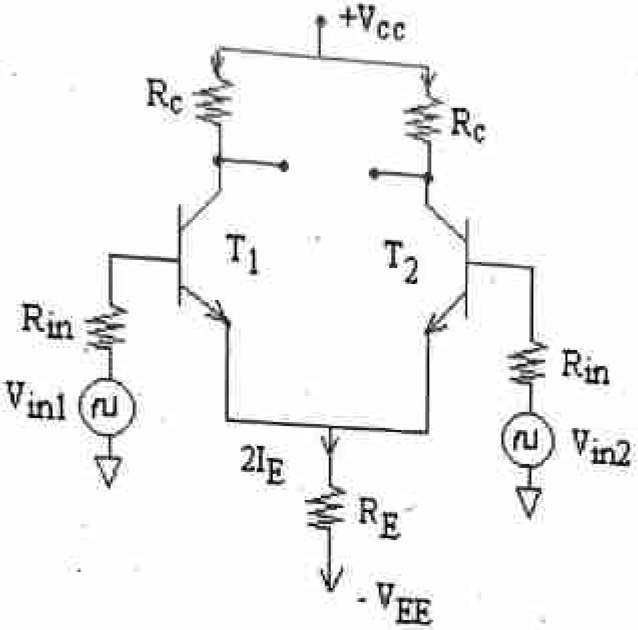
11. Operational Amplif

ERENTIAL AMPLIFIER

The differential amplifier is the most widely used circuit building block in analog integrated c fferential amplifier is also a basis for high speed logic family (ECL). It also has applicatio rators.

Differential amplifier consist of two identical emitter coupled transistor as shown below :



ifferential amplifier amplifies the difference of two input signal $V_0 = A(V_{in1} - V_{in2})$

nt Configurations of Differential Amplifier

ifferential amplifier can work in four different configurations :

1. Dual Input balance output
2. Dual input unbalance output
3. Single input balance output
4. Single input unbalance output.

s of differential amplifier

ifferential amplifier can work in two mode :

1. **Differential mode** : When two different input are applied at input terminals.
2. **Common mode** : When same input is applied to both the input terminals.

R_{in} = input impedance

$R_C = R_{C1} = R_{C2}$ with $R_E >> r_e$

Common Mode :

When common input is applied at both input terminal which is given by $V_{CM} = \frac{V_{in1}+V}{2}$

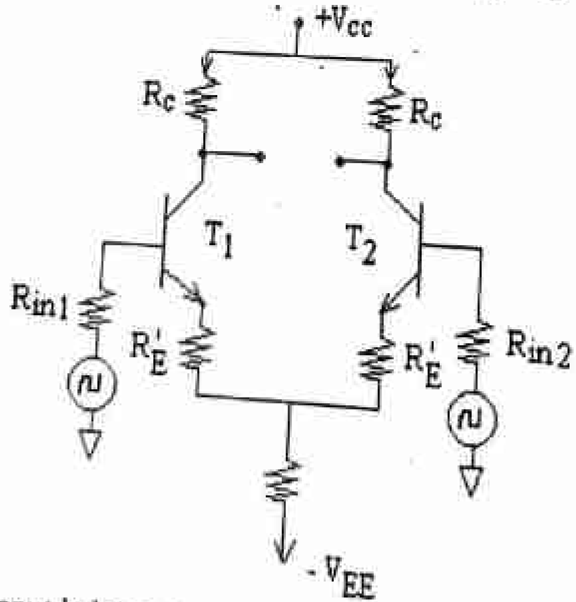
Common mode gain is given by $A_{CM} = \frac{V_0}{V_{CM}} = \frac{R_C}{2R_E}$

Ideally A_{CM} should be zero to avoid noise amplification. In orde to achieve $A_{CM} = 0$ and R_E be infinity. different arrangement are made which we will see later.

Swamping Resistor :

As we know that differential gain of the differential amplifier depends on r_e. r_e itself is a ture dependent which makes A_d temperature dependent in order to avoid this temperature dependan improves the linearity range ω_C incorporate R'_E (called swamping resistor) in series with emitter of transister.

R'_E should be large enough to swamp out the effect of r_e on gain.



Dual input balanced output configuration with swamping resistor.

Differential gain wth $R_E^{'}$

$$A_d = \frac{R_C}{r_e + R_E^{'}}$$

If $R_E >> r_e$ then $A_d = \frac{R_C}{R_E^{|}}$

i.e. A_d is independent of temperature variation.

$$R_{in} = 2\beta_{ac}\left(r_e + R_E^{|}\right); \qquad R_{01} = R_C;\; R_{02} = R_C$$

Similarly the A_d and R_{in} at all other configuration can be achieved by replacing r_e by $\left(r_e + R_E^{|}\right)$.

antages :

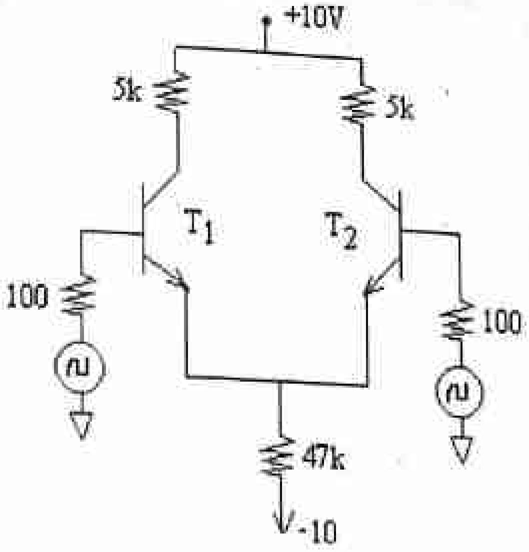
- Swamping resistor removes the temperature dependance of A_d (i.e. provides better stability). But A_d will decrease.
- Addition of swamping resistor also increases the range of linearity.

estion 1: With following specification for the dual input balance output differential amplifier $R_C = 5k$, $R_{in1} = R_{in2} = 100\Omega$, $V_{CC} = 10V$, $-V_{EE} = -10V$, $R_E = 4.7$, $\beta_{ac} = \beta_{dc} = 100$. Determine with and without $R_E^{|} = 200$ the following

(a) Voltage gain

(b) Input and output resistances.

lution : (a) Without $R_E^{|}$

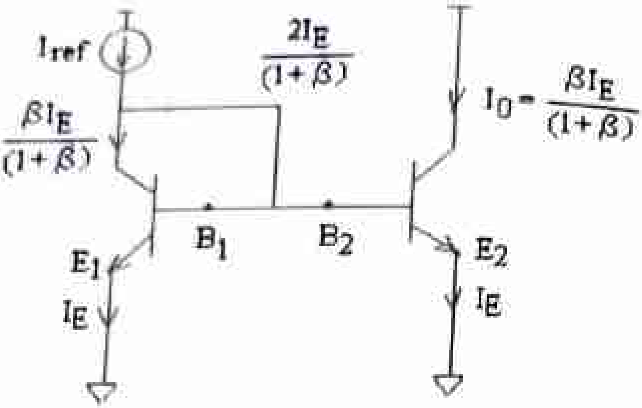


$$I_C = \frac{10-0.7}{2R_E + R_i/\beta_{dc}} = \frac{10-0.7}{9400 + 100/100} = 0.989\text{ mA}$$

