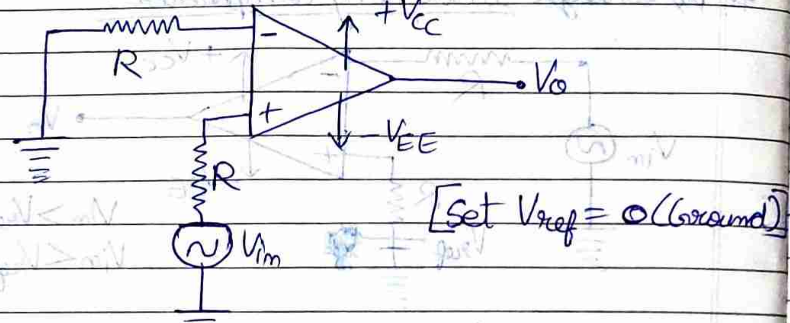
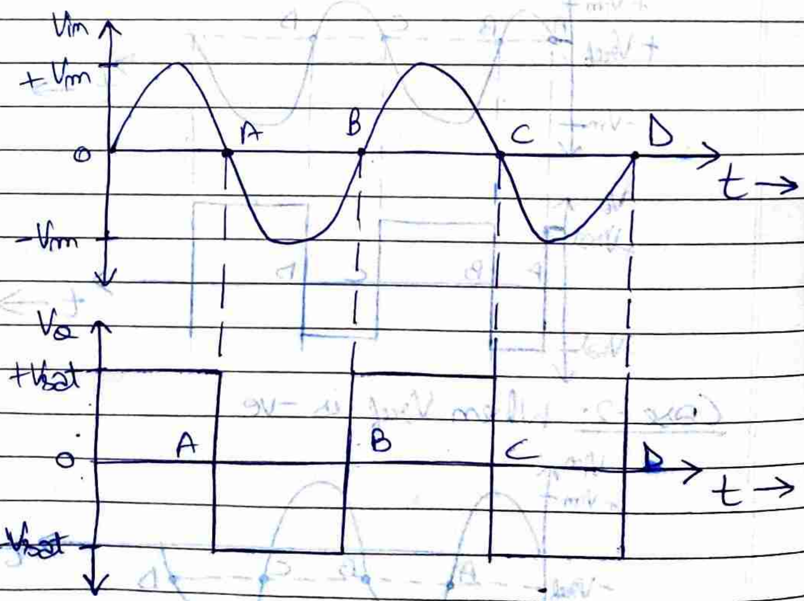


Zero-Cross Detector:



[Set $V_{ref} = 0$ (Ground)]

I/P & O/P Waveform:



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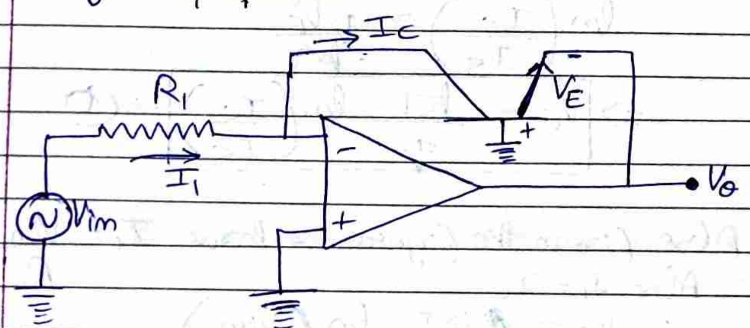
31/01/20 # Log & Antilog Amplifier:

1. To perform the funcn's such as ln(x), log(x) or sinhx.

2. Log Amplifier can perform direct dB (decibal) display on digital voltmeter & spectrum analyser.

3. Log amplifier can also be used to compress the dynamic range of a signal.

(I) Log Amplifier:



Since collector terminal is held at virtual ground & base of transistor is also grounded then, the voltage-current relationship becomes that of a diode & it is written as,

$$\boxed{I_E = I_S(e^{qV_E/kT} - 1)}$$

We know that $I_E = I_B + I_C$

Also $I_B = 0$ (grounded) $\Rightarrow I_E = I_C$

$\boxed{I_C = I_S(e^{qV_E/kT} - 1)}$ where I_S = Saturation current $= 10^{-13}$ A

k = Boltzmann's constant

T = temp. (in K)

$$\Rightarrow \frac{I_C}{I_S} = e^{qV_E/kT} - 1$$

$$\Rightarrow \frac{I_C}{I_S} + 1 = e^{qV_E/kT}$$

$$\Rightarrow \frac{I_C + I_S}{I_S} = e^{qV_E/kT}$$

$$\approx \frac{I_C}{I_S} = e^{qV_E/kT}$$ (because I_S is very small)

Taking natural log on both sides we get,

$$\ln\left(\frac{I_C}{I_S}\right) = \frac{qV_E}{kT}$$

$$\Rightarrow \boxed{V_E = \frac{kT}{q} \ln\left(\frac{I_C}{I_S}\right)} \rightarrow (1)$$

Also from the figure we have, $I_1 = \frac{V_{in}}{R_1}$

Also $I_1 = I_C$

$$\therefore V_E = \frac{kT}{q} \ln\left(\frac{V_{in}}{R_1 I_S}\right)$$

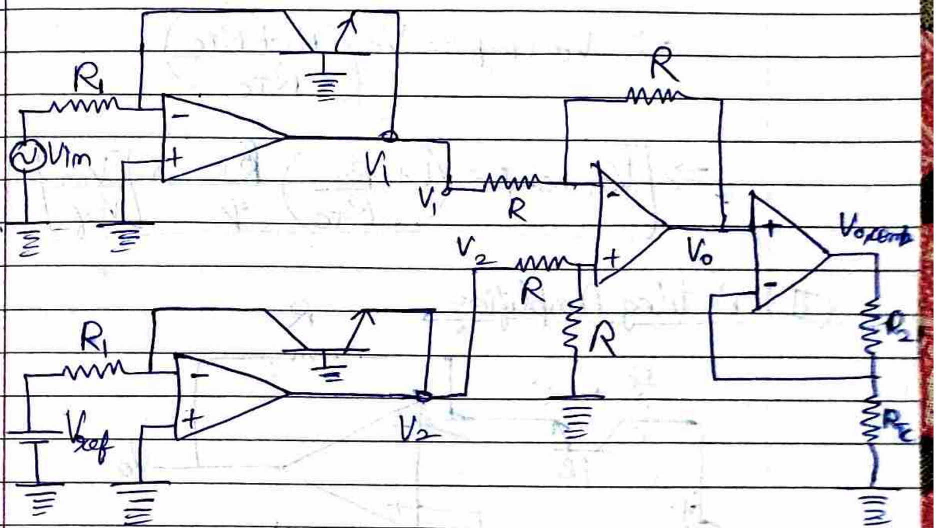
Also $V_o = -V_E \Rightarrow \boxed{V_o = -\frac{kT}{q} \ln\left(\frac{V_{in}}{R_1 I_S}\right)}$

Let $R_1 I_S = V_{ref}$ ($V_{reference}$)

$$\Rightarrow \boxed{V_o = -\frac{kT}{q} \ln\left(\frac{V_{in}}{V_{ref}}\right)}$$

→ From the above expression we have $V_{ref} = R_1 I_S$ & it depends upon the value of I_S. We know that I_S depends on temp.

