UNIT-I

INTEGRATED CIRCUITS

* The integrated circuit or Ic is a miniature, low cost electronic circuit consisting of active and passive components that are irreparably joined together on a single crystal chip of silicon.

Advantages of Ic's:-

1. Miniaturization and hence increased equipment density.
2. Cost reduction due to batch processing.
3. Improved performance
4. Increased operating speed.
5. Low power consumption
6. High reliability.
7. Less weight, volume
8. Easy replacement.

Disadvantages of Ic's:-

* At present inductors and Transformers cannot be in Ic form.
* Limited power rating as it is not possible to manufacture high power Ics.

Types of Ics:-

a. Linear (or) Analogue Ics

b. Digital Ics: The signals are digital signals that have only two values. They contain circuits such as logic gates.

Ic Chip size and circuit Complexity:-

Until the 1950s, the electronic circuit device technology was dominated by Vaccum tube. The invention of the transistor in 1947 by William B. Shockley and John Bardeen of Bell Telephone laboratories was followed by the development of the Integrated circuit.

The concept of IC was introduced at the beginning of 1960 by both Texas Instruments and Fairchild semiconductors. The size and complexity of ICs have increased rapidly.

* Based on the No. of components integrated on the chip, they classified as:

1. SSI (Small-scale integration): upto 100 electronic components

   Ex: Logic gates, Flipflops etc.

   The invention of SSI in 1960-65.

2. MSI (Medium-scale integration): From 100 to 3,000 electronic components per chip. The invention of MSI in 1965-1970.

   Ex: MUX, DEMUX, counters, Adders.

3. LSI (Large-scale integration): From 3,000 to 100,000 electronic components per chip. The invention of LSI in 1970-1980.

   Ex: 8-bit Microprocessor (8085), ROM, RAM.

4. VLSI (Very large-scale integration): From 100,000 to 10,00,000 electronic components per chip. The invention of VLSI in 1980-19

   Ex: 16-bit Processor (8086), ARM Processors, Large Memories etc.

5. ULSI (Ultra large-scale integration): More than 1 million Electronic components per chip. The invention of ULSI in 1990-20

   Ex: Special Processors, Virtual reality machines, Smart sensors.

IC Packages :-

1. Metal can package
2. Dual-in-line package.
3. Ceramic flat package.

→ To manufacture ICs, a wafer of semiconductor is taken and the photolithography technique is used. This type of IC in which the entire circuit is formed on a single silicon crystal is called Monolithic IC.
Large number of monolithic ICs embedded on a ceramic substrate is known as Hybrid IC.

Manufacturer initials of IC's :-

Manufacturer prefix (or) Ic company prefix or IDs are identification codes for various Ic manufacturing companies.

Ex:- 1. μA741 (Military grade op-Amp)

(operating Temperature range $-55°c$ to $125°c$)

2. μA741C (commercial grade op-Amp)

(operating Temperature range is $0°c$ to $70°c$).

Prefix	company Name
MC	Motorola
LM	National semiconductors
μA	Fairchild semiconductors
TI	Texas Instruments
SE/NE	Signetics corporation.

Differential Amplifier :-

* The differential amplifier is designed by using two Transistor amplifier circuit.
* This circuit amplifies the difference between two input voltage levels.
* Its output is proportional to difference between two input voltages.

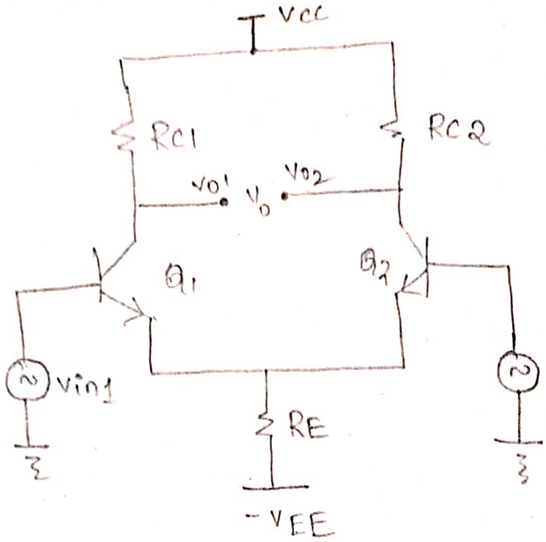
$$V_o = A_d (V_{in1} - V_{in2})$$

A_d is differential voltage gain

$$A_d = V_o / (V_{in1} - V_{in2})$$

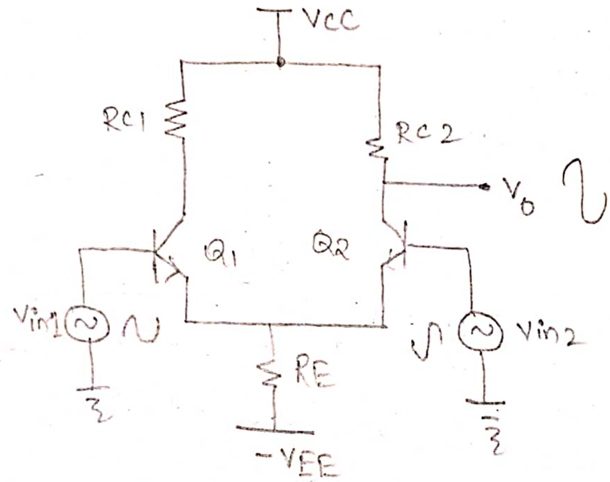
Types of Differential Amplifier :-

1. Dual input Balanced output Differential Amplifier.
2. Dual input Unbalanced output Differential Amplifier.
3. Single input Balanced output Differential Amplifier.
4. Single input unbalanced output Differential Amplifier.



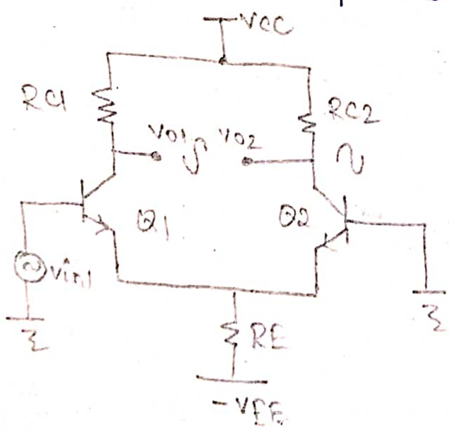
Basic differential Amplifier (Dual input balanced o/p differential amp)

Dual input unbalanced output Differential Amplifier

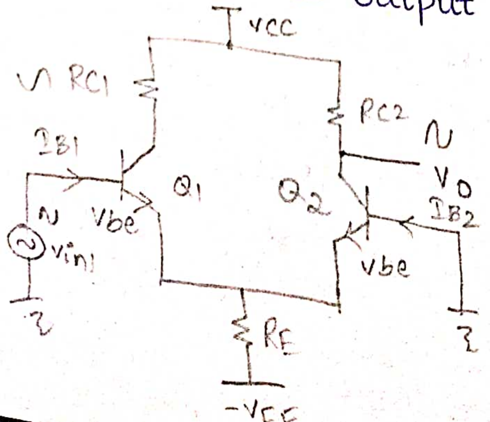


(output is collected only at the collector of one transistor)

Single Input Balanced output Differential Amplifier



Single Input Unbalanced Output Differential Amplifier



Operational Amplifier :-

* An operational Amplifier is a direct coupled high gain amplifier.
* It consists of one or more differential amplifiers, followed by a level shifter and an output stage.
* The first stage circuit provides most of the voltage gain to the op-Amp.
* The second stage differential Amplifier provides additional voltage gain to the op-Amp.
* The output stage is complementary - symmetry push-pull circuit to produce large voltage swing.
* Op-Amp is a versatile device that can be used to amplify both Ac as well as Dc input signals.
* It is designed for computing mathematical functions such as addition, subtraction, multiplication, integration and differentiation

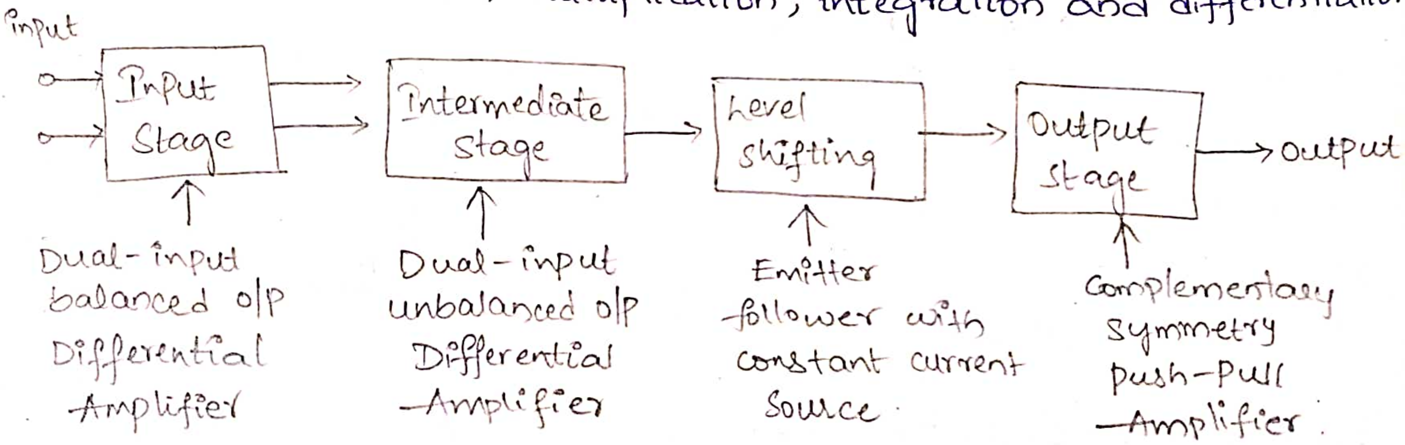
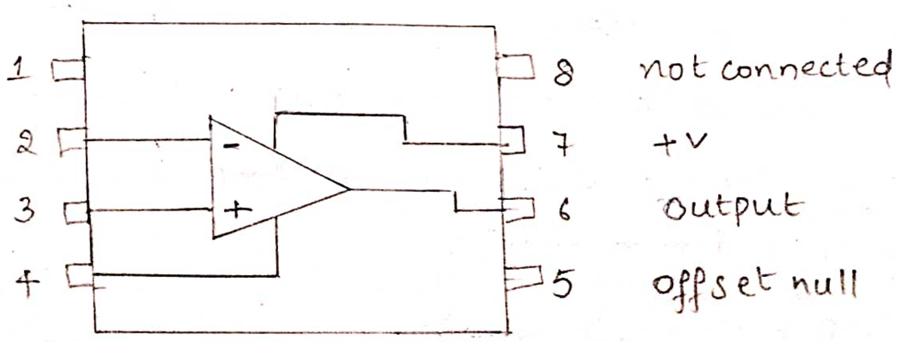
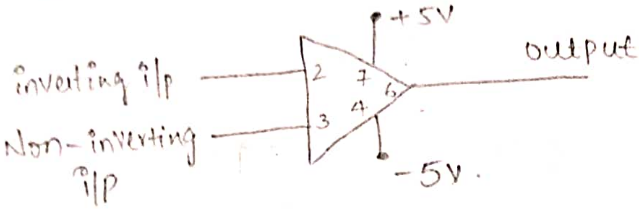