$$r_e = \frac{V_T}{I_C} = \frac{25m}{.989m} = 25.27\Omega$$

$$A_d = \frac{V_0}{V_{id}} = \frac{R_C}{r_e} = \frac{5k}{25.27} = 197.8$$

Simple Current Mirror circuit :-



$$I_E = (1+\beta)I_B = I_C + I_B$$

$$I_0 = \frac{\beta I_E}{(1+\beta)}$$

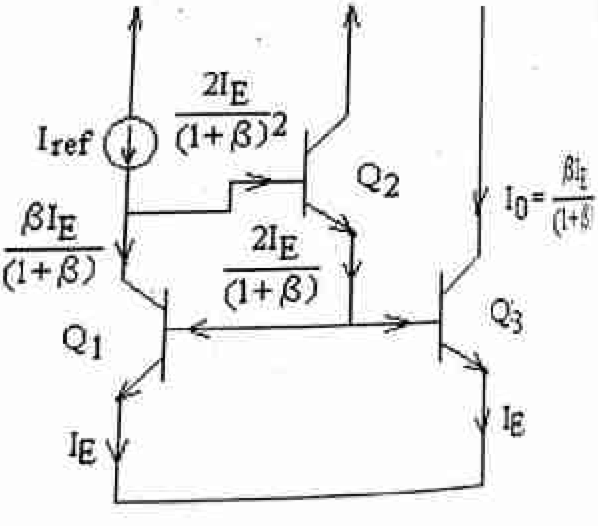
$$I_0 \cong I_{ref}$$

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

$$\frac{I_0}{I_{ref}} = \frac{1}{1+2/\beta} \quad \text{for} \quad \beta >> 2$$

β is temperature dependance. In order to avoid temperature dependency upto some extent we improved mirror circuit.

Improved Current Mirror circuit :-



$$I_{ref} = \left[\frac{\beta}{1+\beta} + \frac{2}{(1+\beta)^2}\right].I_E$$

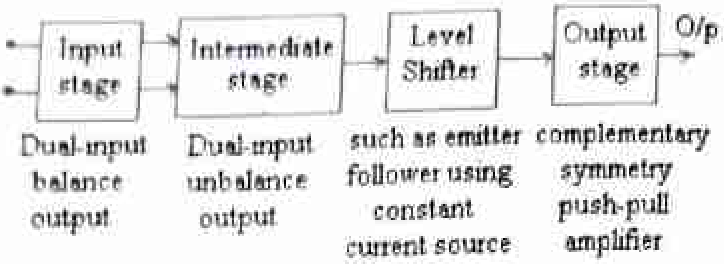
$$I_0 = \frac{\beta I_E}{(1+\beta)} \qquad \frac{I_0}{I_{ref}} = \frac{1}{1+2/(\beta^2+\beta)} \cong \frac{1}{1+2/\beta^2}$$

Now here error due to fixed β is reduced from $2/\beta$ to $2/\beta^2$

But in order to achieve better base current compensation and increase output resistance we us
her circuits explained below :

OPERATIONAL AMPLIFIER

The basis of an Op Amp is a differential amplifier as discussed previously. It is basically a d coupled amplifier. Its block diagram is shown below :



Input Stage :- It provides almost all the voltage gain of Op-amp and also establish the input imped ance of Op-amp.

Intermediate Stage :- It provides remaining gain of Op-amp.

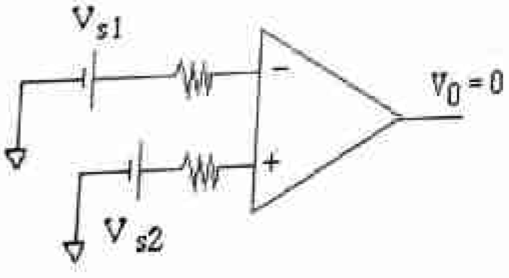
Level Shifting :- Because of the direct coupling d.c. voltage at output is well above the ground level in order to get back the d.c. level to ground potential. So that variation in output is only because of input signal we use level shifting.

Output stage :- It raises the current supplying capability and increases the output voltage swing and this stages proper design will provides the low output resistance.

Definitions :-

Output Offset Voltage :- Output voltage when both the input are grounded is called output offset voltage. It should be zero for ideal voltage.

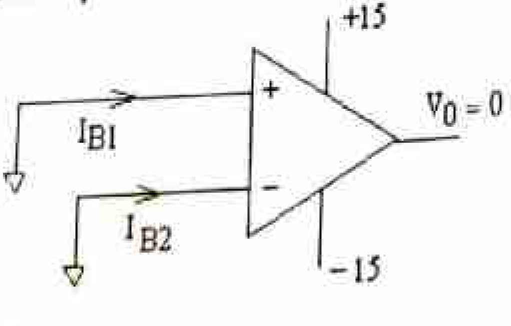
Input Offset Voltage :- The differential input voltage applied at input side to make the output offset voltage zero is called Input Offset Voltage.



$$V_0 = V_{s1} - V_{s2}$$

Input Offset Current :- Algebraic difference between the current of non-inverting and inverting terminals is known as Input Offset Current provided output voltage is zero.

$$I_{i0} = |I_{B1} - I_{B2}|$$



Input Bias Current :- Average of two current that flow through inverting and non-inverting al is known as Input Bias Current provided output voltage is zero.

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

Power Supply Rejection Ratio :- Change in input offset voltage with power supply variation is Power Supply Rejection Ratio.

$$SVVR = \frac{\Delta V_{i0}}{\Delta V_{ii}}$$

Common Mode Rejection Ratio (CMRR) :- It is the most important characteristic of Op-amp. It efined as the ratio of differential gain to common mode gain.

$$CMRR = \frac{A_d}{A_{CM}}$$

It represents the ability of Op-amp to reject the common mode signal.

For practical Op-amp. Output voltage is given by

$$V_0 = A_d\left(V_d + \frac{V_{CM}}{CMRR}\right)$$

A_d = differential voltage gain

V_{CM} = common mode input signal

CMRR = common mode rejection ratio

In order to avoid any common mode amplification CMRR should be infinite which can be achieved increasing R_E because $CMRR = \frac{A_d}{A_{CM}}$

and, $$A_{CM} = \frac{R_C}{2R_E}$$

uestion: Find out R_C, R_E and R_{in} for an unbalance differential amplifier when following data are given

$A_d = 250$ $I_{CQ} = 100\ \mu A$

$\beta = 2000$ CMRR = 74 dB

Solution : We know,

$$A_d = \frac{R_C}{2r_e} \qquad \text{........(i)}$$

$$r_e = \frac{V_T}{I_{CQ}} = \frac{25m}{100\mu} = 250\,\Omega$$

From equation (i)

$$\frac{R_C}{2r_e} = 250 \qquad R_C = 250 \times 2 \times 250 = 125k$$

Given CMMR = 74 dB

$$20\log\frac{A_d}{A_{CM}} = 74$$

$$\frac{A_d}{A_{CM}} = 5000 \Rightarrow A_{CM} = \frac{250}{5000} = .05$$

$$A_{CM} = \frac{R_C}{2R_E} = .05 \quad \Rightarrow R_E = 1.25\,M\Omega$$

$$R_{in} = 2\beta_{ac} r_e \quad \Rightarrow R_{in} = 1\,M\Omega$$

ew Rate :

Maximum rate of change of output voltage w.r.t. time is defined as Slew rate.

$$\left|\frac{dV_0}{dt}\right|_{max} = S.R.$$

It represents the how fast output can change with change in the input frequency.

