

OP- Amps and Linear IC Applications.

Introduction:

- * Operational amplifiers, also known as OP-Amps are voltage amplifying device designed to be used with components like capacitors and resistors between i/p and o/p terminals.
- * They are high-gain amplifiers consisting of one or more differential amplifiers.
- * They are often used in signal conditioning, filtering and operations (mathematical) such as addition, subtraction, multiplication, integration and differentiation.
- * OP-Amps are the most useful device in analog electronic circuitry. With only a few external components it can be made to perform a variety of analog signal processing tasks. It can amplify both ac and dc signals.

History:

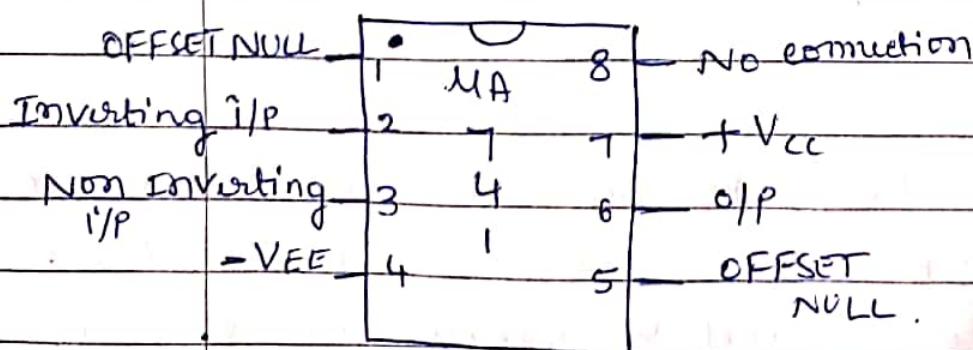
In 1963, the first monolithic integrated circuit (IC) or OP-Amp IC was introduced. It was MA702 from Fairchild Semiconductors - designed by an engineer Bob Widlar.

- * In 1965 it was refined and renamed as UA709. It was the first OPamp that was widely used. In 1968 some of the instability issues in UA709 was resolved and the IC was re-introduced by the name as UA741. It is a widely used IC for many applications and is still manufactured to this day by some of the companies.

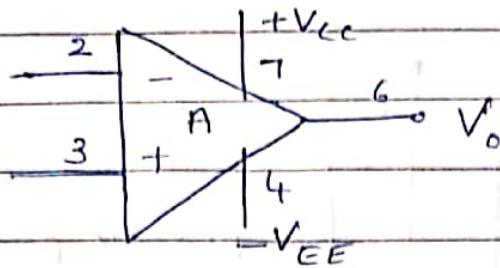
NOTE $\mu\text{A} \rightarrow$ (micro amperes)

- * Op Amp is a very high gain negative feedback amplifier that can amplify signals having wide range of frequencies.
- * With the addition of suitable external feedback components, OPamps can also be used for variety of applications such as signal amplification, filters, oscillators, regulators, comparators etc.

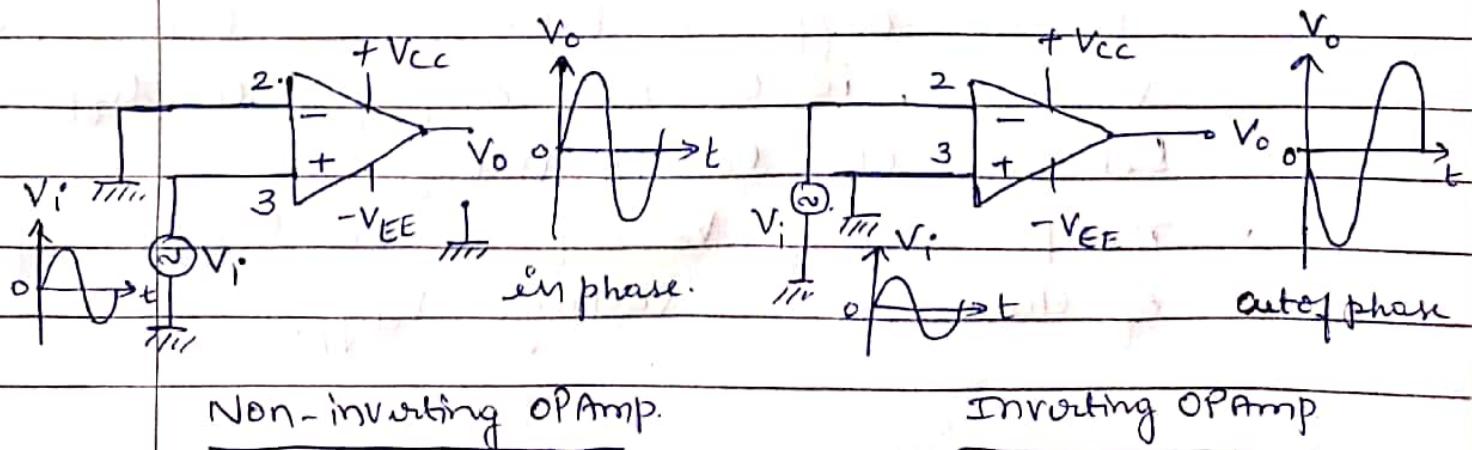
IC diagram : 8 pin IC package of OPamp



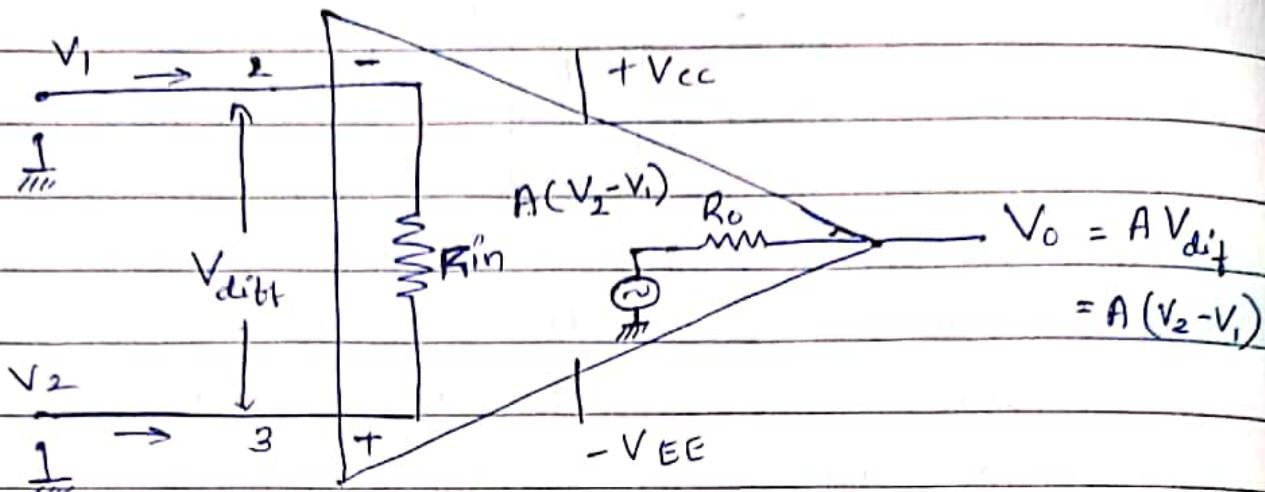
Schematic Symbol of OP-Amp



- + Figure shows the schematic symbol of OP-Amp.
It has 2 inputs and one output terminal.
- + The input with +ve sign is called non-inverting terminal and that with -ve sign is called inverting terminal.
- + The output voltage V_o is in phase with input if the signal is connected to the non inverting terminal.
- + The output voltage V_o is out of phase with the input if the signal is connected to the inverting terminal.
- + $+V_{cc}$ and $-V_{ee}$ are dc power supply terminals. 'A' indicates open-loop gain or open-loop voltage gain of OP-Amp.



Equivalent circuit of an OP-Amp



In the above equivalent circuit, the o/p voltage V_o is given by

$$\begin{aligned} V_o &= A V_{\text{diff}} \\ &= A(V_2 - V_1) \quad \text{--- (1)} \end{aligned}$$

where $V_{\text{diff}} \rightarrow$ differential i/p voltage.

$V_2 \rightarrow$ Voltage at the non inverting terminal w.r.t ground.

$V_1 \rightarrow$ voltage at the inverting terminal. wrt ground.

- * In eq.(1) o/p V_o is directly proportional to the difference between the two input voltages. i.e Op-Amp amplifies the difference between the two i/p voltages.
- * The polarity of V_o depends on the polarity of the difference voltage V_{diff} .

A graph of V_o versus input difference voltage V_{diff} is plotted by keeping A constant.

- * The o/p voltage V_o cannot exceed the positive and negative saturation voltages $+V_{cc}$ & $-V_{ee}$. Hence the o/p V_o is directly proportional to the input difference voltage V_{diff} until it reaches the saturation voltages & later it remains constant as shown in transfer characteristic of OP-Amp in fig below.
- * Since opm loop gain A is very large, a small difference input voltage V_{diff} will produce a large swing as the output voltage that may reach $\pm V_{sat}$ ($+V_{cc}, -V_{ee}$)

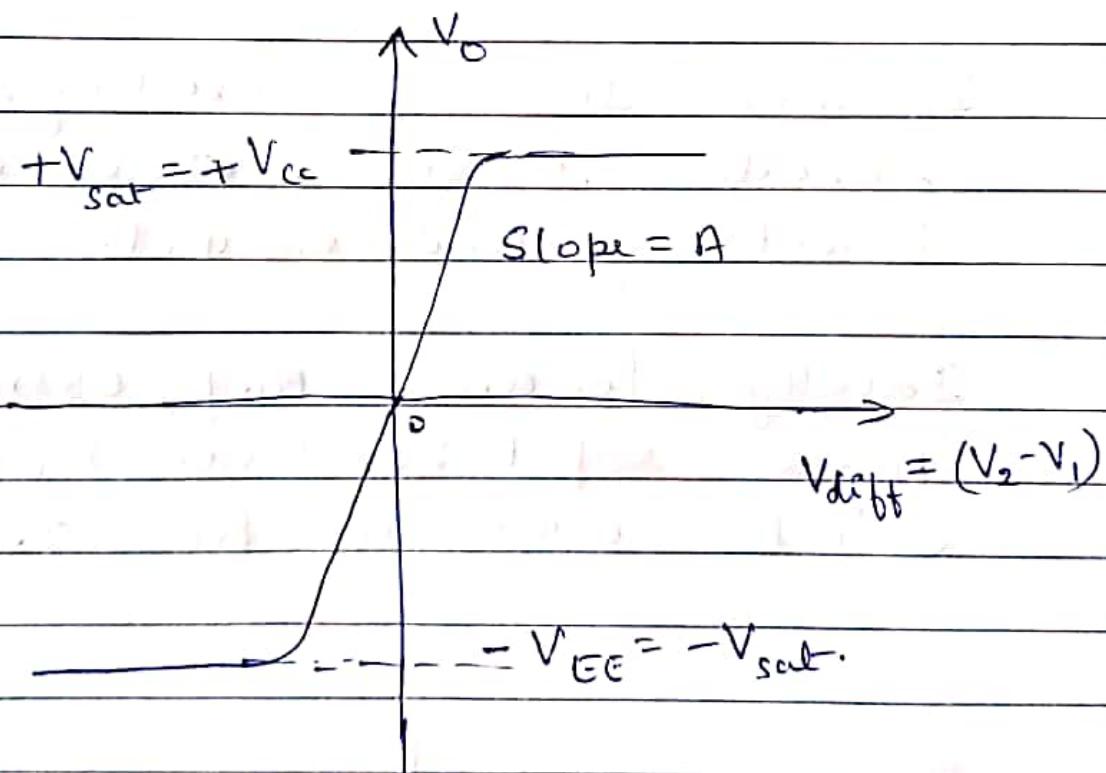
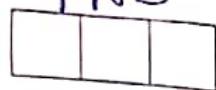


Fig: Transfer characteristics of an OP-Amp.



From the equivalent circuit,

$$V_o = A V_{\text{diff}}$$

$$= A (V_2 - V_1)$$

$$\text{or } (V_2 - V_1) = \frac{V_o}{A}$$

Ideally, the open loop voltage gain A of an OP-Amp is infinity ($A = \infty$)

$$\therefore (V_2 - V_1) = \frac{V_o}{\cancel{A}} = \frac{V_o}{\infty} = 0$$

$$\Rightarrow (V_2 - V_1) = 0$$

$$\text{or } \underline{V_2 = V_1}$$

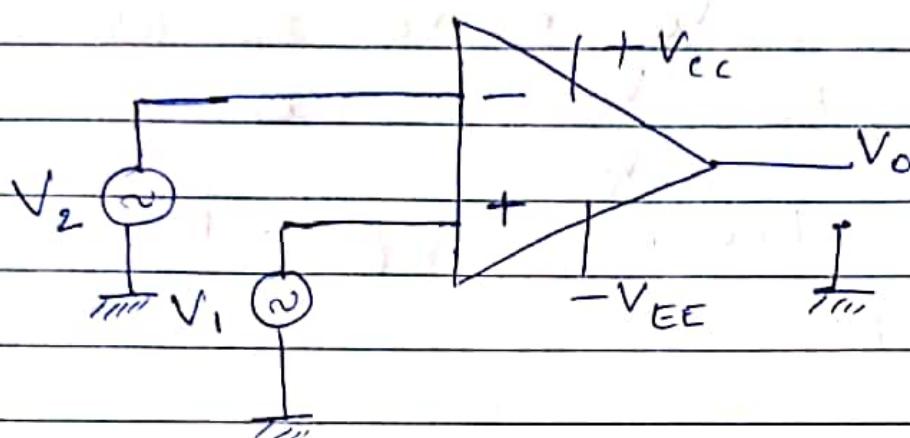
It means that the inverting and non-inverting terminals are at same potential w.r.t ground terminal.

Ideally, for an OP-Amp, open-loop gain $A = \infty$, input resistance $R_i = \infty$ and output resistance $R_o = 0$.

Differential Amplifier.

Op-Amp differential amplifier is an amplifier that amplifies the difference between two i/p voltage levels.

- Circuit diagram is as shown below.



- Here V_1 and V_2 are the i/p signals and V_o is the o/p signal each measured w.r.t ground.
- The o/p voltage is V_o and is directly proportional to the difference b/w the 2 i/p signals. Hence, we can write

$$V_o \propto (V_1 - V_2) \quad \text{--- (1)}$$

- Differential gain (A_d) :

Equation (1) can be written as

$$V_o = A_d (V_1 - V_2) \quad \text{where } A_d \text{ is}$$

a constant of proportionality and is known as the differential gain of the amplifier.

* Differential Voltage (V_d) :

The difference between the 2 i/p voltages ($V_1 - V_2$) is called as differential voltage or difference voltage and is denoted as V_d .

$$\text{ie } V_d = V_1 - V_2 \quad \text{--- (3)}$$

\therefore equation (2) can be rewritten as

$$V_o = A_d V_d \quad \text{--- (4)}$$

$$\text{or } A_d = \frac{V_o}{V_d} \quad \text{--- (5)}$$

Eq.(5) is known as differential gain of an opamp.

* Common mode gain (A_c) :

The gain with which the differential amplifier amplifies the common mode signal to produce the output voltage is called as common mode gain A_c .

* When 2 i/p voltages are applied as inputs to an opamp that are equal, ie $V_1 = V_2$ then the output voltage $V_o = (V_1 - V_2)$ must be zero. (ideal opamp).

* But the output voltage of a practical differential amplifier not only depends on difference voltage, but also depends on average common level of 2 i/p voltages.

Common mode voltage (V_c):

Such an average level of i/p voltages is called as common mode voltage V_c .

$$\therefore V_c = \frac{V_1 + V_2}{2} \quad -(6)$$

Hence the output voltage V_o due to a common mode voltage V_c with a common mode gain A_c is given by

$$V_o = A_c V_c. \quad -(7)$$

$$\text{or } A_c = \frac{V_o}{V_c} \quad -(8)$$

Hence there exists some finite output for $V_1 = V_2$ due to common mode gain A_c in case of practical differential amplifiers.

So the overall (total) o/p of any differential amplifier can be expressed as

$$V_o = A_d V_d + A_c V_c \quad -(9)$$

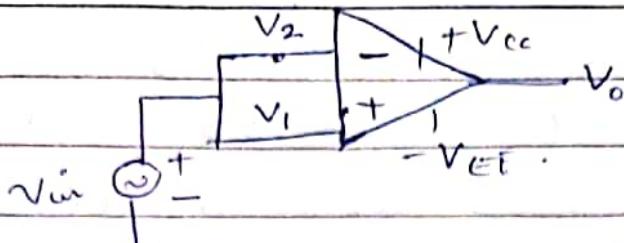
Op-Amp Parameters:

Common mode rejection ratio (CMRR):

CMRR is defined as the ratio of the differential gain A_d to the common mode gain A_c .

$$\therefore CMRR = \frac{A_d}{A_c} \quad -(1)$$

When same voltages are applied to both the i/p terminals of a differential amplifier, it is said to be operating in common mode configuration



As shown in the figure, when 2 i/p terminals of an OP-Amp are shorted and a common signal V_{in} is applied as the i/p b/w the two terminals and ground, the o/p V_o must be zero.

$$\text{ie } V_o = A(V_1 - V_2)$$

$$= A(V_{in} - V_{in})$$

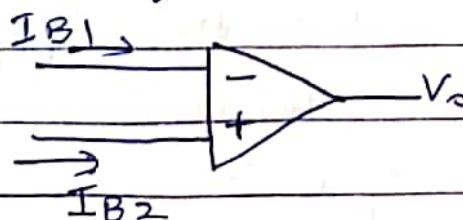
$$= 0$$

But in practical, the output voltage V_o is non-zero and the ratio of the output voltage V_o to the input voltage V_{in} is known as common mode gain A_c . Since CMRR is very large, it can be expressed in dB. (decibel)

$$\text{CMRR}_{dB} = 20 \log_{10} \left| \frac{A_d}{A_c} \right|_{dB} - (2)$$

2. Input bias current : (I_B) :

It is the average value of the current that flows into the inverting and non inverting i/p terminals of the OP-Amp.



