OPERATIONAL AMPLIFIER (OPAMP)

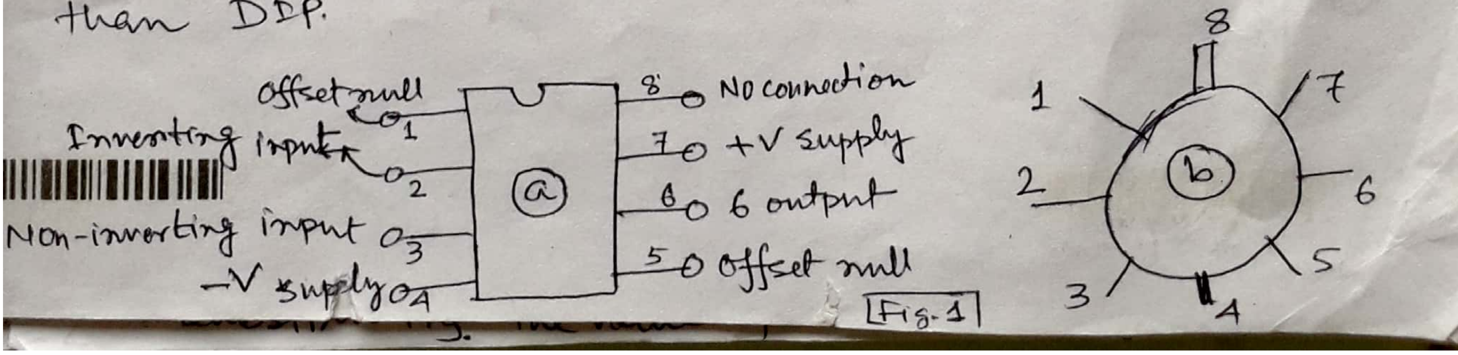
~~Page No.~~ 3

(~~ANSWER SHEET~~)

The operational amplifier (OPAMP) is a direct-coupled amplifier with very high voltage gain, very high input impedance and very low output impedance. It can be applied to perform a wide variety of linear and non-linear operations by changing a few external circuit elements. This type of amplifier is usable in the frequency range from 0 to few MHz.

Originally OP AM was designed to perform some mathematical operations such as summation, subtraction, multiplication, differentiation, integration etc in analog computer. However, at the present days, a large variety of OP AMP are avialable almost all in IC forms and sold at relatively low cost. Thereby, OP AMP has become very popular in electronic industry.

OP-AMP is available in different packages such as 8-lead dual-in-line package (DIP) with two parallel lines of pins. The OP-AMP can also be fabricated in the form of TO-5 metal case with a circular array of wire leads or the flat-pack. The metal case has the advantage of somewhat higher power dissipation but it is costlier than DIP.



[Fig. 1]

The pin configaration of the IC of widely used DIP-OPMP and metal case packages are shown in figure 1(a) and b respectively.

The positive (+V) and negative (-V) supply voltages are connected at the pins 7 and 4 respectively. No connection required at the connection 8. The input is given in the terminals 2 or 3. If the input is given to the terminal 2, then the output will change its phas by 180° i.e. the output signal is inverted. Thats why this input terminal is called inverting input terminal. However, if the input is given to the input terminal 3, then the output signal will be in the same phase of input signal. So this terminal is called non-inverting terminal. The output is measured across the pin 6. Terminals 1 and 5 are used for offset nulling, i.e. to make the output zero, when the input signal is zero.

The standard circuit symbol of an OP-AMP is shown in figure 2.

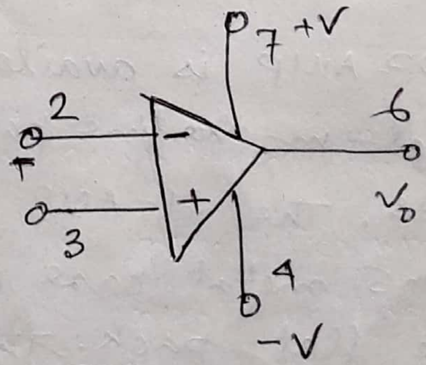


Fig-2

Characteristics of an ideal OPAMP:

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[redacted])

The characteristics of an ideal OP-AMP ~~is~~ are given below:

(i). The open loop voltage gain of an ideal OPAMP is infinity ($A = \infty$).