Let output voltage be = $V_m \sin\omega t$

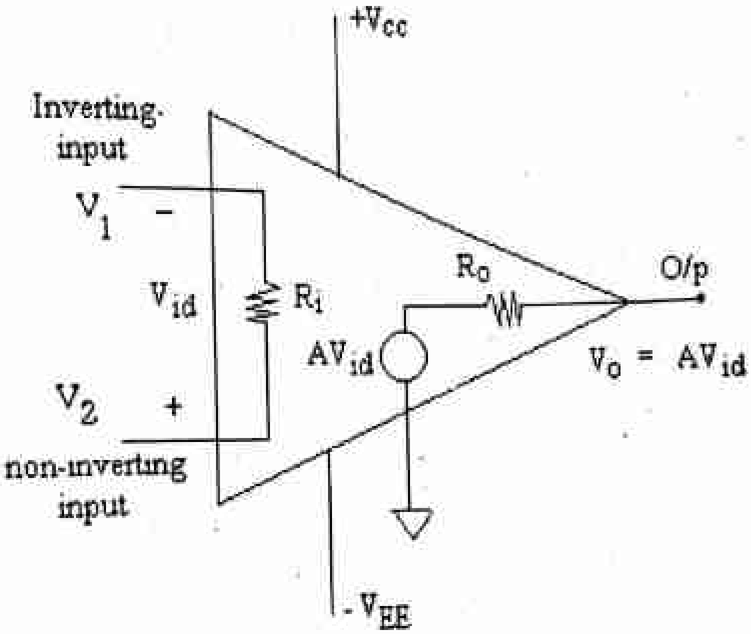
$$\text{Slew rate} = \left|\frac{dV_0}{dt}\right|_{max} = |V_m\omega|$$

ax. frequency variation is the sinusoidal output depends on $\frac{S.R.}{V_m 2\pi} = f_{max}$

eristic of Op-amp :

- It should have very high voltage gain.
- It should have very high input resistance.
- It should have very low output resistance.
- Output voltage should be zero. for zero input. i.e. noise should not be amplified.
- It should have very wide B.W. from 0 Hz to MHz.
- CMRR should be very high to avoid any common mode noise at output.
- It should have very high slew rate so that output can follow the input instataneously.

valent Circuit of an Op-amp :



$$V_0 = A(V_1 - V_2) = AV_d$$

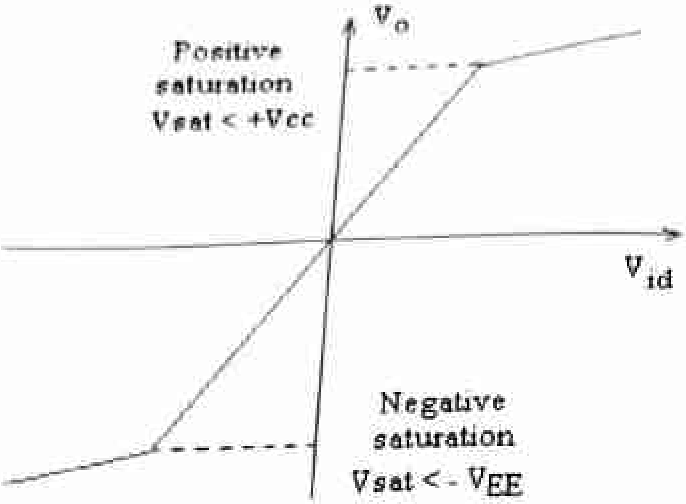
ual Ground :- Since open loop voltage gain A of operational amplifier is infinity.

therefore, $V_d = V_1 - V_2 = \frac{V_0}{A} = 0$

or, $V_1 = V_2$

If non-inverting terminal is connected to ground (i.e. $V_2 = 0$) then inverting terminal voltage also be zero (as $V_1 = V_2 = 0$). This condition is called virtual grounding. Because input resistnace ∞, therefore input is also zero. Virtual Grounding is conceptually different from the actual ground-erminal is zero, but it can handle infinite current.

Ideal voltage transfer curve :



As we already seen that differential amplifier works as an limiter because $V_{B1} - V_{B2} >$ turates the transistor as seen from the transfer characteristic of differential amplifier. Hence ideal vol nsfer curve of Op-amp also saturates at positive and negative saturation level.

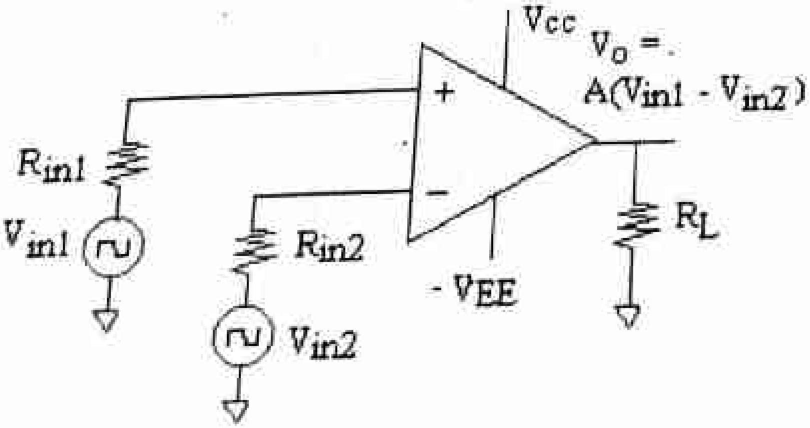
This characteristic is very useful in sine to square wave conversion.

en loop configuration :

When there is no direct or indirect connection from output to input then the configuration are cal loop configuration.

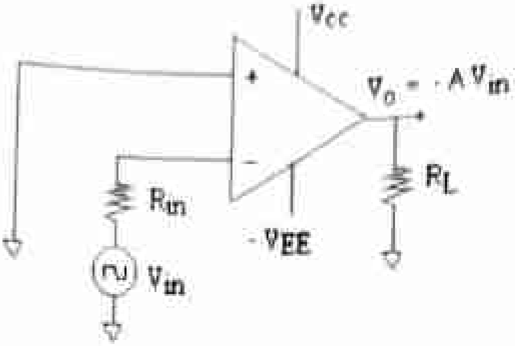
There are three open loop configurations :

The differential amplifier :-



= open loop gain

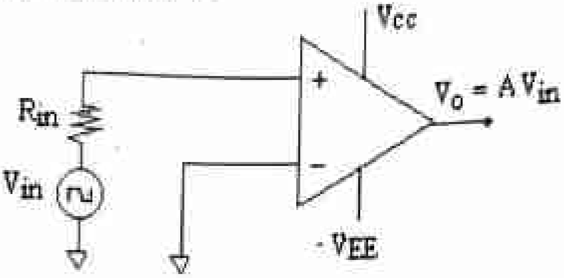
Inverting amplifier :-



$V_o = -AV_{in}$

180° phase shifter

The Non-inverting amplifier :-



In all three open loop configuration the open loop gain is so high that even any differential input
slightly greater than zero volt drives output to saturation level. Therefore the Op-amp works as
only rather than working as amplifier. This is the reason why the open loop Op-amp are not pre-
n linear application however it has few of its unique advantages

antage of Open loop Op-amp :

t has very high voltage gain which makes open loop configuration more susceptible to noise.

cause of such a high voltage gain op-amp always works on saturation mode even though the
nput signal is very small.

andwidth of open loop op-amp is negligibly small. $(\text{Gain} \times \text{Bandwidth} = \text{cons}\tan t)$

rder to sort out the problem listed above. We use feedback configuration.

of feedback :-

Positive or regenerative feedback.

Negative or degenerative feedback.

egative feedback is of our concern here because of numerous advantages. It has at the cost of
in gain which is also advantageous in Op-amp.

edback may be of four type as already discussed in feedback section.