\therefore Input bias current is

$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

3. Input offset current (I_{io}):

It is the algebraic difference between the currents flowing into inverting and non-inverting terminals.

i.e. Input offset current

$$I_{io} = |I_{B1} - I_{B2}|$$

4. Input offset voltage (V_{io}):

It is the voltage that must be applied between the two i/p terminals such that the o/p voltage becomes zero.

5. Input impedance (R_i):

It is the equivalent resistance that can be measured at either the inverting or non-inverting terminal with the other terminal connected to ground.

6. Output impedance (R_o):

It is the equivalent resistance that can be measured between the output terminal of OPAMP and the ground.

7. Slew rate (S):

It is defined as maximum rate of change of o/p voltage per unit time.

$$\text{Slew rate} = \frac{dV_o}{dt} / V_{\text{max}}$$

Ideal OPAMP characteristics

1. Infinite voltage gain ($A_{OL} = \infty$)

It is the differential open loop gain.

$$\text{Wkt } V_o = A(V_1 - V_2)$$

$$\text{or } \frac{V_o}{A} = V_1 - V_2. \text{ if } V_1 = V_2 = 0,$$

$$\text{then, } \frac{V_o}{A} = 0.$$

$$\text{or } \frac{V_o}{0} = A = \infty = \underline{A_{OL}}$$

2. Infinite input impedance (R_i) :

An ideal Op-Amp draws no current at both the i/p terminals.

$$\text{i.e. } I_1 = I_2 = 0$$

$$R_i = \frac{V_{in}}{I_i} = \frac{V_{in}}{0} = \infty.$$

Thus its input impedance is infinity. This ensures that no current can flow through an ideal OP-Amp.

3. Zero output impedance ($R_o = 0$)

4. Zero input offset voltage. ($V_{io} = 0$).

5. Zero input offset current ($I_{io} = 0$)

If $I_{B1} = I_{B2} = 0$,

then $I_{io} = |I_{B1} - I_{B2}| = 0$.

6. Infinite Bandwidth. ($BW \approx \infty$)

It is the range of frequencies over which the o/p of OP-Amp is constant.

7. Infinite CMRR: ($CMRR = \infty$)

The ratio of differential gain A_d to common mode gain A_c is defined as CMRR.

$$\text{ie } CMRR = \frac{A_d}{A_c}$$

if $CMRR = \infty$, then $\frac{A_d}{A_c} = \infty = CMRR$

This implies that an ideal opamp ensures zero common mode gain ($A_c = 0$)

8. Infinite Slew rate ($S = \infty$)

Slew rate indicates how fast the o/p of an OP-Amp can change in response to changes in the input signal frequency.

Higher the Slew rate, better is the performance of the OP-Amp. (S depends on $f + V_{in}$).

Hence ideally it is infinity. (∞)



9. Zero input bias current. (I_B)

$$\text{if } I_{B1} = I_B = 0, \\ I_B = \frac{I_{B1} + I_{B2}}{2} = 0.$$

NOTE : Practical values:

Voltage gain ($A_{OL} = 2 \times 10^5$)

Input impedance ($R_i = 2M\Omega$)

Output impedance ($R_o = 75\Omega$)

Input offset voltage ($V_{IO} = 2mV$)

Input offset current ($I_{IO} = 20nA$)

Bandwidth ($BW = 1MHz$)

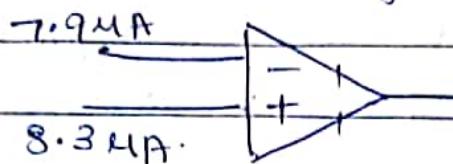
CMRR ($CMRR = 90dB$)

Slew Rate ($s=\infty$) = $0.5V/\mu\text{sec}$

Input bias current $I_B = 84\mu A$.

Numericals:

1. Determine the input bias current and input offset current I_B & I_{IO} to an OPAMP if the current into noninverting terminal is 8.3mA & inverting terminal is 7.9mA .



$$I_B = \frac{I_{B1} + I_{B2}}{2} = \underline{8.1\text{mA}}$$

$$I_{IO} = |I_{B1} - I_{B2}| = |8.3\text{mA} - 7.9\text{mA}| = \underline{0.4\text{mA}}$$

2. A certain OP Amp has a differential voltage gain of $1,00,000$ and common mode gain of $A_c = 0.25$. Determine CMRR & express it in dB.

Given $A_d = 1,00,000$.

$$A_c = 0.25$$

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{1,00,000}{0.25} = 4,00,000$$

$$\text{in dB, } \text{CMRR}_{\text{dB}} = 20 \log_{10} (4,00,000) = \underline{112.04 \text{ dB}}$$

3. An OP Amp has a differential voltage gain of $2,500$ and a CMRR of $30,000$.

- Determine common mode gain A_c
- Express CMRR in dB

given $A_d = 2500$ CMRR = 30,000

$$i) \text{ CMRR} = \frac{A_d}{A_c}$$

$$\therefore A_c = \frac{A_d}{\text{CMRR}} = \frac{2500}{30,000} = \underline{\underline{0.083}}$$

$$ii) \text{ CMRR in dB} = 20 \log_{10} (30,000)$$

$$= \underline{\underline{89.54 \text{ dB}}}$$

4. An OPamp has a common mode input signal of 3.2V to both the input terminals. This results in an o/p signal of 26mV. Determine common mode gain A_c & CMRR in dB. given that the differential gain is 100.

$$\text{given } V_c = 3.2V, V_o = 26 \text{ mV}$$

$$A_c = \frac{V_o}{V_c} = \frac{26 \text{ mV}}{3.2V} = \underline{\underline{0.0081}}$$

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{100}{0.0081} = \underline{\underline{12345.6}}$$

$$\therefore \text{CMRR}_{\text{dB}} = 20 \log_{10} (12345.6)$$

$$= \underline{\underline{81.83 \text{ dB}}}$$

Virtual ground concept.

Virtual ground means, the differential i/p voltage V_d between the non-inverting and inverting terminal is zero.

Eg: If o/p voltage is 10V, Open loop gain ie A_{OL} is 10^4 , then

$$V_o = A_{OL} V_d.$$

$$V_d = \frac{V_o}{A_{OL}} = \frac{10}{10^4} = 1mV.$$

Hence, V_d is very small

It means that- $A_{OL} \rightarrow \infty$ (large)
The difference voltage $V_d \rightarrow 0$ (small)
and in practice is assumed to be zero.

$$\therefore V_{d1} = \frac{V_o}{A_{OL}}$$

$$\Rightarrow (V_1 - V_2) = \frac{V_o}{\infty} = 0.$$

$$\Rightarrow V_1 = V_2.$$

i.e There exists a virtual short circuit between the two i/p terminals, in the sense that these voltages are the same.

So if one terminal is at ground (grounded), other terminal is at virtual

ground. If one terminal is at a particular voltage level, the other terminal is at the same voltage level. This is the concept of virtual ground.

Saturable property of an OP-Amp.

- * The property by which OP-Amp output saturates at two saturation levels ($\pm V_{sat}$) decided by the supply voltage is called as saturable property of OP-Amp.
- * Every OPamp has a property that its o/p can swing between two levels decided by supply voltage. i.e $+V_{cc}$ & $-V_{EE}$
- * Thus if the output tries to rise more than $+V_{cc}$ or less than $-V_{EE}$, then the output signal gets clipped off and shows that saturation limit has reached. Output signal cannot be produced exceeding the saturation voltage levels.

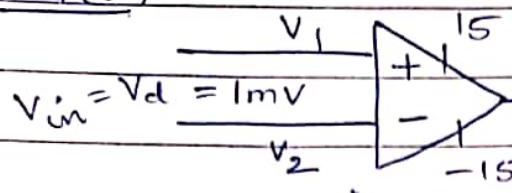
Eg: Problem: Let a sine wave of 1mV-pp be applied as the i/p to OP-Amp with gain $A_{OL} = 10^5$. Then the o/p voltage is obtained as a wave that is clipped at

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$$\pm V_{sat} = \pm 15V.$$

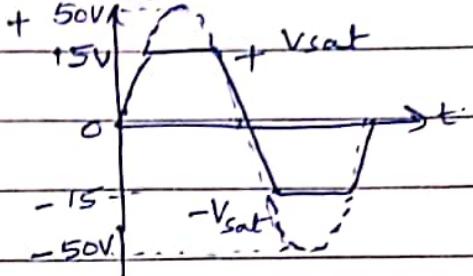
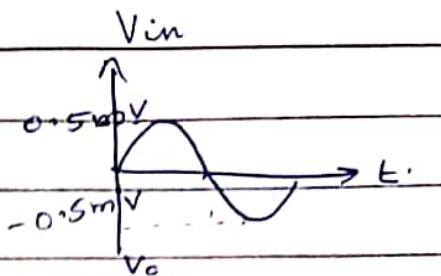
Solution

$$V_o = A_{OL} V_d.$$

$$= 10^5 \times 1mV$$

$$= 10^5 \times 1 \times 10^{-3}$$

$$= 100V_{p-p}$$



This saturable property of OP-Amp can be effectively used to obtain a device called as comparator.

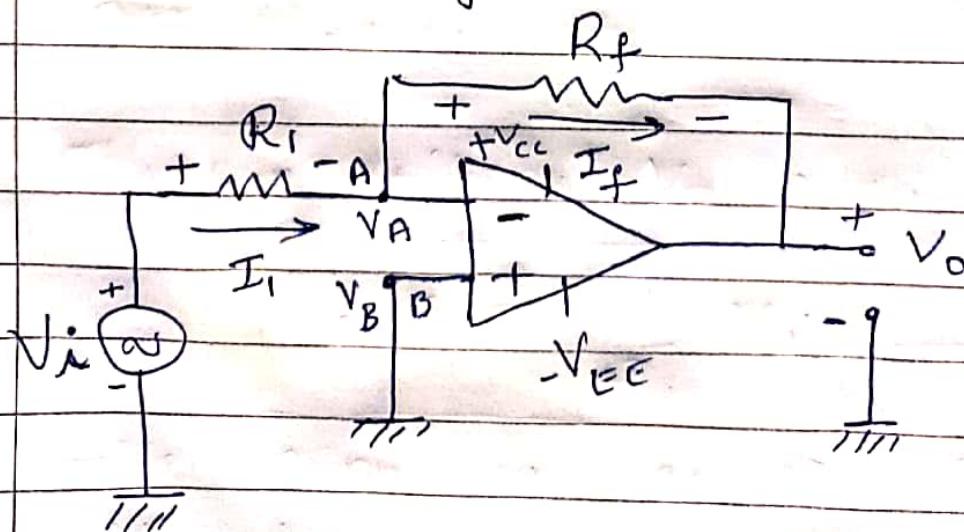
OP-Amp Applications.

1. Inverting amplifier
2. Non Inverting amplifier
3. Voltage follower
4. Inverting Summator
5. Integrator
6. Differentiator
7. Comparator
8. IC Voltage regulator.

1. Inverting amplifier.

An Amplifier that has a phase shift of 180° at the o/p compared to that of the applied i/p signal is known as inverting amplifier.

Circuit diagram.



In the circuit figure shown, V_i is applied to the inverting terminal through the resistor R_1 . The non-inverting terminal is grounded.

A feedback from the output to the inverting i/p terminal is provided through the resistor R_f .

Since the non-inverting terminal is grounded, potential at node B is V_B & $V_B = 0$.

According to virtual ground concept, node A is at virtual short with node B. Therefore $V_A = 0$.

$$\Rightarrow V_A = V_B = 0.$$

From the i/p side, applying KVL, we have

$$V_i - I_1 R_1 - V_A = 0.$$

$$\text{or } I_1 = \frac{V_i - V_A}{R_1}$$

$$V = \frac{V_i}{R_1} \quad \text{--- (1)} \quad \therefore V_A = 0.$$

From the o/p side, applying KVL,

$$V_A - I_f R_f - V_o = 0$$

$$\text{or } I_f = \frac{V_A - V_o}{R_f}$$

$$= -\frac{V_o}{R_f} \quad \text{--- (2)} \quad \because V_A = 0.$$

Since current flowing through i/p terminals of an OP-Amp is zero, entire current I_i flows through R_f as I_f .

\therefore equating (1) and (2) we have

$$I_i = I_f$$

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

. or
$$\left| \frac{V_o}{V_i} = -\frac{R_f}{R_i} = A \right|$$
 is the — (3)

closed loop gain of an inverting amplifier.

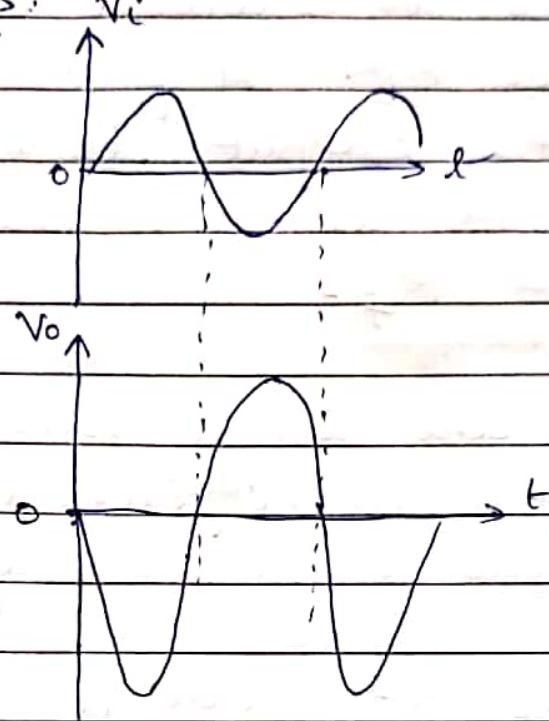
The o/p voltage V_o is given by

$$\left| V_o = -\frac{R_f}{R_i} V_i \right| \quad \text{--- (4)}$$

-ve sign in eq (4) indicates the presence of phase shift

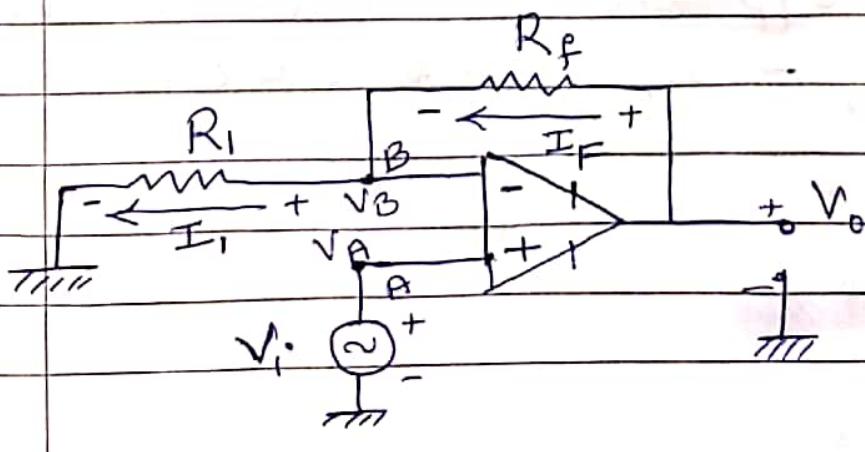
of 180° b/w i/p and o/p signal
 V_i and V_o .

waveforms:



2. Non Inverting Amplifier.

An amplifier that amplifies the input signal V_i without generating any phase shift between i/p and o/p is called as non inverting amplifier.
circuit diagram.



In the circuit diagram, V_i is connected to the non-inverting terminal of the Op-amp. Inverting terminal is connected to ground through the resistor R_1 . A feedback is provided from the output to the inverting terminal through the feedback resistor R_f .

From the input side, node A is connected to the ^{non}inverting terminal and also to the i/p signal V_i .

Hence, at node A, $V_A = V_i$.

According to virtual ground concept, potential at node B is same as potential at node A. ie

$$V_B = V_A = V_i.$$

$$\Rightarrow V_B = V_i \quad \text{--- (1)}$$

From o/p side we have, (kvl)

$$V_o - I_f R_f - V_B = 0.$$

$$\text{or } I_f = \frac{V_o - V_B}{R_f} = \frac{V_o - V_i}{R_f} \quad \text{--- (2)}$$

At the inverting terminal, we have,

$$V_B - I_1 R_1 = 0.$$

$$\text{or } I_1 = \frac{V_B}{R_1} = \frac{V_i}{R_1} \quad \text{--- (3)}$$

Current flowing through i/p terminals of an OP-Amp is zero.

