Operational Amplifier (OP-Amp) :-

→ An operational Amplifier (op-Amp) is a circuit that can perform such mathematical operations as addition, Subtraction, integration and Differentiation.

→ It's key electronic circuit ~~is an op-Amp~~ is the differential amplifier. Where the input stage is a differential amplifier and the output stage is typically a class B push-pull emitter follower.

→ Differential amplifier is a circuit that can accept two input signals and amplify the difference b/w these two input signals.

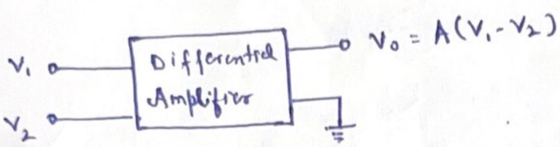


Fig.1. Block diagram of a Diffential Amplifier.

Fig.1. Shows the block diagram of a Differential Amplifier. This amplifier amplifies the difference b/w the two input voltages (V_1 & V_2)

∴ the output voltage is

$$\boxed{V_0 = A(V_1 - V_2)}$$

Where, A → gain of the Amplifier.

→ Difference b/w conventional and differential Amplifier :-

In a conventional amplifier, the signal (i.e input) is applied at the input terminal and amplified output is obtained at the output terminal.

Diffential Amplifier accepts two input signals and amplifies the difference b/w these two input signals.

Basic Circuit of Differential Amplifier: (DA)

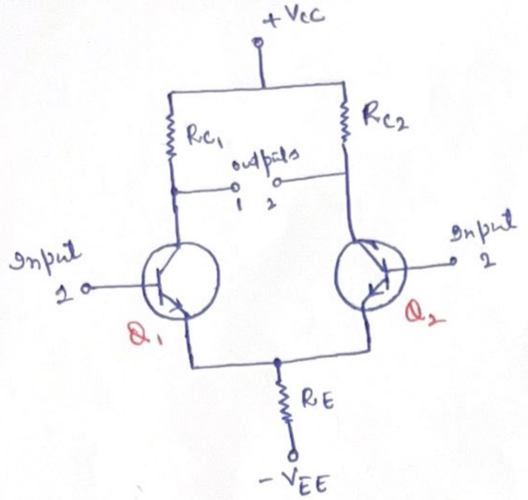


fig. Differential Amplifier.

Symbol of DA:-

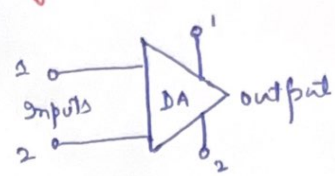


Fig. shows the basic circuit of a differential amplifier. It consist of two transistors (Q_1 and Q_2) that have identical characteristics. They share a common positive supply V_{CC}, R_E and negative supply V_{EE}. Circuit is Symmetrical.

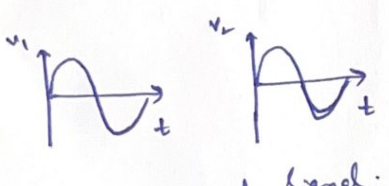
→ Input Signals to a DA are defined as:-

Common-mode Signals.

When the input Signals to a DA are in phase and exactly equal in Amplitude, they are called Common-mode signals.

i.e the difference b/w The two input signals is zero.

as $\boxed{V_1 = V_2}$.



Common-mode Signal.

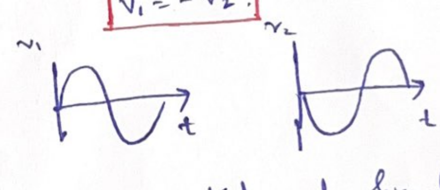
Differential-mode Signals

When the input signals to a DA is 180° out of phase and exactly equal in amplitude, they are called Differential-mode Signals.

i.e. DA amplifies the Differential mode Signals and Rejects the Common-mode Signals.

For differential mode signal.

$\boxed{V_1 = -V_2}$



Differential-mode Signals.

Voltage Gain of DA:

$A_{DM} \rightarrow$ Differential-mode voltage gain of DA operating in differential mode.

$A_{CM} \rightarrow$ Common-mode voltage gain of DA operating in common-mode.

Ideally,
DA provides a very high voltage gain for differential-mode signal and Zero gain for common-mode signals.

Practically, DA do exhibits a very small common-mode gain (< 1) while providing a high differential voltage gain.
The higher the differential gain w.r.t the common-mode gain, the better performance of the DA in terms of rejection of common-mode signals.