(ii) The input impedance is infinite, whereas the output impedance in zero.

(iii) Band gap of an ideal OP-AMP is infinite.

(iv) An ~~of~~ ideal OP-AMP is perfectly balanced i.e. when the input voltage is zero, then the output voltage will also be zero.

(v) The characteristics of an ideal OP-AMP do not change with temperature i.e. it is linear.

(vi) Common mode rejection ratio is infinite

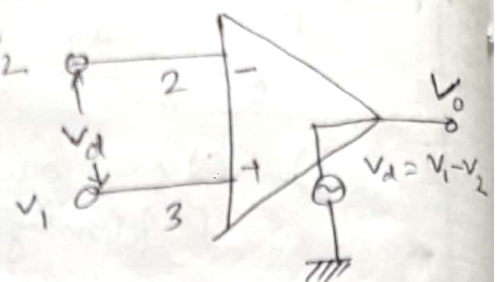
(vii) Slew rate is infinite so that the output voltage changes simulteneously with input voltage-changes.

However, a practical OPAMP deviates from these ideal characteristics. For example, the open loop gain is not infinite, rather it $\approx 2\times10^5$, input impedance $\approx 2\,M\Omega$, output impedance $\approx 75\,\Omega$, input offset voltage $\sim 1\,mV$.

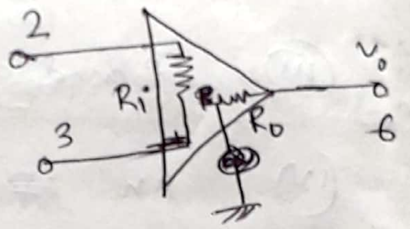
The a.c equivalent circuit of an OP AMP is shown in figure 3. For an ideal OP-AMP, the input resistance R_i is infinite and the output impedance R_o is zero. For the practical OP-AMP, the output voltage (V_o) is equal to the amplifier voltage gain A multiplied by the difference voltage ($v_d = v_1 - v_2$)

i.e. $V_o = A(V_1 - V_2)$.

which is measured through the ~~terminal 6.~~ resistance R_o.



(a)



(b)

Fig-3

Common mode rejection ratio (CMRR):

The OP-AMP is basically an amplifier which amplifies the difference in the input terminals. Therefore, if V_1 and V_2 are the input voltages given to the non-inverting and inverting terminals respectively, then the output voltage V_o of an ideal OPAMP is given by,

$$V_o = A_d(V_1 - V_2) \longrightarrow (1)$$

where A_d is the gain for the difference voltage

$$V_d = V_1 - V_2$$

Thus, if $V_1 = V_2$, then the output voltage V_o should be zero. But this does not happen in reality, because the output of an op-AMP does not depend only on the difference voltage (V_d) but also on the average voltage $V_c = \frac{V_1+V_2}{2}$, called the common mode signal. This happens so due to lack in perfect ckt. symmetry.

<u>Therefore,</u> $V_o = A_d V_d + A_c V_c$ ---- (2)

where, A_c is the voltage gain for common mode signal.

In ideal case, we expect $A_d = \infty$ and $A_c = 0$. But in practice this is not true.

To express how successfull the differential amplifier is in providing gain, one has to introduce a factor, called the common mode rejection ratio (CMRR) and defined as,

$$CMRR = \left|\frac{A_d}{A_c}\right| \quad \text{———— (3)}$$

This CMRR actually considers as the figure of merit of a differential amplifier. Higher the value of CMRR, better is the performance.

For large values of CMRR, it often expresses in dB as,

$$CMRR\,(dB) = 20\log_{10}\left|\frac{A_d}{A_c}\right|. \quad \text{——— (4)}$$

DC OPAMP 741 has a CMRR of about 90 dB.