Therefore, entire current I_f through R_f also flows through R_1 as I_1 .

$$\therefore I_f = I_1$$

equating ② and ③ we have

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

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

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

Simplifying the above eqn we get,

$$\boxed{\frac{V_o}{V_i} = A = 1 + \frac{R_f}{R_1}} \quad \text{is the gain} \quad \text{--- (4)}$$

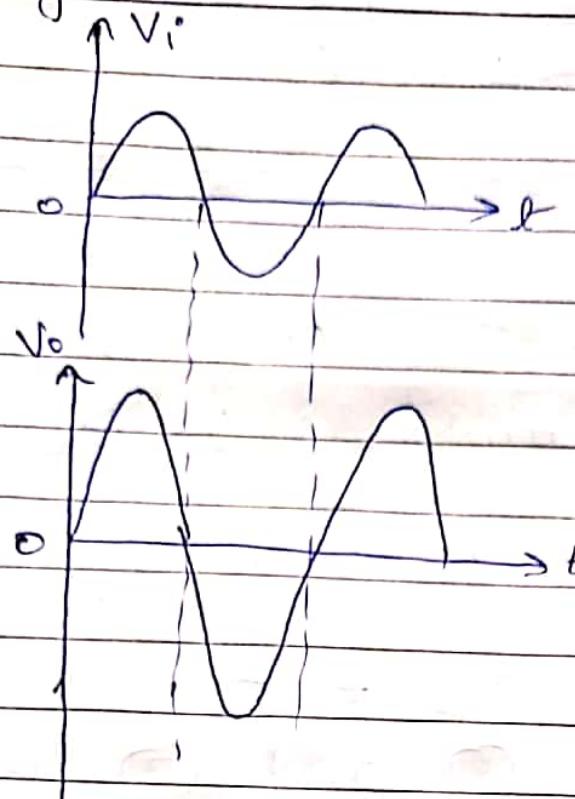
of a non-inverting amplifier.

and

$$\boxed{V_o = V_i \left(1 + \frac{R_f}{R_1} \right)} \quad \text{--- (5)}$$

Eq (4) indicates the closed loop gain.

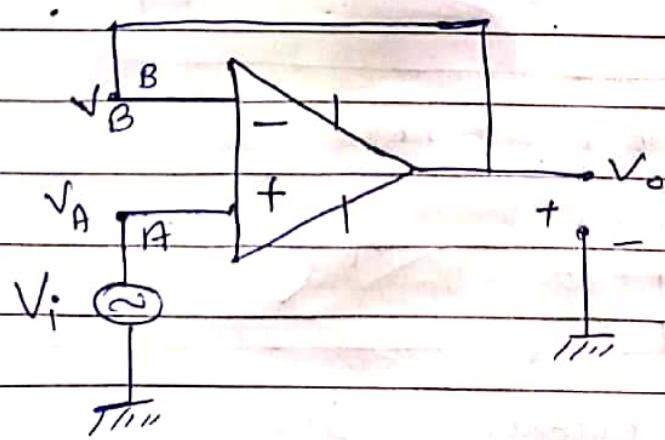
Wavforms



3. Voltage follower.

An voltage follower is a circuit in which o/p voltage V_o follows the applied i/p voltage V_i .

Circuit diagram.



In the circuit diagram non-inverting terminal is connected to the input signal V_i .

Hence at node A, $V_A = V_i$.

Node B is at virtual short with node A.

According to virtual ground concept,

$$V_B = V_A = V_i$$

$$\Rightarrow V_B = V_i$$

Output terminal is connected to the inverting terminal.

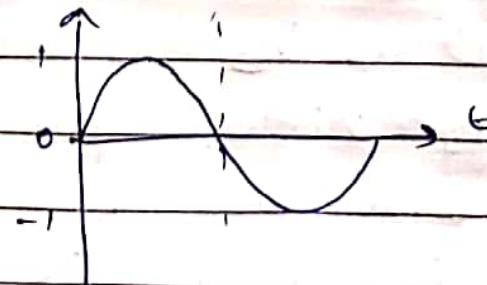
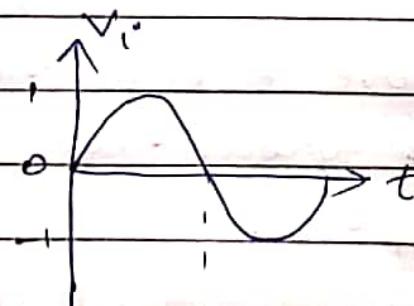
$$\therefore V_o = V_B = V_i$$

$$\Rightarrow V_o = V_i$$

or $\left| \frac{V_o}{V_i} \right| = 1$

Hence voltage follower is known as a unity gain amplifier or a buffer amplifier.

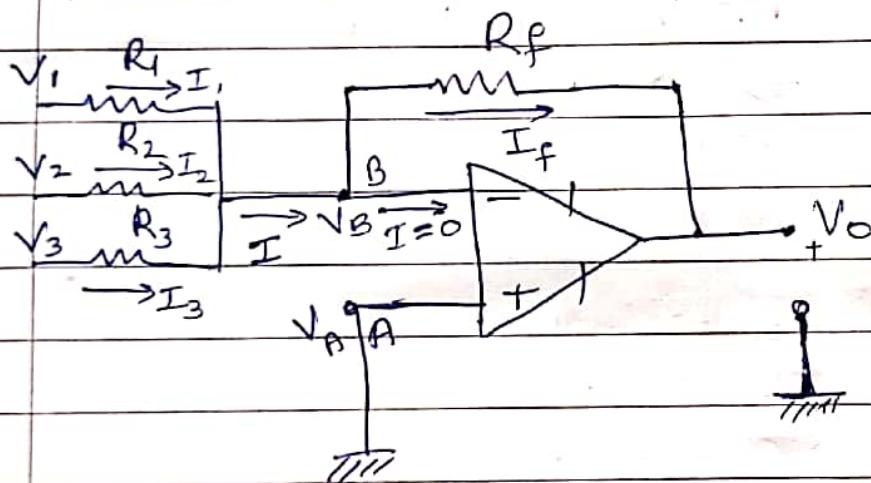
Waveforms.



4. Inverting summer / adder.

In this circuit, all the input signals to be added are applied to the inverting input terminal of the OP-Amp. The o/p signal V_o obtained is the sum of the applied i/p signals with a negative sign indicating the 180° phase shift between the i/p and o/p signals. Hence the name inverting summer.

Circuit diagram.



In the above circuit, non-inverting terminal is grounded. Potential at node A is V_A $\therefore V_A = 0$.

According to virtual ground concept,
 $V_A = 0 \therefore V_B = 0$ at node B.

Because of high input impedance, current flowing into the i/p terminals of the OP-Amp is zero. i.e. $I = 0$.

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From i/p side,

three i/p voltages V_1 , V_2 & V_3 are applied as i/p's to inverting terminal of the OP-Amp.

R_1 , R_2 and R_3 are the current limiting resistors.

Applying KVL, we have

$$V_1 - I_1 R_1 - V_B = 0.$$

$$\text{or } I_1 = \frac{V_1 - V_B}{R_1}$$

$$I_1 = \frac{V_1}{R_1} \quad (\because V_B = 0)$$

Similarly,

$$V_2 - I_2 R_2 - V_B = 0 \quad (1)$$

$$\text{or } I_2 = \frac{V_2}{R_2} \quad (2)$$

$$\text{& } I_3 = \frac{V_3}{R_3} \quad (3).$$

Total current 'I' at node B is

$$I = I_1 + I_2 + I_3 \quad (4) \text{ by KCL}$$

Since current entering into the i/p terminals of OP-Amp is zero ($I=0$), entire I flows through R_f as I_f .

$$\text{i.e. } I = I_f \quad (5)$$

∴ using (5) in (4),

$$I_f = I_1 + I_2 + I_3. \quad (6)$$

From o/p side, applying KVL, we have

$$V_B - I_f R_f - V_o = 0.$$

$$\text{or } I_f = \frac{V_B - V_o}{R_f}$$

$$I_f = -\frac{V_o}{R_f} \quad (\because V_B = 0) \quad (7)$$

using (6) & (7) with (1), (2) & (3) we get

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

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

If $R_f = R_1 = R_2 = R_3$, then

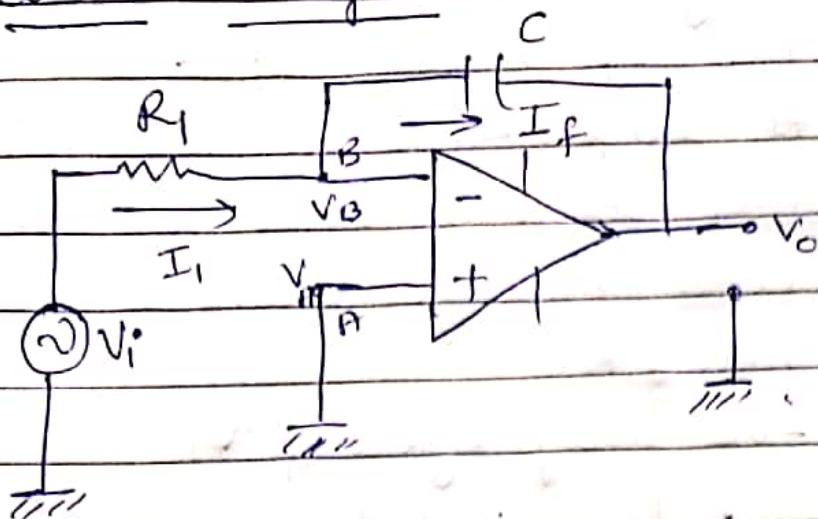
$$V_o = - [V_1 + V_2 + V_3]$$

Hence, o/p voltage of an inverting summer is an algebraic sum of applied i/p voltages $V_1, V_2, V_3 \dots V_n$. Negative sign indicates the presence of 180° phase shift b/w i/p and o/p.

5. OP-Amp Integrator.

Output of an OP-Amp integrator is an integration of applied i/p voltage V_i .

Circuit diagram.



In the above circuit, the non-inverting terminal is connected to ground. Potential at node A is V_A . Inverting terminal is connected to i/p signal V_i through a resistor R_1 . From the output terminal, a capacitor C is connected through feedback path to the inverting terminal.

Since node A is connected to ground, $V_A = 0$. According to virtual ground concept, node B is virtually shorted with node A. Hence $V_B = V_A = 0$.

$$\Rightarrow V_B = 0.$$

Due to high input impedance of OP-Amp, current flowing into the i/p terminals of an OP-Amp is zero.

when a i/p signal V_i is applied, initially capacitor C is not charged and maximum current flows through the resistor R_1 .

when C begins to charge until the peak value of the i/p voltage V_i during +ve half cycle, its impedance X_C increases slowly proportional to its ratio of charge.

The capacitor charges upto a rate determined by RC network.

During -ve half cycle of V_i , capacitor discharges. The o/p voltage V_o obtained is inverted since V_i is applied to inverting terminal thereby generating a phase shift of 180° b/w i/p & o/p signal.

Voltage a/c the capacitor C is

$$V_c = \frac{Q}{C} \quad \text{--- (1)}$$

From i/p side applying KVL, we have

$$V_i - I_1 R_1 - V_A = 0.$$

$$\text{or } I_1 = \frac{V_i - V_A}{R_1} = \frac{V_i}{R_1} \quad (\because V_A = 0) \quad \text{--- (2)}$$

Applying KVL at node B (o/p side)

$$V_B - V_c - V_o = 0.$$

$$\text{or } V_c = V_B - V_o.$$

$$V_c = -V_o \quad (\because V_B = 0)$$

--- (3)

But voltage a/c 'c' is $\frac{Q}{C}$.

$\therefore \text{eq } (3)$

$$V_C = -V_o$$

$$\text{or } Q_C = -C V_o \quad \text{--- (4)}$$

Differentiating (4)

$$\frac{1}{C} \frac{dQ}{dt} = -\frac{dV_o}{dt}$$

The rate of change of charge is current I .

$$\text{ie } \frac{dQ}{dt} = -C \frac{dV_o}{dt}$$

$$\text{or } I_f = -C \frac{dV_o}{dt} \quad \text{--- (5)}$$

We know that current flowing into the i/p terminals is zero and hence entire current I_i flows through C as I_f .

\therefore equating $(2) \& (5)$ we have

$$I_i = I_f$$

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

Integrating on both sides,

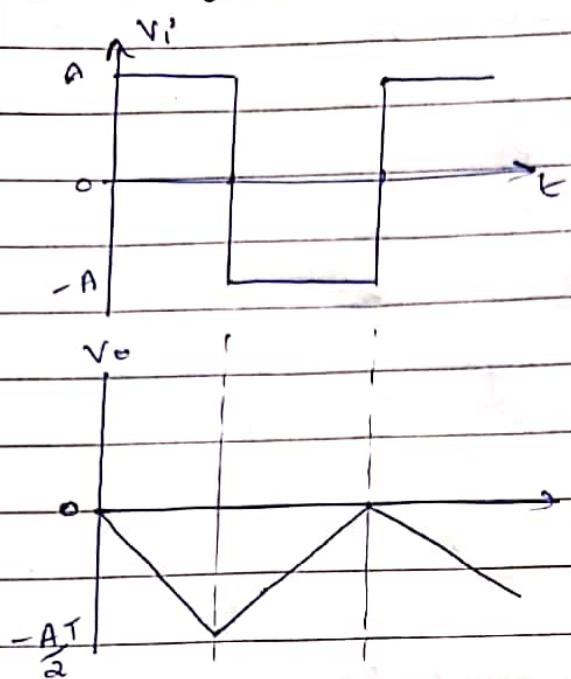
$$\int_0^t \frac{V_i}{R_i} dt = -C V_o$$

or

$$V_o = -\frac{1}{RC} \int_0^t V_i dt \quad \text{--- (6)}$$

-ve sign in (6) indicates the presence of 180° phase shift b/w i/p V_i & o/p V_o .

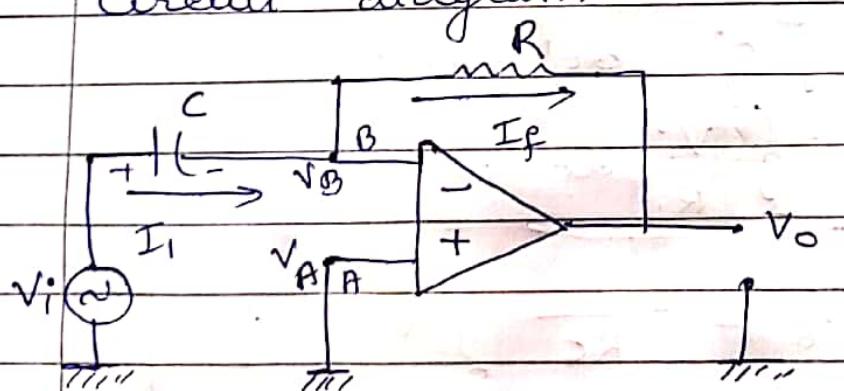
Waveforms



6. OP-Amp Differentiator

The circuit that generates the differentiation of the i/p voltage V_i at the o/p is called as differentiator.

Circuit diagram:



The i/p signal V_i is applied to a capacitor. The capacitor blocks dc and allows only

ac voltages to pass. It will charge to reach the peak value of the i/p voltage V_i .

In the above circuit, node A is at ground potential. Hence $V_A = 0V$.

According to virtual ground concept, node B is at virtual short with node A.

$$\therefore V_B = V_A = 0$$

$$\Rightarrow V_B = 0.$$

Applying KVL at i/p side,

$$V_i - V_C - V_A = 0.$$

As capacitor charges, voltage a/c it is V_C

$$\therefore V_C = Q/C.$$

$$\text{Hence } \frac{Q}{C} = V_i - V_A.$$

Differentiating on both sides,

$$\frac{1}{C} \frac{dQ}{dt} = \frac{dV_i}{dt} \quad (\because V_A = 0).$$

$$\therefore \frac{dQ}{dt} = C \frac{dV_i}{dt}$$

Ratio of change of charge is current I_f ,

$$\therefore I_f = C \frac{dV_i}{dt} \quad (1)$$

From o/p side,

$$V_B - I_f R - V_o = 0.$$

$$\text{or } I_f = \frac{V_B - V_o}{R} = -\frac{V_o}{R} \quad (\because V_o = 0) \quad (2)$$

Current flowing (I_f) into the i/p terminals of the

OP-Amp is zero. Hence entire current I_i flows through R as I_f .

Hence equating ① & ② we get

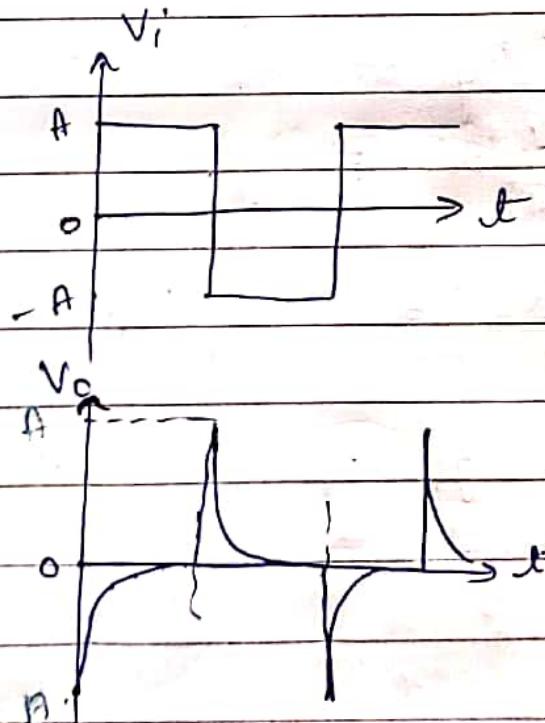
$$I_i = I_f$$

$$C \frac{d}{dt} V_i = -\frac{V_o}{R}$$

$$\therefore V_o = -R_C \frac{d}{dt} V_i \quad \text{--- (3)}$$

-ve sign in (3) indicates that there exists a phase shift of 180° b/w i/p & o/p voltages.
 R_C is a time constant.