Log Amplifier with Saturation Current & Temperature Compensation:



Since $V_1 = -\frac{kT}{q} \ln\left(\frac{V_{in}}{R_1 I_S}\right) \rightarrow (1)$

$$V_2 = -\frac{kT}{q} \ln\left(\frac{V_{ref}}{R_1 I_S}\right) \rightarrow (2)$$

Also Second circuit is a subtractor & hence

$$V_o = V_2 - V_1$$

$$V_o = -\frac{kT}{q} \ln\left(\frac{V_{ref}}{R_1 I_S}\right) + \frac{kT}{q} \ln\left(\frac{V_{in}}{R_1 I_S}\right)$$

$$V_o = \frac{kT}{q} \left[\ln\left(\frac{V_{in}}{R_1 I_S}\right) - \ln\left(\frac{V_{ref}}{I_S R_1}\right)\right]$$

$$\boxed{V_o = \frac{kT}{q} \left[\ln\left(\frac{V_{in}}{V_{ref}}\right)\right]} \text{ or } -\frac{kT}{q} \ln\left(\frac{V_{ref}}{V_{in}}\right) \rightarrow (3)$$

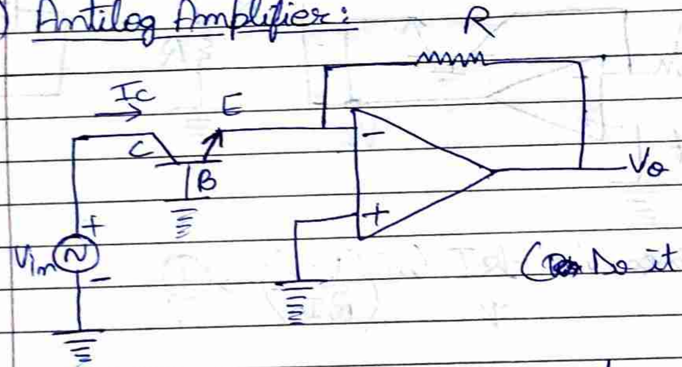
→ ~~$V_{o,comp}$~~ Also from the above ~~eqn~~ figure,

$$V_o = \frac{V_{o,comp} \times R_{TC}}{R_2 + R_{TC}}$$

$$\Rightarrow V_{o,comp} = V_o\left(\frac{R_2 + R_{TC}}{R_{TC}}\right)$$

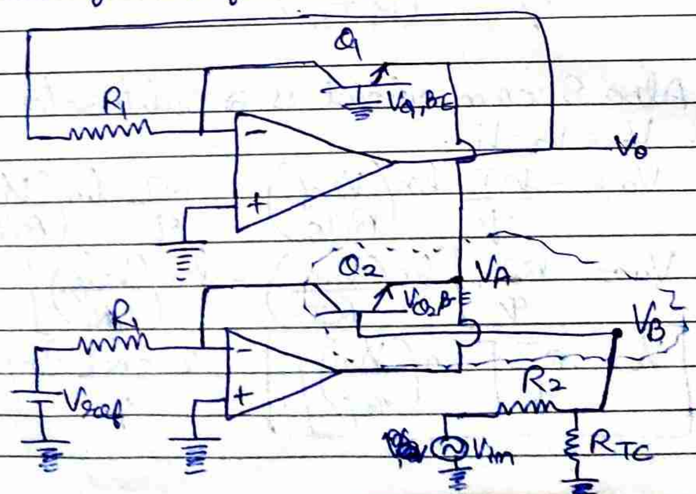
$$\Rightarrow \boxed{V_{o,comp} = \left(1 + \frac{R_2}{R_{TC}}\right)\frac{kT}{q}\ln\left[\frac{V_{in}}{V_{ref}}\right]}$$

(II) Antilog Amplifier:



(~~Do~~ Do it yourself)

Antilog Amplifier with Temperature Compensation:



$$V_{o1,B-E} = \frac{kT}{q}\ln\left(\frac{V_o}{R_1 I_S}\right) \to (1)$$

$$V_{o2,B-E} = \frac{kT}{q}\ln\left(\frac{V_{ref}}{R_1 I_S}\right) \to (2)$$

Since Emitter terminal of transistor Q_1 is connected to V_A. Hence V_A can be written as,

$$V_A = -V_{o1,B-E} = -\frac{kT}{q}\ln\left(\frac{V_o}{R_1 I_S}\right) \to (3)$$

(highlighted Part)

$$V_B \xrightarrow{V_{o2,B-E}} V_A \qquad \Rightarrow V_B - V_A = V_{o2,B-E}$$

$$\Rightarrow V_B - V_A = \frac{kT}{q}\ln\left(\frac{V_{ref}}{R_1 I_S}\right) \to (4)$$

Now putting the value of V_B, V_A & $V_{o2,BE}$, we get,

From figure $V_B = \frac{V_{in} R_{TC}}{R_2 + R_{TC}}$

$$\Rightarrow \frac{V_{in} R_{TC}}{R_2 + R_{TC}} + \frac{kT}{q}\ln\left(\frac{V_o}{R_1 I_S}\right) = \frac{kT}{q}\ln\left(\frac{V_{ref}}{R_1 I_S}\right)$$

$$\Rightarrow \frac{V_{in} R_{TC}}{R_2 + R_{TC}} = \frac{kT}{q}\ln\left(\frac{V_{ref}}{R_1 I_S}\right) - \frac{kT}{q}\ln\left(\frac{V_o}{R_1 I_S}\right)$$

To convert natural log into $\log_{10}$, multiply 0.4343 both sides we get,

$$\Rightarrow \frac{-q}{kT}(0.4343)\left(\frac{V_{in} R_{TC}}{R_2 + R_{TC}}\right) = (0.4343)\,\cancel{\log}\ln\left(\frac{V_o}{V_{ref}}\right)$$

$$= \log_{10}\left(\frac{V_o}{V_{ref}}\right)$$

Let $K' = \frac{q}{RT}(0.4343)\left(\frac{R_{TC}}{R_2+R_{TC}}\right)$

$\Rightarrow -K'V_{in} = \log_{10}\left(\frac{V_o}{V_{ref}}\right)$

$\Rightarrow \frac{V_o}{V_{ref}} = 10^{-K'V_{in}}$

$\Rightarrow \boxed{V_o = V_{ref}\,10^{-K'V_{in}}}$

Precision Rectifier Using Op-amp:

→ Precision Rectifier using op-amp circuit also known as a super diode.

→ The basic circuit of precision rectifier is

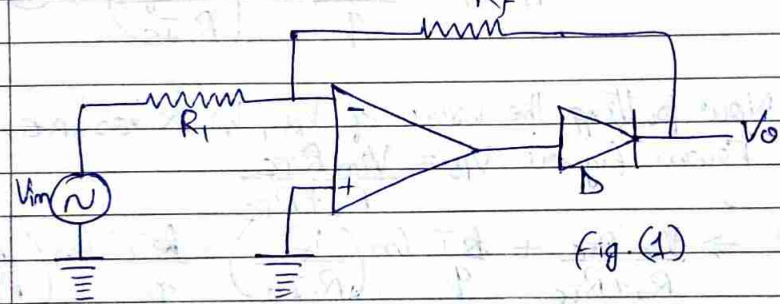


fig. (1)

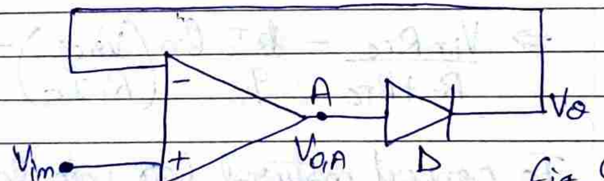
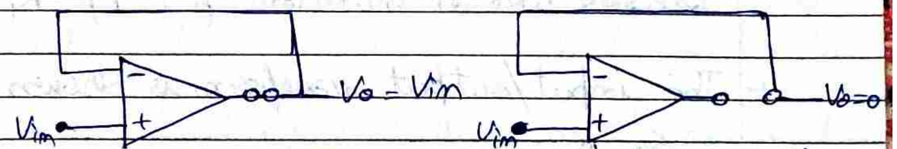


fig. (2)

Rule/Note: When $V_{in} > V_\gamma$ (voltage drop across diode) then the voltage at point A is +ve & when $V_{in} < V_\gamma$ (V_γ(Ge)=0.3, V_γ(Si)=0.7) then voltage at point A is -ve.

→ If sinusoidal input is applied to figure 2 then for +ve half cycle diode D conducts and output follows the input when diode is ideal.

→ For -ve half cycle of input diode D is reverse biased and output is zero.