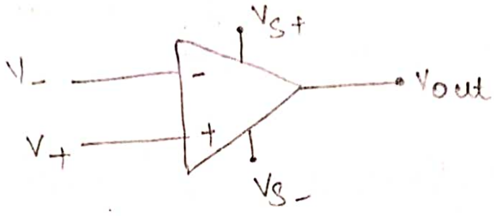
Fig: Block Diagram of a Typical op-Amp.

Pin diagram of op-Amp :-



Operational Amplifier Symbol :-





The circuit schematic of an op-Amp is a triangle. It has two input terminals and one output terminal. The terminal with a negative sign is called inverting input terminal and terminal with a positive sign is called non-inverting input terminal.

Applications of op-Amp :-

* Integrators
* Differentiators
* Filters
* Oscillators
* Voltage regulators.

Ideal op-Amp characteristics :-

1. Input Impedance (R_i):

The ideal op-Amp has infinite input impedance ($R_i=\infty$)

2. Output Impedance (R_o):

The ideal op-Amp has zero output impedance ($R_o=0$). Due to this characteristics the op-Amp can be used as impedance matching device.

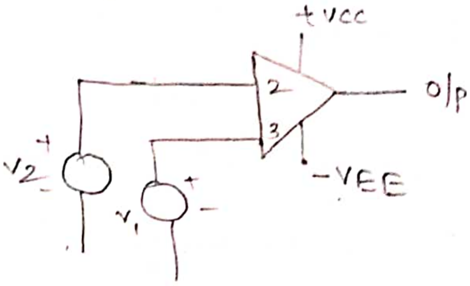
3. Open loop Voltage gain (A_{OL}):-

The ideal op-Amp has infinite voltage gain ($A_{OL}=\infty$). It is the voltage gain in open loop configuration.

4. CMRR (Common mode Rejection Ratio):

It is the ratio of differential voltage gain to common mode gain.

$$CMRR = A_d / A_{cm}.$$



For ideal op-Amp;

$A_{cm} = 0$; $CMRR = \infty$.

But practical op-Amps have small value of A_{cm}.

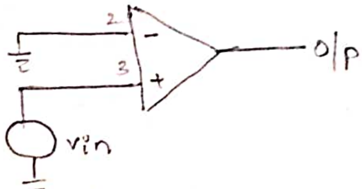
for μA741C op-Amp ; CMRR = 90dB.

5. Slew Rate :

It is defined as the maximum rate of change of output voltage per unit time.

$$SR = dV_o/dt$$

Units :- Volts / μsec.

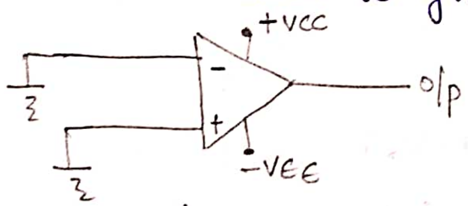


But 741C op-amp has low slew rate. There is limited application at high frequencies.

6. Input offset voltage (V_{ios}):

when both input terminals of op-amp are connected to ground, the output must be zero.

For practical op-amp produces small output voltage when both input terminals are connected to ground.



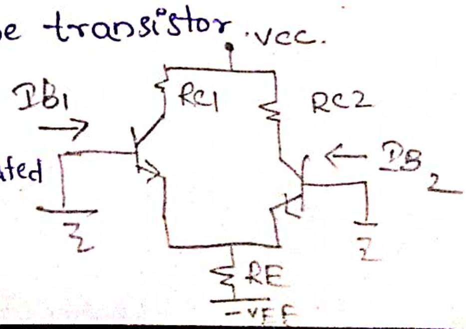
7. Input Bias current (I_B):

In op-amp ; we are using differential amplifier as input stage. Due to the mismatch present in two transistors small DC currents are flowing through the transistor.

The Bias current will be in nA.

The overall DC bias current can be calculated

$$I_B = |I_1 + I_2| / 2$$



8. Input offset current (I_{ios}):

The difference in magnitudes of I_1 and I_2 is called input offset current.

$I_{ios} = |I_1 - I_2|$.

for ideal input offset current is zero ($I_{ios} = 0$).

9. Bandwidth (BW):

The ideal op-amp has infinite Bandwidth. Any frequency from 0Hz to ∞ can be amplified without attenuation.

10. Power Supply Rejection Ratio (PSRR):

PSRR is the ratio of change in input offset voltage (V_{ios}) due to the change in supply voltage (V_{cc}). Ideally its value should be zero.

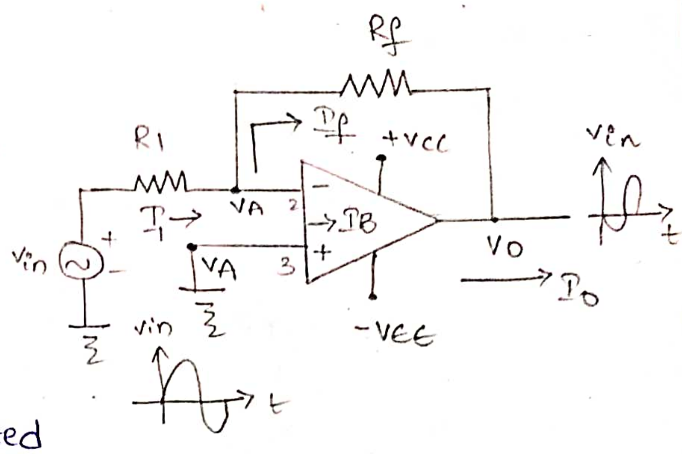
$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{cc}} \Big| V_{EE} \text{ constant}.$$

Ideal and Practical op-Amp characteristics :-

S.NO	Parameter	Ideal op-Amp characteristics	Practical op-Amp characteristics.
1	Input impedance (Ri)	∞	2MΩ
2	Output impedance (Ro)	0	75Ω
3	Open loop voltage gain	∞	2×10^5
4	CMRR	∞	90dB.
5	PSRR	0	30μV/V
6	Input offset voltage (V_{ios})	0	1mV.
7	Input Bias current (I_B)	0	80nA.
8	Input offset current (I_{ios})	0	20nA.
9	Bandwidth (BW)	∞	1MHz
10.	Slew rate (SR)	∞	0.5V/μsec.

Modes of operation of OP-Amp :-

1. Inverting Amplifier :-



The first useful op-amp circuit that we will consider is the inverting Amplifier.

* Here the non inverting input is grounded.
* The inverting terminal is connected to the output via a feedback resistor, Rf.
* The input is also connected to the inverting terminal via another resistor, R_1.

Analysis :-

Apply KCL at node V_A :

$$I_1 = I_f + I_B \quad \therefore (I_B = 0).$$

$$I_1 = I_f$$

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

According to virtual ground concept $V_A = 0V$.

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

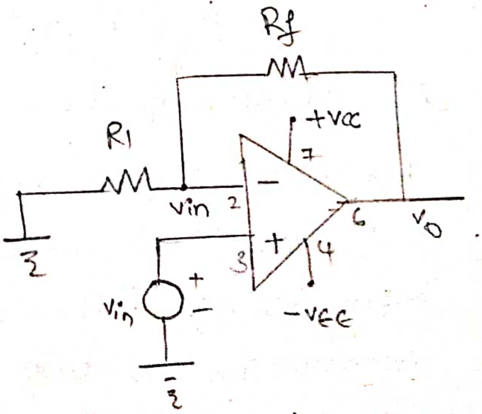
$$V_o = \frac{-V_{in} R_f}{R_1} = \left(-\frac{R_f}{R_1}\right) V_{in}$$

$$V_o = A_{CL} \cdot V_{in}.$$

**

$$\boxed{A_{CL} = -\frac{R_f}{R_1}}$$

2. Non-inverting Amplifier :-



Another important op-amp circuit is the non inverting Amplifier.

Here the signal is applied to the positive input terminal and feedback is given.

The circuit amplifies without inverting the input signal. Hence it is called non-inverting amplifier.

According to the Voltage division rule;

At node vin;

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

$$\frac{V_{in}}{V_o} = \frac{R_1}{R_1+R_f}$$

$$\frac{V_o}{V_{in}} = \frac{R_1+R_f}{R_1}$$

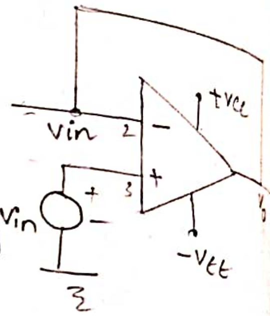
$$\frac{V_o}{V_{in}} = 1+\frac{R_f}{R_1}$$

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

The gain can be adjusted to unity or more by Proper selection of resistors R_f and R_1. comparing with inverting Amplifier the input resistance R_i is extremely large.

Voltage follower:

The output voltage follows the input voltage exactly hence the circuit is called a Voltage follower voltage follower is obtained from the non inverting amplifier if $R_f = 0$ and $R_1 = \infty$.