Wavforms



Op-Amp Comparator

- * Comparator is decision making electronic circuit.
- * OP-Amp comparators compare the magnitude of 2 voltage levels at the i/p and determines as which is the largest of the two.

Types:

1. Inverting comparator

(i) with +ve reference voltage

(ii) with -ve reference voltage

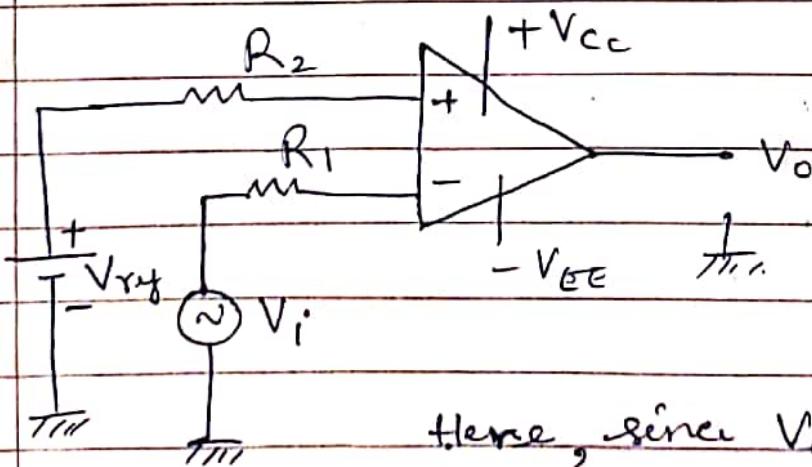
2. Non-Inverting Comparator

(i) with +ve reference voltage

(ii) With -ve reference voltage.

1. Inverting comparator.

(i) with +ve reference +V_{ref}.
circuit diagram.



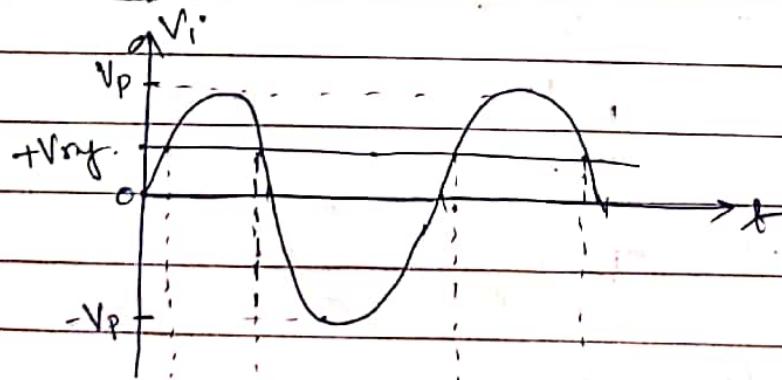
Here, since V_i is applied to the inverting terminal of OP-Amp, it is called as inverting comparator.

Working :

A fixed dc reference voltage $+V_{ref}$ is connected to the non inverting terminal.

$R_1 + R_2$ are the current limiting resistors.

- * when time varying signal V_i is less than $+V_{ref}$ ($V_i < +V_{ref}$) O/p voltage V_o is at $+V_{sat}$ ($\therefore +V_{ref}$ is connected to non inverting terminal)
- * when time varying signal V_i exceeds $+V_{ref}$, (ie $V_i > +V_{ref}$) voltage level at non inverting terminal is less compared to that of voltage at inverting terminal. Hence, the output of OP-Amp swings to $-V_{sat}$ from $+V_{sat}$. This process repeats for next cycles as in waveforms below.

waveforms

when

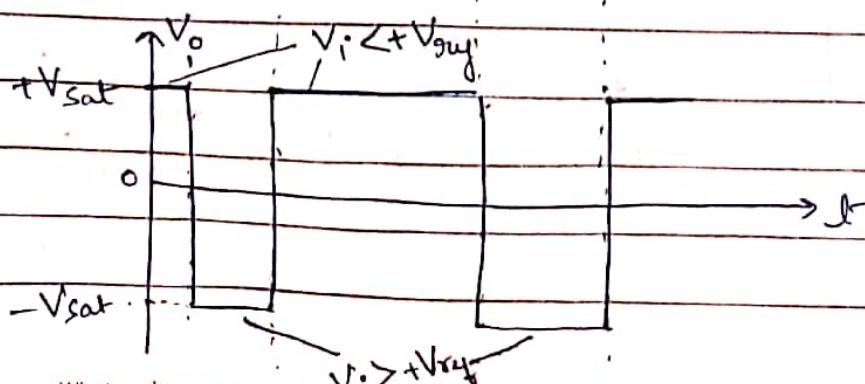
$$V_i < +V_{ref}$$

$$V_o = +V_{sat}$$

when

$$V_i > +V_{ref}$$

$$V_o = -V_{sat}$$



What makes you happy?

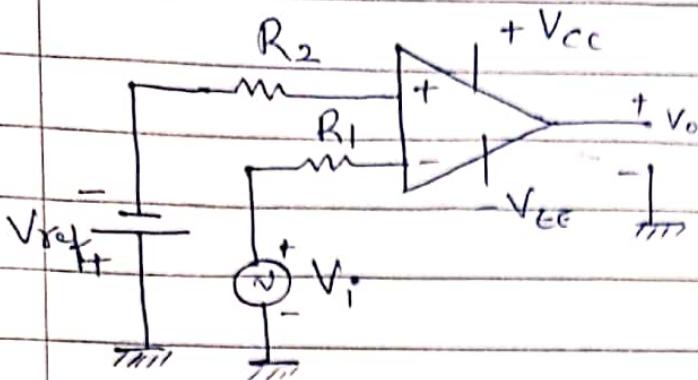
#HappyCollegeDays

#

#

ii) with -ve reference -V_{ref}.

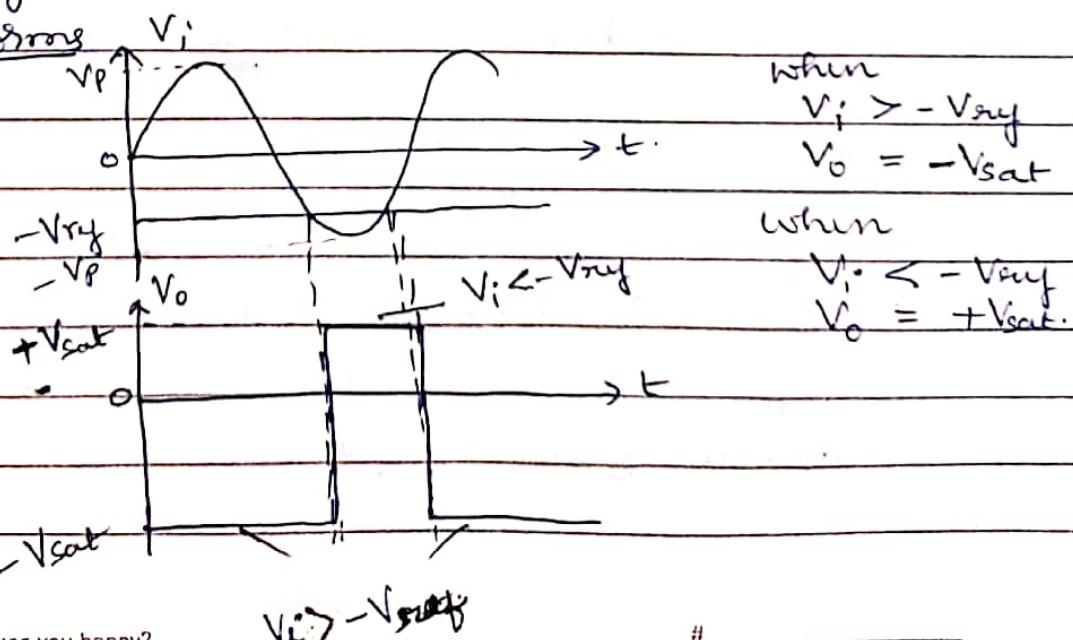
Circuit diagram:



Working: When $V_i > -V_{ref}$ o/p voltage V_o is at $-V_{sat}$. This is because, time varying signal V_i at inverting terminal is more positive than $-V_{ref}$ voltage at the non-inverting terminal. Hence o/p voltage V_o is at $-V_{sat}$.

When $V_i < -V_{ref}$ o/p voltage V_o swings to $+V_{sat}$ from $-V_{sat}$. This is because $-V_{ref}$ at non inverting terminal is more +ve than V_i at inverting terminal. Hence o/p voltage V_o is at $+V_{sat}$.

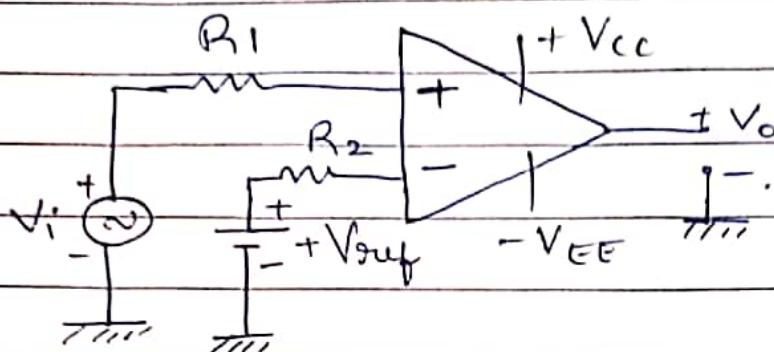
Wavesforms



2. Non Inverting Comparator.

(i) With $+V_{ref}$ Voltage.

Circuit diagram.



Here, since V_i is applied to the non-inverting terminal of OP-Amp, the circuit is called as non-inverting comparator.

Working:

A fixed dc reference voltage $+V_{ref}$ is connected to inverting terminal and a time varying signal V_i is connected to the non-inverting terminal.

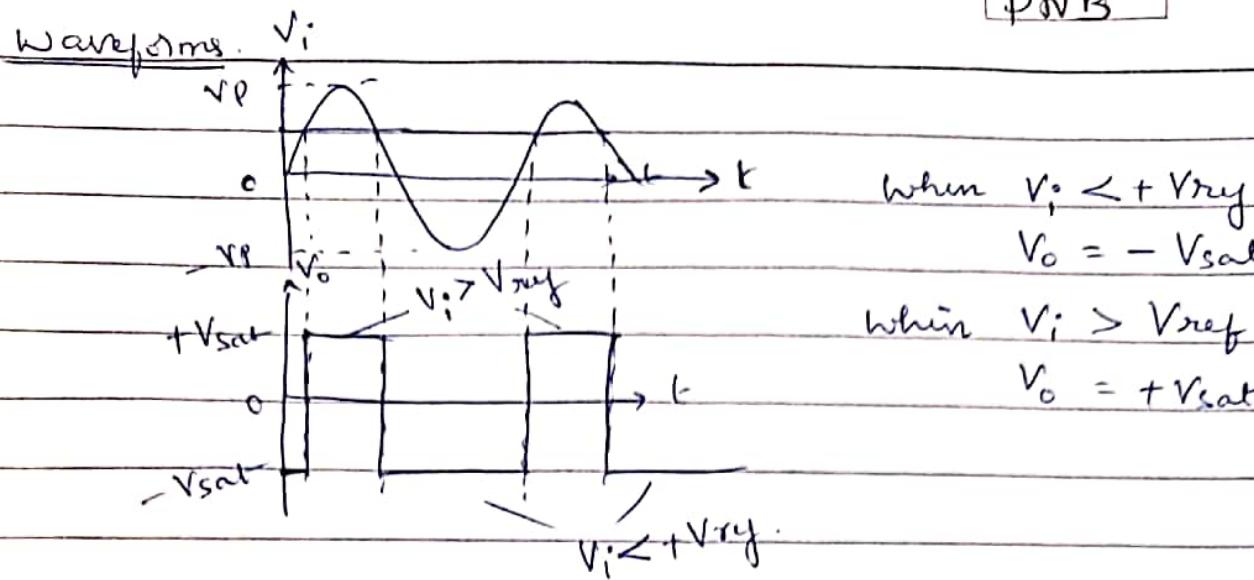
* when V_i is less than $+V_{ref}$ ($V_i < +V_{ref}$)

OP-Amp o/p voltage V_o is at $-V_{sat}$.

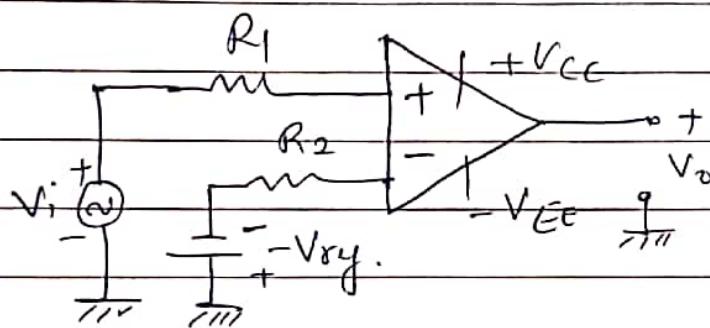
This is because voltage level at inverting terminal is greater than the voltage level at non-inverting terminal.

* when V_i exceeds beyond $+V_{ref}$ ($V_i > +V_{ref}$)

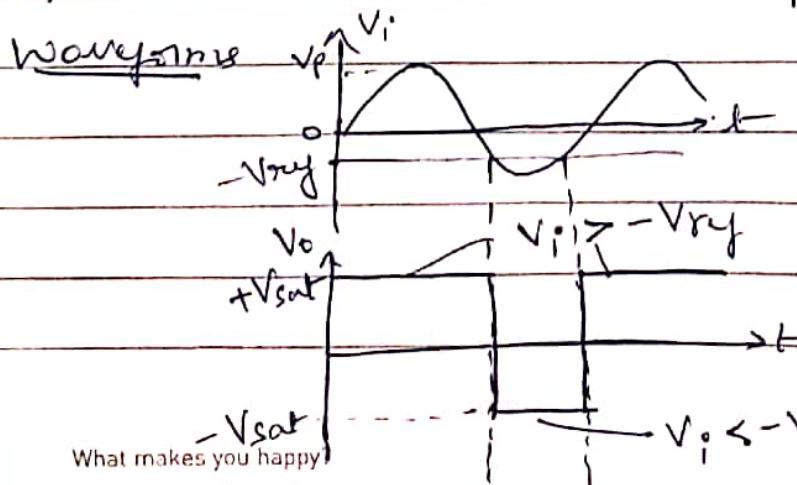
O/P voltage of OP-Amp V_o switches to $+V_{sat}$ from $-V_{sat}$.



(ii) With $-V_{ref}$ voltage.
Circuit diagram.



Working: When $V_i > -V_{ref}$, o/p voltage V_o is at $+V_{sat}$. Because V_i is connected to non-inverting terminal + it's voltage level is greater than $-V_{ref}$. When $V_i < -V_{ref}$, o/p voltage V_o switches to $-V_{sat}$ from $+V_{sat}$. This is because V_i becomes more -ve compared to $-V_{ref}$.



IC 555 timer as Astable multivibrator

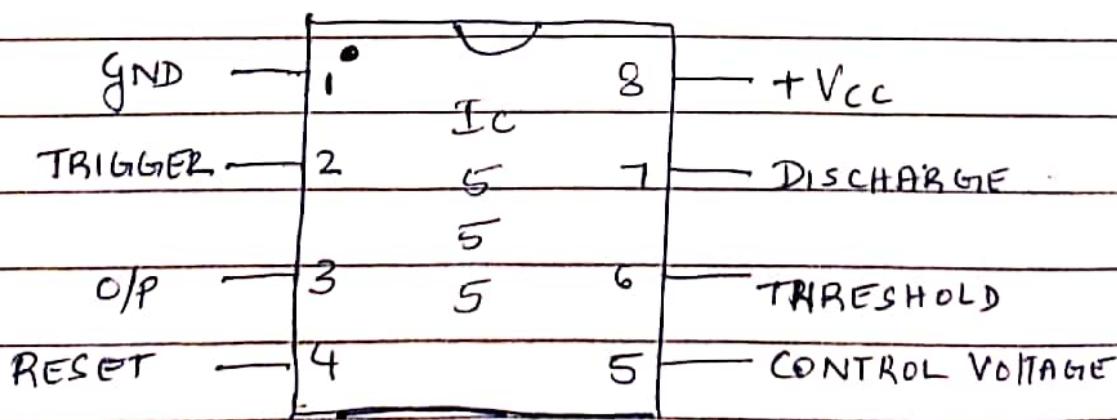
(Astable mode or Free running oscillator)

- * IC 555 timer is a versatile linear IC introduced during 1970.
- * It is a monolithic IC timer circuit used for many applications such as astable multivibrator, missing pulse detector, automatic battery charger, decorative lights, displays etc.
- * It can produce accurate time delays or oscillations ranging from few usec to several hours.
- * 2 modes of operation are:
 - Monostable and Astable mode.

Supply voltage range used is 4.5V to 15V and current is 200mA.

It is a 8 pin IC package.

IC diagram.