OP AMP offset voltage and current

An ideal OPMP is perfectly balanced i.e. the output $V_0 = 0$ when the two inputs are equal ($V_1 = V_2$). In practical OP-AMP an unbalance is caused due to mismatch of input transistors. This mismatch causes the flow of unequal bias currents through the input terminals, which results in a non-zero output voltage, without any input voltage. This ~~of~~ output voltage is called offset voltage and can be balanced by applying a small d.c. voltage (~ mV) between the input terminals.

The voltage which should be applied betn the input terminals to balance the amplifier is called input offset voltage. The voltage that appears at the output terminal with the two input terminals grounded is called the output offset voltage.

* The input offset voltage is usually very small (~ mV) and hence can be neglected in many applications with relatively large input voltages. But there are some certain cases where its effect can not be neglected.

** The input offset current is defined as the difference between the two bias currents entering into the input terminals of balanced amplifier. Further, the input bias current is defined as the average of two separate currents entering

Concept of Virtual ground:

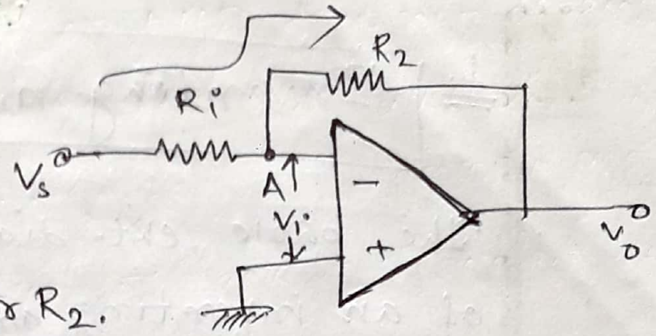


Fig 4.

Figure 4 shows the basic diagram of an inverting OPAMP which employs −ve feedback through the resistor R_2. The −ve feedback voltage tries to cancell the input voltage at A and tries to keep the voltage at A to ground potential.

Let, the potential at A is V_i, then the output voltage $V_0 = -AV_i$. Since the open loop gain (A) is infinite, for a finite V_0 we must have $V_i \to 0$. Furthermore since the input impedance $R_I \to \infty$, practically no current passes through the OPAMP. This point A is called a virtual ground.

The word virtual is used to imply that ~~through the~~ though the point A is not directly connected to the ground but it behaves like a ground point. However, it is not the actual ground.

APPLICATIONS OF OPAMP

1. Inverting amplifier

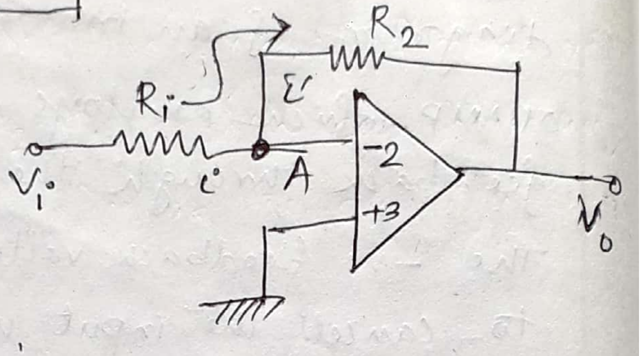


Fig5

The basic ckt diagram of an inverting amplifier using an OPAMP is shown in fig5. Here, the input voltage (V_i) is applied to the inverting input terminal through the resistor R_i. The non-inverting terminal is grounded. Since the input impedance of an ideal OPAMP is infinite, hence the point A will behave as virtual ground. The point A is connected to the output through the feedback resistance R_2. The output voltage is V_0.