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

$$\frac{V_o}{V_{in}} = 1+\frac{R_f}{R_1}$$

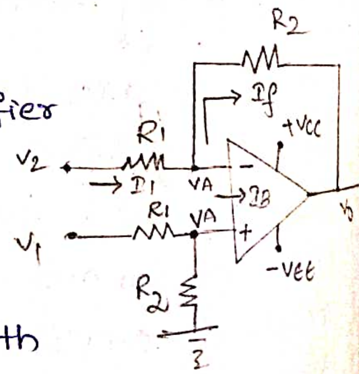
$$\frac{V_o}{V_{in}} = 1$$

$$V_o = V_{in}$$

Voltage follower is used as buffer for impedance matching i-e to connect a high impedance source to a low impedance load.

Differential Amplifier:-

The main function of the differential amplifier is, it amplifies the changes between two input voltages. But conquers, any voltage common to the two inputs. It gives an overview of differential amplifier along with its mathematical expression.



1. Apply voltage division at V_A (non inverting).

$$V_A = V_1 \times \frac{R_2}{R_1 + R_2}$$

2. Apply KCL at V_A (inverting terminal)

$$I_1 = I_f + I_B$$

$$I_1 = I_f \quad (I_B = 0).$$

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

$$\frac{(V_2 - V_A)R_2 - (V_A - V_0)R_1}{R_1 R_2} = 0.$$

$$(V_2 - V_A)R_2 - (V_A - V_0)R_1 = 0$$

$$V_2 R_2 - V_A R_2 - V_A R_1 + V_0 R_1 = 0.$$

$$V_2 R_2 - V_A (R_1 + R_2) + V_0 R_1 = 0.$$

$$V_2 R_2 - V_1 \times \left(\frac{R_2}{R_1 + R_2}\right)(R_1 + R_2) + V_0 R_1 = 0.$$

$$V_2 R_2 - V_1 R_2 = -V_0 R_1$$

$$R_2 (V_2 - V_1) = -V_0 R_1$$

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

** $\boxed{A_{CL} = \frac{R_2}{R_1}}$ for Differential Amplifier.

* $\boxed{V_0 = \left(\frac{R_2}{R_1}\right)(V_1 - V_2)}$

If $R_1 = R_2$;

* $\boxed{V_0 = V_1 - V_2}$

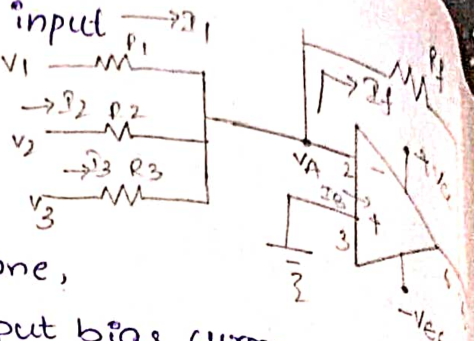
Summing Amplifier :-

OP-amp may be used to design a circuit whose output is the sum of several input signals. Such a circuit is called a summing amplifier or a summer.

1. Inverting summing amplifier
2. Non inverting summing amplifier

Inverting Summing Amplifier :-

A typical summing amplifier with three input voltages V_1, V_2 and V_3 three input resistors R_1, R_2 and R_3 and a feedback resistor R_f.



Assuming that the op-amp is an ideal one, that is $A_{OL} = \infty$ and $R_i = \infty$. Since the input bias current is assumed to be zero, there is no voltage drop across the resistor. Hence, the non-inverting terminal is at ground.

The voltage at node V_A is zero as the non-inverting input terminal is grounded. The nodal equation by KCL at node V_A is.

$$I_1 + I_2 + I_3 = I_f + I_B \quad [\because I_B = 0 \text{ because } R_i = \infty \text{ for ideal op-Amp}]$$

$$I_1 + I_2 + I_3 = I_f$$

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

According to Virtual Ground concept $V_A = 0V$.

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

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

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

If $R_1 = R_2 = R_3 = R_f$

$V_o = -(V_1 + V_2 + V_3) \rightarrow$ Adder

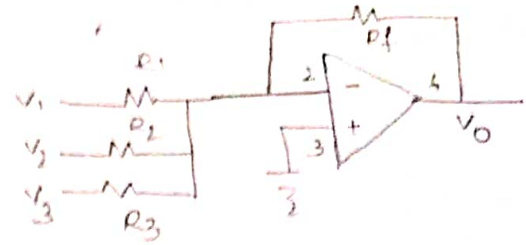
Thus, the output is an inverted, weighted sum of inputs. The output V_o is the inverted sum of input signals.

If $R_1 = R_2 = R_3 = 3R_f$.

$$V_o = -\left[\frac{V_1 + V_2 + V_3}{3}\right] \longrightarrow \text{Average}$$

Thus, the output is the average of the input signals. Under this condition, op-amp acts as average amplifier. So, it performs arithmetic mean.

Q. calculate output voltage V_o for the circuit shown below.



Sol: $V_o = -(V_1+V_2+V_3)$.

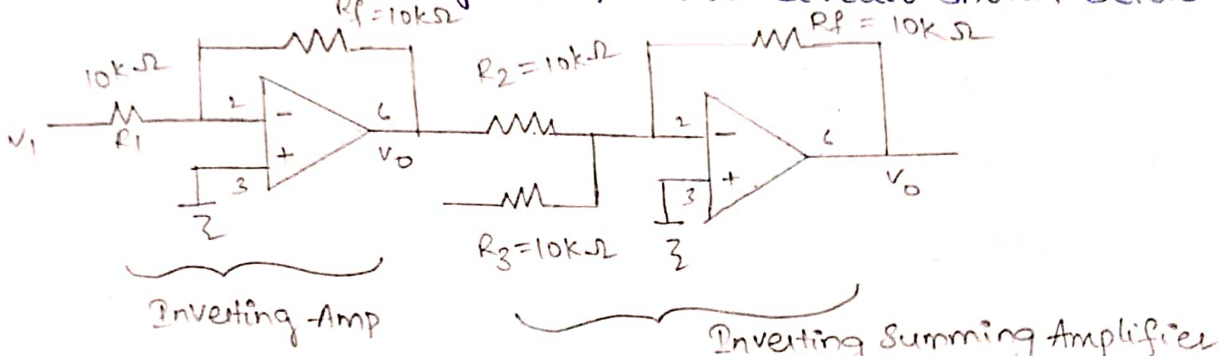
$V_1 = 1V,\ V_2 = 2V,\ V_3 = 3V.$

$R_1 = R_2 = R_3 = R_f = 1k\Omega$

$V_o = -(1+2+3)$

$= -6V.$

Q. calculate output voltage V_o for the circuit shown below.



Sol: $V_1 = 5V;\ V_2 = 2V.$

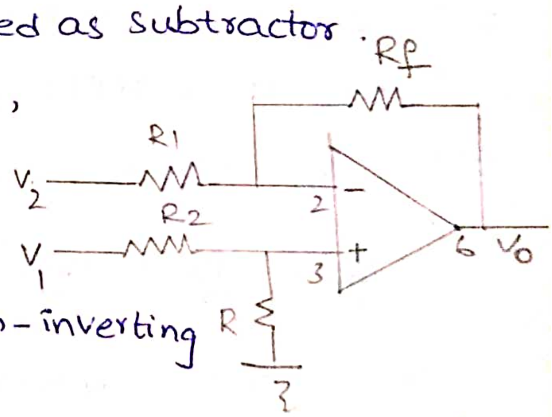
$$V_{o1} = -\frac{R_f}{R_1} \times V_1 = -5V.$$

$$V_o = -(V_{o1}+V_2)$$

$$V_o = -(\cancel{-}5+2) = 3V.$$

Subtractor:-

A basic differential amplifier can be used as subtractor. If all the resistors are equal in value, the output voltage can be derived. The circuit becomes a non-inverting amplifier having input voltage V_1 at non-inverting input terminal.



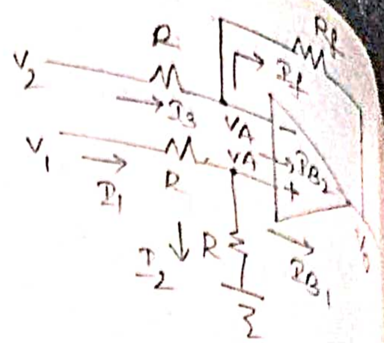
The Output Voltage V_o due to both inputs

$$V_o = \frac{R_2}{R_1}(V_1 - V_2)$$

If $R_1 = R_2$

$$V_o = V_1 - V_2$$

Apply KCL at node V_A (non inverting i/p)



$$I_1 = I_2 + I_{B1}$$

$$I_1 = I_2$$

$$\frac{V_1 - V_A}{R} = \frac{V_A - 0}{R}$$

$$\frac{V_1}{R} - \frac{V_A}{R} - \frac{V_A}{R} = 0.$$

$$V_1 - 2V_A = 0.$$

$$V_1 = 2V_A.$$

Apply KCL at node V_A (inverting i/p)