Common-mode Rejection Ratio (CMRR):-

The DA should have high A_{DM} and very low A_{CM}.
The ratio of A_{DM}/A_{CM} is called CMRR.

i.e

$$\boxed{CMRR = \frac{A_{DM}}{A_{CM}}}$$

It is ~~meas~~ expressed in decibels (dB). As.

$$CMRR_{dB} = 20\log_{10}\frac{A_{DM}}{A_{CM}}$$

$$\boxed{CMRR_{dB} = 20\log_{10} CMRR}$$

The CMRR is the ability of a DA to reject the common-mode signals. The larger the CMRR, the better the DA is at eliminating common-mode signals.

→ Parameters of an Op-Amp due to Mismatch of Transistors:-

DA has been based on the assumption that the transistors are perfectly matched i.e they have the same electrical characteristics. In pratical, this can't happen. There will always be some difference between the characteristics of the two transistors. Which results in following two parameters of op-amp.

① Output offset voltage:- ($V_{out(offset)}$)

Even though the transistors in the DA are very closely matched, there are some differences in their electrical characteristics. One of these differences is found in the values of V_{BE} for the two transistors.

When $\boxed{V_{BE1} \neq V_{BE2}}$, an imbalance is created in the DA (op-Amp). In such situation, op-Amp may show some voltage at the output even when the voltage applied b/w two input terminals is zero. This is called output offset voltage.

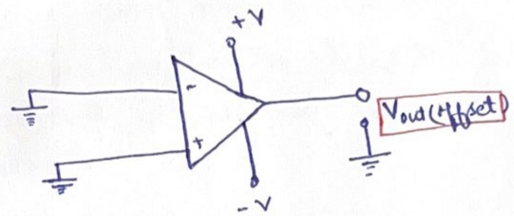
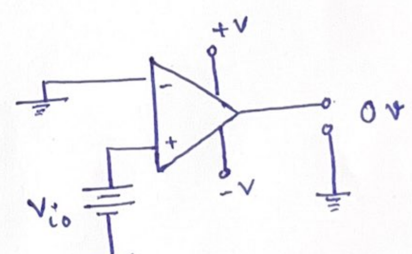


Fig.

Method to Eliminate $V_{out(offset)}$:

One way to eliminate $V_{out(offset)}$ is to apply an input offset voltage b/w the input terminals of op-amp, so to make the output 0V.

The input offset voltage (V_{io}) is required to eliminate the output offset voltage and is given by



$$\boxed{V_{io} = \frac{V_{out(offset)}}{A}}$$

Where A is the gain.

2. Input offset Current :-

When the output offset voltage of a op-amp is eliminated, there will be a slight difference b/w the input currents to the noninverting and inverting inputs of the device. This slight difference in input currents is called Input offset Current, which is caused by a mismatch (β) b/w the transistors.

e.g. $I_{B1} = 75\,\mu A$ and $I_{B2} = 65\,\mu A$.

Then

$$I_{in(offset)} = 75 - 65 = 10\,\mu A.$$

If the transistors are identical, then input offset current is zero i.e. both currents will be equal. But practically, the two transistors are different and the base currents are not equal.

→ Input Bias Current :-

The inputs to an op-amp require some amount of d.c biasing current for the transistors in the differential Amplifier.

The input bias current is defined as the average of the two d.c base current

i.e

$$\boxed{I_{in(bias)} = \frac{I_{B1} + I_{B2}}{2}.}$$

op- Amp:

Properties of op-Amp:

i) An op-amp is a multistage amplifier. The input stage of an op-amp is a differential amplifier stage.

ii) An inverting input and a non-inverting input.

iii) High input impedance (usually ∞).

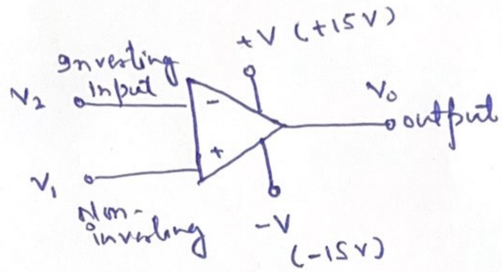
iv) Low output impedance ($< 200\,\Omega$)

v) A large open-loop voltage gain.

vi) Voltage gain remains constant over a wide frequency range.

vii) Large CMRR (> 90 dB).