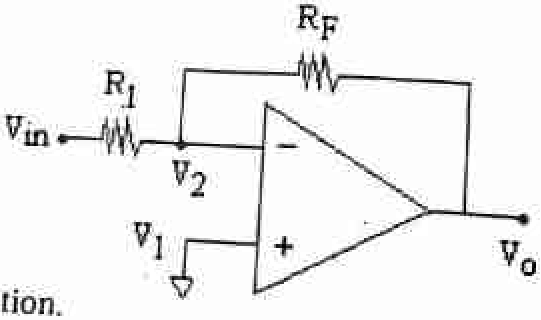
1. Voltage series
2. Voltage shunt
3. Current series
4. Current shunt

Mode of operation with negative feedback :-

As far as Op-amp is concerned there are three mode of operation with negative feedback

1. Inverting mode.
2. Non-inverting mode.
3. Differential mode.

1. Inverting mode :-



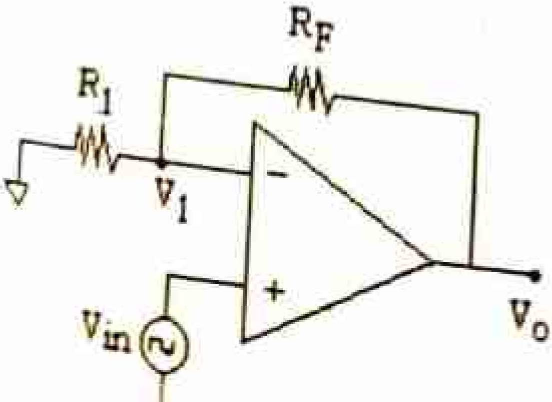
It is a voltage shunt configuration.

$$\frac{V_{in}-0}{R_1} = \frac{0-V_0}{R_F} \text{ using virtual ground concept}$$

$$\frac{V_0}{V_{in}} = -\frac{R_F}{R_1}$$

$$A_{VF} = \frac{V_0}{V_{in}} = -\frac{R_F}{R_1}$$

n-inverting mode :-



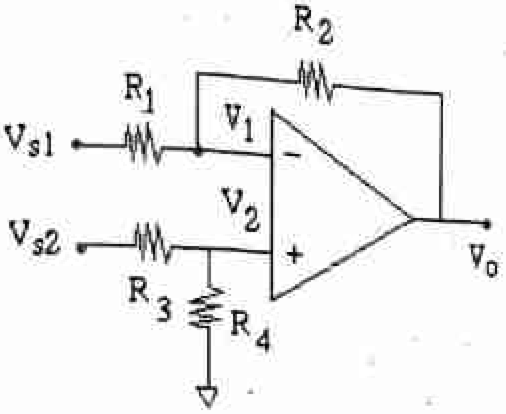
$$V_1 = V_{in}$$

at V_1

$$\frac{V_{in}}{R_1} = \frac{V_{in} - V_0}{R_F} \quad => \quad \frac{V_0}{V_{in}} = \left(1 + \frac{R_F}{R_1}\right)$$

erential mode :-

ircuit of differential amplifier (also sometimes called substractor) is given below :



tput voltage is given by, $V_0 = V_{01} + V_{02}$ ....(i)

is the voltage due to V_{s1} when $V_{s2} = 0$

$$V_0 = V_{s2} + V_{02}$$

$$V_{01} = -\frac{R_2}{R_1} V_{s1} \qquad \text{............(ii)}$$

is the voltage due to V_{s2} when $V_{s1} = 0$

$$V_{02} = V_2\left(1 + \frac{R_2}{R_1}\right) \quad \text{and} \quad V_2 = \frac{R_4}{R_4 + R_3} V_{s2}$$

$$V_{02} = V_{s2}\left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_4 + R_3}\right) \qquad \text{............(iii)}$$

m equation (i), (ii) and (iii)

$$V_0 = V_{01} + V_{02} = V_{s2}\left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_4 + R_3}\right) - \frac{R_2}{R_1} V_{s1} \qquad \text{............(iv)}$$

$R_2 = R_4$ and $R_3 = R_1$

$$V_0 = \frac{R_2}{R_1}(V_{s2} - V_{s1})$$

if $R_2 = R_1$

$$V_o = V_{s2} - V_{s1}$$

Common Mode :

If $V_{s1} = V_{s2}$, $V_o = 0$. This is called common mode. This mode is helpful to noise which is same at both the input terminals.

Common Mode Rejection Ratio (CMRR) :

Common mode signal, $V_C = \dfrac{V_{s1} + V_{s2}}{2}$ ……………(v)

Differential signal $V_d = V_{s2} - V_{s1}$ ……………(vi)

Then from equation (v) and (vi)

$$V_{s1} = V_c - \frac{V_d}{2}, \quad V_{s2} = V_c + \frac{V_d}{2}$$

Now substituting the value of V_{s1} and V_{s2} in equation (iv)

$$V_0 = V_c\left[\left(\frac{R_1+R_2}{R_3+R_4}\right)\frac{R_4}{R_1} - \frac{R_2}{R_1}\right] - \frac{V_d}{2}\left[\left(\frac{R_1+R_2}{R_3+R_4}\right)\frac{R_4}{R_1} + \frac{R_2}{R_1}\right]$$

$$A_d = \left.\frac{V_0}{V_d}\right|_{V_C=0} \quad \text{and} \quad A_{CM} = \left.\frac{V_0}{V_c}\right|_{V_d=0}$$

and $$\text{CMRR} = \frac{A_d}{A_{CM}} = \frac{\dfrac{1}{2}\left[\left(\dfrac{R_1+R_2}{R_3+R_4}\right)\dfrac{R_4}{R_1} + \dfrac{R_2}{R_1}\right]}{\left[\left(\dfrac{R_1+R_2}{R_3+R_4}\right)\dfrac{R_4}{R_1} - \dfrac{R_2}{R_1}\right]}$$

ondition for maximum CMRR :

To obtain $\text{CMRR} = \infty$, common mode gain should be zero.

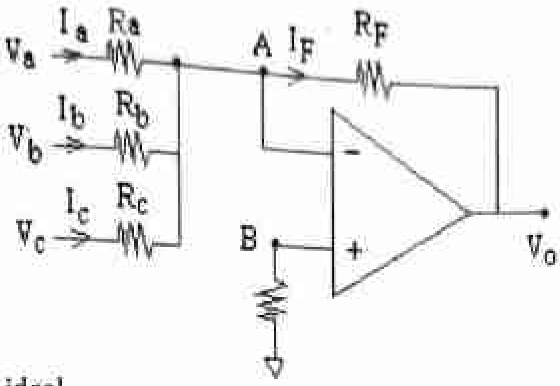
$$A_{CM} = \left(\frac{R_1+R_2}{R_3+R_4}\right)\frac{R_4}{R_1} - \frac{R_2}{R_1}$$

if, $R_3 = R_1$ and $R_4 = R_2$ then $A_{CM} = 0$

APPLICATIONS OF OP-AMP only remember

p-Amp can be used as Summing, Scaling and Averaging Amplifiers.

verting amplifier



Considering Op-amp ideal.

$$I_a + I_b + I_c = I_F \qquad ....(i)$$

voltage at node B is zero therefore by using virtual ground concept voltage at node A is also 0 volt.

equation (i) can be written as

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} = -\frac{V_0}{R_F}$$

$$V_0 = -R_F\left(\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c}\right)$$

raging amplifier :

If $R_1 = R_2 = R_3 = 3R_F$ $\qquad V_0 = \left(\frac{V_a + V_b + V_c}{3}\right)$

mer :

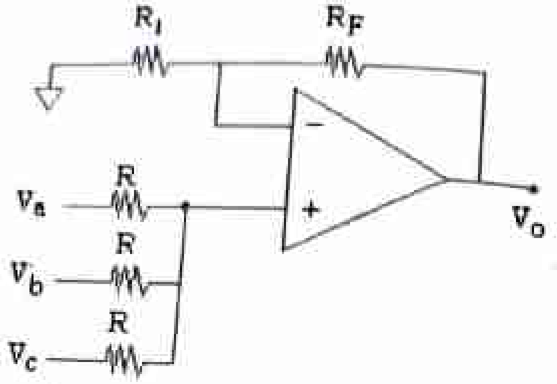
If $R_a = R_b = R_c = R_F$ $\qquad V_0 = -(V_a + V_b + V_c)$

ling amplifier :

$V_0 = -\left(\frac{R_F}{R_a}V_a + \frac{R_F}{R_b}V_b + \frac{R_F}{R_c}V_c\right)$ $\qquad \frac{R_F}{R_a} \neq \frac{R_F}{R_b} \neq \frac{R_F}{R_c}$

by selecting proper values of $\frac{R_f}{R_a}$, $\frac{R_f}{R_b}$, $\frac{R_f}{R_c}$ proper weighted might be given to eac

Non-inverting amplifier :



$$V_0 = -\left(1+\frac{R_F}{R_1}\right)\left(\frac{V_a+V_b+V_c}{3}\right)$$

Averging amplifier :

It is a averaging which is amplifying the average of three signal by gain $\left(1+\frac{R_1}{R}\right.$

king $\left(1+\frac{R_F}{R_1}\right)=1$. The circuit will work as averager.