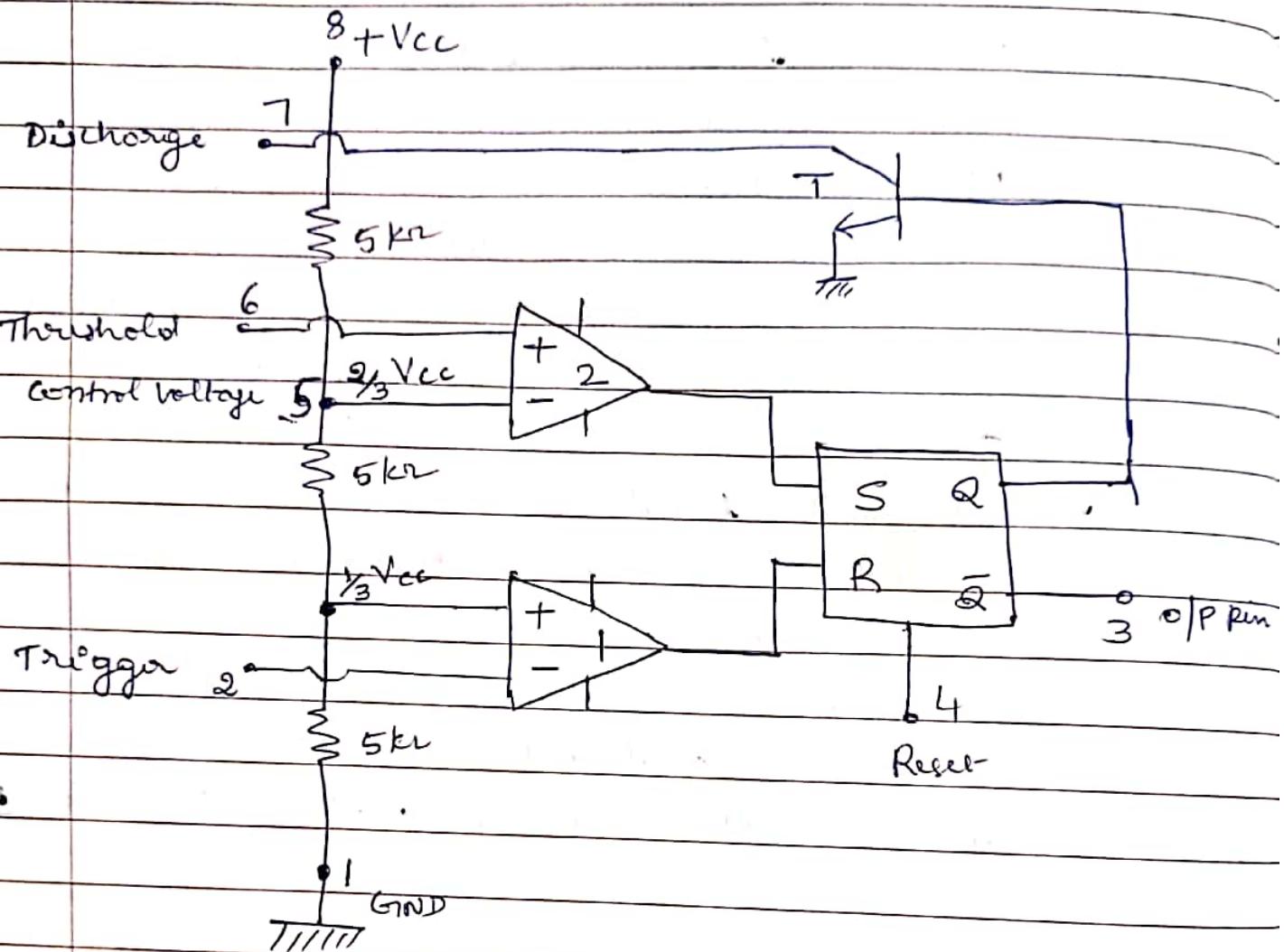
Internal diagram and pin description.

Fig: Internal Architecture of IC 555.

Pin 1: Ground. All voltages are measured with respect to ground.

Pin 2 & Pin 6: Trigger and Threshold pins.

Pin 2 is called trigger pin. It is connected to the inverting terminal of 1st OP-Amp comparator. If the voltage at trigger pin goes below $\frac{1}{3} V_{cc}$, then the output of comparator 1 goes high that sets the RS flip flop.

Pin 6 is called the threshold pin. It is connected to the non inverting terminal of Comparator 2. When the voltage level at threshold pin is greater than $\frac{2}{3} V_{cc}$, the o/p of Comparator 2 goes high that sets the RS flip flop.

Hence pin 2 + pin 6 are used to control the o/p's of the comparators.

Pin 3: It is an o/p pin.

Pin 4: It is used to reset the flip flop.

It can be used to interrupt the operation and make the capacitor discharge.

Pin 5: Pin 5 is called as control voltage pin. It is directly connected to the inverting terminal of the first comparator. The reference voltage of $\frac{2}{3} V_{cc}$ is set at pin 5.

Pin 7: It is called as discharge pin.

It is connected to the collector terminal of the transistor.

Pin 8: Pin 8 is $+V_{cc}$. It is used to give power supply to IC 555. The voltage from 4.5V to 15V can be given to the IC.

Additional points:

- * A chain of 3 resistors each of values 5k Ω are connected through $+V_{cc}$. Hence a reference voltage of $\frac{2}{3} V_{cc}$ appears at Comparator 2 and a voltage of $\frac{1}{3} V_{cc}$ appears at Comparator 1.

using Voltage divider concept.

* S R - Flip-flop.

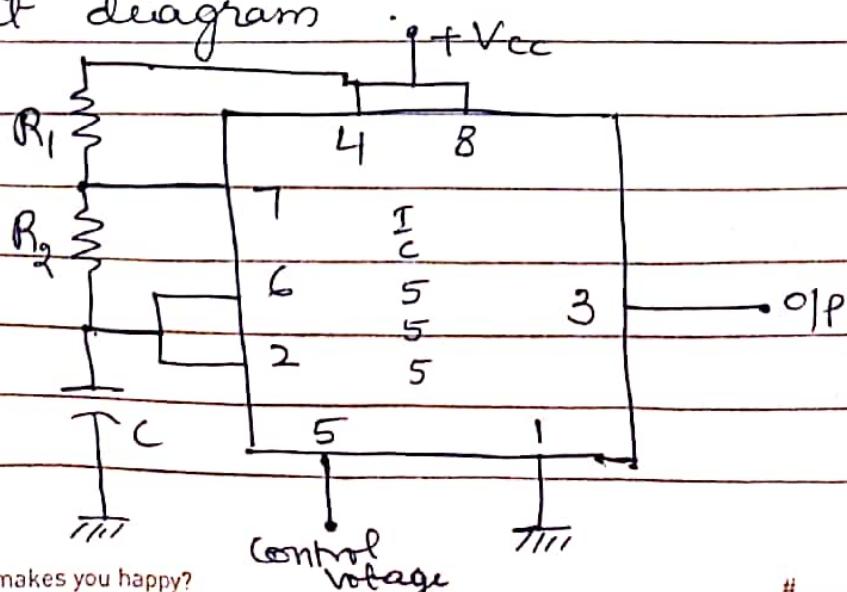
Set - Reset - flip-flop is a basic sequential logic circuit. It is a one-bit memory device that has two inputs - one which will 'SET' the device (means the output = 1) and is labelled as 'S'. Other one which will 'RESET' the device (means output = 0) labelled as 'R'.

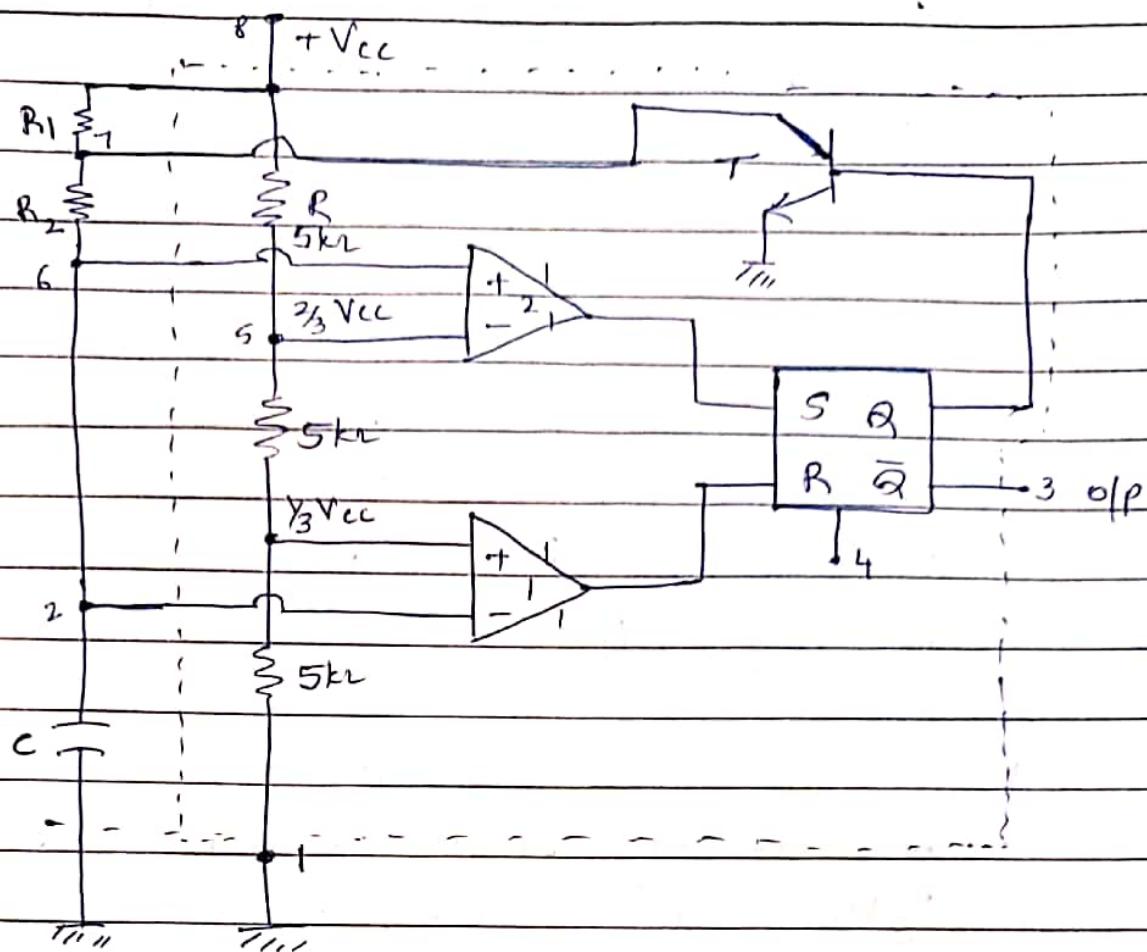
Truth Table

S	R	Q	\bar{Q}
0	0	Invalid condition	
0	1	0	1
1	0	1	0
1	1	NO change. (previous state itself)	

IC 555 timer for astable operation.

circuit diagram





Working :

- * Initially, when the power supply +V_{cc} is ON, capacitor C starts charging through resistors R₁ and R₂ to reach the peak value +V_{cc}.
- * As C charges, when the voltage level at pin 2 (trigger) is less than $\frac{1}{3}V_{cc}$, comparator 1 output goes high ('1'). $\therefore R = 1$ and $S = 0$. Hence $Q = 0$ and o/p at pin 3 is high ('1').
- * The capacitor C continues to charge beyond $\frac{1}{3}V_{cc}$ and when the voltage at threshold pin 6 goes slightly above $\frac{2}{3}V_{cc}$, o/p of

comparator 2 goes high ('1'). $\therefore S=1$ and $R=0$. Hence $Q=1$ and o/p at pin 3 goes low ('0').

- * Since $Q=1$, there is a base drive to the transistor T and hence it is ON. Now the collector of the transistor is connected to discharge pin 7. The capacitor C which had charged to $\frac{2}{3} V_{cc}$ now starts discharging through R_2 to ground.
- * But on its way of discharging, when the voltage level at pin 2 goes just below $\frac{1}{3} V_{cc}$, comparator 1 o/p goes high. $\therefore R=1$ and $S=0$. Hence $Q=0$ and o/p at pin 3 is high ('1').
- * When $Q=0$, there is no base drive to the transistor T. Hence T is at cut off. ie collector terminal gets disconnected from discharge pin 7.
- * Capacitor C continues to charge from $\frac{1}{3} V_{cc}$ through R_1 and R_2 . This process continues that generates square wave oscillations.

Waveforms: V_o (pin 3)O/p
Voltage $+V_{cc}$

0

 T_{ON} T_{OFF} t V_c (pin 2)Voltage
a/c
capacitor $+V_{cc}$ $\frac{2}{3}V_{cc}$ $\frac{1}{3}V_{cc}$

0

charging

discharging

 t

Time taken by the capacitor to charge is

$$T_{ON} = 0.693(R_1 + R_2)C \quad (\text{from } \frac{1}{3}V_{cc} \text{ to } \frac{2}{3}V_{cc})$$

Time taken to discharge is

$$T_{OFF} = 0.693 R_2 C.$$

$$\text{Total time } T = T_{ON} + T_{OFF}.$$

Frequency of oscillations is

$$f = \frac{1}{T} = \frac{1}{T_{ON} + T_{OFF}}$$

$$f = \frac{1.44}{(R_1 + 2R_2)C}$$

Date

P NB

--	--	--

$$\text{Duty cycle} = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{T_{ON}}{T}$$

$$\therefore D = \left(\frac{R_1 + R_2}{R_1 + 2R_2} \right) \times 100$$

Voltage levels.	Comp1 O/P	Comp2 O/P	S	R	Q	\bar{Q}
$V_c < \frac{1}{3}V_{cc}$	1	0	0	1	0	1
$\frac{1}{3}V_{cc} < V_c < \frac{2}{3}V_{cc}$	0	0	0	0	0	1
$V_c > \frac{2}{3}V_{cc}$	0	1	1	0	1	0
$\frac{2}{3}V_{cc} < V_c < V_{cc}$	0	0	0	0	1	0
$V_c < \frac{1}{3}V_{cc}$	1	0	0	1	0	1

78XX Series IC Voltage Regulator

One of the important sources of DC supply are batteries. But using batteries in sensitive electronic circuits is not a good idea, since batteries eventually drain out and lose their potential over time.

Hence for obtaining constant and steady output, voltage regulators are implemented.

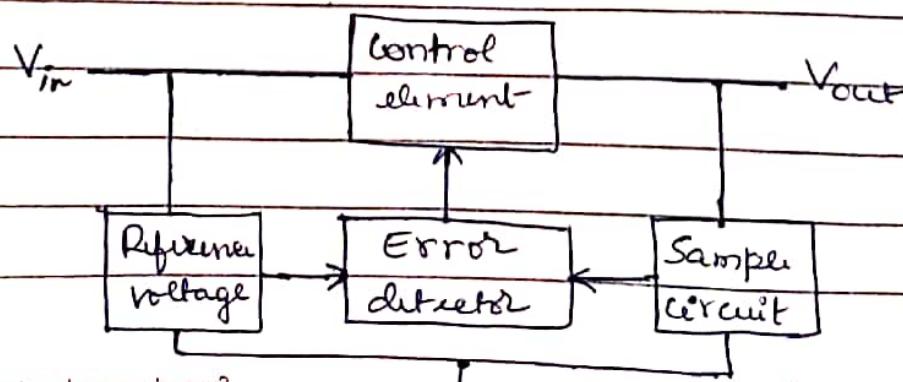
The integrated circuits which are used for the regulation of voltage are termed as

voltage regulator ICs. 78XX family of linear voltage regulators produce a regulated output voltage. XX in 78XX series represents the value of the fixed output voltage that the particular IC provides.

Eg : TC7805 is a 3 terminal linear voltage regulator IC with a fixed output voltage of 5V.

The functional diagram of a 78XX series based fixed IC voltage regulator is shown below.

(XX can be 05, 06, 08, 10, 12, 15, 18 or 24)



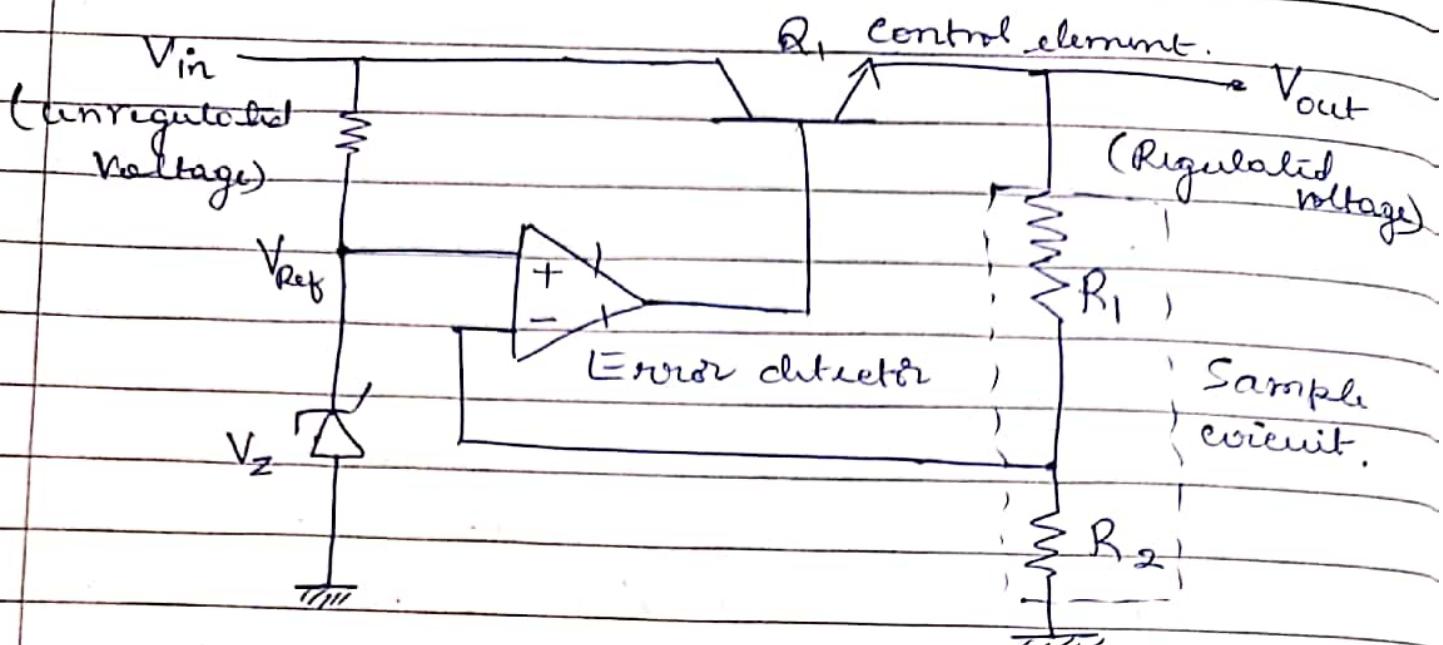


Fig : OP-Amp Series regulator with feedback

Description :

IC voltage regulators can be used to regulate the unregulated i/p voltage and provide a constant regulated o/p voltage.