Schematic Symbol:



Summary:

Practical op-amp	Ideal op-amp
$Z_{in} = 2\,M\Omega$	$Z_{in} \rightarrow \infty$
$A_v = 1 \times 10^5$	$A_v \rightarrow \infty$
$Z_{out} = 100\,\Omega$	$Z_{out} \rightarrow 0\,\Omega$

Bandwidth of an op-amp :-

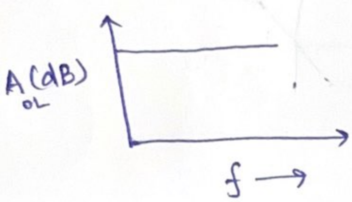
The electronic devices work only over a limited range of frequencies. This range of frequencies is called Bandwidth.
i.e Every op-amp has a bandwidth, over which it will work properly. Bandwidth of an op-amp depends upon the ~~close~~ open loop gain of the op-amp circuit.
Moreover, The Gain-Bandwidth product (GBW) is defined as

$$\boxed{GBW = f_{unity} = A_{OL} \times f_x}$$

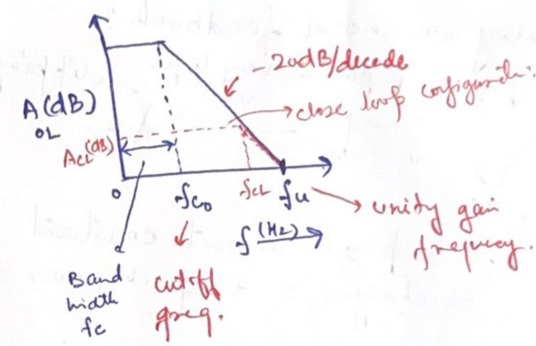
Where,
A_{CL} is the ~~closed~~ open-loop gain at frequency f_x
f_{unity} is the frequency at which the closed-loop gain is unity

variation of gain w.r.t frequ.

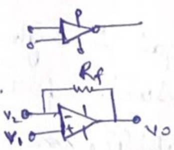
Frequency Response of Ideal op-amp :-



frequency response of practicle op-amp:



* op-amp Configuration → open-loop.
→ close-loop.



mostly -ve feedback. (∵ bandwidth ↑es
distortion ↓es
stability ↑es.
gain ↓es.

Slew Rate :-

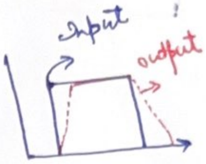
The slew rate of an op-amp is a measure of how fast the output voltage can change and is measured in volts per microsecond (V/μs).

e.g. If slew rate of an op-amp is 0.5 V/μs, it means the output from the amplifier can change by 0.5 V every μs.

$$\boxed{\text{Slew rate} = \left.\frac{dV_o}{dt}\right|_{max}}$$

As frequency is a function of time, the slew rate can be used to determine the maximum operating frequency of the op-amp as

Maximum operating frequency. $\boxed{f_{max} = \dfrac{\text{slew rate}}{2\pi V_{pk}}}$



Where,

$V_{pk} \rightarrow$ Peak output voltage.

i.e peak output voltage limits the maximum operating frequency.

Open loop Configuration

$GBP = f_u \times A_{OL}$

$GBP = f_u$ (∵ at $f_u \to A_{OL} = 1$)

For f_c

$GBP = f_c \times A_{OL}$

$f_u = f_c \times A_{OL}$

$$\boxed{f_c = \frac{f_u}{A_{OL}}}$$

cutoff frequency in open loop.

Close loop Configuration

$f_c' \times A_{CL} = GBP$

again $GBP = f_u$

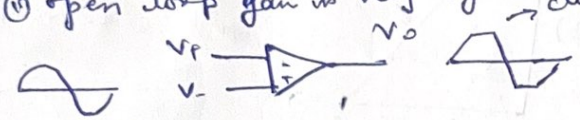
$$\Rightarrow \boxed{f_c' = \frac{f_u}{A_{CL}}}$$

cutoff frequency in closed loop

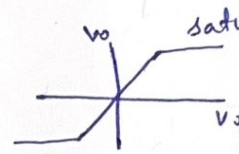
→ Feedback
- → +ve (used in Oscillators, Square wave generator
- → −ve (Amplifiers, adder, Subtractor, Integrator, Differentiator

Why we need feedback?

(i) open loop gain is very high. → clipping



large signal



(ii) open loop gain is not constant.
It changes c̄ temp. & power supply.

iii) Bandwidth.
For open loop Gain is high which implies.
BW is small. Such op-amp can't be used for ac application.

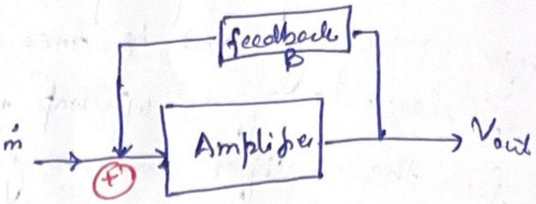
closed loop gain of op-amp: (A_{CL})

$$V_{out} = \overset{\text{Gain}}{A} \times V_{in}$$

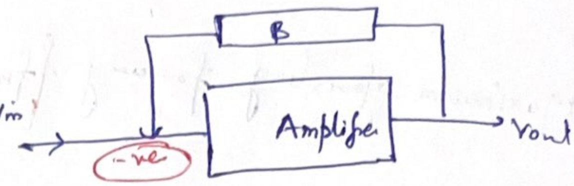
$$= A\,(V_{in} + \beta V_{out})$$

$$V_{out}(1 - A\beta) = A\,V_{in}$$

$$\boxed{A_{CL} = \frac{V_{out}}{V_{in}} = \frac{A}{1 - A\beta}}$$



Positive feedback.