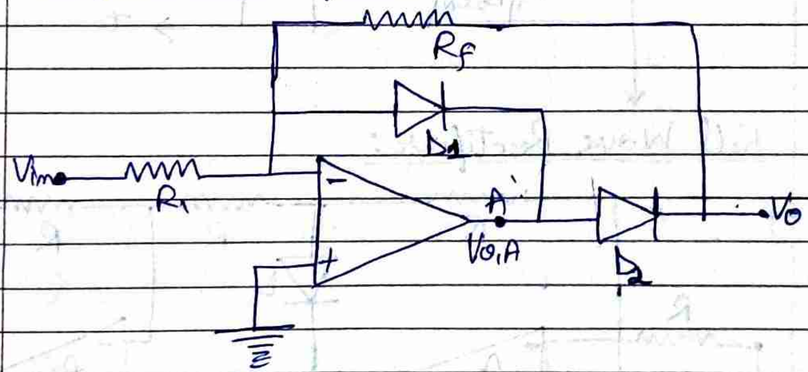


(+ve half Cycle) (-ve half cycle)

Types of Rectifiers:

(I) Half wave Rectifier
(II) Full wave Rectifier

Half Wave Rectifier:

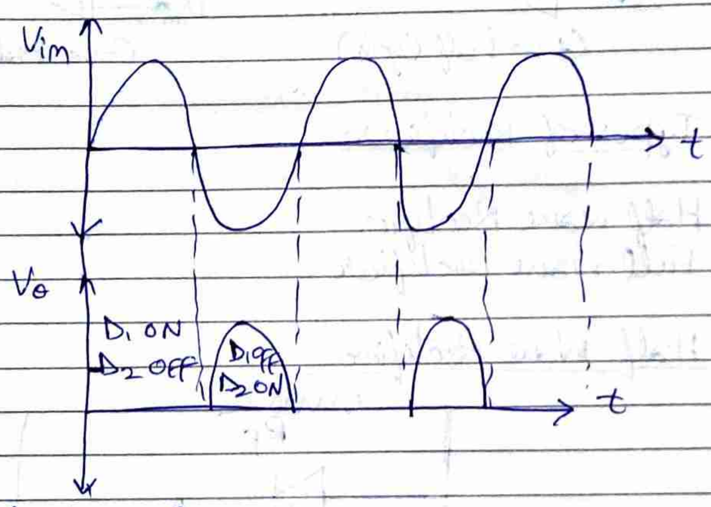


Operation (1):

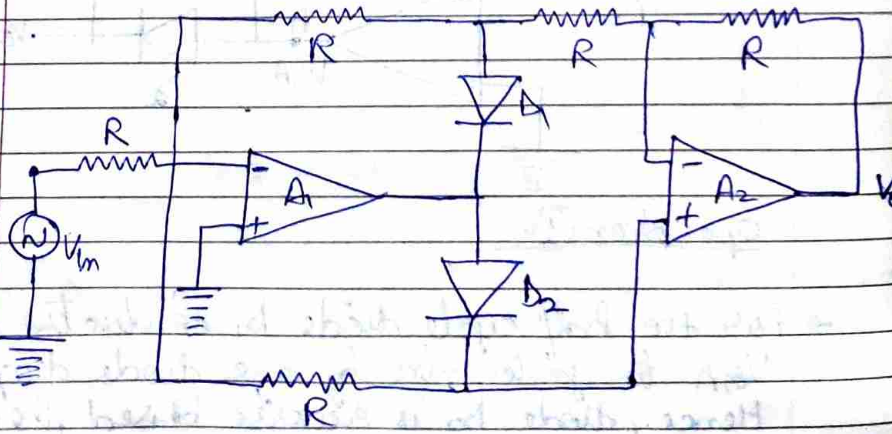
→ For +ve half cycle diode D_1 conducts causing $V_{o,A}$ to go to -ve by one diode drop (0.6V). Hence, diode D_2 is reverse biased, then the output will be 0.

→ For −ve half cycle of the input diode D_2 conducts and D_1 will be off. The −ve input V_{in} forces the op-amp output $V_{o,A}$ to go to +ve & causes D_2 to conduct, then the circuit behaves like an inverter for $R_f = R_1$.

→ The input/output waveform is shown below;



Full Wave Rectifier:

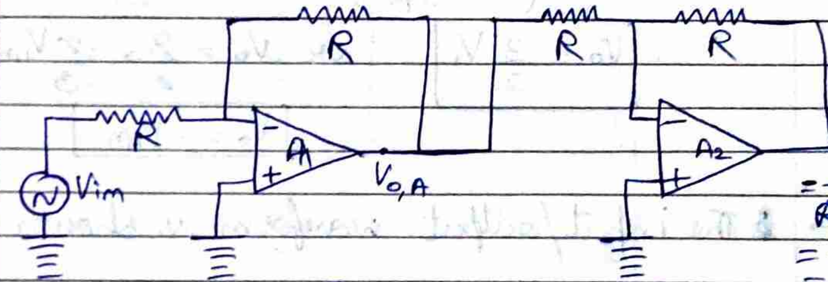


Operation:

→ For +ve half cycle of the input diode D_1 conducts and D_2 will be off. Hence, both op-amps A_1 & A_2 works as an inverter.

→ ~~For −ve half cycle of the input diode D_2 conducts and D_1 will be off. The −ve input V_{in} forces The~~

→ For −ve half cycle of the input D_2 conducts & D_1 will be off. The equivalent circuit can be drawn as,

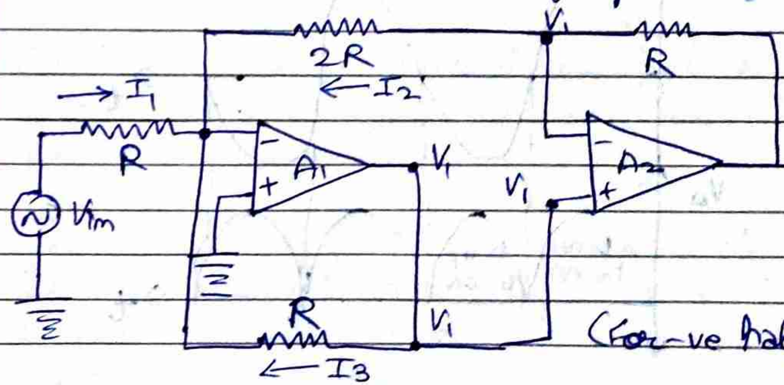


$= \frac{-R}{R} V_{o,A}$

$= -(-V_{in})$

$= +V_{in}$

(For +ve half cycle)



(For −ve half cycle)

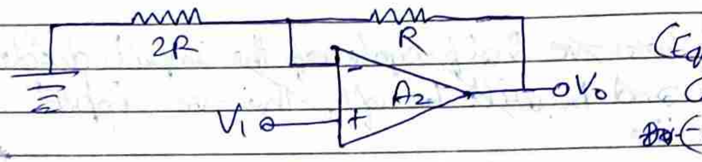
Consider the output of op-amp A_1 is V_1

Applying KCL we get,

$I_1 + I_2 + I_3 = 0$

$$\Rightarrow \frac{V_{in}}{R} + \frac{V_1}{2R} + \frac{V_1}{R} = 0$$

$$\boxed{V_1 = -\frac{2}{3} V_{in}}$$



(Equivalent circuit) -ve half)

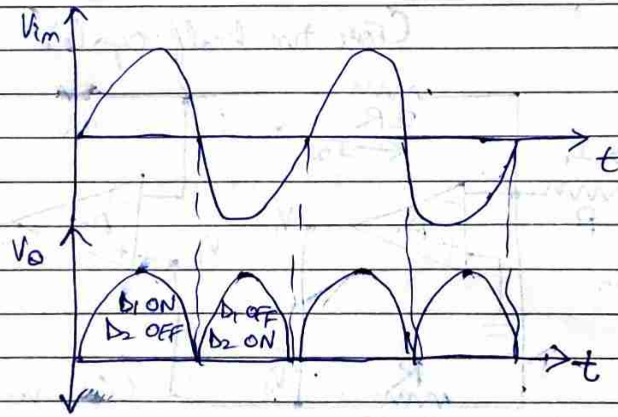
$$\Rightarrow V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

$$V_o = \left(1 + \frac{R}{2R}\right) V_{in}$$

$$\boxed{V_o = \frac{3}{2} V_1} \quad \text{or} \quad V_o = \frac{\cancel{3}}{\cancel{2}} \times \frac{-\cancel{2}}{\cancel{3}} V_{in}$$

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

→ The input/output waveform is shown below.

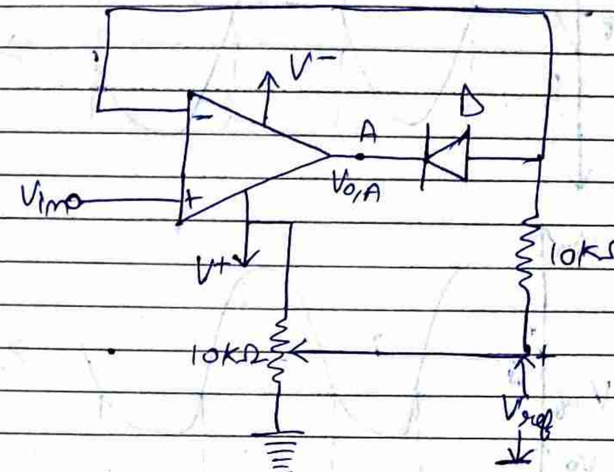


Clipper:

→ Clipper circuit is used to clip off certain portion of the sinusoidal input.