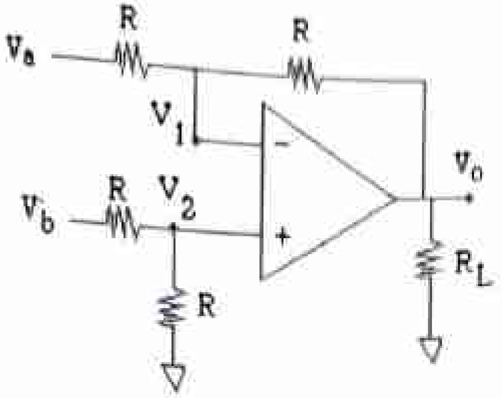
nmer :

By making $\left(1+\frac{R_F}{R_1}\right)=3$

i.e. $R_F = 2R_1$ the circuit provides sum of three input signal.

$V_q = V_a + V_b + V_c$

ctor :

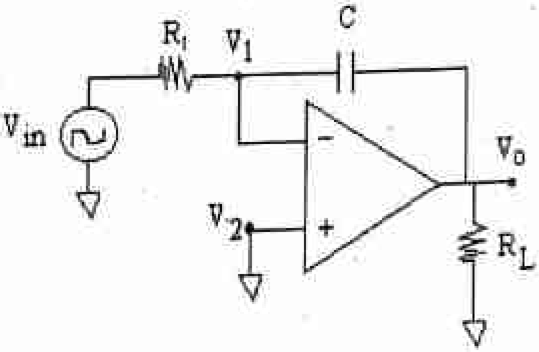


$$V_0 = -V_a + V_2\left(1+\frac{R}{R}\right) \quad \text{and} \quad V_2 = \frac{V_b R}{R+R} = \frac{V_b}{2}$$

$$V_0 = -V_a + \frac{V_b}{2}\left(1+\frac{R}{R}\right) \qquad V_0 = V_b - V_a$$

uit provides substraction of two circuits.

grator :



$= V_2 = 0$

at node V_1

$$\frac{-0}{R_1} = C\frac{d(0-V_0)}{dt} \qquad \frac{V_{in}}{R_1} = -C\frac{dV_0}{dt}$$

$$= -\frac{1}{R_1C}\int V_{in}dt \qquad T > R_fC_f$$

proper functioning of Integrator $T > R_1C$

T = Time period of signal

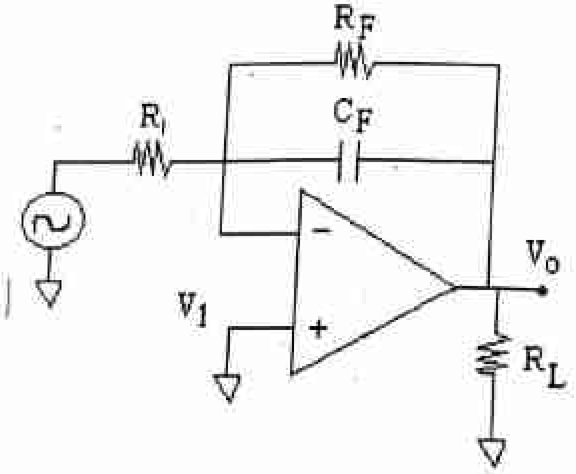
R_1C = Time constant of integrator.

Limitations :

1. In the absence of input voltage the Op-amp will work on open loop Op-amp and shows towards noise.
2. It also has low frequency Roll off problem

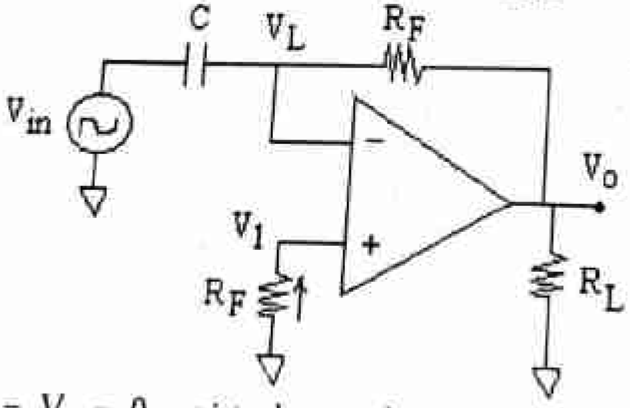
Practical Op-amp :

Both the limitations can be corrected by using, practical op-amp



Differentiator :-

Output voltage is differentiation of Input voltage.



$V_1 = V_2 = 0$ virtual ground

$$V_0 = -R_F C \frac{dV_{in}}{dt}$$

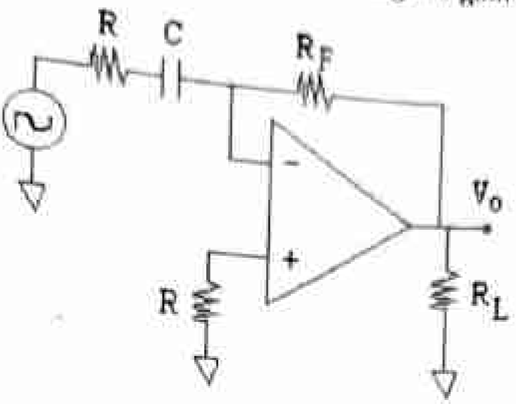
imitation :-

Above differential amplifier has higher frequency noise, sensitivity. high frequency noise p ces spike at the output.

ical differentiator :-

Practical differentiator reduce the high frequency noise significantly.

Practical differentiator provides more stability by preventing the gain to be very high at high frequency.



$$T > R_F C$$

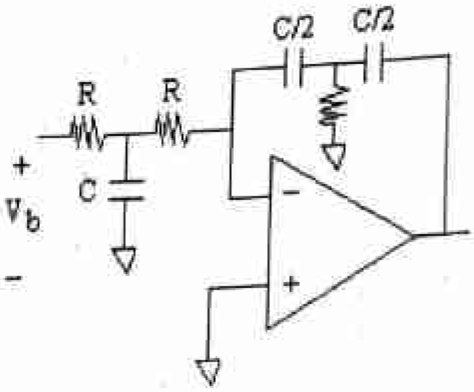
T = Time period of signal

$R_F C$ = Time constant of differentiator.

other important Linear Op-amp circuit :