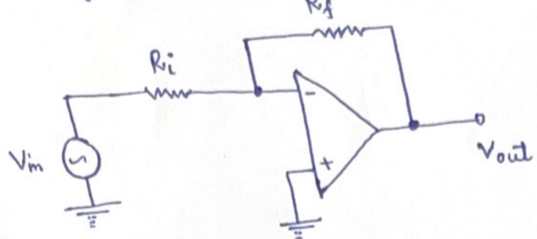
Negative feedback.

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

Applications of op amp:

Inverting Amplifier :-

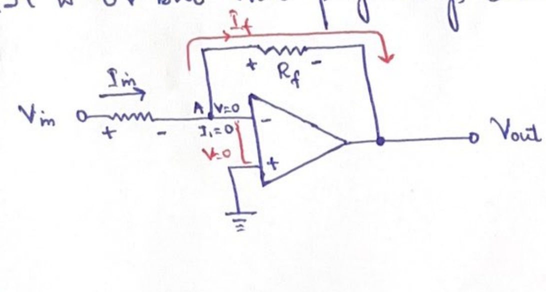
An op-amp can be operated as an inverting amplifier as in fig. 1.
An input signal v_{in} is applied through input resistance R_i to the inverting input (-ve). The output is fed back to the same (-ve) input throu' feedback resistor R_f.
The non-inverting (+ve) input is grounded.



$R_f \rightarrow$ provides the negative feedback.
Since, the input signal is applied to the inverting input, the output will be inverted (i.e 180° out of phase) as compared to input.
Hence the name inverting amplifier.

Voltage gain:

An op-amp has an infinite impedance, that means there is zero current at the inverting input. If there is zero current through the input, then there must be no voltage drop b/w the inverting & non-inverting inputs. which means the voltage at the inverting input is zero.
The 0V at the inverting input terminal (A) is referred as Virtual Ground. (It is 0V but not physically connected to the ground).



to

fig. 1, the current I_1 to the inverting input is zero. $(I_1 = 0)$

$\therefore$ current I_{in} flowing through R_i entirely flows through feedback resistor R_f.

i.e $I_f = I_{in}$.

as

$$I_{in} = \frac{\text{Voltage across } R_i}{R_i}$$

$$= \frac{V_{in} - V_A}{R_i}$$

$$I_{in} = \frac{V_{in}}{R_i} \quad (\text{as } V_A = 0). \rightarrow (1)$$

and

$$I_f = \frac{\text{Voltage across } R_f}{R_f}$$

$$= \frac{V_A - V_{out}}{R_f}$$

$$I_f = -\frac{V_{out}}{R_f} \quad (\text{as } V_A = 0) \longrightarrow (2)$$

We know, $I_{in} = I_f$.

$$-\frac{V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

$$\therefore \boxed{\text{Voltage gain } (A_{CL}) = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}}$$

-ve sign indicates that the output signal is inverted as compared to input signal.

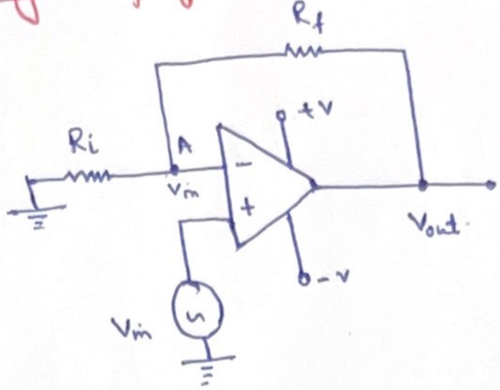
NOTE:

i) The closed-loop voltage gain (A_{CL}) is independent of op-amp internal open-loop voltage gain. The -ve feedback stablizes the voltage gain.

ii). If $R_f = R_i$, then A_{CL} is unity with $180°$ phase inversion.

iii) If R_f is some multiple of R_i, the amplifier gain is constant. Thus, the amplifier provides constant voltage gain.