Since, the input impedance is infinite, current will flow through A to the output via R_2. Let the current entering at A is i and that leaving A is i'. Then according to KCL,

$$i = i'$$

Now, $i = \dfrac{V_i - V_x}{R_i}$

$\boxed{V_x = \text{potential at A which is essentially} = 0}$

also, $i' = \dfrac{V_x - V_0}{R_2}$

$$\therefore \frac{V_i - V_x}{R_i} = \frac{V_x - V_0}{R_2} \Rightarrow \frac{-V_0}{R_2} = \frac{V_i}{R_i} \quad [V_x = 0]$$

$$\Rightarrow \boxed{V_0 = -\frac{R_2}{R_i} V_i} \longrightarrow (5)$$

So the closed loop gain is $= \frac{V_o}{V_i} = -\frac{R_2}{R_1}$.

The negative sign indicates that the output is 180° out of phase with the input i.e. the output voltage is in opposite phase of the input voltage, which means this amplier inverts the input voltage. Thus, it is called an inverting amplifier.

The gain depends only on the ratio of R_2 and R_1 and therefore independent of OPAMP parameters.

2. Scale changer

For an inverting amplifier using OPAMP, the output voltage is obtained as,

$$v_o = -\frac{R_2}{R_1} v_i = -K v_i$$

where, $K = \frac{R_2}{R_1}$ is an accurately known constant.

Thus, the ckt multiplies the input voltage by $-K$, called the scale factor. Therefore the output voltage scale is obtained by multiplying the input voltage scale by $-K$. Thus, the inverting amplifier can act as a scale changer.

(3) Phase shifter

Let, the resistances R_1 and R_2 of an inverting amplifier are replaced by the impedances Z_1 and Z_2, then,

$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1}$$

If, Z_1 and Z_2 are so chosen that they have same amplitude but different phases, then

$$\frac{V_o}{V_i} = -\frac{Z_2 e^{j\phi_2}}{Z_1 e^{j\phi_1}}$$ where ϕ_1 and ϕ_2 are the angles of Z_1 and Z_2.

$$\therefore \frac{V_o}{V_i} = e^{j(\pi+\phi_2-\phi_1)}$$

Therefore, OPAMP can shift the phase of input voltage V_i by the angle $(\pi+\phi_2-\phi_1)$, which can have any value between 0 to 360°, whereas the amplitudes remain constant.

NON-INVERTING AMPLIFIER

The basic ckt. diagram of a non-inverting amplifier using OPAMP is shown in Fig. 6. Here the input voltage is applied to the non-inverting terminal. The inverting input terminal is ~~gou~~ grounded through a resistance R_1.

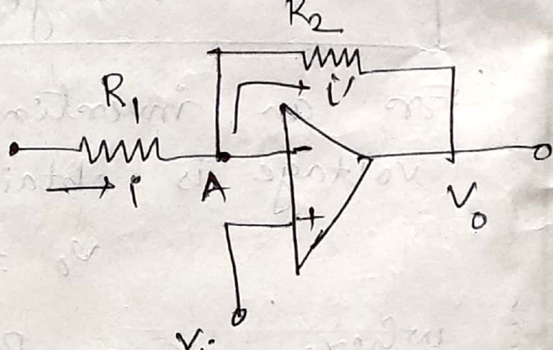


Fig. 6

Since, the input impedance of the OPAMP is infinite, no current will pass through the OPAMP. Therefore, the potential at the point A is equal to V_i.

Let, i and i' current flows through R_1 and R_2 respectively. Then applying KCL at A, we have, $i = i'$

Now, $i = \frac{-V_i+0}{R_1} = -\frac{V_i}{R_1}$ and, $i' = \frac{V_i - V_o}{R_2}$

$$\therefore \frac{V_i - V_o}{R_2} = -\frac{V_i}{R_1} \Rightarrow \frac{V_o}{R_2} = V_i\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\Rightarrow V_o = R_2\left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_i$$

$$\Rightarrow \boxed{V_o = \left(1 + \frac{R_2}{R_1}\right) V_i}$$

The gain of the amplifier $(A) = \left(1 + \frac{R_2}{R_1}\right)$.

The output voltage V_o is in the same phase as that of V_i i.e. the phase of the output does not change. Hence, the amplifier is called non-inverting amplifier.