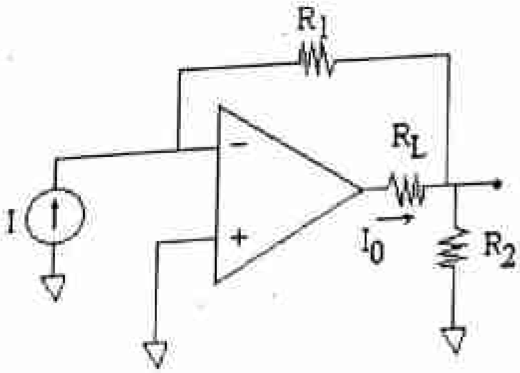
Double Integrator :-

$$V_0 = \frac{-4}{(RC)^2}\iint V_i \, dt \, dt$$



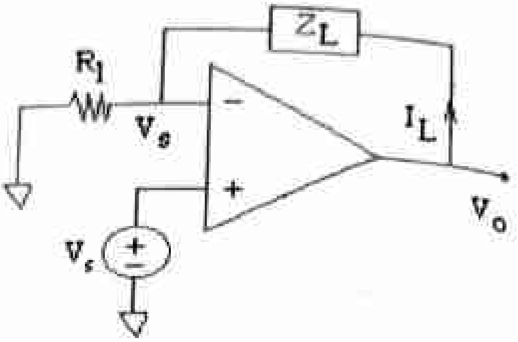
Current amplifier :-

$$\frac{I_0}{I} = -\left(\frac{R_1}{R_2}+1\right)$$



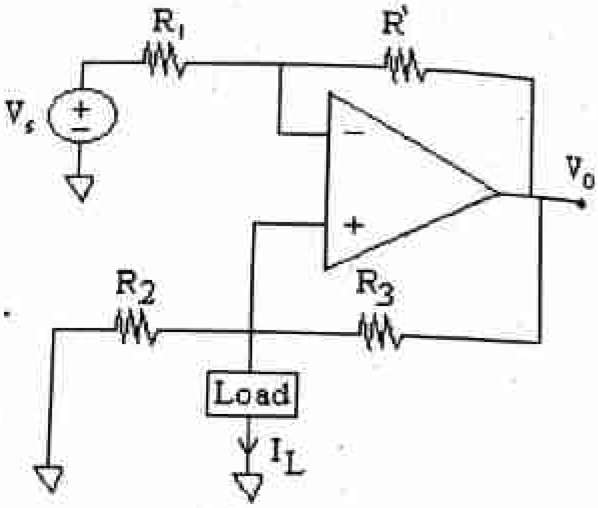
3. Floating load voltage to current convertor :-

$$I_1 = \frac{V_s}{R_1}$$



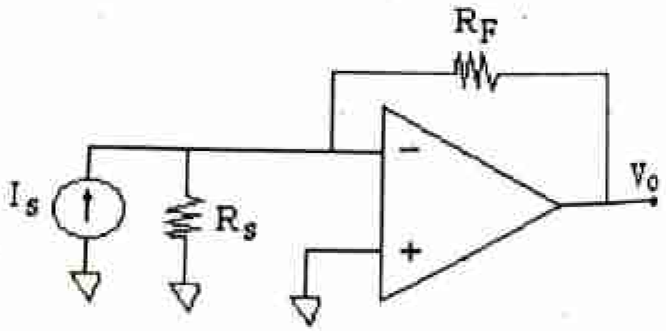
4. Grounded load voltage to current convertor :-

$$I_L = \frac{V_s}{R_2}$$

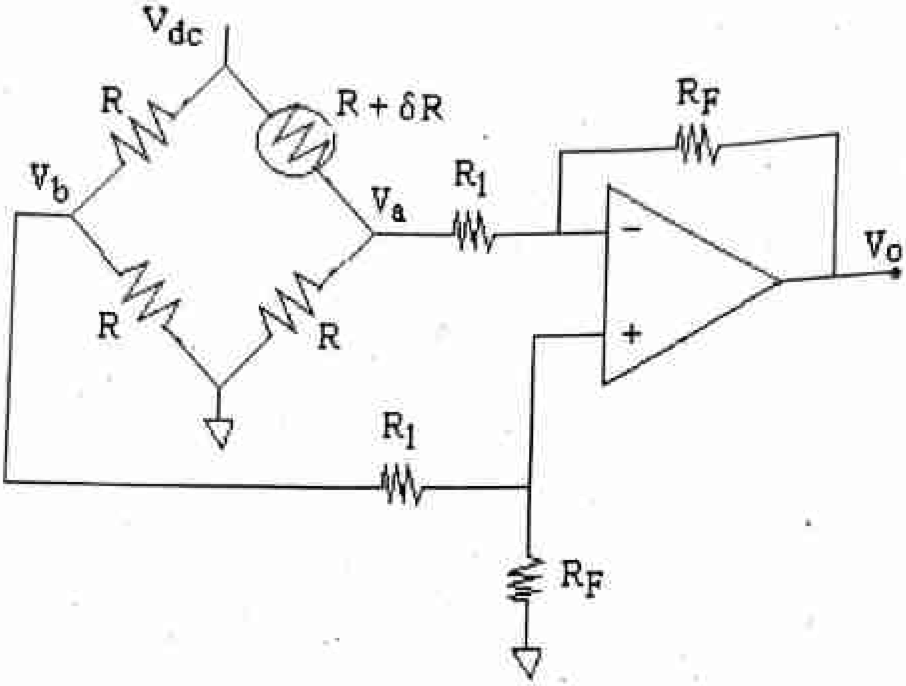


5. Current to voltage convertor :-

$$V_0 = -I_sR_F$$



Instrumentation amplifier :-



$$= \frac{R_F}{R_1}\cdot\frac{\delta R}{4R} V_{dc}$$

lters :

passes or reject the band of frequency and reject or pass the all other frequencies.

e of active filter over passive

and frequency adjustment is available.

high input and low output impedance therefore it does not suffers from loading problem.

filters are cheaper than the passive filter.

filter does not requires inductor.

lter

ss (passes a band of frequency upto a highest frequency)

ss (passes all frequencies higher than specific frequency)

ass (pass a band of frequency in mid range)

ject (reject a band of frequency in mid range)

filter (passes all the frequencies)

s are of following types :

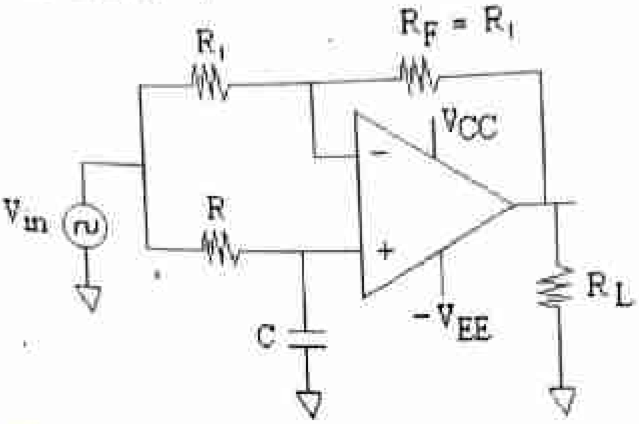
h Filter :- It has flat pass band and flat stop band.

Pass filter :

All pass filters passes all the frequency without any attenuation, while provides predictable phase different frequencies of input signal.

All pass filter is used as a phase corrector or delay equalizers.

$$V_o = \frac{1-j2\pi f_R C}{1+j2\pi f_R C} V_{in}$$



$$\text{Phase shift} = \phi = -2\tan^{-1}(2\pi fCR)$$

with interchanging the position of R and C we can achieve positive phase variation.