→ The clipping level is obtained by the reference voltage, V_{ref} and could be obtained from the +ve supply voltage.

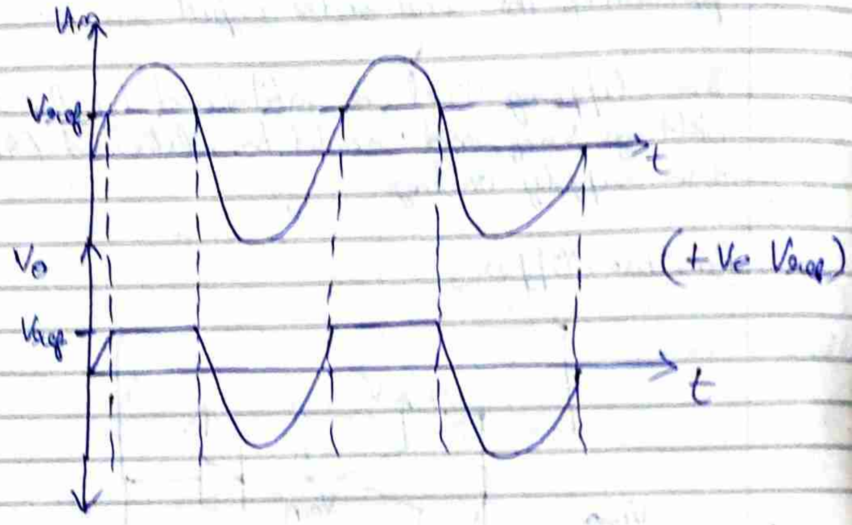
Positive Clipper:

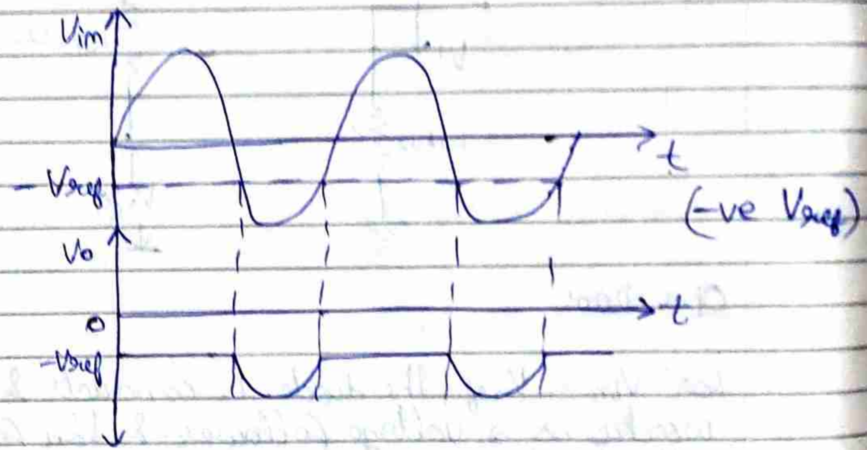


Operation:

→ For $V_{in} < V_{ref}$, the diode D conducts & op-amp works as a voltage follower & V_{out} follows V_{in} till $V_{in} \leq V_{ref}$.

→ When $V_{in} > V_{ref}$, the output $V_{o,A}$ of op-amp is large enough to drive the diode into cutoff region. The op-amp operates in open loop & hence $V_o = V_{ref}$. However if, V_{ref} is -ve then the entire output waveform above V_{ref} will get clipped off.





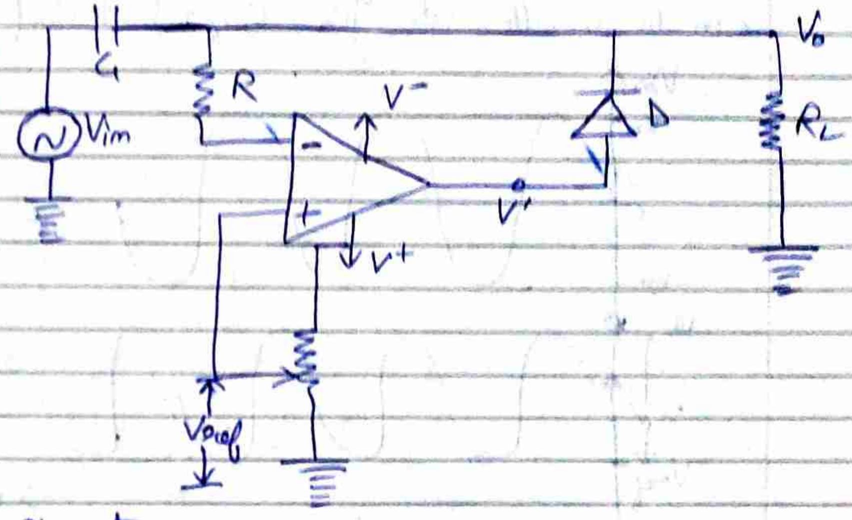
Note:
Negative clipper can be obtained by just reversing the diode & provide supply through V^- for Vref.

Clamper:

→ Clamper is called dc inserter or restorer.

→ The circuit is used to add a desired dc level to the o/p voltage i.e. the output is clamped to a desired dc level.

→ If the clampped dc level is +ve, then it is called +ve clamper & if clampped dc level is -ve, then it is called -ve clamper.

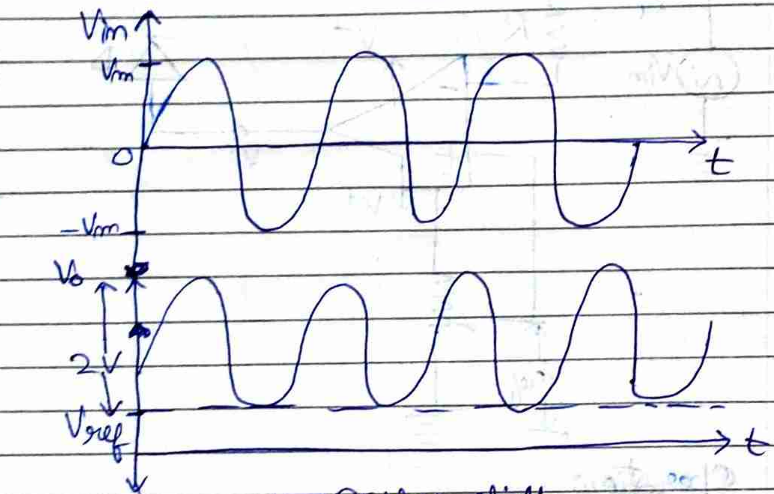


Operation:

→ The output voltage in the circuit is the net result of ac & dc input voltages applied at inverting & non-inverting terminals respectively.

→ For +ve Vref, the voltage at V' is also +ve and hence, the diode D will be forward biased. Then the output $V_o = V_{ref}$.