$$I_3 = I_f + I_B$$

$$\frac{V_2 - V_A}{R} = \frac{V_A - V_0}{R.}$$

$$\frac{V_2 - V_A}{R} - \left(\frac{V_A - V_0}{R}\right) = 0.$$

$$V_2 - 2V_A + V_0 = 0.$$

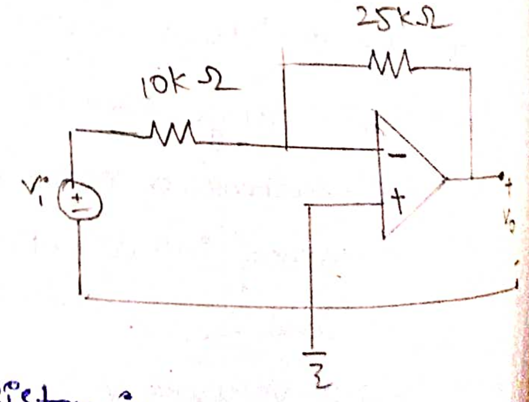
$$V_2 - V_1 + V_0 = 0.$$

$$\boxed{V_0 = V_1 - V_2.}$$

Problems:-

Q. If $V_i = 0.5V$, calculate the output voltage V_0 and the current in the $10k\Omega$ resistor.

Sol:- a. $V_0 = -\frac{R_f}{R_1} V_i$



$$\frac{V_0}{V_i} = -\frac{R_f}{R_1} = \frac{-25}{10} = -2.5$$

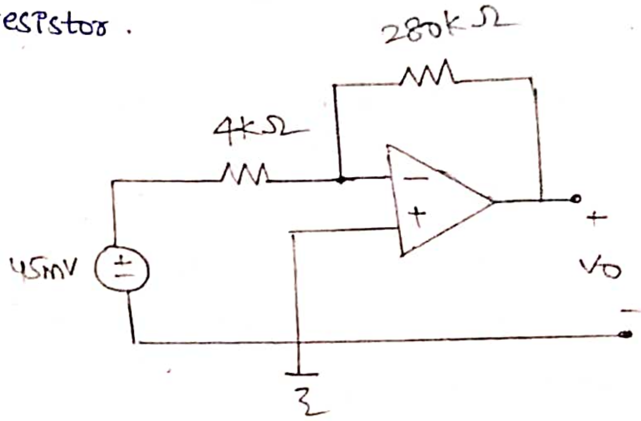
$$V_0 = -2.5V_i = -2.5 \times 0.5 = -1.25V.$$

b) The current through the $10k\Omega$ resistor is

$$i = \frac{V_i - 0}{R_1}$$

$$= \frac{0.5 - 0}{10 \times 10^3} = 50\,\mu A.$$

Q. Find the output of op-amp circuit shown in figure. calculate the current through the feedback resistor.



Sol:- $V_o = -\left(\frac{R_f}{R_1}\right)V_1$

$V_o = -\left(\frac{280}{4}\right)45mv$

$= -315mv$

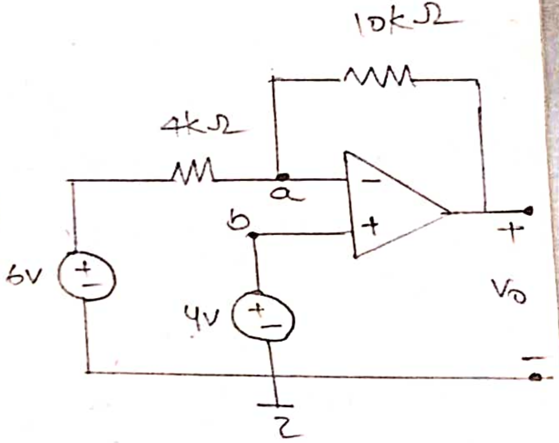
$= -3.15V$

$I = \frac{3.15}{280 \times 10^3}$

$= 0.01125 \times 10^{-3}$

$I = 11.25 \mu A$.

Q. calculate the output voltage Vo.



Sol:- Method 1:

Using superposition theorem; (V is shorted and I is open), only one voltage is considered at a time,

we let $V_{o1} = V_{o1} + V_{o2}$

$V_{o1} = -\frac{10}{4}(6) = -15V$ (using 6v, inverting i/p)

$V_{o2} = \left(1 + \frac{10}{4}\right)4 = 14V$ (Using 4V, non inverting i/p)

Thus, $V_o = V_{o1} + V_{o2} = -15V + 14V = -1V$.

Method 2:

Apply KCL at node a;

$\frac{6 - V_a}{4} = \frac{V_a - V_o}{10}$

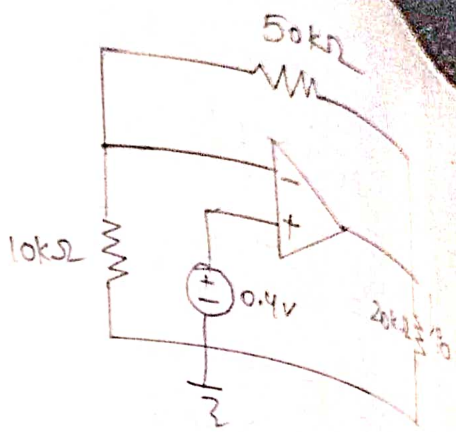
But $V_a = V_b = 4$ and so.

$\frac{6-4}{4} = \frac{4 - V_o}{10}$

$5 = 4 - V_o$

$V_o = -1V$.

Q. Find i_o in the op-amp circuit of figure.



Sol:- Method 1 :-

At node 1 ; $\frac{0-V_1}{10k} = \frac{V_1-V_o}{50k}$

But $V_1 = 0.4V$.

$-5V_1 = V_1 - V_o$, leads to

$V_o = 6V_1 = 2.4V$.

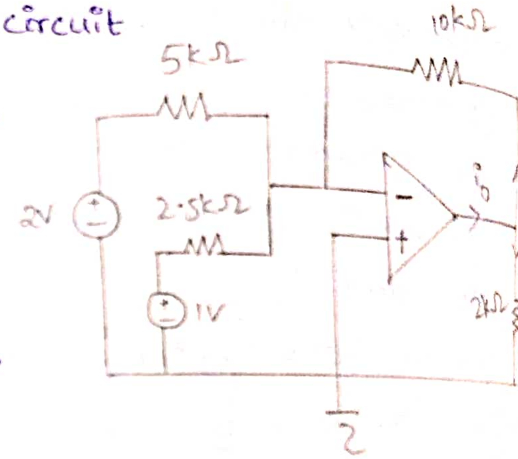
Method 2 :-

Viewed as a non inverting amplifier

$$V_o = \left(1+\frac{R_f}{R_1}\right)(V_1) = \left(1+\frac{50}{10}\right)(0.4) = 2.4V.$$

$$i_o = \frac{V_o}{20k} = \frac{2.4}{20k} = 120\mu A$$

Q. Calculate v_o and i_o in the op-amp circuit



Sol: This is a summer with two inputs

$$V_o = -\left[\frac{10}{5}(2) + \frac{10}{2.5}(1)\right]$$

$$= -8V.$$

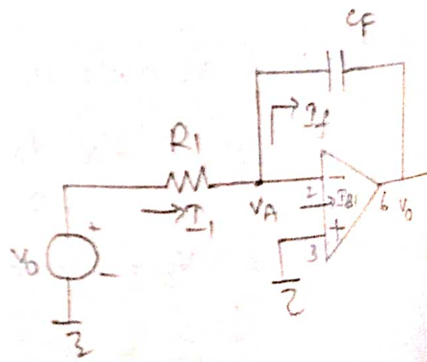
The current i_o is the sum of currents through the 10kΩ and 2kΩ resistors

both of these resistors have voltage $V_a = -8V$ across them.

Since $V_a = V_b = 0$. Hence,

$$i_o = \frac{V_o-0}{10} + \frac{V_o-0}{2} = -\frac{8}{10} + \left(\frac{-8}{2}\right) = -4.8mA.$$

Integrator Circuit



A circuit in which the output voltage waveform is the integral of input voltage waveform is called integrator.

Here, the feedback element is a capacitor

According to the virtual Ground concept $V_A = 0V$.

Apply KCL at node V_A;

$$I_1 = I_F + I_B \quad (\because I_B = 0)$$

$$I_1 = I_F$$

$$\frac{V_{in} - V_A}{R_1} = I_F$$

Voltage across the capacitor $V_C = \frac{1}{C_F} \int i_F \cdot dt$

$$\frac{V_{in} - V_A}{R_1} = C_F \cdot \frac{d}{dt} V_C$$

Application :-
1. It is used in analog computer.

$$\frac{V_{in} - V_0}{R_1} = C_F \cdot \frac{d}{dt} (V_A - V_0)$$

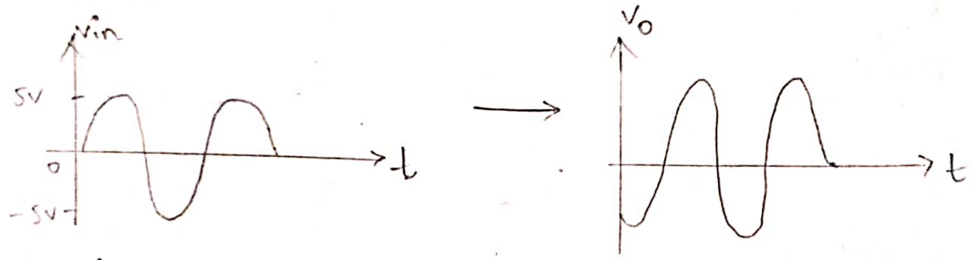
$$\frac{V_{in}}{R_1} = C_F \cdot \frac{d}{dt} (-V_0)$$

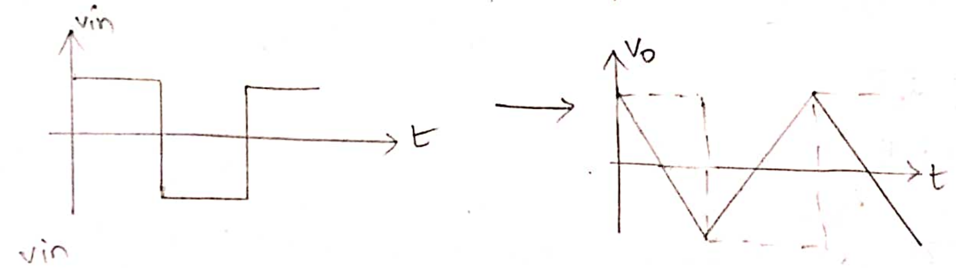
$$\int -\frac{1}{C_F} \cdot \frac{V_{in}}{R_1} = V_0 .$$

$$V_0 = -\frac{1}{R_1 C_F} \int_0^t V_{in} \cdot dt .$$

Here negative sign is included as the input voltage is given to the inverting terminal.

waveforms :-





V to I converter :-

Op-amp used as V to I converter. Since, the input voltage V_i is connected to non-inverting terminal. The input voltage V_i is converted into an output current I_L. The resistor is connected to non inverting terminal and it is grounded.

Let V_1 be the voltage at node 1.