Non-Inverting Amplifier :-



Voltage gain:

Voltage across $R_i = V_{in} - 0$

" " $R_f = V_{out} - V_{in}$

as $I_{in} = I_f$

$$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

$$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

$$V_{in} (R_f + R_i) = V_{out} R_i$$

$$\frac{V_{out}}{V_{in}} = \frac{R_f + R_i}{R_i}$$

$$= 1 + \frac{R_f}{R_i}$$

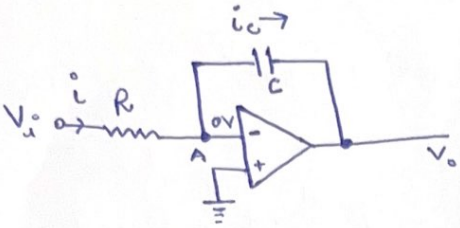
$\therefore$ closed-loop voltage gain, $\boxed{A_{cl} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_i}}$

→ Op-amp Integrator :-

A circuit that performs the mathematical integration of input signal is called as an Integrator.

The output of an integrator is proportional to the area of the input waveform over a period of time.

Fig. i shows the circuit of an op-amp Integrator.



(ideal).

Since point A is at virtual ground, voltage drop at A is 0V

Impedance is infinite, Thus all the input current i flows through the capacitor

$$\left[i = i_{op} + i_c \atop \quad\; \downarrow \atop \quad\; 0 \right]$$

i.e $\boxed{i = i_C}$

as
$$i = \frac{V_i - 0}{R} = \frac{V_i}{R} \rightarrow (1)$$

and voltage across capacitor c is $V_c = 0 - V_o = -V_o$

$$\because \left\{ \begin{array}{l} Q = CV_c \\ \frac{dQ}{dt} = C\frac{dV_c}{dt} \Rightarrow i_c = C\frac{dV_c}{dt} \end{array} \right\}$$

$$\therefore \quad i_c = C\frac{dV_c}{dt}$$

$$i_c = -C\frac{dV_o}{dt} \quad (\text{as } V_c = -V_o) \rightarrow (2)$$

from (1) & (2) $\quad i = i_c$

$$\frac{V_i}{R} = -C\frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = -\frac{1}{RC} V_i \longrightarrow (3)$$

to get output voltage, Integrate Eqn (3)

$$\boxed{V_o = -\frac{1}{RC}\int_0^t V_i \, dt}$$

which shows that output is integral of input signal with an inversion and scale multiplier of $1/RC$

Limitation:

Let us see, what will be the result for different frequencies.

The reactance across the capacitor is

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

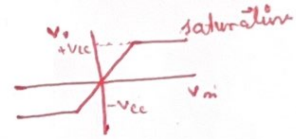
$$V_{out} = -\frac{X_C}{R} \times V_{in} \qquad \left(\because \text{In case of Inverting op-amp } V_{out} = -\frac{R_f}{R_{in}} \times V_{in}\right)$$

i.e $A_V = \frac{V_{out}}{V_{in}} = -\frac{X_C}{R} = \frac{1}{2\pi RCf}$

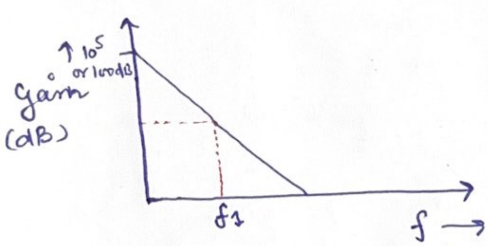
that means, $\boxed{A_V \propto \frac{1}{f}}$

for 0Hz or lower frequencies gain of op-amp is very high i.e Ideally it is infinite and practically the gain of the op-amp is limited by the open-loop gain of the op-amp.

at 0 Hz the capacitor act as a open circuit and because of that the input signal is amplified by the open loop gain of the op-amp, so output will get always saturated.



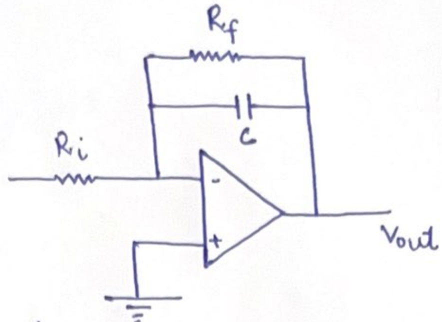
i.e



(frequency response of Ideal Integrator)

- At zero Hz the gain of integrator op-amp is equal to the open loop gain of the op-amp (i.e $10^5 - 10^6$), and as f ↑es gain will ↓es.
- Now, let's use the op-amp at frequency f_1, then one should not face the very high gain. But it is quite possible that at this frequency, the output gets saturated or distorted. The reasons is the Input offset voltage of the op-amp.

in Practical every kind of op-amp has some input voltage i.e a few millivolts of input offset voltage is present at the input terminal which is integrated by the capacitor and eventually the output will reach saturation. So to avoid this saturation, we introduce a feedback resistance ||ar c̄ the capacitor.