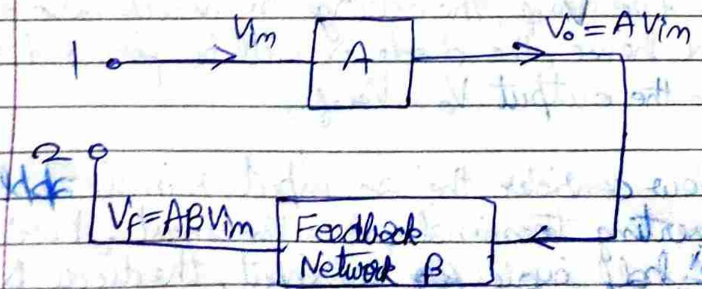
→ Now consider the ac input signal applied at inverting terminal, $V_{in} = V_m \sin\omega t$. During the -ve half cycle of input, the diode D conducts and capacitor C_1 charges to diode D upto −ve peak of input. However, during +ve half cycle of input diode D is reversed biased & the capacitor retains its previous voltage V_m. Since, this voltage V_m is in series with ac input signal, then the voltage can be written as $V_{in}+V_m$. Therefore total output voltage can be written as, $\boxed{V_o = V_{ref} + V_{in} + V_m}$



Oscillator:

- RC phase shift
- Wein Bridge
- Hartley
- Colpitt

Basic Principle of Oscillator:



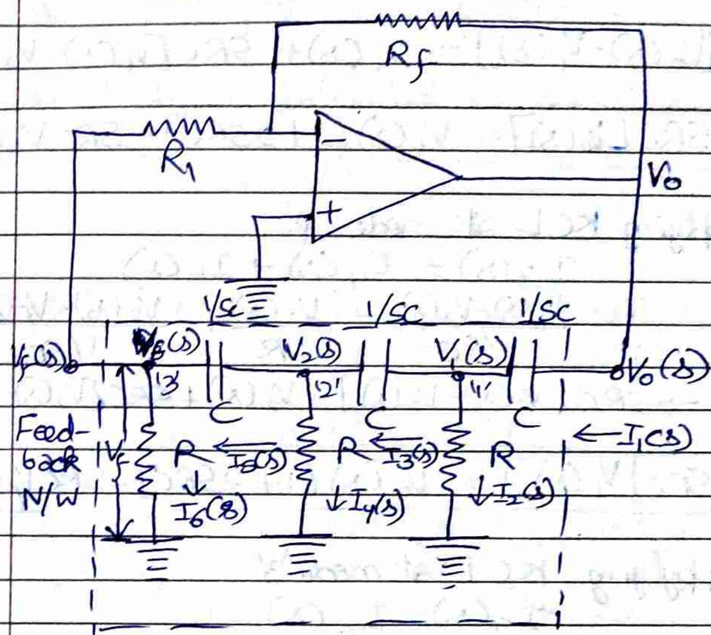
Barkhausen Criteria of Oscillation:

$A\beta = 1$

$|A\beta| = 1$

$\angle A\beta = 0°$ or multiples of 2π.

RC Phase Shift Oscillation:



We know, that $A\beta = 1$ where $\beta = \frac{V_f}{V_o}$ & A = gain

→ Since, feedback network is applied at inverting terminal hence, phase shift provided due to inverting configuration is 180°.

→ One RC section will provide 60° phase shift. Hence, all the 3 R-C sections will provide 180° phase shift. Therefore total phase shift is equal to $180° + 180° = 360°$.

∴ Applying KCL at node '1',

$$I_1(s) = I_2(s) + I_3(s)$$

$$\frac{V_0(s) - V_1(s)}{1/SC} = \frac{V_1(s)}{R} + \frac{V_1(s) - V_2(s)}{1/SC}$$

$$SRC[V_0(s) - V_1(s)] = V_1(s) + SRC[V_1(s) - V_2(s)]$$

$$\boxed{SRC[V_0(s)] = V_1(s)[1+2SRC] - SRC\,V_2(s)} \rightarrow (1)$$

Applying KCL at node '2'.

$$I_3(s) = I_4(s) + I_5(s)$$

$$\Rightarrow \frac{V_1(s) - V_2(s)}{1/SC} = \frac{V_2(s)}{R} + \frac{V_2(s) - V_f(s)}{1/SC}$$

$$\Rightarrow SRC[V_1(s) - V_2(s)] = V_2(s) + SRC[V_2(s) - V_f(s)]$$

$$\Rightarrow \boxed{SRC[V_1(s)] = V_2(s)[1+2SRC] - SRC\,V_f(s)} \rightarrow (2)$$

Applying KCL at node '3'.

$$I_5(s) = I_6(s)$$

$$\Rightarrow \frac{V_2(s) - V_f(s)}{1/SC} = \frac{V_f(s)}{R}$$

$$\Rightarrow SRC[V_2(s)] = V_f(s)[1+SRC]$$

$$\Rightarrow \boxed{V_2(s) = \frac{V_f(s)(1+SRC)}{SRC}} \rightarrow (3)$$

Putting value of $V_2(s)$ in eq^n (2) we get,

$$SRC[V_1(s)] = \frac{V_f(s)[1+SRC](1+2SRC)}{SRC} - SRC\,V_f(s)$$

$$\Rightarrow S^2R^2C^2 V_1(s) = V_f(s)(1+SRC)(1+2SRC) - S^2R^2C^2 V_f(s)$$

$$\Rightarrow S^2R^2C^2 V_1(s) = V_f(s)[1+3SRC+2S^2R^2C^2 - S^2R^2C^2]$$

$$\Rightarrow \boxed{V_1(s) = \frac{V_f(s)[S^2R^2C^2+3SRC+1]}{S^2R^2C^2}} \rightarrow (4)$$

Now putting the values of $V_1(s)$ & $V_2(s)$ in eq^n (1)

$$\Rightarrow SRC\,V_0(s) = \frac{V_f(s)(S^2R^2C^2+3SRC+1)(1+2SRC)}{S^2R^2C^2} - SRC\left[\frac{V_f(s)(1+SRC)}{SRC}\right]$$

$$\Rightarrow SRC\,V_0(s) = \frac{V_f(s)[S^2R^2C^2+3SRC+1+2S^3R^3C^3+6S^2R^2C^2+2SRC]}{S^2R^2C^2} - V_f(s)[1+SRC]$$

$$\Rightarrow S^3R^3C^3 V_0(s) = V_f(s)[S^3R^3C^3 + 6S^2R^2C^2 + 5SRC + 1]$$

$$\Rightarrow \boxed{\frac{V_f(s)}{V_0(s)} = \beta = \frac{S^3R^3C^3}{S^3R^3C^3+6S^2R^2C^2+5SRC+1}} \rightarrow (5)$$

~~Now from imaginary part~~ Since $\frac{V_f(s)}{V_0(s)} = \beta$

⇒ From Barkhausen Criteria we have,

$A\beta = 1$ & from fig. $A = -\frac{R_f}{R_1}$

$$\Rightarrow \left(\frac{-R_f}{R_1}\right)\left(\frac{S^3R^3C^3}{S^3R^3C^3+6S^2R^2C^2+5SRC+1}\right) = 1$$

put $S = j\omega$

$$\Rightarrow \left(\frac{-R_f}{R_1}\right)\frac{(j\omega)^3R^3C^3}{(j\omega)^3R^3C^3+6(j\omega)^2R^2C^2+5(j\omega)RC+1} = 1$$

$$\left(\frac{-R_f}{R_1}\right)\frac{-j\omega^3R^3C^3}{-j\omega^3R^3C^3-6\omega^2R^2C^2+5j\omega RC+1} = 1$$

$$\left(\frac{R_f}{R_1}\right) j\omega^3R^3C^3 = -j\omega^3R^3C^3-6\omega^2R^2C^2+5j\omega RC+1$$

$$\left(\frac{R_f}{R_1}\right) j\omega^3R^3C^3 = 1-6\omega^2R^2C^2+j[5\omega RC-\omega^3R^3C^3]$$

Equating real & img. part on both sides we get,

For Real part, $0 = 1-6\omega^2R^2C^2$

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

$$\Rightarrow \omega = \frac{1}{\sqrt{6}\, RC}$$

Also $\omega=2\pi f = \frac{1}{\sqrt{6}\, RC}$

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

For Img. part, $\frac{R_f}{R_1}\omega^3R^3C^3 = 5\omega RC-\omega^3R^3C^3$

$$\frac{R_f}{R_1} = \frac{5}{\omega^2R^2C^2}-1$$

Putting value of ω^2 in above eq^n we have,

$$\frac{R_f}{R_1} = \frac{5}{\frac{R^2C^2}{6R^2C^2}}-1 = 30-1$$

$$\Rightarrow \boxed{\frac{R_f}{R_1}=29}$$

Q1. Design the RC phase shift oscillator for $f_o=100Hz$

Ans. In RC phase shift oscillator we have 3 different RC sections so we have to find the value of R for all the 3 sections by taking the value of capacitor, $C=0.1\mu F$

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

$$\Rightarrow R = \frac{1}{2\times3.14\times\sqrt{6}\times100\times0.1\times10^{-6}}$$

$$\Rightarrow \boxed{R=6.5K\Omega}$$

To prevent loading effect of amplifier because of RC network, it is necessary to take $R_1 \geq 10R$