Advantages : Inexpensive, versatile, provides current/voltage boosting, internal short circuit, current limiting and thermal shutdown.

Working :

An unregulated i/p voltage V_{in} is applied to the series voltage regulator. A regulated o/p voltage V_{out} is measured at the o/p terminal.

A pass transistor Q_1 is connected as a control element in series with load b/w i/p and o/p.

- + A Zener diode reference voltage V_{ref} drives the non-inverting terminal of a high gain amplifier.
- + An voltage divider network with resistors R_1 and R_2 samples the o/p voltage and returns a feedback voltage to the inverting i/p terminal of a high gain amplifier.

$$V_o = \left(1 + \frac{R_1}{R_2}\right) V_{ref}. \quad \text{--- (1)}$$

$$= \left(1 + \frac{R_1}{R_2}\right) V_Z. \quad \text{where the reference}$$

Voltage V_{ref} is equivalent to the zener voltage V_Z . R_1 and R_2 are internal to the IC.

They are already trimmed to get different o/p voltages (5V to 15V) in 78xx series.

The pass transistor enhances the regulator's o/p current. It can handle 1A of load current with proper heat sink.

The o/p sample circuit senses a change in the output voltage. The error detector compares the sample voltage with a fixed reference Voltage V_{ref} .

The resulting difference voltage causes the transistor Q_1 to control the conduction & to compensate the variation in the o/p voltage. The o/p V_{out} will be maintained at a constant value as in eq (1).

Numericals.

1. An inverting amplifier has $R_i = 1\text{ k}\Omega$ and $R_f = 20\text{ k}\Omega$. Calculate the gain A.

Solu: Given $R_i = 1\text{ k}\Omega$ $R_f = 20\text{ k}\Omega$

$$\therefore A = -\frac{R_f}{R_i} = -\frac{20\text{ k}\Omega}{1\text{ k}\Omega} = -20.$$

2. An OP-Amp in inverting configuration has a gain of +40. If the applied i/p voltage is 3mV what is V_o ?

Solu: given $A = +40$.

$$V_i = 3\text{ mV}$$

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

$$\therefore V_o = -40 (3\text{ mV})$$

$$V_o = -120\text{ mV}$$

3. Design an inverting amplifier with a gain of -50 and a $2\text{ k}\Omega$ resistance R_i . Draw the circuit fig.

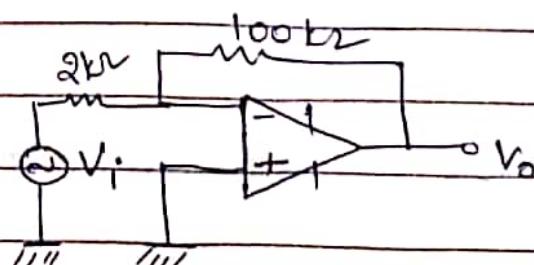
Solu: given $R_i = 2\text{ k}\Omega$. $A = -50$.

To calculate feedback resistor R_f .

Wkt $A = -\frac{R_f}{R_i}$ for inverting amplifier.

$$\therefore -50 = -\frac{R_f}{2\text{ k}\Omega}$$

$$\Rightarrow R_f = 100\text{ k}\Omega$$



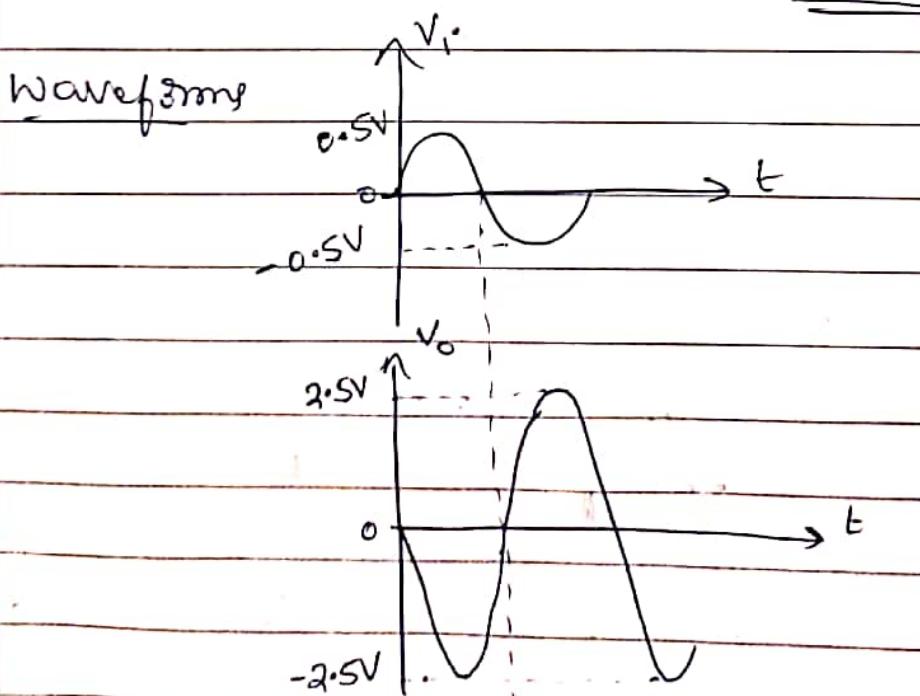
4. A sine wave of 0.5V peak value is applied as an i/p to an inverting amplifier with $R_i = 10\text{ k}\Omega$ and $R_f = 50\text{ k}\Omega$. It uses a power supply of $\pm 12\text{ V}$. Determine the output voltage and sketch i/p & o/p waveform. If now an i/p voltage of 5V peak is applied, what is the o/p. Sketch the waveforms.

Solu Given $V_i = 0.5\text{ V}_p$ $R_i = 10\text{ k}\Omega$ $R_f = 50\text{ k}\Omega$

(i) It gives an o/p voltage for a supply of $\pm 12\text{ V}$. So $V_o = ?$

$$\text{But } V_o = -\frac{R_f}{R_i} V_i = -\frac{50\text{ k}\Omega}{10\text{ k}\Omega} V_i = -5(0.5\text{ V}_p)$$

$$\therefore V_o = -2.5\text{ V}_p \text{ or } -5\text{ V}_{P-P}$$

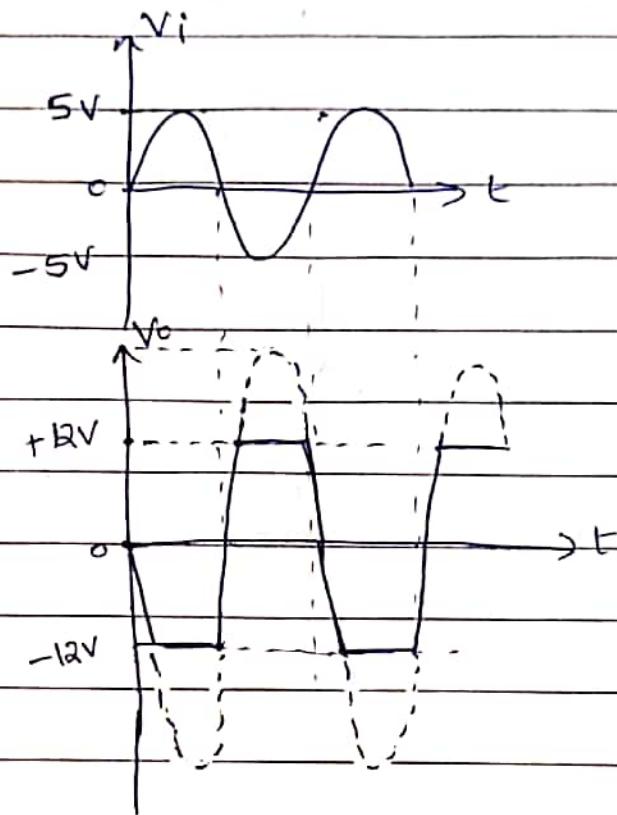


(1) If a 5V_p is applied as i/p voltage
 $V_o = ?$

$$V_o = -\frac{R_f}{R_i} V_i = -5 \times 5 V_p = -25 V_p \text{ or } -50 V_{p-p}$$

But gain + V_{cc} & -V_{ee} supplies as $\pm 12V$.
Hence the o/p voltage will saturate at $\pm 12V$.
(The peak levels get clipped off after $\pm 12V$).

Waveforms



5. In a non-inverting amplifier using OP-Amp,
 $R_i = 2k\Omega$, $R_f = 200k\Omega$. Supply voltages are $\pm 15V$. calculate V_o if the applied i/p voltage is $1.5V_{pp}$

Soln: given : $R_i = 2k\Omega$, $R_f = 200k\Omega$,
 $\pm V_{cc}, -V_{ee} = \pm 15V$.

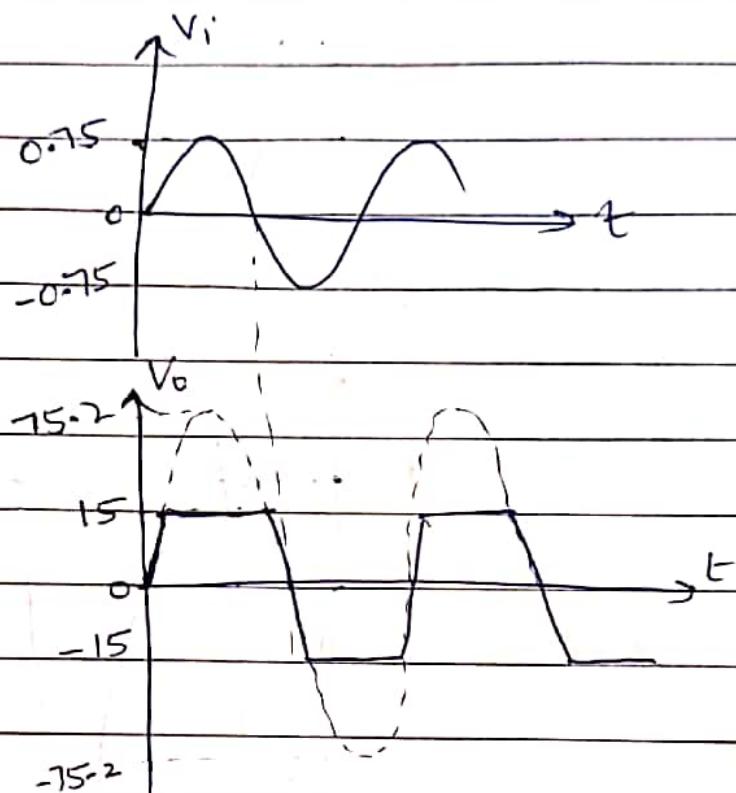
$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_i$$

$$V_o = \left(1 + \frac{200k\Omega}{2k\Omega}\right) 1.5V_{pp}$$

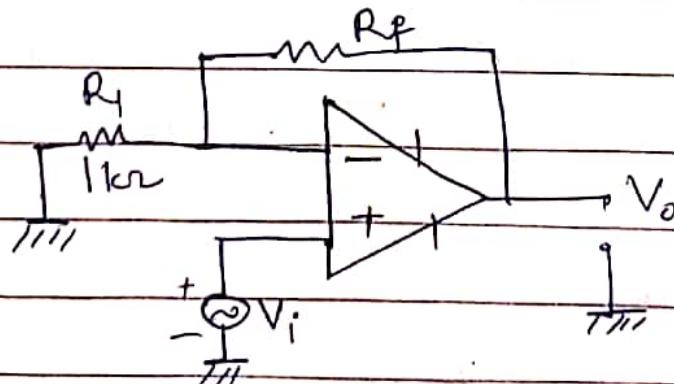
$$= \underline{151.5 V_{p-p}}$$

Given $V_i = 1.5V_{pp}$ with $\pm 15V$ supply voltages.
 O/P will saturate at $\pm 15V$.

Waveforms



6. For an OP-Amp circuit shown in figure below
 gain is 60. $R_f = 1k\Omega$ what is R_i ?



It is a non inverting amplifier circuit.

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

where closed loop gain

$$A = 1 + \frac{R_f}{R_1} \quad \text{given } A=6.$$

$$60 = 1 + \frac{R_f}{1\text{k}\Omega}$$

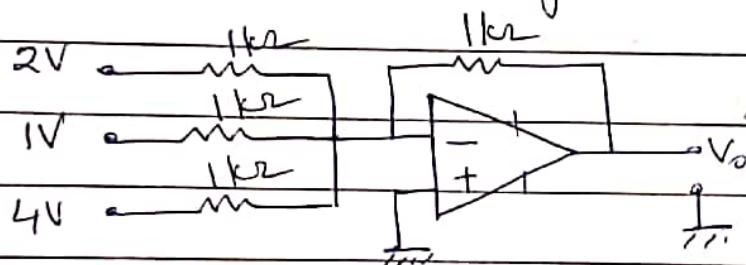
$$\text{or } \frac{R_f}{1\text{k}\Omega} = 59$$

$$\text{or } R_f = 59 \times 1\text{k}\Omega$$

$$R_f = \underline{\underline{59\text{k}\Omega}}$$

Inverting Summer.

7. In the circuit figure of an inverting summer determine the o/p voltage.



Solu. o/p voltage of an inverting summer

is $V_o = - \left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 \right)$

Since $R_f = R_1 = R_2 = R_3 = 1\text{k}\Omega$,

$$V_o = - (2V + 1V + 4V)$$

$$= - \underline{\underline{7V}}$$

For the same circuit if $R_1 = 2\text{k}\Omega$, $R_2 = 1\text{k}\Omega$

$$+ R_3 = 4\text{k}\Omega, R_f = 20\text{k}\Omega, V_o = ?$$

$$\begin{aligned}
 V_o &= -\left(\frac{\frac{10}{2k\Omega}}{2k\Omega} + \frac{20k\Omega}{1k\Omega} + 1 \cdot \frac{20k\Omega}{4k\Omega}\right) \\
 &= -(20 + 20 + 20) \\
 &= -60V
 \end{aligned}$$

8. Design an inverting summer using OP-Amp to give an o/p voltage $V_o = -(3V_1 + 4V_2 + 5V_3)$, with $R_f = 120k\Omega$.

Soln: For an inverting summer,

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

$$R_f = 120k\Omega.$$

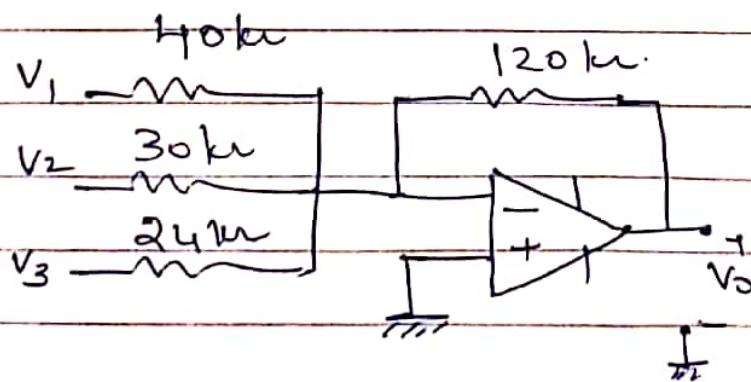
$$\text{Given } V_o = -(3V_1 + 4V_2 + 5V_3) \quad \text{--- (2)}$$

Equate (1) & (2),

$$\frac{R_f}{R_1} = 3 \Rightarrow \frac{120k}{3} = R_1 = \underline{\underline{40k\Omega}}$$

$$\frac{R_f}{R_2} = 4 \Rightarrow \frac{120k}{4} = R_2 = \underline{\underline{30k\Omega}}$$

$$\frac{R_f}{R_3} = 5 \Rightarrow \frac{120k}{5} = R_3 = \underline{\underline{24k\Omega}}$$



9. Design an inverting summer for

$$V_o = 0.2V_1 + 1V_2 + 4V_3 \text{ with } R_f = 20k\Omega$$

Soln: Output voltage for an inverting summer is

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

Given $V_o = 0.2V_1 + 1V_2 + 4V_3$.