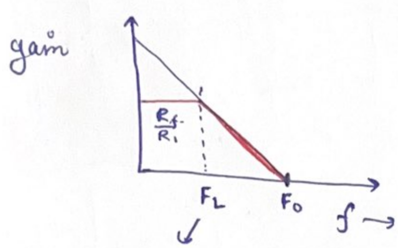


(Practical Integrator using op-amp)

So at low frequencies the C act as a ~~op-amp~~ open circuit

So at low frequencies the gain is

$$\boxed{A_v = -\frac{R_f}{R_i}}$$



cut off frequency.

$$\boxed{f_L = \frac{1}{2\pi R_f C}} \quad , \quad f_o = \frac{1}{2\pi RC}$$

So, for proper integration of a signal the frequency of op-amp show lies b/w f_L + f_o.

eg. 1: $V_{in} = \sin t$.

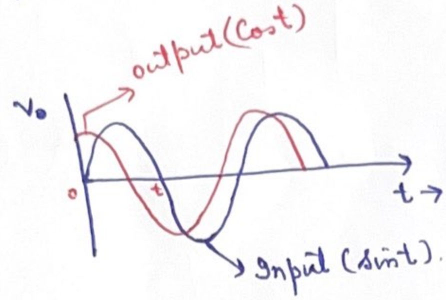
$$V_o = -\frac{1}{RC}\int_0^t v_i\,dt$$

Let assume $R = 1\,M\Omega$ & $C = 1\,\mu F$. $\Rightarrow RC = 1$.

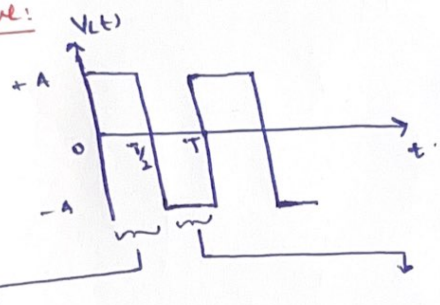
$$V_o = -\int \sin(t)\,dt$$

$$= -(-\cos t).$$

$$V_o = \cos t$$



2. Square wave:



$V_{in}(t) = A \quad 0 < t < \frac{T}{2}$

$$V_o = -\int_0^{T/2} A\,dt$$

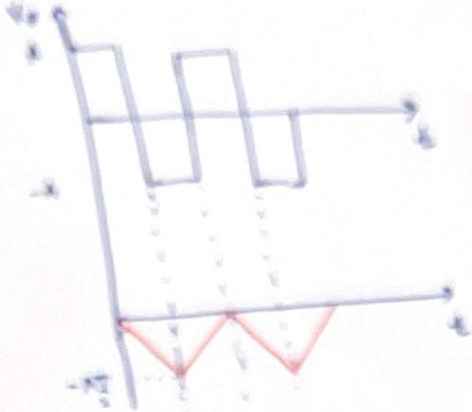
$$= A[t]_0^{T/2}$$

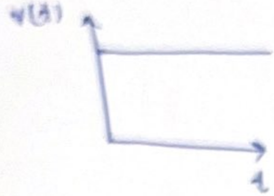
$$\boxed{V_o = -\frac{AT}{2}}$$

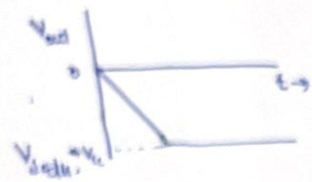
$V_{in}(t) = -A \quad \frac{T}{2} < t < T$

$$V_o = -\int_{T/2}^{T} -A\,dt$$

$$\boxed{V_o = \frac{AT}{2}}$$

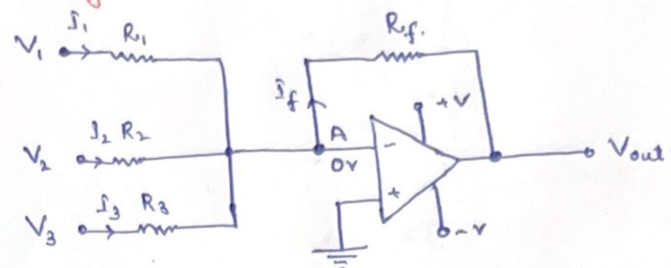






The Summing Amplifiers / op-amp voltage adder:-

i) Inverting:-



A summing amplifier is an Inverted op-amp that can accept two or more inputs. The ~~input~~ output voltage of a summing amplifier is proportional to the negative of the algebraic sum of its input voltages. Hence the name Summing amplifier. (or op-amp voltage adder).

Circuit Analysis:

Here $I_f = I_1 + I_2 + I_3$

$$V_{out} = -I_f R_f$$

$$= -R_f (I_1 + I_2 + I_3)$$

thus.