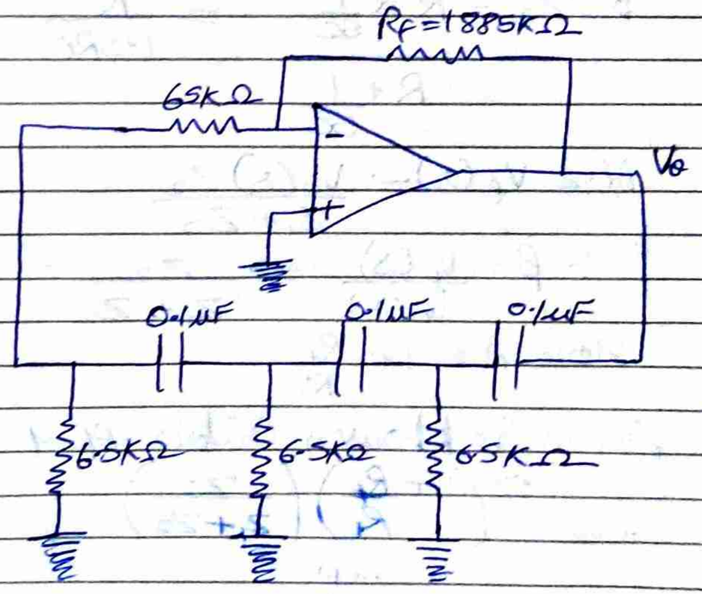
$$\Rightarrow R_1 = 10R = 10\times6.5K\Omega$$

$$\Rightarrow \boxed{R_1=65K\Omega}$$

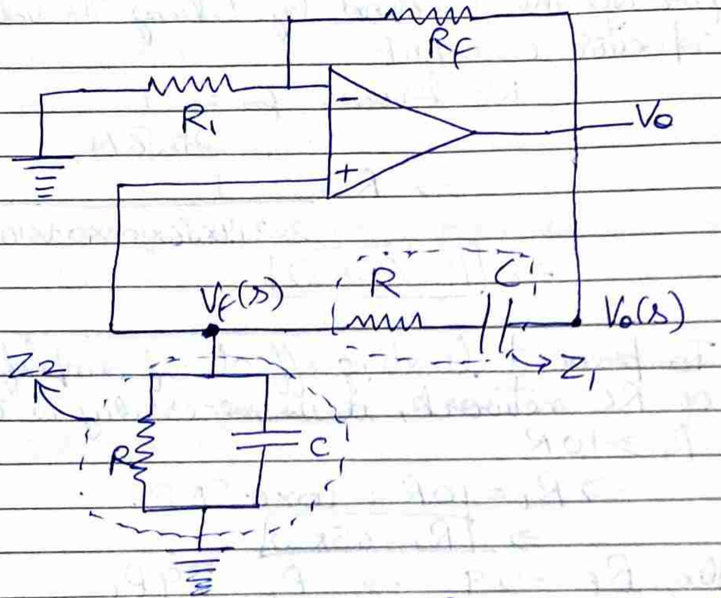
Also, $\frac{R_f}{R_1}=29 \Rightarrow R_f = 29R_1$

$$R_f = 29\times65K\Omega$$

$$\Rightarrow \boxed{R_f=1885K\Omega}$$



Wein Bridge Oscillator:



From above fig. $Z_1 = R + \frac{1}{SC} = \frac{1+SRC}{SC}$

& $Z_2 = \dfrac{R \times \frac{1}{SC}}{R + \frac{1}{SC}} = \dfrac{R}{1+SRC}$

Also $V_f(s) = \dfrac{V_o(s) Z_2}{Z_1 + Z_2}$

& $\beta = \dfrac{V_f(s)}{V_o(s)} = \dfrac{Z_2}{Z_1 + Z_2}$

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

From Barkhausen Criteria $A\beta = 1$

$$\Rightarrow \left(1 + \frac{R_F}{R_1}\right)\left(\frac{Z_2}{Z_1 + Z_2}\right) = 1$$

$$\left(1 + \frac{R_F}{R_1}\right)\left[\frac{\frac{R}{1+SRC}}{\frac{1+SRC}{SC} + \frac{R}{1+SRC}}\right] = 1$$

put $S = j\omega$

$$\left(1 + \frac{R_F}{R_1}\right)\left[\frac{RSC}{1+S^2R^2C^2+2SRC+SRC}\right] = 1$$

$$\Rightarrow \left(1 + \frac{R_F}{R_1}\right)\left[\frac{j\omega RC}{1+(j\omega)^2R^2C^2+3j\omega RC}\right] = 1$$

$$\Rightarrow \left(1 + \frac{R_F}{R_1}\right)\left[\frac{j\omega RC}{1-\omega^2R^2C^2+3j\omega RC}\right] = 1$$

$$\Rightarrow \left(1 + \frac{R_F}{R_1}\right) j\omega RC = 1 - \omega^2R^2C^2 + 3j\omega RC$$

Equating Real & img. part we get,

$$1 - \omega^2R^2C^2 = 0$$

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

$$\omega = \frac{1}{RC}$$

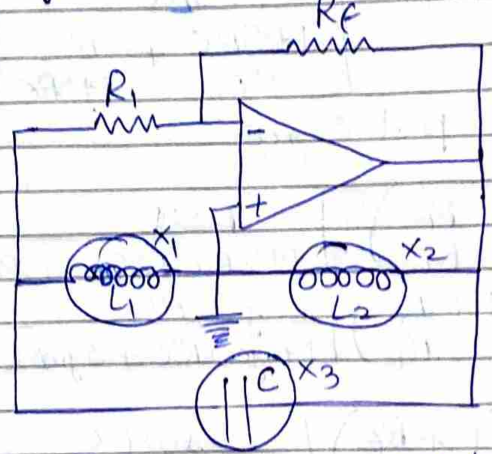
$$\boxed{f = \frac{1}{2\pi RC}}$$

& $\left(1 + \frac{R_F}{R_1}\right) \cancel{\omega RC} = 3\cancel{\omega RC}$

$$\boxed{\frac{R_F}{R_1} = 2}$$

So, in Wein bridge Oscillator we have frequency, $f = \frac{1}{2\pi RC}$ & ratio of $\frac{R_F}{R_1} = 2$

Hartley oscillator:



To find the freq. of oscillation in hartley oscillator, the sum of total reactance of tank circuit must be zero.

i.e. $X_1 + X_2 + X_3 = 0$

$$\Rightarrow SL_1 + SL_2 + \frac{1}{SC} = 0$$

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

$$\Rightarrow j\omega(L_1+L_2) = \frac{-1}{j\omega C}$$

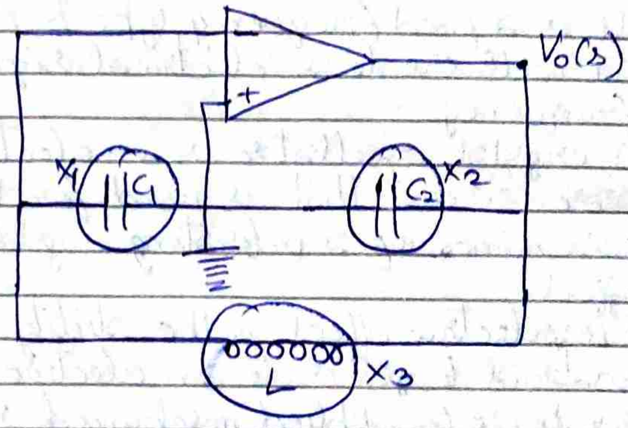
$$\Rightarrow (L_1+L_2) = \frac{1}{\omega^2 C}$$

$$\Rightarrow \omega^2 = \frac{1}{C(L_1+L_2)} \quad \Rightarrow \omega = \frac{1}{\sqrt{C(L_1+L_2)}}$$

$$\Rightarrow \boxed{f = \frac{1}{2\pi\sqrt{C(L_1+L_2)}}} \quad \& \ |A| \geq \frac{L_2}{L_1}$$

$$\Rightarrow \boxed{|A| \geq \frac{L_2}{L_1}}$$

Colpitt Oscillator:



To find freq. of oscillation, the sum of total reactance of the tank circuit must be zero.