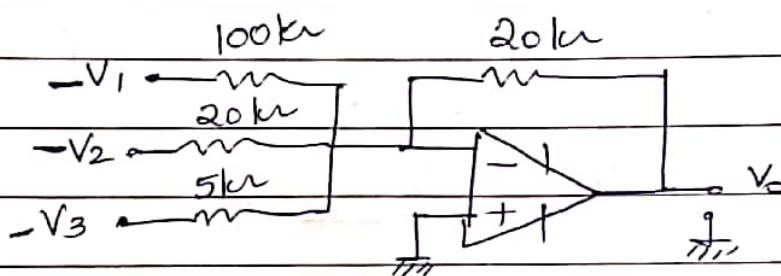
$$\text{i.e } V_o = - (0.2(-V_1) + 1(-V_2) + 4(-V_3)) \quad (2)$$

Comparing (1) & (2)

$$\frac{R_f}{R_1} = 0.2 \Rightarrow \frac{20\text{k}\Omega}{0.2} = R_1 = \underline{\underline{100\text{k}\Omega}}$$

$$\frac{R_f}{R_2} = 1 \Rightarrow \frac{20\text{k}\Omega}{1} \Rightarrow R_2 = \underline{\underline{20\text{k}\Omega}}$$

$$\frac{R_f}{R_3} = 4 \Rightarrow \frac{20\text{k}\Omega}{4} = R_3 = \underline{\underline{5\text{k}\Omega}}$$



Numericals on IC 555 timer.

10. For an IC 555 timer to work in astable mode the components considered are $R_1 = 1\text{k}\Omega$, $R_2 = 10\text{k}\Omega$ with $C = 0.014\text{F}$. What is the frequency of oscillations generated? Duty cycle?

Soln. Given $R_1 = 1\text{k}\Omega$, $R_2 = 10\text{k}\Omega$, $C = 0.014\text{F}$.

$$f = \frac{1}{T}, \quad T = T_{ON} + T_{OFF}.$$

$$\begin{aligned} T_{ON} &= 0.693(R_1 + R_2)C \\ &= 0.693(1\text{k}\Omega + 10\text{k}\Omega)0.014\text{F} \\ &= 0.693(11\text{k}\Omega)0.014\text{F} \end{aligned}$$

$$= 0.693 (11 \times 10^3 \times 0.01 \times 10^{-6})$$

$$= 0.693 (11 \times 0.01 \times 10^{-3})$$

$$T_{ON} = \underline{76.23 \mu\text{sec}}$$

$$T_{OFF} = 0.693 R_2 C = 0.693 \times 10 \text{ k}\Omega \times 0.01 \mu\text{F}$$

$$= 0.693 \times 10 \times 10^3 \times 0.01 \times 10^{-6}$$

$$= 0.0693 \times 10^{-3}$$

$$= \underline{69.3 \times 10^{-6} \text{ sec}}$$

$$\therefore T = \underline{145.53 \mu\text{sec}}$$

$$f = \underline{6.871 \text{ kHz}} \quad (f = \frac{1}{T})$$

$$\text{Duty cycle} = \frac{T_{ON}}{T} = \frac{76.23 \mu\text{sec}}{145.53 \mu\text{sec}}$$

$$= 0.5238$$

$$\therefore D = \underline{52.38 \%}$$

11. A 555 timer IC has $R_1 = 4 \text{ k}\Omega$, $R_2 = 4 \text{ k}\Omega$, $C = 0.01 \mu\text{F}$, $f = ?$ $D = ?$

$$\text{Ans: } f = 12 \text{ kHz} \quad D = 66.67 \%$$

12. For an IC timer based astable multivibrator given $D = 75\%$, $f = 1 \text{ kHz}$, $R_2 = 3.6 \text{ k}\Omega$, $C = 0.1 \mu\text{F}$, calculate T_{ON} and R_1 .

Solu: Given $D = 0.75$, $f = 1 \text{ kHz}$, $R_2 = 3.6 \text{ k}\Omega$, $C = 0.1 \mu\text{F}$.

$$\therefore T = \frac{1}{f} = \underline{1 \text{ msec}}$$

$$\text{Duty cycle} = \frac{T_{ON}}{T}$$

$$\begin{aligned}\therefore T_{ON} &= D \times T \\ &= 0.75 \times 1 \times 10^{-3} \\ &= \underline{\underline{750 \mu\text{sec}}}\end{aligned}$$

$$T_{ON} = 0.693 (R_1 + R_2) C$$

$$\begin{aligned}750 \times 10^{-6} &= 0.693 (R_1 + 3.6 \text{ k}\Omega) 0.1 \times 10^{-6} \\ &= 6.93 \times 10^{-8} R_1 + 2.4948 \times 10^{-4}.\end{aligned}$$

$$\therefore 750 \times 10^{-6} - 2.4948 \times 10^{-6} = 6.93 \times 10^{-8} R_1.$$

$$501 \times 10^{-6} = 6.93 \times 10^{-8} R_1$$

$$\begin{aligned}\therefore R_1 &= 72.29 \times 100 \\ &= \underline{\underline{7.229 \text{ k}\Omega}}\end{aligned}$$

13. For an IC 555 timer, $D = 60\%$, $f = 2 \text{ kHz}$

$$R_2 = 3 \text{ k}\Omega, C = 0.1 \mu\text{F}, R_1 = ?$$

Solve the problem.

Feedback and oscillator circuits.

- Feedback plays an important role in electronic circuits. It is used in amplifiers to improve its performance and make it more ideal.
- * In feedback amplifiers, a part of the O/P is sampled and fed back to the I/P of the amplifier.
 - * At the I/P there will be two signals. Input signal and a part of the O/P. Both may be in phase or out of phase with each other.
 - * Depending on the polarity of the signal fed back into the circuit, it can be negative or positive feedback.
 - * When the I/P signal and the feedback signal are out of phase, it is negative feedback.
 - When the I/P signal and the feedback signal are in phase, it is positive feedback.
 - * Negative feedback results in decreased voltage gain, for which a number of circuit features are improved.
 - * Positive feedback drives the circuit into oscillations.

Feedback concepts

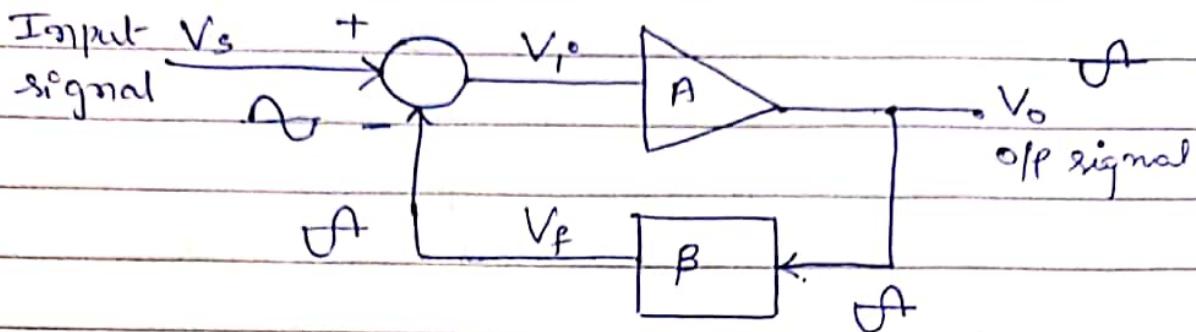


Fig: Simple block of Feedback amplifier.

- * A typical feedback connection is shown in figure above. The i/p signal V_s is applied to the mixer network, where it is combined with a feedback signal V_f . V_i is the difference of these two signals. It is then applied as the i/p to the amplifier whose gain is A . A portion of the amplifier o/p V_o is connected to the feedback network (β), which provides a reduced portion of the output as feedback signal to the input mixer network.

- * Negative feedback is shown in the figure above. Advantages of negative feedback are
 - 1) Reduced overall voltage gain
 - 2) Higher input impedance
 - 3) Improved frequency response
 - 4) Lower output impedance
 - 5) Reduced noise
 - 6) More linear operation.

Voltage Series feedback amplifier

Here voltage refers to connecting the output voltage as input to the feedback network.

Series refers to connecting the feedback signal in series with the input signal.

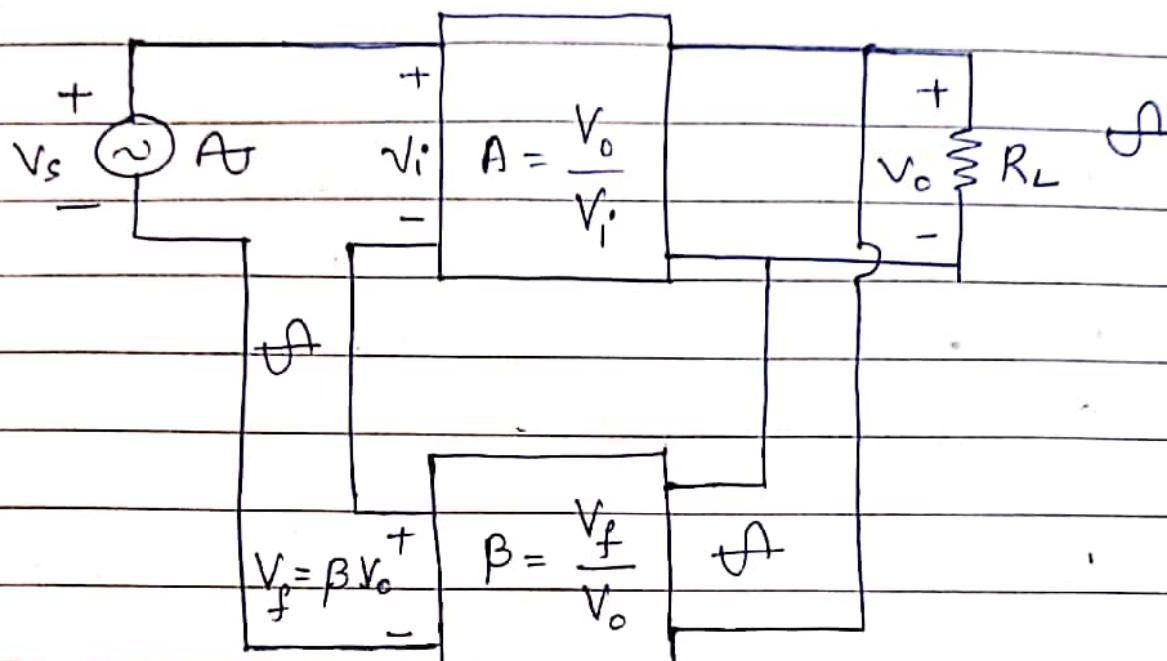


Fig: Voltage-series feedback amplifier. ($A_f = \frac{V_o}{V_s}$)

- * Series feedback connections tend to increase the input resistance. Voltage feedback tends to decrease output resistance (impedance).
- * Most of the cascade amplifiers require higher input impedance and lower output impedance. Both of these are provided using the voltage-series feedback connection.

* In the above figure, V_s is the overall i/p signal. V_i is the difference signal connected to the amplifier. 'A' is the gain without feedback of amplifier stage.

The feedback factor is ' β ' of the feedback network. A_f is the gain with feedback.

* With feedback, the overall gain of the circuit is reduced by a factor of $(1 + A\beta)$.

In voltage-series feedback connection, a part of the output voltage is fed back in series with the i/p signal that results in an overall gain reduction.

If there is no feedback ($V_f = 0$), the voltage gain of the amplifier stage is

$$A = \frac{V_o}{V_s} = \frac{V_o}{V_i} \quad \text{---(1)}$$

If a feedback signal V_f is connected in series with the input, then

$$\begin{aligned} V_i &= V_s - V_f \\ \text{Since } V_o &= AV_i = A(V_s - V_f) \\ &= AV_s - AV_f \\ &= AV_s - A(\beta V_o) \end{aligned}$$

then,

$$\begin{aligned} V_o &= AV_s - A\beta V_o \\ \text{or } V_o(1 + A\beta) &= AV_s \end{aligned}$$

So that the overall gain with feedback is

$$\boxed{A_f = \frac{V_o}{V_s} = \frac{A}{(1+AB)}} \quad (2)$$

In negative feedback systems, the feedback voltage V_f is subtracted from the i/p signal V_s .

$$\therefore |A_f| < |A|.$$

i.e Negative feedback reduces the gain of the amplifier by a factor of $(1+AB)$.

Problem:

Determine the voltage gain with feedback for voltage series feedback having $A = -100$ for $B = -0.1$ & $B = -0.5$.

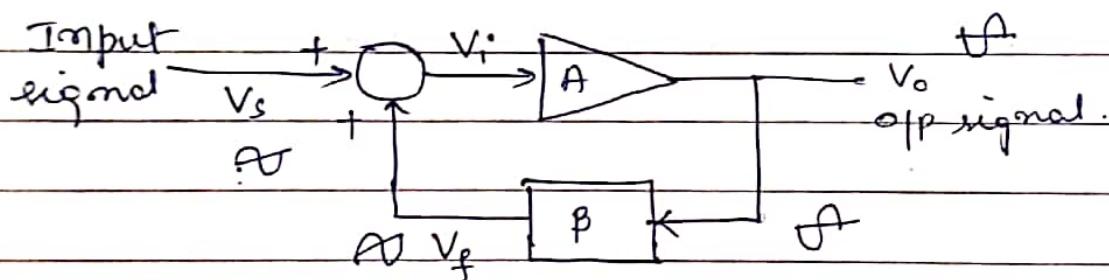
$$(i) A_f = \frac{A}{1+AB} = \frac{-100}{1+(-0.1)(-100)} = \frac{-100}{11} = -9.09$$

$B = -0.1$

$$(ii) B = -0.5, \quad A_f = \frac{A}{1+AB} = \frac{-100}{51} = -1.96.$$

Concept of positive feedback

- * when the i/p signal and the feedback signal are in phase with each other it is known as positive feedback.
- * Feedback amplifier with positive feedback having closed loop or overall gain $|A_f| > 1$ will result in operation as an oscillator circuit.
- * If the output signal varies sinusoidally, it is referred to as sinusoidal oscillator.
- * If the output signal rises quickly to one voltage level and later drops to another level, it is referred to as a square wave oscillator.



Here the overall gain with feedback is

$$A_f = \frac{A}{1 - A\beta}$$

Both V_s and the feedback signal V_f are in phase with each other. The gain with feedback increases as the amount of positive feedback increases and thus becomes infinity.

consider various values of β and corresponding values of A_f for a constant amplifier gain

$$A = 20$$

A	β	A_f
20	0.005	22.22
20	0.04	100
20	0.045	200
20	0.05	∞

Oscillator operation

Consider the block diagram shown below with positive feedback.

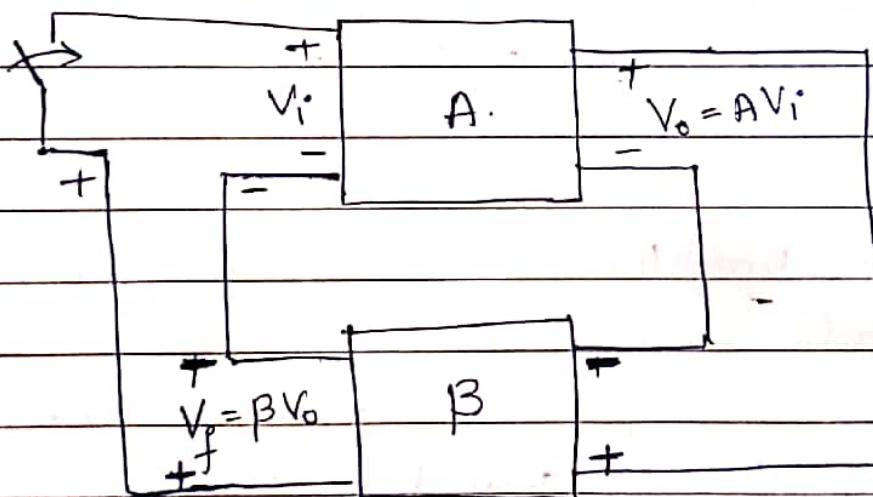


Fig: Feedback circuit used as an oscillator.

when the switch at the amplifier input is open, no oscillations occur.

consider that we have a fictitious voltage ~~at~~ V_i at the amplifier input.

- * This results in an output voltage $V_o = AV_i$ after the amplifier stage and in a voltage $V_f = \beta V_o$ after the feedback stage. Thus we have a feedback voltage $V_f = \beta V_o = \beta(AV_i)$, where βA is referred to as the loop gain.
- * For the circuit to work as an oscillator, the feedback voltage V_f should drive the amplifier and hence V_f must act as V_i .
- * Then, when the switch is closed & the fictitious voltage V_i is removed, the circuit continues to operate since the feedback voltage is sufficient to drive the amplifier.
- * The output waveform will still exist after the switch is closed if the condition $\beta A = 1$ is met.

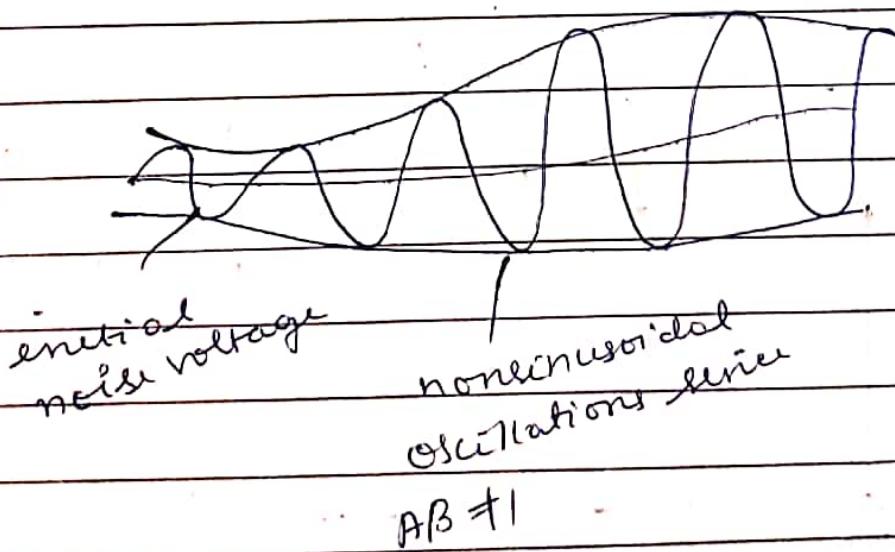
Hence Barkhausen criterion states that

1. Total phase shift around the loop, as the signal proceeds from i/p through amplifier, feedback n/w and back to i/p again completing a loop is 0° or 360° .
2. The magnitude of product of the open loop gain A and feedback factor β is unity.

$$|AB| = 1.$$

Satisfying these conditions the circuit works as an oscillator producing sustained oscillations.