Linear Applications of Op-amp

mparator : -

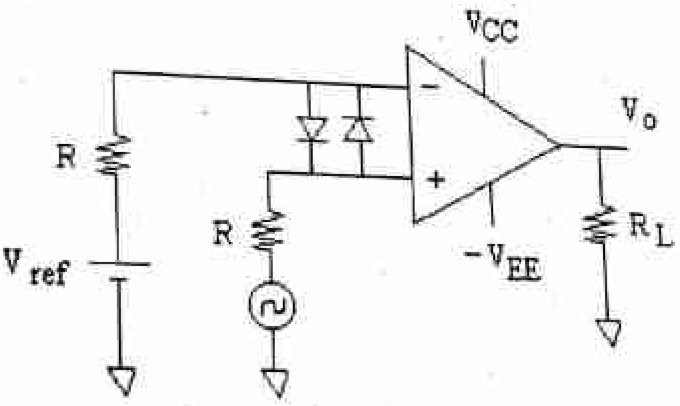
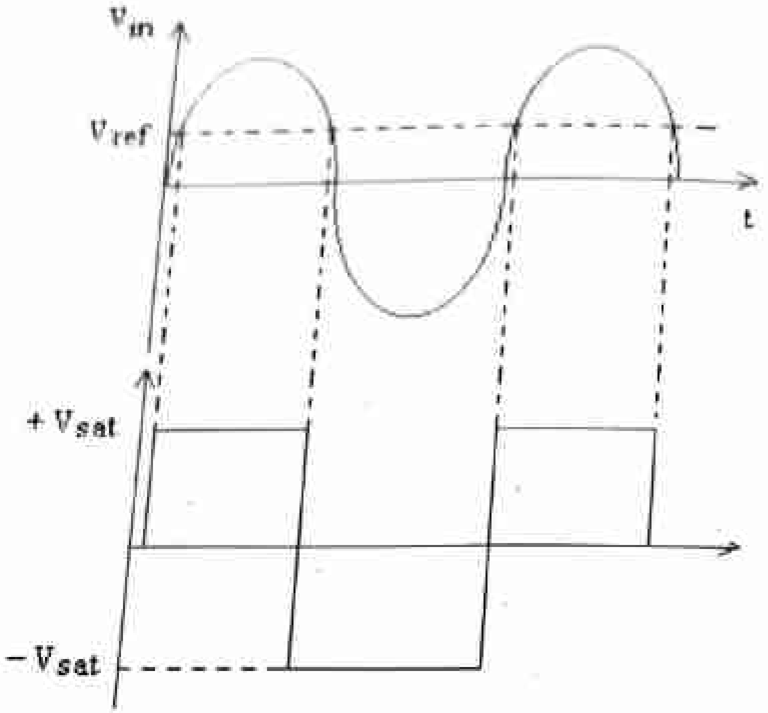


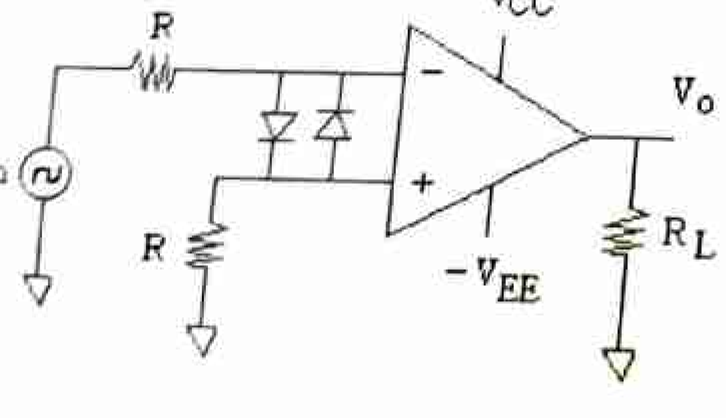
fig. non-inverting comparator.

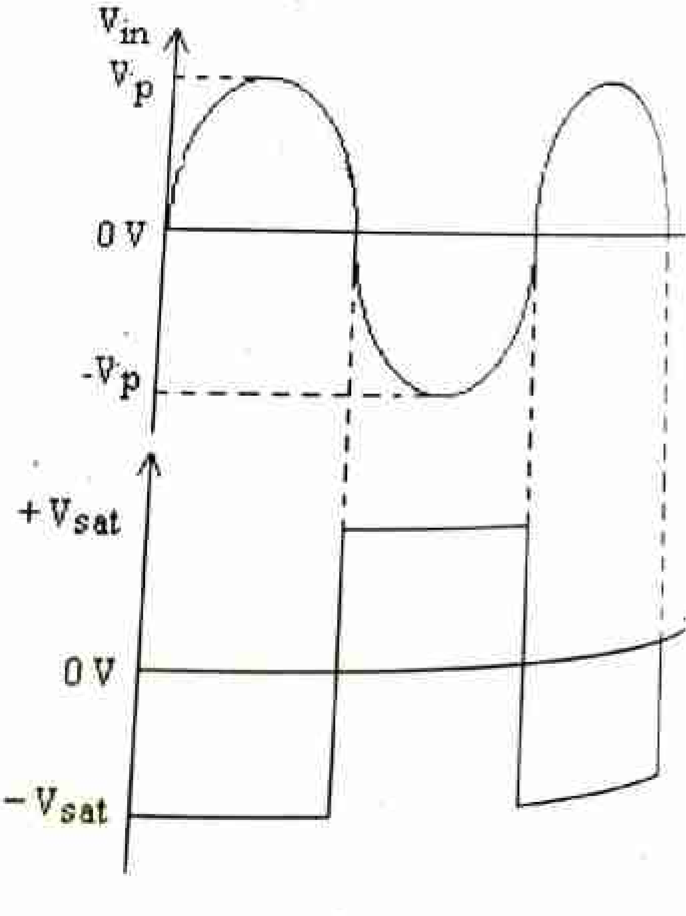
Comparator is a circuit which compares the input signal with reference signal and gives output tage either $+V_{sat}$ or $-V_{sat}$ as per the comparison of signals.



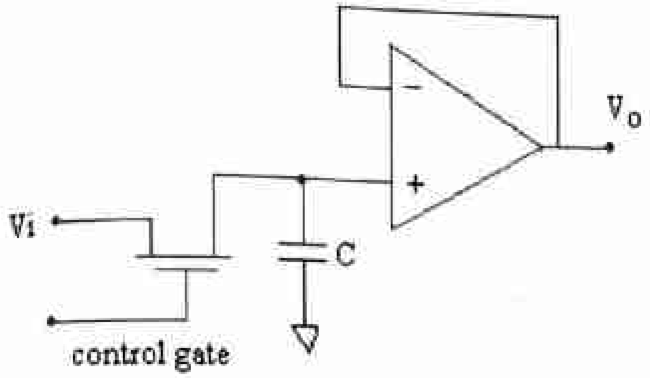
Zero Crossing Detector : -

You might say the zero crossing detector in application of comparator in which the transitio output voltage from $+V_{sat}$ *to* $-V_{sat}$ or vice versa take place. Whenever the input signal crosses the *level.*





nd Hold Circuit :-



roviding proper control negative pulse at control gate. We takes the sample at input signal and e same value for a while.

Rectifiers :-

le diode can rectify the signal that must be greater than 0.7 V. In order to rectify the signal at precision rectifiers are used.

rectifier :-

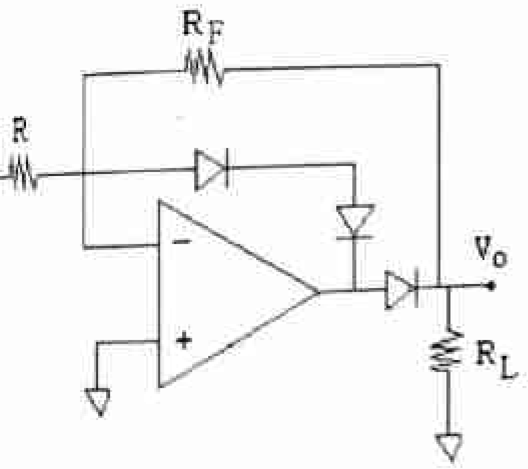


Fig. Circuit of half wave rectifier.