Apply KCL at node 1.

$$I_1 + I_2 = I_L + I_B$$

$$I_1 + I_2 = I_L$$

$$\frac{V_{in} - V_1}{R} + \frac{V_0 - V_1}{R} = I_L$$

$$V_{in} + V_0 - 2V_1 = I_L R$$

$$2V_1 = V_{in} + V_0 - I_L R$$

The gain of the circuit of Non-inverting amplifier is

$$A_{CL} = 1 + \frac{R_f}{R_1} = \frac{V_0}{V_{in}}$$

If $R_f = R$, $R_1 = R$.

$$A_{CL} = 1 + \frac{R}{R} = 2.$$

$$V_0 = 2V_{in} = 2V_1$$

$$V_0 = V_{in} + V_0 - I_L R$$

$$+V_{in} = \cancel{+} I_L R$$

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

As the input impedance of a non-inverting amplifier is very high this circuit has the advantage of drawing very little current from the source. A voltage to current converter is used for low voltage dc and ac voltmeter, LED and zener diode tester.

Current to voltage converter :-

Op-amp used as I to V converter. Since the input terminal is at virtual ground, no current flows through R_0 and current i_0 flows through the feedback resistor R_f.

The Resistor R_F is sometimes shunted with a capacitor C_1 to reduce high frequency noise

According to Virtual Ground;

$V_A = 0V$

Apply KCL at node V_A

$$I_S = I_f + I_B \quad [I_B = 0V]$$

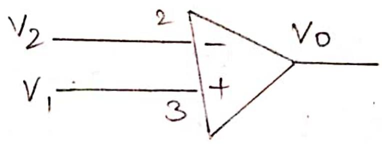
$$I_S = I_f$$

$$I_S = \frac{V_A - V_o}{R_F}$$

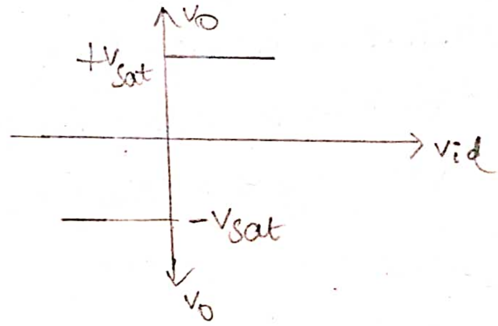
$$I_S = -\frac{V_o}{R_F}$$

$$V_o = -I_S R_F$$

* If there is no feedback in op-amp; (open loop configuration)



Transfer curve of AOL :-



$V_{id} = V_1 - V_2$

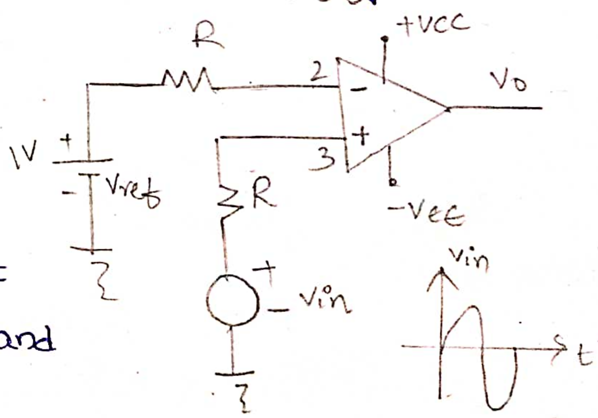
1) V_{id} is +ve ; $V_o = +V_{sat}$.

2) V_{id} is -ve ; $V_o = -V_{sat}$

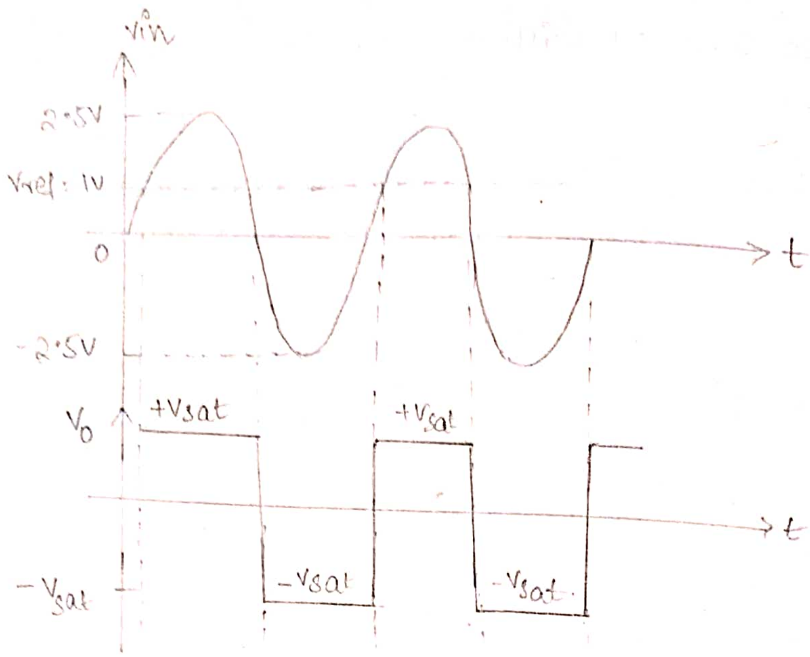
Comparators :-

1. Non-Inverting comparator with reference voltage.

A fixed reference voltage V_{ref} is applied to inverting terminal and a input signal V_{in} is applied to the non-inverting terminal. The output voltage is at $-V_{sat}$ for $V_{in} < V_{ref}$ and V_o goes to $+V_{sat}$ for $V_{in} > V_{ref}$.



The output waveform for a sinusoidal input signal for Positive and negative V_{ref} respectively.

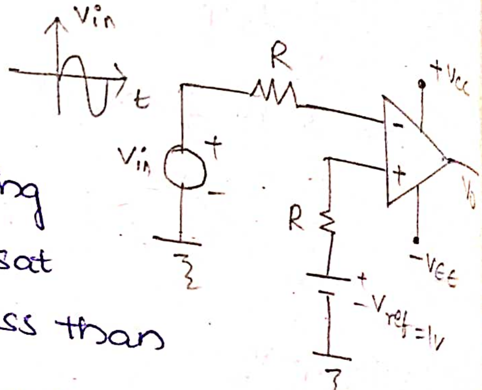


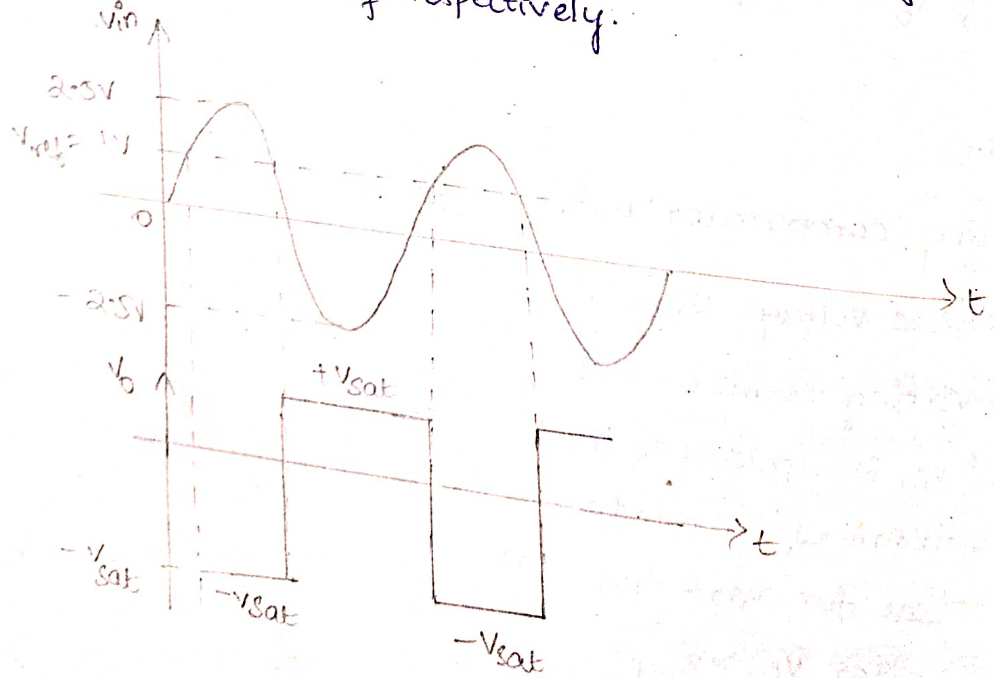
Characteristics of comparator:-

1. Speed of operation
2. Accuracy.
3. compatibility of the output

2. Inverting comparator with reference voltage:-

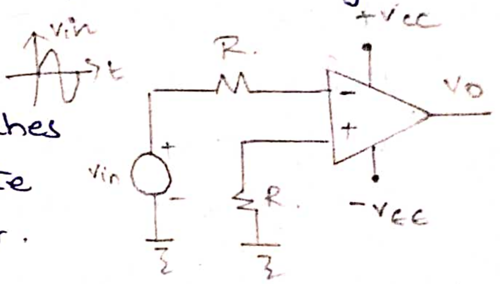
A fixed V_{ref} is applied to non-inverting terminal and a input voltage V_{in} is applied to the inverting terminal. The output voltage V_o is $-V_{sat}$ for $V_{in} > V_{ref}$. If input voltage is less than reference voltage (V_{ref}), the output voltage V_o is $+V_{sat}$. The output waveform for a sinusoidal input signal for positive and negative V_{ref} respectively.





3. Inverting comparator without reference voltage (zero crossing detector)

* Voltage comparator is a circuit which compares two voltages and switches the output to either high or low state depending upon which voltage is higher. A voltage comparator based on opamp.



Inverting Comparator :-

An inverting comparator is an op-amp based circuit comparator for which input voltage is applied to its inverting terminal.

The operation of an inverting comparator is very simple. It produces one of the two values, $+V_{sat}$ and $-V_{sat}$ at the output based on the values of its input voltage V_i and the reference voltage V_{ref}.