i.e. $X_1 + X_2 + X_3 = 0$

$$\Rightarrow \frac{1}{SC_1} + \frac{1}{SC_2} + SL = 0$$

$$\Rightarrow \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} + j\omega L = 0$$

$$\Rightarrow \frac{1}{j\omega}\left[\frac{1}{C_1} + \frac{1}{C_2}\right] = -j\omega L$$

$$\Rightarrow \left[\frac{1}{C_1} + \frac{1}{C_2}\right] = \omega^2 L$$

$$\Rightarrow \omega^2 = \frac{1}{L}\left[\frac{C_1+C_2}{C_1C_2}\right]$$

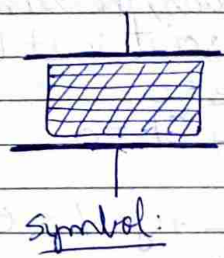
$$\Rightarrow \omega = \sqrt{\frac{1}{L}\left(\frac{C_1+C_2}{C_1C_2}\right)}$$

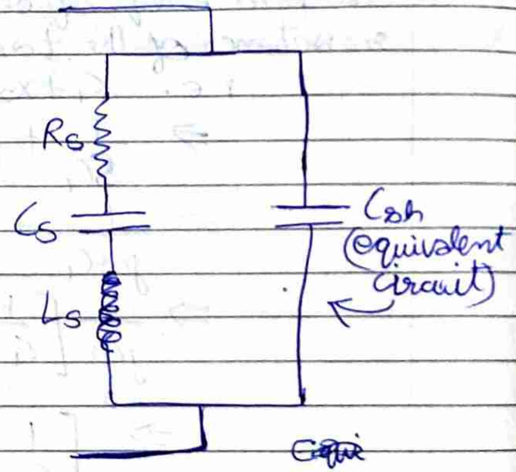
$$\Rightarrow \boxed{f = \frac{1}{2\pi}\sqrt{\frac{1}{L}\left(\frac{C_1+C_2}{C_1C_2}\right)}}$$

$$\& \ \boxed{|A| \geq \frac{C_1}{C_2}}$$

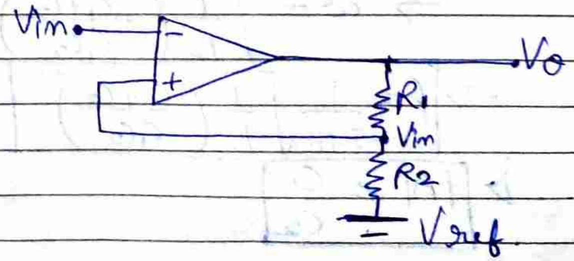
Crystal Oscillator:

→ It is a fixed frequency type & RF oscillator.
→ It will create an electrical signal with even frequency.
→ A crystal oscillator is an electronical oscillator circuit that is used for the mechanical resonance of a vibrating crystal of piezoelectric effect.
→ Piezoelectric effect is the ability of certain material to generate an electric charge in response to applied mechanical stress.





Schimitt Trigger circuit / regeneration Comparator:



→ A schimitt trigger circuit can be obtained by providing positive feedback in basic comparator circuit.
→ In comparator circuit output saturates b/w positive & negative max. supply of voltage.

→ Consider $\boxed{V_o = +V_{sat}}$ then, voltage at positive terminal is called upper threshold voltage & it can be obtained by,

$$V_{UT} = \frac{V_o R_2 + V_{ref} \times R_1}{R_1 + R_2}$$

$$V_{UT} = \frac{+V_{sat} R_2 + V_{ref} R_1}{R_1 + R_2} \rightarrow (1)$$

→ Now consider $\boxed{V_o = -V_{sat}}$, then voltage at positive terminal is called lower threshold voltage & it can be obtained as,

$$V_{LT} = \frac{-V_{sat} R_2 + V_{ref} R_1}{R_1 + R_2} \rightarrow (2)$$

→ The difference b/w upper threshold & lower threshold voltage is called Hysteresis Voltage.

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

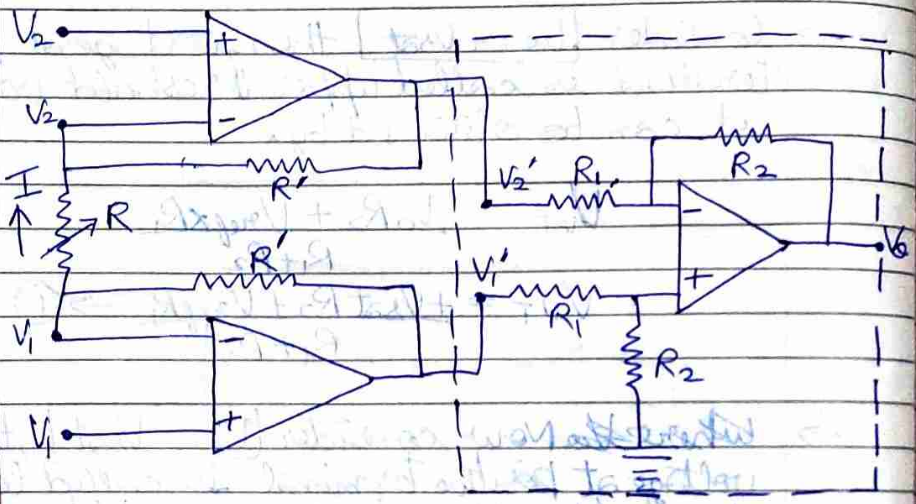
$$\boxed{V_H = \frac{2 V_{sat} R_2}{R_1 + R_2}}$$

Instrumentation Amplifier:

→ In a number of industrial and common

applications, it is required to measure & control physical quantities.

→ Some examples are measurement control of temperature, humidity, light intensity, water flow etc.



In above Fig. we have,

$$V_0 = \frac{R_2}{R_1}(V_1' - V_2') \rightarrow (1)$$

$$\text{Also } I = \frac{V_1 - V_2}{R} \rightarrow (2)$$

$$\text{Also } I = \frac{V_1' - V_1}{R'}$$

$$\Rightarrow IR' = V_1' - V_1 \Rightarrow V_1' = V_1 + IR'$$

$$V_1' = V_1 + (V_1 - V_2)\frac{R'}{R} \rightarrow (3)$$

$$\text{Also } I = \frac{V_2 - V_2'}{R'}$$

$$V_2' = V_2 - IR'$$

$$\Rightarrow V_2' = V_2 - (V_1 - V_2)\frac{R'}{R} \rightarrow (4)$$

Now putting the value of V_1' & V_2' in eqⁿ (1) we get,

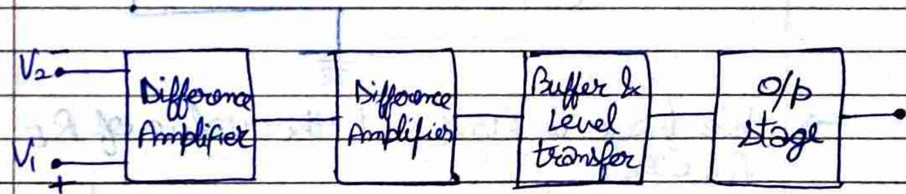
$$V_0 = \frac{R_2}{R_1}\left[V_1 + (V_1 - V_2)\frac{R'}{R} - V_2 + (V_1 - V_2)\frac{R'}{R_1}\right]$$

$$\Rightarrow \boxed{V_0 = (V_1 - V_2)\frac{R_2}{R_1}\left(1 + 2\frac{R'}{R}\right)}$$

Features of Instrumentation Amplifier:

1.) High gain accuracy.
2.) High CMRR
3.) High gain stability with temperature coefficient.
4.) Low dc offset.

Block Schematic of Op-Amp:

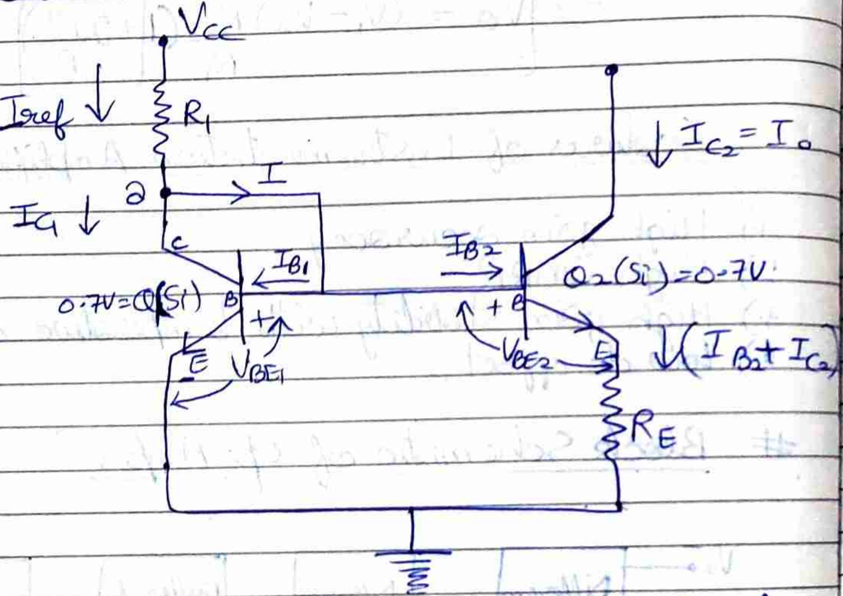


1.) 2 stage difference amplifier provides high gain and high input resistance.
2.) Buffer circuit is an emitter follower circuit, whose input impedence is very high, so that it prevents from loading of the high stage gain.
3.) The level translator adjust the dc voltages, so that output is zero for zero input voltage.