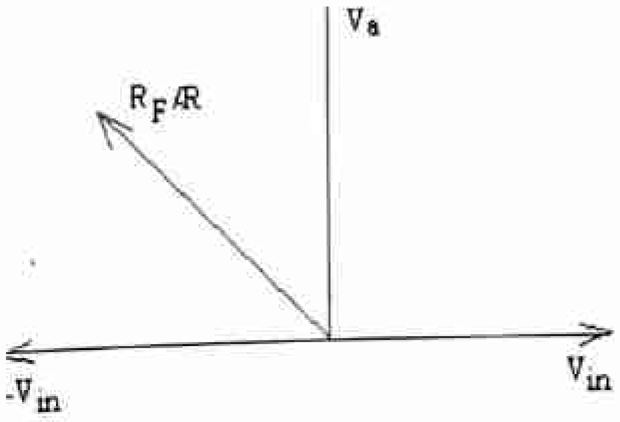


Fig. Transfer characteristic

Full wave rectifier :

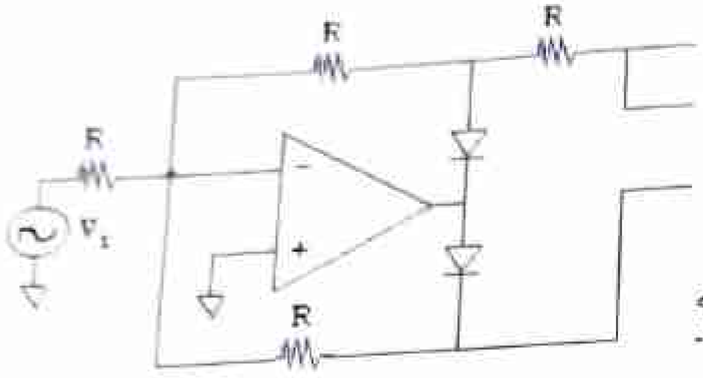
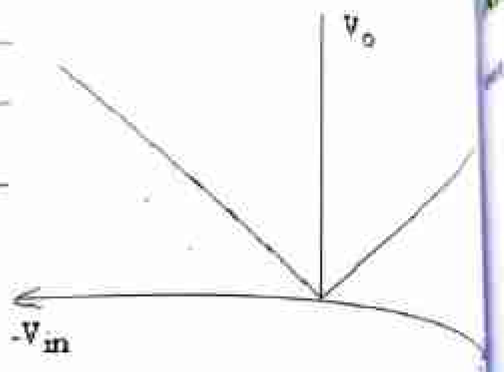
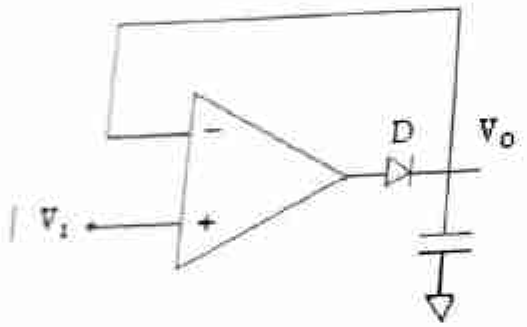


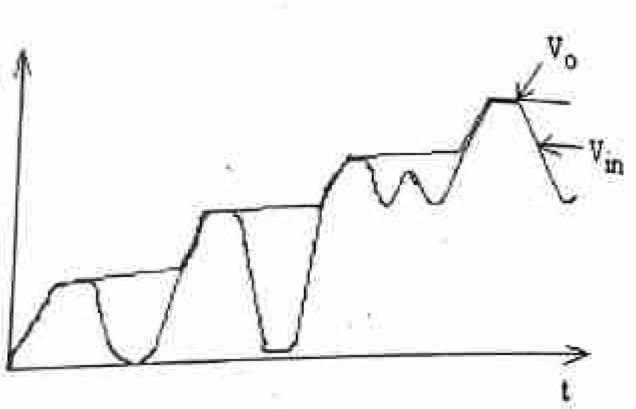
Fig. Circuit of full wave rectifier.



Transfer characteristic.

Active Peak detector :-

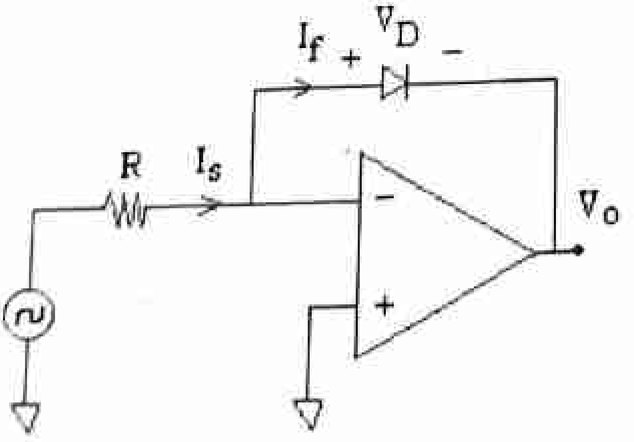




It detects the peak of the input signal and does not follow the instantaneous variation of

ignal.

ogrithmic amplifiers :-

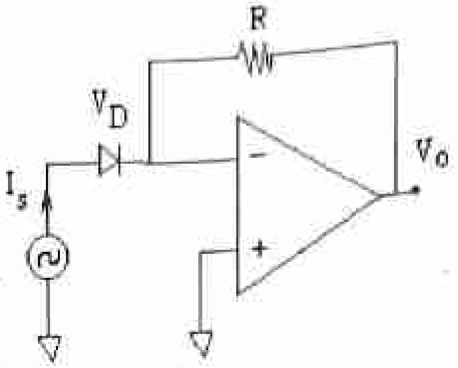


In logrithmic amplifier the output is the log of input. $V_0 = -V_T \ln \frac{V_i}{I_S R}$

ogrithmic Amplifier :-

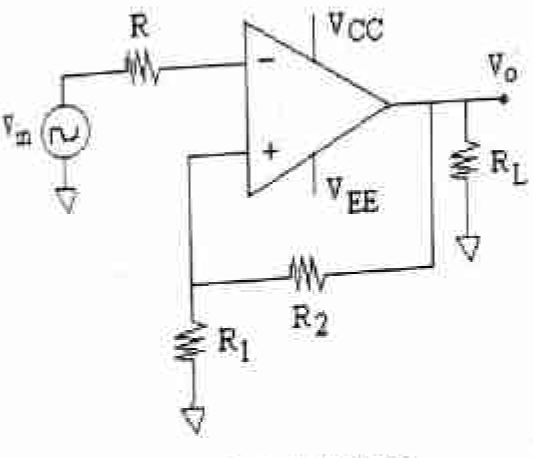
It perform exactly opposite function of logrithmic amplifier. It provides the antilog of input at

$$V_0 = -RI_S \ln^{-1}\frac{V_i}{V_T}$$



itt Trigger :-

Schmitt trigger circuit is a positive feedback circuit which converts any irregular wave into sqaure



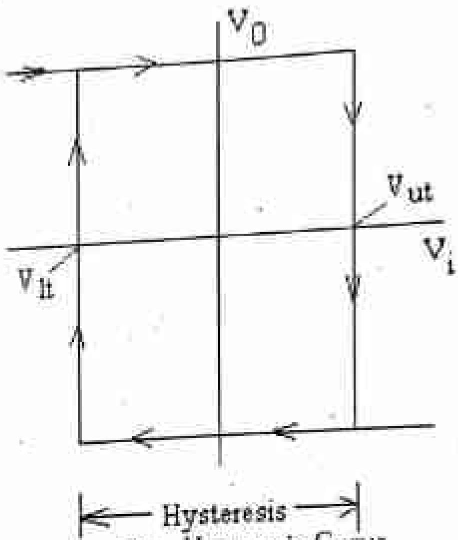


Fig. Hysteresis Curve

Fig. Inverting Schmitt Trigger

Figure shows the circuit arrangement of inverting Schmitt trigger.

Figure shows the circuit arrangement of inverting Schmitt trigger. Figure shows the circuit arrangement of inverting Schmitt trigger.

It has two threshold level which are decided by the voltage divider feedback made by R_1 and R_2

$$V_{ut} = \frac{R_1}{R_1 + R_2}(+V_{sat}) \qquad V_{lt} = \frac{R_1}{R_1 + R_2}(-V_{sat})$$

when the V_{in} is greater than V_{ut} the output changes from $+V_{sat}$ to $-V_{sat}$ and with $V_{in} > V_{lt}$ output nges from $-V_{sat}$ to $+V_{sat}$

Hysteresis voltage is given by

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