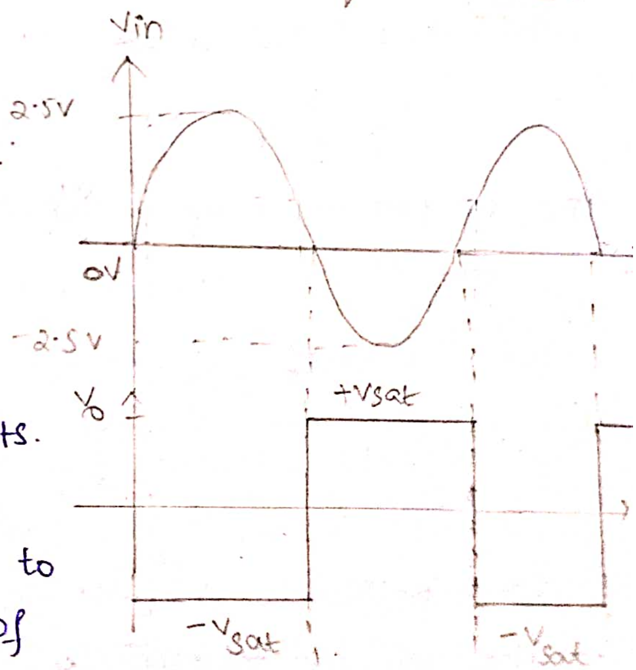
* The output value of an inverting comparator will be $-V_{sat}$ for which input voltage V_i is greater than the reference voltage(V_{ref}

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

* The output value for an inverting comparator will be $+V_{sat}$. for which input voltage V_i is less than the reference voltage V_{ref}

$$V_i < V_{ref} ; V_o = +V_{sat}.$$

Sine to square wave



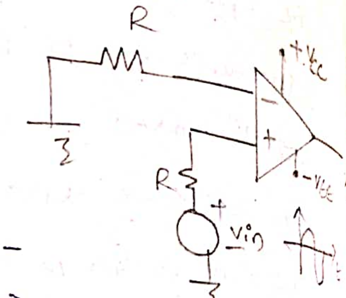
The output waveform of an inverting comparator, when $V_{ref} = 0V$.

During the positive halfcycle of the sinusoidal input signal, the voltage present at the inverting terminal of op-amp is greater than zero volts. Hence, the outputvalue of the inverting comparator will be equal to $-V_{sat}$ during positive halfcycle of sinusoidal input signal.

During, the negative half cycle of the sinusoidal input signal the voltage present at the inverting terminal of the op-amp is less than zero volts. Hence, the output value of the inverting comparator will be equal to $+V_{sat}$ during negative half cycle of the sinusoidal input signal.

We can observe that the output transitions either from $-V_{sat}$ to $+V_{sat}$ or from $+V_{sat}$ to $-V_{sat}$. whenever the sinusoidal input signal is crossing zero volts. In other words, output changes its value when the input is crossing zero volts. Hence, the above circuit is also called as inverting zero crossing detector.

4) Non inverting comparator without reference voltage:-



A non-inverting comparator is an op-amp based comparator for which a reference voltage is applied to its inverting terminal and the input voltage is applied to its non-inverting terminal. when reference voltage is equal to zero volts.

* The operation of non-inverting comparator is very simple. It produces one of the two values, $+V_{sat}$ and $-V_{sat}$ at the output based on the values of input voltage V_i and the reference voltage V_{ref}.

* The output value of non-inverting comparator will be $+V_{sat}$, for which the input voltage V_i is greater than the reference voltage

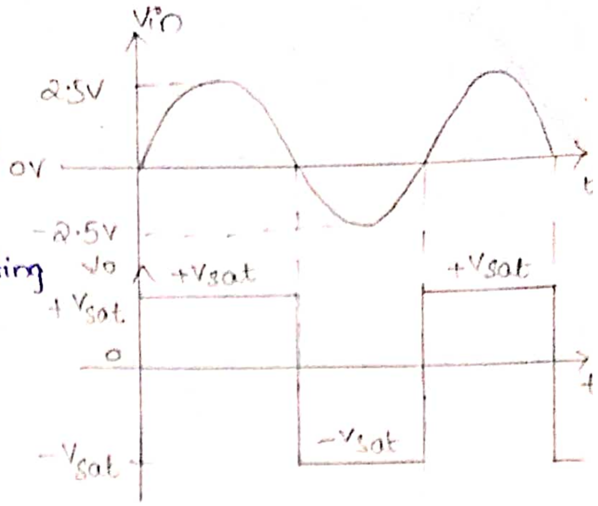
$$\therefore V_i > V_{ref} ; V_o = +V_{sat}$$

* The output value of a non-inverting comparator will be $-V_{sat}$ for which the input voltage V_i is less than the reference voltage

$$V_i < V_{ref} ; V_o = -V_{sat}.$$

* The output waveform of a non-inverting comparator, when a sinusoidal input signal and reference voltage of zero volts are applied to the non-inverting and inverting terminals of the op-amp respectively.

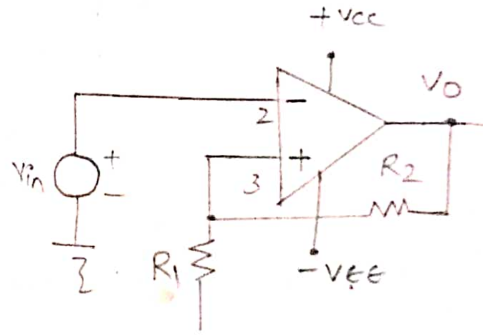
* During the positive halfcycle of the sinusoidal input signal, the voltage present at the non-inverting terminal of op-amp is greater than zero volts Hence, the output value of a non-inverting comparator will be equal to $+V_{sat}$ during the positive half cycle of the sinusoidal input signal.



* During the negative halfcycle of the sinusoidal input signal, the voltage present at the non-inverting terminal of op-amp is less than zero Volts. Hence, the output value of non-inverting comparator will be equal to $-V_{sat}$ during the negative halfcycle of the sinusoidal input signal.
* we observe that the output transitions either from $+V_{sat}$ to $-V_{sat}$ or from $+V_{sat}$ to $+V_{sat}$ whenever the sinusoidal input signal crosses zero volts. That means, the output changes its value when the input is crossing zero volts. Hence, the above circuit is also called as non-inverting zero crossing detector.

Schmitt Trigger:-

A Schmitt trigger is also called a regenerative comparator circuit. The circuit is designed with a positive feedback and hence will have a regenerative action which will make the output switch levels.



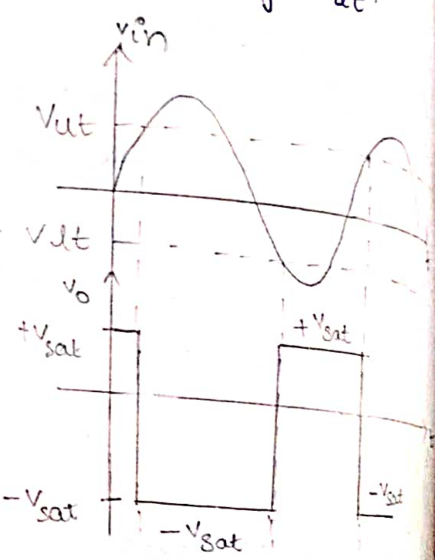
The use of positive voltage feedback instead of a negative feedback, aids the feedback voltage to the input voltage, instead of opposing it. The use of regenerative circuit is to remove the difficulties in a zero crossing detector circuit due to low frequency signals and input noise voltages.

It is basically an inverting comparator circuit with a positive feedback. The purpose of the schmitt trigger is to convert any regular or irregular shaped input waveform into a square wave output voltage or pulse. Thus, it can also be called a squaring circuit.

In the circuit diagram, a voltage divider with resistors R_1 and R_2 is set in the positive feedback of op-amp. The Resistor R_1 is applied to the non-inverting terminal. The input voltage V_i triggers or changes the state of output V_o every time it exceeds its voltage levels above a certain threshold value called upper threshold voltage V_{ut} and Lower threshold voltage V_{lt}.

When $V_o = +V_{sat}$; the voltage R_1 is called upper threshold voltage (V_{ut}). The input voltage V_{in} must be slightly more positive than V_{ut} inorder to cause the output V_o to switch from $+V_{sat}$ to $-V_{sat}$.

When the input voltage is less than V_{ut} ($V_i < V_{ut}$), the output voltage V_o is $+V_{sat}$.



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

$\therefore V_i < V_{ut}$; $V_o = +V_{sat}$

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

When $V_o = -V_{sat}$, the voltage across R_1 is called lower threshold voltage. The input voltage V_{in} must be slightly more negative than V_{lt} inorder to cause the output V_o to switch from $-V_{sat}$ to $+V_{sat}$. When the input voltage is ~~less~~ greater than V_{lt} ($V_i < V_{lt}$), the output voltage V_o is $-V_{sat}$.

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

$\therefore V_i > V_{lt}$; $V_o = -V_{sat}$.

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

If the value of V_{ut} and V_{lt} are higher than the input voltage, the positive feedback will eliminate the false output transitions. With the help of positive feedback and its regenerative behaviour, the output voltage will switch fast between the positive and negative saturation voltages.

Hysteresis characteristics:-

Since, a comparator circuit with a positive feedback is used, a dead band condition hysteresis can occur in the output. When the input of the comparator has a value higher than V_{ut}, its output switches from $+V_{sat}$ to $-V_{sat}$ and reverts back its original state, $+V_{sat}$, when the input value goes below V_{lt}.

The hysteresis voltage can be calculated as the difference between the upper and lower threshold voltages.