4.) The output stage provides low output impedance

Widlar Current Source:

→ It can be obtained by providing emitter resistance in basic constant current source circuit.



→ We have to find out the value of R_E & I_{C_2} (I_o).

→ The collector current for transistor Q_1 & Q_2 in forward active mode can be written as,

$$I_{C_1} = \alpha_F I_{ES} e^{V_{BE1}/V_T} \rightarrow (1)$$

$$I_{C_2} = \alpha_F I_{ES} e^{V_{BE_2}/V_T} \rightarrow (2)$$

where I_{ES} → Reverse saturation current of emitter-base

Dividing eqn (1) by (2) we get,

$$\frac{I_{C_1}}{I_{C_2}} = e^{V_{BE_1}-V_{BE_2}/V_T} \rightarrow (3)$$

Now apply KVL, which contains emitter-base juncn of both transistors,

$$V_{BE_1} - V_{BE_2} = (I_{B_2} + I_{C_2}) R_E \rightarrow (4)$$

Now taking natural log on both sides of eqn (3), we get,

$$\ln\left(\frac{I_{C_1}}{I_{C_2}}\right) = \frac{V_{BE_1} - V_{BE_2}}{V_T}$$

$$\Rightarrow V_{BE_1} - V_{BE_2} = V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right) \rightarrow (5)$$

From eqn (4) & (5) we have

$$(I_{B_2} + I_{C_2}) R_E = V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right)$$

$$\left(\frac{1}{\beta} + 1\right) I_{C_2} R_E = V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right)$$

$$R_E = \frac{V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right)}{\left(\frac{1}{\beta} + 1\right) I_{C_2}} \rightarrow (6)$$

Now apply KCL at node 'a',

$$I_{ref} = I_{C_1} + I_{B_1} + I_{B_2}$$

$$\Rightarrow I_{ref} = I_{C_1} + \frac{I_{C_1}}{\beta} + \frac{I_{C_2}}{\beta}$$

$$I_{ref} = I_{C_1}\left(1 + \frac{1}{\beta}\right) + \frac{I_{C_2}}{\beta}$$

Consider transistor Q_1 & Q_2 are identical i.e. $\beta_1 = \beta_2 = \beta$

In widlar current source,

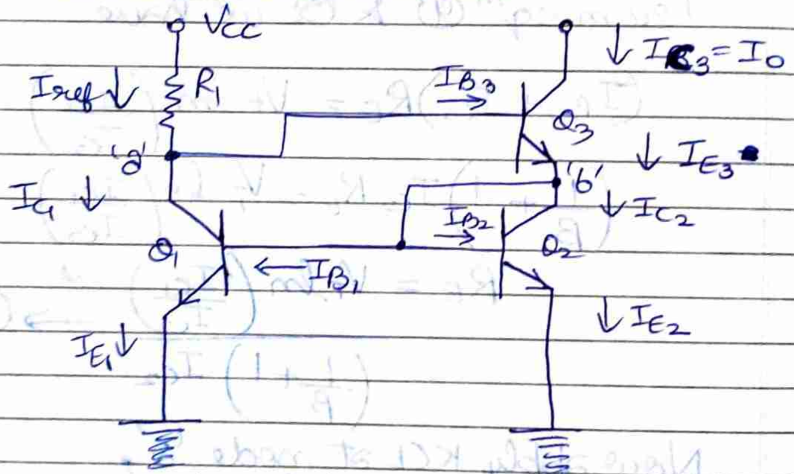
$I_{C_2} \ll I_{C_1}$, $\frac{I_{C_2}}{\beta}$ can be neglected

$$\Rightarrow I_{ref} = I_{C_1}\left(1+\frac{1}{\beta}\right)$$

$$\Rightarrow \boxed{I_{C_1} = \frac{I_{ref}}{1+\frac{1}{\beta}}}$$

where $I_{ref} = \frac{V_{CC}-V_{BE_1}}{R_1}$

Wilson's Current Source:



Consider transistor Q_1 & Q_2 are identical

i.e. $V_{BE_1} = V_{BE_2}$, $I_{C_1} = I_{C_2}$, $I_{B_1} = I_{B_2} = I_B$

Applying KCL at node 'b',

$$\Rightarrow I_{E_3} = I_{C_2} + I_{B_1} + I_{B_2}$$

$$I_{E_3} = I_{C_2} + \frac{I_{C_1}}{\beta} + \frac{I_{C_2}}{\beta}$$

$$I_{E_3} = \frac{I_{C_1}}{\beta} + I_{C_2}\left(1+\frac{1}{\beta}\right)$$

Since $I_{C_1} = I_{C_2}$, so $I_{E_3} = \left(1+\frac{2}{\beta}\right) I_{C_2} \rightarrow (1)$

I_{E_3} can also be written as,

$$I_{E_3} = I_{B_3} + I_{C_3}$$

$$I_{E_3} = \frac{I_{C_3}}{\beta} + I_{C_3} = \left(1+\frac{1}{\beta}\right) I_{C_3} \rightarrow (2)$$

Equating eq^n (1) & (2) we get,

$$\left(1+\frac{2}{\beta}\right) I_{C_2} = \left(1+\frac{1}{\beta}\right) I_{C_3}$$

$$\boxed{I_{C_2} = \frac{(1+1/\beta)\, I_{C_3}}{(1+2/\beta)}}$$

$$\boxed{I_{C_3} = \frac{(1+2/\beta)}{(1+1/\beta)} I_{C_2}}$$

$$\Rightarrow \boxed{I_{C_3} = \frac{\beta+2}{\beta+1} I_{C_2}}$$

Since $I_{C_1} = I_{C_2}$, $\therefore$ I_o or collector current of transistor Q_3 will be,

$$\boxed{I_o = \frac{(\beta+2)}{(\beta+1)} I_{C_1}}$$

Now apply KCL at node 'a',

$$\Rightarrow I_{ref} = I_{C_1} + I_{B_3}$$

$$I_{ref} = I_{C_1} + \frac{I_{C_3}}{\beta}$$

$$I_{ref} = \frac{(\beta+1)}{(\beta+2)} I_o + \frac{I_o}{\beta}$$

$$\Rightarrow I_{ref} = \left(\frac{\beta+1}{\beta+2} + \frac{1}{\beta}\right) I_o$$

$$\Rightarrow I_{ref} = \left(\frac{\beta^2+\beta+\beta+2}{\beta(\beta+2)}\right) I_o$$

$$\Rightarrow \boxed{I_{ref} = \left(\frac{\beta^2+2\beta+2}{\beta(\beta+2)}\right) I_o}$$

where, $I_{ref} = \frac{V_{CC} - V_2}{R_1}$

where $V_2 - V_{BE_3} - V_{BE_2} = 0$

$V_2 = V_{BE_3} + V_{BE_2}$

Also $V_{BE_3} = V_{BE_2} = V_{BE}$

$$\Rightarrow \boxed{V_2 = 2V_{BE}}$$

$$\Rightarrow \boxed{I_{ref} = \frac{V_{CC} - 2V_{BE}}{R_1}}$$

<u>Thermal Drift of an Op-amp:</u>

The dependence of op-amp parameters, with temp which affects its performance is specified as op-amp thermal drift.

There can be changes in op-amp bias currents, input offset voltage and input offset current with temp. as given in the manufacturer's data sheet of specific op-amp.

$$\frac{I_{C_1}}{I_{C_2}} = e^{V_{BE_1} - V_{BE_2}/V_T} \rightarrow (3)$$

Now apply