- * In reality, no i/p signal is needed to start oscillations. Only the condition $AB = 1$ must be satisfied to result in sustained oscillations.
- * But in practice, BA is set > 1 and the system is started oscillating by amplifying the noise voltage.
- * The resulting waveforms are not exactly sinusoidal. But, closer the value of $AB = 1$, more sinusoidal is the output waveform.



OP-Amp oscillators.

RC phase shift oscillator.

RC phase shift oscillator consists of an amplifier and a feedback network. In this circuit, OP-Amp with inverting configuration is used as an amplifier that generates a phase shift of 180° .

Feedback network consists of 3 RC sections connected in ladder form. Each RC section generates a phase shift of 60° . Hence a total of 180° phase shift is generated by the feedback network.

Circuit diagram :

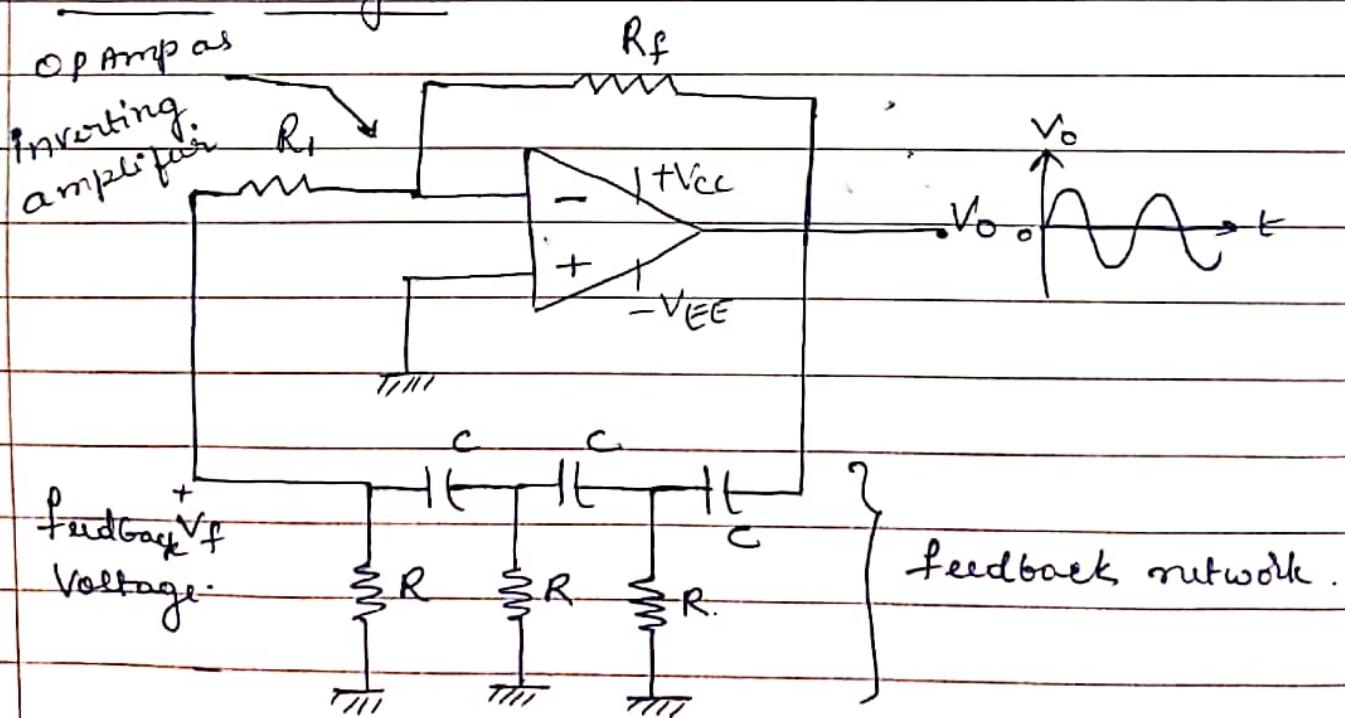


Fig: RC phase shift oscillator using OP-Amp.

The output of the amplifier is given to the feedback network. The output of the feedback network drives the amplifier.

Hence, the total phase shift around the closed loop is 180° due to the inverting amplifier and 180° due to 3 RC sections. Thus 360° . This satisfies the required condition for positive feedback and circuit works as an oscillator.

The frequency of oscillations is given by

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

These oscillators are used over the audio frequency range i.e. about 20Hz to 20kHz .

The circuit is simple to design, but the values of $R + C$ of all the three sections must be changed simultaneously to satisfy the criteria.

LC oscillators.

1. Colpitts oscillator :

The feedback network comprises of 2 capacitors and 1 inductor in Colpitts oscillator.

Circuit diagram :

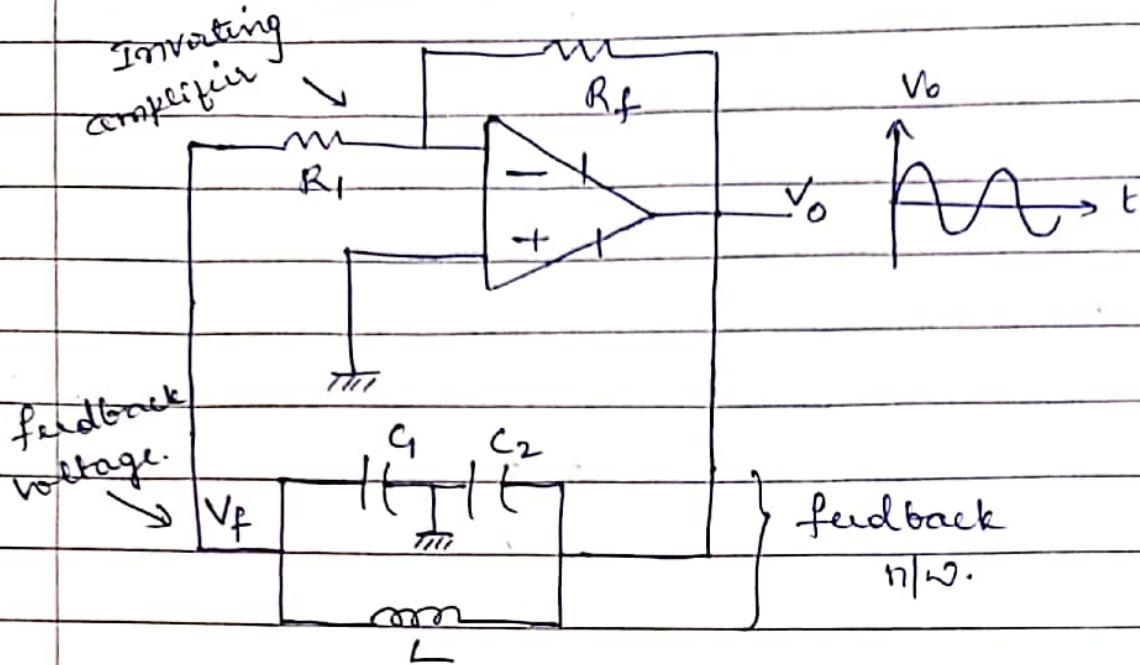


Fig: Op-Amp Colpitts Oscillator.

Colpitts oscillator consists of an inverting amplifier using Op-Amp that generates a phase shift of 180° .

The feedback network consists of a parallel LC resonant tank circuit. The feedback is achieved by the way of a capacitive divider to feed a fraction of the output signal back to the inverting terminal of the amplifier.

When the power supply is switched on, capacitors C_1 and C_2 charges up and then discharges through inductor L . A phase shift of 180° is achieved through the tank circuit resulting in overall phase shift of 360° .

The amount of feedback depends on the values of G_1 and C_2 . Large amount of feedback voltage may generate distortion in the output sine wave. while small amount of ~~fb~~^{f_{fb}} feedback may not allow the circuit to oscillate.

The frequency of oscillations is

$$f = \frac{1}{2\pi\sqrt{L C_{eq}}} \quad \text{where}$$

$$C_{eq} = \frac{G_1 C_2}{G_1 + C_2}$$

The feedback factor is $\beta = \frac{C_2}{C_1}$.

The condition for sustained oscillations is

$$|AB| > 1.$$

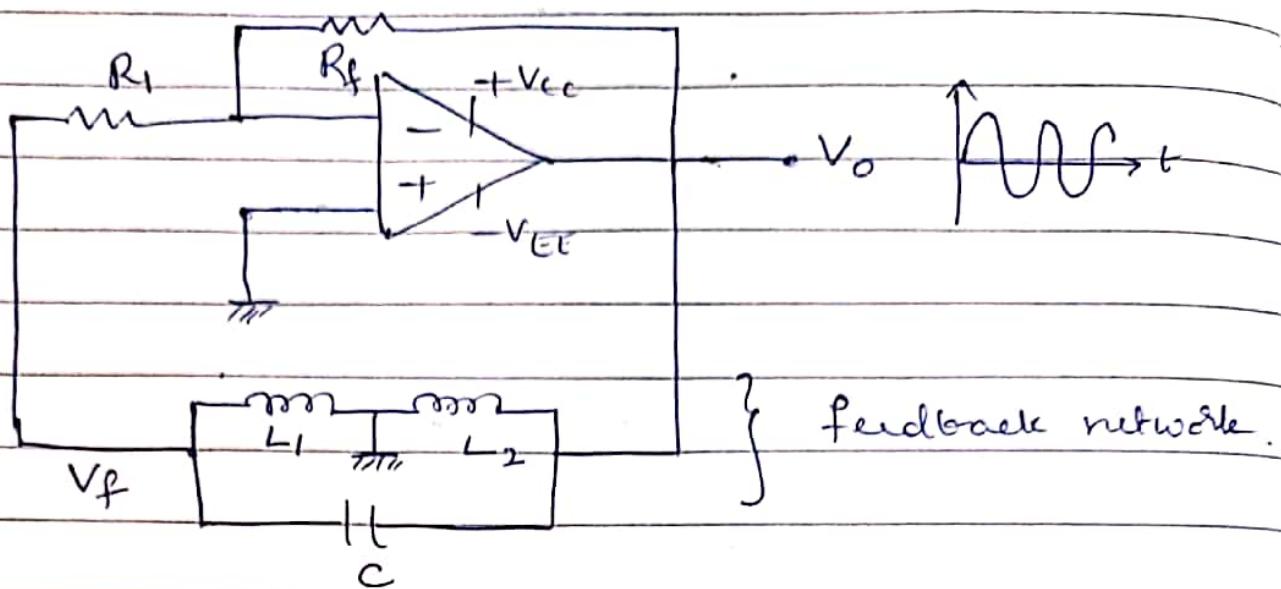
$$\text{or } |A| > \frac{1}{\beta}$$

$$\text{or } |A| > \frac{G_1}{C_2}$$

2. Hartley oscillator:

The feedback network consists of 2 inductors and 1 capacitor in Hartley oscillator.

Circuit diagram:



Hartley oscillator consists of an OP-Amp circuit in inverting configuration that generates a phase shift of 180° . It consists of an LC tank circuit where two inductors L_1 and L_2 in series are connected in parallel with a single capacitor C .

When the DC power supply is switched on, the capacitor C starts charging. When the capacitor is fully charged, it starts discharging through inductors L_1 and L_2 . Then an oscillatory current is generated to provide a phase shift of 180° . The voltage across C is the feedback voltage V_f connected to the inverting terminal of the OP-Amp. Thus a total phase shift of 360° is achieved.

Frequency of oscillations is given by

$$f = \frac{1}{2\pi\sqrt{L_{eq}C}} \quad \text{where } L_{eq} = L_1 + L_2$$

$$\text{Feedback factor } \beta = \frac{L_1}{L_2}$$

Condition for sustained oscillations is

$$|AB| > 1$$

$$\text{or } |A| > \frac{1}{\beta} \quad \text{or } |A| > \frac{L_2}{L_1}$$

If mutual inductance exists between L_1 & L_2 , then
with M ,

$$L_{eq} = L_1 + L_2 + 2M.$$

Numericals :

- In an RC phase shift oscillator, $R = 500\Omega$ and $C = 0.1\mu F$. Calculate the frequency of oscillations

Soln. Given : $R = 500\Omega$, $C = 0.1\mu F$.

$$f = \frac{1}{2\pi RC\sqrt{6}} = \frac{1}{2\pi \times 500 \times 0.1 \times 10^{-6} \times \sqrt{6}}$$

$$f = \underline{\underline{1.299 \text{ kHz}}}$$

- Q. In an RC phase shift oscillator, $R = 1 \text{ k}\Omega$. If the frequency of oscillations is 5 kHz , calculate the value of C .

Solu: $R = 1 \text{ k}\Omega$, $f = 5 \text{ kHz}$.

$$f = \frac{1}{2\pi\sqrt{RC}} \quad \text{or} \quad C = \frac{1}{2\pi R f \sqrt{6}}$$

$$\therefore C = \underline{\underline{0.0129 \text{ nF}}}$$

3. Find the frequency of oscillations in a Colpitts oscillator with $C_1 = 150 \text{ pF}$, $C_2 = 1.5 \text{ nF}$ & $L = 50 \mu\text{H}$.

Solu: Given $C_1 = 150 \text{ pF}$ $C_2 = 1.5 \text{ nF}$, $L = 50 \mu\text{H}$.

$$f = \frac{1}{2\pi\sqrt{L C_{eq}}} \quad C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

$$C_{eq} = \frac{150 \times 10^{-12} \times 1.5 \times 10^{-9}}{150 \times 10^{-12} + 1.5 \times 10^{-9}} = \underline{\underline{136.36 \text{ pF}}}$$

$$\therefore f = \frac{1}{2\pi\sqrt{50 \times 10^{-6} \times 136.36 \times 10^{-12}}} \\ = \underline{\underline{1.927 \text{ MHz}}}$$

4. In a Colpitts oscillator, $C_1 = 100\text{ pF}$, $C_2 = 260\text{ pF}$
 Find the value of L if the frequency of oscillations is 40 kHz .

Solu. Given: $C_1 = 100\text{ pF}$ $C_2 = 260\text{ pF}$.
 $L = ?$ $f = 40\text{ kHz}$.

$$f = \frac{1}{2\pi\sqrt{LC_{eq}}} \quad C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

$$C_{eq} = \frac{100 \times 10^{-12} \times 260 \times 10^{-12}}{100 \times 10^{-12} + 260 \times 10^{-12}} = 37.5 \text{ pF}$$

To find L . Square both sides of f .

$$f^2 = \frac{1}{4\pi^2 L C_{eq}}$$

$$\therefore L = \frac{1}{4\pi^2 f^2 C_{eq}}$$

$$= \frac{1}{4\pi^2 (40 \times 10^3)^2 (37.5 \times 10^{-12})}$$

$$\therefore L = 0.422 \text{ H}$$

5. In a Colpitts oscillator, $L = 5\text{ mH}$. Find C_1 and C_2 if the frequency of oscillations is $f = 50\text{ kHz}$. Assume a feedback factor of $\beta = 10\%$.

$$\text{Given } L = 5 \text{ mH}, f = 50 \text{ kHz}, \beta = 10\% = 0.1$$

$$f = \frac{1}{2\pi \sqrt{L C_{eq}}} \quad C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

Squaring f,

$$f^2 = \frac{1}{4\pi^2 L C_{eq}}$$

$$C_{eq} = \frac{1}{4\pi^2 L f^2} = \frac{1}{4\pi^2 \times 5 \times 10^{-3} \times (50 \times 10^3)^2}$$

$$C_{eq} = \underline{2.02 \text{ nF}}$$

$$\text{Wkt } C_{eq} = \frac{C_1 C_2}{C_1 + C_2}, \beta = 0.1 = \frac{C_2}{C_1}$$

$$\therefore \underline{C_2 = 0.1 C_1}$$

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{C_1 \times 0.1 C_1}{1.1 C_1} = \underline{\frac{0.1 C_1}{1.1}}$$

$$\Rightarrow C_{eq} = \frac{0.1 C_1}{1.1}$$

$$2.02 \text{ nF} = \underline{\frac{0.1 C_1}{1.1}}$$

$$\therefore \underline{C_1 = 22.22 \text{ nF}}$$

$$+ C_2 = 0.1 \times 22.22 \text{ nF}$$

$$= \underline{2.222 \text{ nF}}$$

5. Design a Colpitts oscillator whose frequency of oscillation is 40kHz , $L = 10\text{mH}$ and $C_1 = C_2 = C$.

Soln. $C_1 = C_2 = C$, $f = 40\text{kHz}$, $L = 10\text{mH}$.

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{C^2}{2C} = \frac{C}{2}$$

$$\therefore f = \frac{1}{2\pi\sqrt{C_{eq}L}} \quad \text{Equating } f,$$

$$f^2 = \frac{1}{4\pi^2 C_{eq} L}$$

$$C_{eq} = \frac{1}{4\pi^2 L f^2}$$

$$\frac{C}{2} = \frac{1}{4\pi^2 (40 \times 10^3)^2 \times 10 \times 10^{-3}}$$

$$\therefore C = 3.166 \text{nF}$$

$$C_1 = C_2 = \underline{\underline{3.166 \text{nF}}}$$

— 0 —