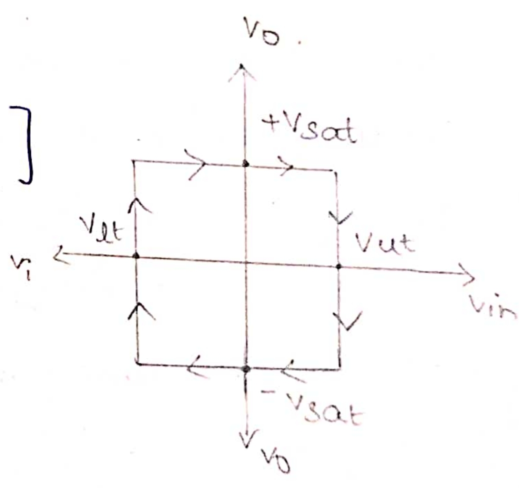
$$V_{hy} = V_{ut} - V_{lt}$$

Substituting the values of V_{ut} and V_{lt}.

$$V_{hy} = +V_{sat} \times \frac{R_1}{R_1+R_2} - \left[-V_{sat} \times \frac{R_1}{R_1+R_2}\right]$$

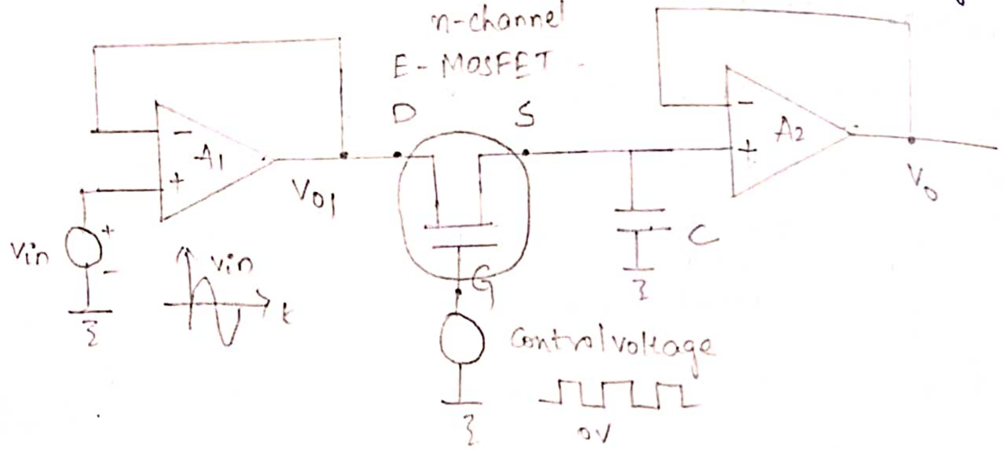
$$V_{hy} = \frac{R_1}{R_1+R_2}\left[2V_{sat}\right].$$

Hysteresis voltage loop



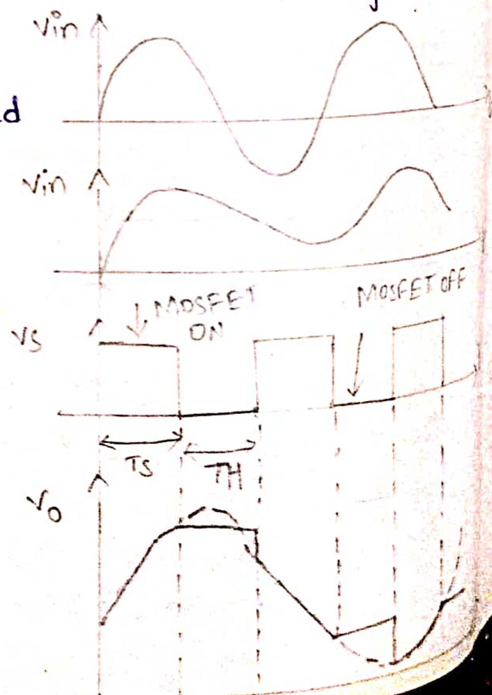
Sample and Hold circuit :-

The sample and hold circuit samples an input signal and holds on to its last sampled value until the input is sampled again. This type of circuit is very useful in digital interfacing and analog to digital and pulse code modulation systems.



The n-channel E-MOSFET works as a switch and is controlled by the control voltage and the capacitor C stores the charge. The analog signal V_i to be sampled is applied to the drain of E-MOSFET and the control voltage is applied to its gate. The source pin of MOSFET is connected to the non-inverting input of the op-amp.

During the positive half cycle of V_{GS}, the MOSFET is ON which acts like a closed switch and the capacitor c is charged by Vin and the same voltage Vin appears at the output of the op-amp.



when V_{GS} is zero, MOSFET is switched off and only the discharge path for c is through the inverting input of op-amp. since the input impedance of opamp is too high the voltage vin is retained and it appears at the output of opamp.

If $V_{GS} > 0$; MOSFET is ON.

$V_{GS} \leq 0$; MOSFET is OFF.

The time period of V_{GS} during which the voltage across the capacitor V_c is equal to Vin are called sample period Ts and the time period of V_s during which the Voltage across the capacitor $C(V_c)$ is held constant are called hold periods T_H.

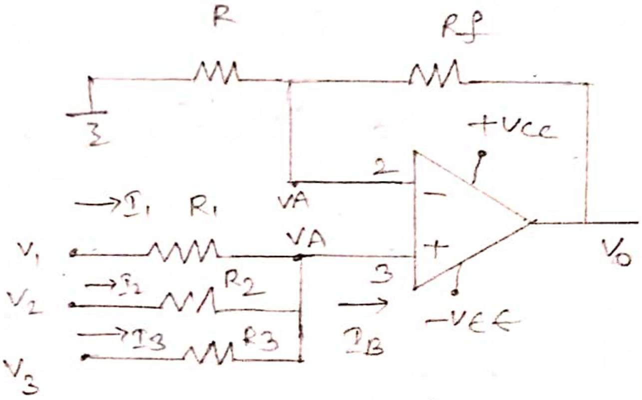
Advantages of sample and Hold circuit :-

* The main and important advantage of typical SH circuit is to aid an Analog to Digital Conversion Process by holding the sampled analog input voltage.
* In multichannel ADCs, where synchronization between different channels is important, an SH circuit can help by sampling analog signals from all the channels at a same time.
* In multiplexed circuits, the crosstalk can be reduced with an SH circuit.

Applications

1. operational Amplifiers
2. Analog De-multiplexers
3. Analog to Digital Converter circuits
4. Digital interface circuits
5. Data distribution system.

Non-inverting Adder :-



A typical summing amplifier with three input voltages V_1, V_2, V_3 and three resistors R_1, R_2, R_3 is applied to the non-inverting terminal and feedback resistor R_f is applied to the inverting terminal.
The inverting terminal is at ground.

The voltage V_A is ~~zero~~ V_A as the inverting terminal is grounded

Apply KCL at node V_A in non-inverting terminal.

$$I_1 + I_2 + I_3 = I_B.$$

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

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

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

$$V_A = \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}.$$

The op-amp and two resistors R_f and R constitute a non-inverting amplifier with.

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

The output voltage is ;

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

If $R_1 = R_2 = R_3 = R = \frac{R_f}{2}$

$$V_o = (1+2)\left[\frac{2(V_1 + V_2 + V_3)}{2+2+2}\right]$$

$$V_o = \frac{6(V_1 + V_2 + V_3)}{6}$$

$$V_o = V_1 + V_2 + V_3.$$

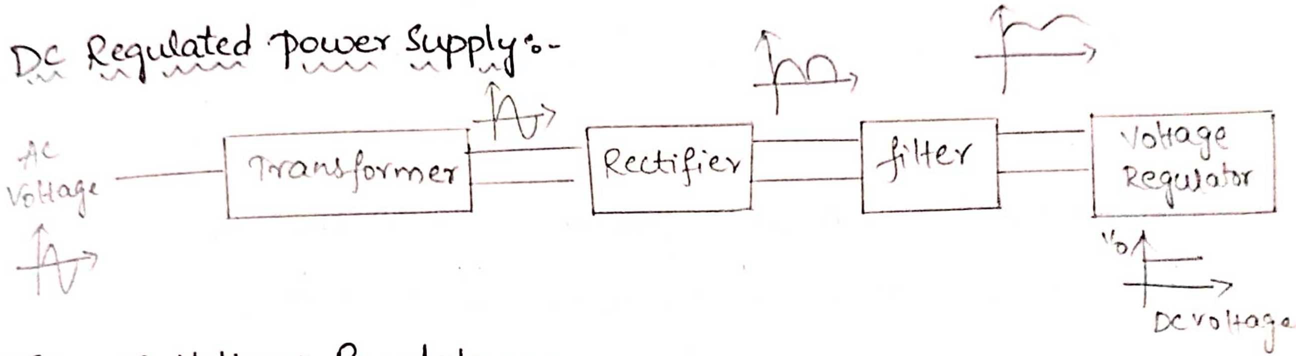
Voltage Regulator :-

Voltage regulators are also available in integrated circuits forms. These are called as Voltage regulator Ics.

* The function of Voltage regulator is to maintain a constant Dc voltage at the output irrespective of voltage fluctuations at the input and or Variations in the load current.

Voltage regulator produce a regulated Dc output Voltage.

Dc Regulated power Supply :-



Types of Voltage Regulators :-

There are two types of Voltage regulators. They are :-

1. Fixed voltage regulator.
2. Variable Voltage regulator

Fixed Voltage regulator :-

* A fixed voltage regulator produces a fixed Dc Output Voltage, which is either positive or negative. In other words, some fixed voltage regulators produce positive fixed Dc voltage values, which other produce negative fixed Dc voltage values.

* 78XX Voltage regulator Ics produce positive fixed Dc Voltage values, whereas, 79XX Voltage regulator ICs produce negative fixed Dc voltage values.

The following points are to be noted while working with 78XX and 79XX Voltage regulator Ics.

* "XX" Corresponds to a two digit number and represents the amount of voltage that voltage regulator Ic produces.

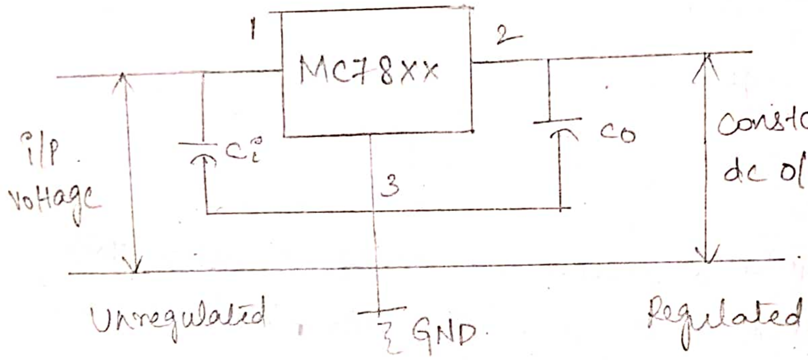
* Both 78xx and 79xx Voltage regulator ICs have 3 Pin each them and the third pin is used for collecting the output from them.
* The purpose of the first and second pins of these two types of ICs is different :-

1. The first and second pins of 78xx voltage regulator ICs are used for connecting the input and ground respectively.
2. The first and second pins of 79xx voltage regulator ICs are used for connecting the ground and input respectively.