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

If.
i) $R_1 = R_2 = R_3 = R$, then

$$V_{out} = \frac{-R_f}{R} (V_1 + V_2 + V_3)$$

i.e output voltage is proportional to the algebraic sum of the input voltage.

ii) If gain is unity. ($A_v = 1$).
then in such case $R_1 = R_2 = R_3 = R_f$

So, that $\boxed{V_{out} = -(V_1 + V_2 + V_3)}$ $\left(\text{as } A_v = -\frac{R_f}{R} = 1 \right)$.

iii) Gain is greater than unity: ($A_v > 1$)

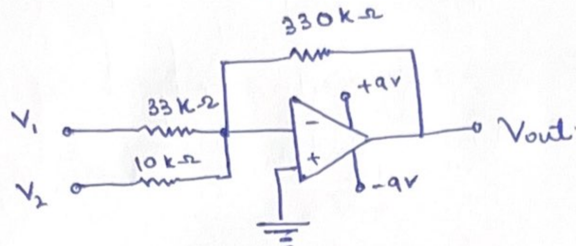
In such case, the ~~#~~ R_f is larger than the input resistors. The general expression for the output voltage is

$$V_{out} = -\frac{R_f}{R_s}(V_1 + V_2 + V_3 + \cdots)$$

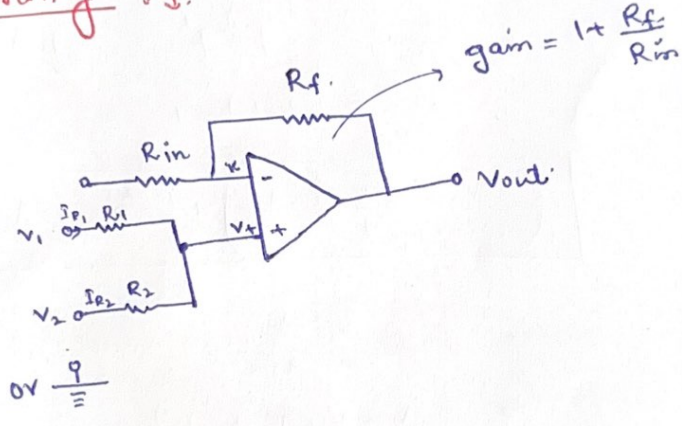
example: Calculate the output voltage for the circuit of fig. 1.

The inputs are $V_1 = 50 \sin(1000t)\,mV$

$V_2 = 10 \sin(3000t)\,mV$.



ii) Non-Inverting :-



here $I_{R_1} + I_{R_2} = 0$ (KCL)

$$\frac{V_1 - V_+}{R_1} + \frac{V_2 - V_+}{R_2} = 0$$

$$\therefore \left(\frac{V_1}{R_1} - \frac{V_+}{R_1}\right) + \left(\frac{V_2}{R_2} - \frac{V_+}{R_2}\right) = 0 \quad \rightarrow (1)$$

→ If $R_1 = R_2 = R$
then Eqn. (1) becomes

$$V_+ = \frac{\frac{V_1}{R} + \frac{V_2}{R}}{\frac{1}{R} + \frac{1}{R}}$$

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

Then,

$$\boxed{V_+ = \frac{V_1 + V_2}{2}}$$

Now, for non-inverting voltage gain is given as

$$A_v = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_{in}}$$

i.e. $V_+ = V_{in}$

So

$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right) V_+$$

Thus,

$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right)\left(\frac{V_1 + V_2}{2}\right)$$

→ If $R_f = R_{in}$, then.
Then, in such case, the output voltage (V_o) becomes
Equal to the sum of the input voltage.

$$V_{out} = 2 \times \frac{V_1 + V_2}{2}$$

$$\boxed{V_{out} = V_1 + V_2.}$$

Comparators :-

In the case, where we want to see or Compare one voltage to another, which one is larger. In Such cases we use a Comparator. It is an op-amp circuit without negative feedback and take advantage of very high open-loop gain of an op-amp.

∵ of The high-open loop voltage gain, a very Small difference voltage b/w the two inputs drives the amplifier to Saturation.

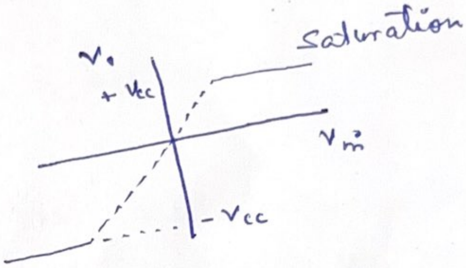
e.g. If gain is $A_{OL} = 10^5$

voltage difference is only 0.25 mV

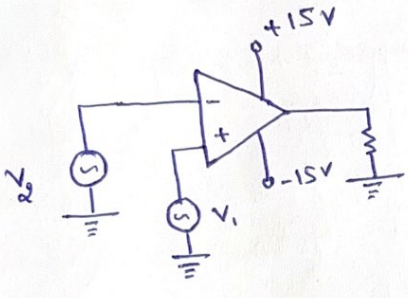
then $V_o = \text{gain} \times V_{in}$

$= 10^5 \times 0.25\,mV$

$V_o = 25\,V$.



Circuit Diagram :



* It Compares V_1 & V_2 to produce a saturated positive or negative output voltage.

If $V_1 > V_2 \longrightarrow +V_{sat}$

$V_1 < V_2 \longrightarrow -V_{sat}$.

i.e $+V_{sat} = +V_{supply} - V_o$

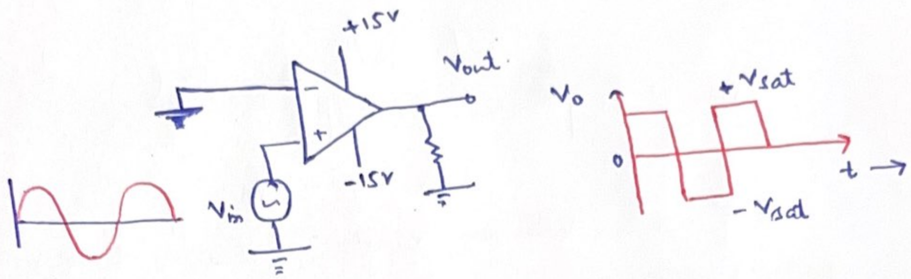
$-V_{sat} = -V_{supply} + V_o$

Characteristics of a Comparator circuit:-

i) It uses no feedback so that the voltage gain is equal to the open-loop voltage gain (A_{OL}) of an op-amp.

ii) It is operated in a non-linear mode.

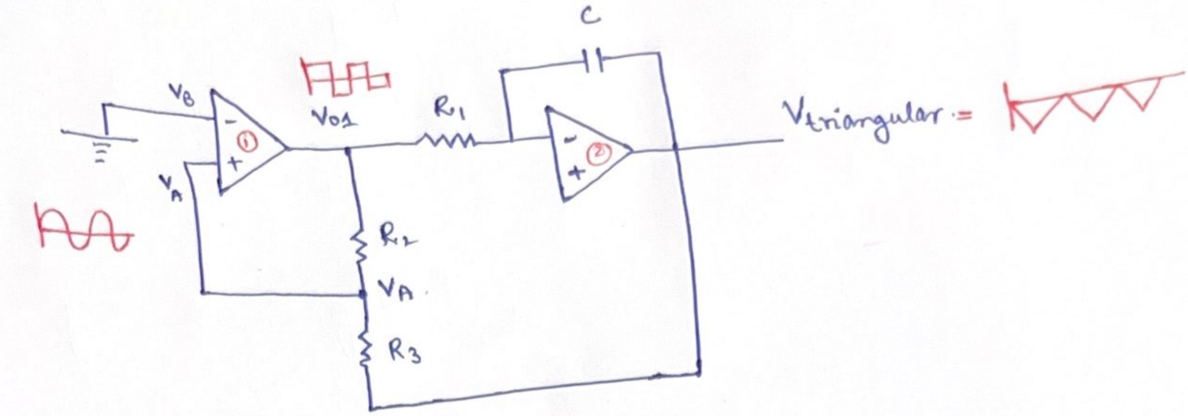
Square wave generator :-



here at non-inverting terminal Vin is applied and inverting terminal is grounded.

Since, gain of comparator is A_{OL}, Virtually any difference voltage at the inputs will cause the output to go to one of the voltage extremes (i.e V_+ or V_- saturation). The polarity of the input voltage difference will determine to which extreme (+V or -V saturation) the output of the comparator goes.

Triangular wave generator :-



i.e → Comparator → Integrator →

① op-amp 1 acts like comparator, So V_{o1} may be +ve or -ve Saturation depending on the input differences.

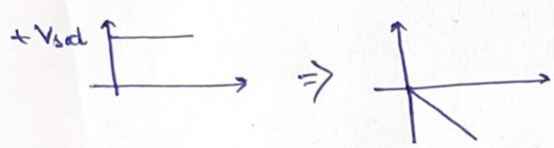
If

$V_A > 0$ i.e $V_A - V_B > 0 \Rightarrow +V_{sat} = V_{o1}$.

$V_A < 0$ i.e $(V_A - V_B) < 0 \Rightarrow -V_{sat} = V_{o1}$

② op-amp ② acts as an Integrator.

If $V_{o1} = +V_{sat}$ then $V_{triangular}$ = -Ve going ramp.



If $V_{o1} = -V_{sat}$ then V_{tri} = +Ve going ramp