Examples :-

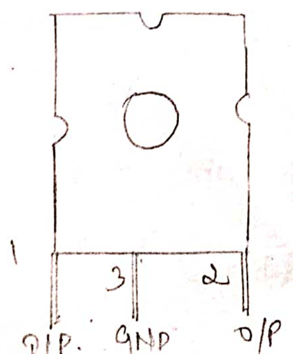
1. 7805 Voltage regulator IC produce a DC voltage of +5V.
2. 7905 Voltage regulator IC produces a DC Voltage of -5V.

Block diagram of 78xx :-



It shows a fixed positive voltage regulator, the input capacitor C_i is used to prevent unwanted oscillations and the output capacitor C_o acts as a line filter to improve transient response.

Symbol of 78xx



Characteristics of fixed voltage Regulator:-

1. o/p voltage is always fixed.
2. Thermal shutdown : Temperature Sensor senses temperature value

Drawbacks of fixed Voltage Regulators:-

1. Output Voltage is always fixed.
2. Input - output short circuit protection is not available.

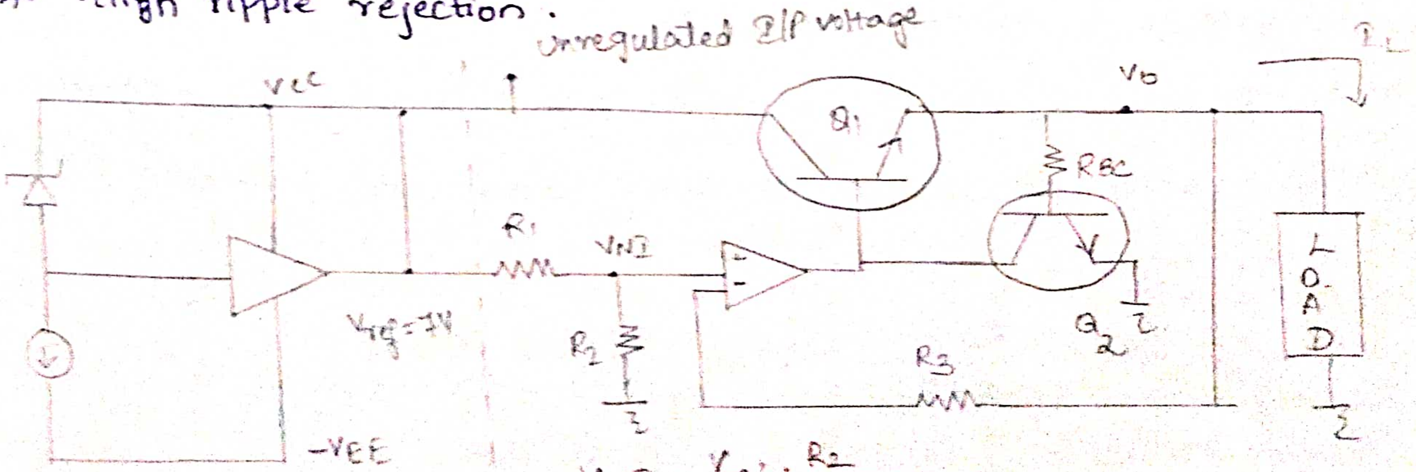
Variable Voltage Regulator:-

* An variable voltage regulator produces a DC output voltage, which can be adjusted to any other value of certain voltage range. Hence, variable voltage regulator is also called as a Variable (Adjustable) voltage regulator.
* The DC output voltage of an adjustable voltage regulator can be either negative or positive.

Ex: IC723

Features of IC723:-

1. Its output voltage varies from 2-37V.
2. Input-output short circuit protection is available.
3. It has good line and load regulation.
4. The IC is in small size and low cost.
5. Positive or Negative supply operation.
6. It has low temperature drift.
7. High ripple rejection.



$$V_{NI} = V_{ref} \cdot \frac{R_2}{R_1+R_2}$$

The functional block diagram of a IC 723 regulator. It has two seperate sections.

* The temperature compensated zener diode, constant current source and voltage reference amplifier together produce a fixed voltage of about 7 volts at the terminal V_{ref}. The constant current source forces the zener to operate at a fixed point so that zener outputs a fixed voltage.

* The other section of the IC consists of an error amplifier. Error amplifier is a high gain differential amplifier with 2 inputs (inverting and Non-inverting terminals). The Non-inverting terminal is connected to the internally generated reference voltage. The inverting terminal is connected to the full regulated output voltage.

Series pass Transistor:-

Q_1 is the internal series pass transistor which is driven by the error amplifier. This transistor actually acts as a variable resistor and regulates the output voltage. The collector of transistor Q1 is connected to the unregulated power supply.

Circuitry to limit the current:-

The internal transistor Q_2 is used for current sensing and limiting. Q_2 is normally OFF transistor. It turns ON when I_L exceeds a predetermined limit.

The R_1 and R_2 are potential divider between Vref and GND. The voltage across R_2 is connected to the non-inverting terminal of the regulator

$$V_{NI} = \frac{R_2}{R_1+R_2} V_{ref}.$$

Gain of the internal error amplifier is large.

$V_{NI} = V_i$

Therefore, the V_o is connected to the inverting terminal through R_3 and R_{SC} must also be equal to V_{NI}.

$$V_o = V_{NI} = \frac{R_2}{R_1+R_2} \cdot V_{ref}$$

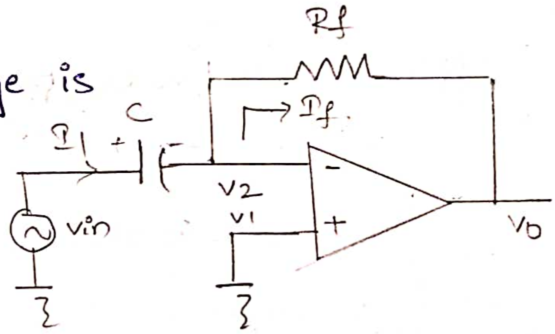
R_1 and R_2 can be in the range of $1k\Omega$ to $10k\Omega$ and value of R_3 is given by $R_3 = R_1 || R_2 = \frac{R_1R_2}{R_1+R_2}$

R_{SC} (current sensing resistor). The voltage drop across R_{SC} is proportional to the I_L.

The output voltage; $V_o = V_{ref} \cdot \frac{R_2}{R_1+R_2}$

Differentiator :-

A circuit in which the output voltage is the differentiation of input voltage is called differentiator.



Here, the inverting terminal is connected to capacitor and input voltage is grounded. The non-inverting terminal is connected to ground.

According to virtual Ground Concept, $V_1 = V_2 \Rightarrow V_1 = 0, V_2 = 0$.

Apply KCL at inverting terminal.

$$I_1 - I_f = 0 \quad \text{——(1)}$$

$$I_1 = I_f$$

But, $$I_f = \frac{-V_o + V_2}{R_f} \quad \text{——(2)}$$

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

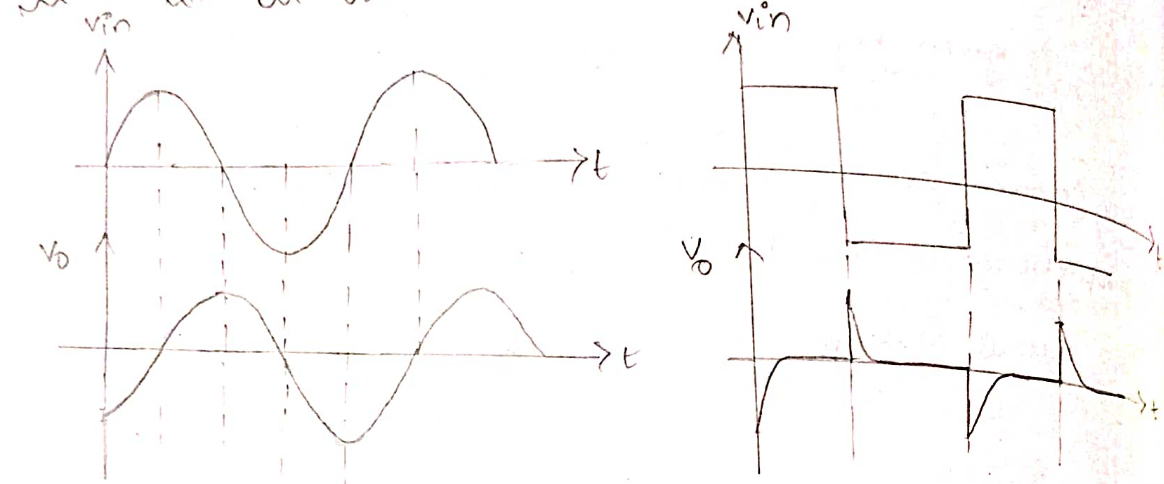
$$I_1 = C \cdot \frac{d}{dt}(V_{in} - 0) \quad \text{——(3)}$$

$$C \cdot \frac{d}{dt}(V_{in} - 0) = \frac{0 - V_o}{R_f}$$

$$V_o = -R_f C \cdot \frac{dV_{in}}{dt}$$

Thus, the output voltage V_o is equal to the R_fC times the negative instantaneous rate of change of the input voltage V_{in} with time.

Input and o/p waveforms:-



Difference between comparator and Schmitt Trigger:-

Comparator	Schmitt Trigger
* A comparator is a circuit which compares a signal voltage applied at one input of an op-amp with a known reference voltage at the other input.	* Schmitt Trigger is a regenerative comparator. It converts sinusoidal input into a square wave output
* It is an open loop op-amp with output $+V_{sat}$ or $-V_{sat}$.	* It is closed loop mode in op-amp.
* The hysteresis does not exist	* The output of Schmitt Trigger swinges between upper and lower threshold voltages
* Applications:- * Phase detector * Zero crossing detector. * window detector * Time marker generator.	* The hysteries exist with a width $H = V_{UT} - V_{LT}$. * Applications:- It is used in digital ckts, oscillators, power supplies.