Unity gain follower:

We have the gain of a non-inverting amplifier using OPAMP is

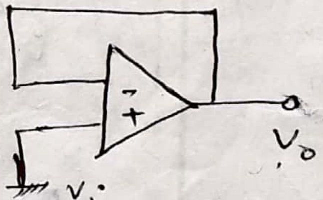


Fig-7

$$A = \left(1 + \frac{R_f}{R_1}\right)$$

It is clear from this equation that the loop gain becomes unity when $\frac{R_f}{R_1} = 0$ that means either $R_f = 0$ or $R_1 = \infty$. The amplifier is then called a unity gain buffer or unity gain follower.

Figure 7 represents a unity gain follower using an OPAMP. It has actually infinite input resistance and zero output resistance. So the amplifier can be used as a buffer or isolation amplifier.

- It allows the input voltage to be transferred to the output without any change.
- It can be used as an impedance matching device between a high impedance source and a low impedance load.

ADDER OR SUMMING AMPLIFIER

An OP-AMP can be used as an adder or summing amplifier. The necessary circuit arrangement is shown in figure 8.

This amplifier basically added algebraically a number of voltages, each multiplier by a constant gain factor.

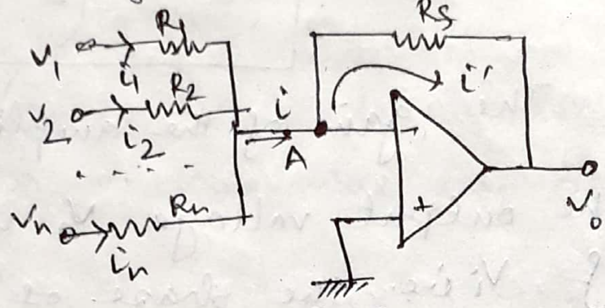


Fig.8

Let, the input voltages $V_1, V_2, \cdots V_n$ are connected to the inverting input terminal of an OPAMP through the resistances $R_1, R_2, \cdot\cdot R_n$. Let the current passes through these resistances are $i_1, i_2, \cdots i_n$. Then the total current flowing through the point A is given by

$$i = i_1 + i_2 + \cdots + i_n \longrightarrow (1)$$

Since, the point A is virtually grounded, the potential of A is zero.

$$\therefore \; i_1 = \frac{V_1 - 0}{R_1} = \frac{V_1}{R_1}, \text{ Similarly } i_2 = \frac{V_2}{R_2}, \cdots i_n = \frac{V_n}{R_n}$$

$\therefore$ From eq^n 1, $i = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \longrightarrow (2)$

Let i' current flows through the feedback resistance R_f. Applying KCL at A, we have, $i = i'$

Now, $i' = \frac{0 - V_o}{R_f} = -\frac{V_o}{R_f} \longrightarrow (3)$

$$\therefore \; -\frac{V_o}{R_f} = \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n}\right)$$

$$\Rightarrow V_o = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n}\right)$$

Now, if $R_1 = R_2 = \cdots = R_n = R$ then,

$$V_o = -\frac{R_f}{R}\left(V_1 + V_2 + \cdots + V_n\right)$$

$$V_o = -\frac{R_f}{R}\sum V_n \longrightarrow (4)$$

Therefore, the output voltage is proportional to the algebraic sum of the input voltages.

* If $R_f = R$ then,

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

In this case, the output voltage is exactly equal to the sum of the input voltages with a negative sign which may inverted using another inverting amplifier with unity gain.

* Choosing $\frac{R_f}{R} = \frac{1}{n}$, we may obtain the average of n - input voltages.

DIFFERENTIAL AMPLIFIER

The circuit diagram of a differential (or difference) amplifier using OPAMP is shown in Fig 9, whose function is to amplify the difference between two input signals V_1 and V_2. Since the open loop gain and input impedance of the OPAMP are infinite there exists a virtual short circuit at the input terminals of the OPAMP.

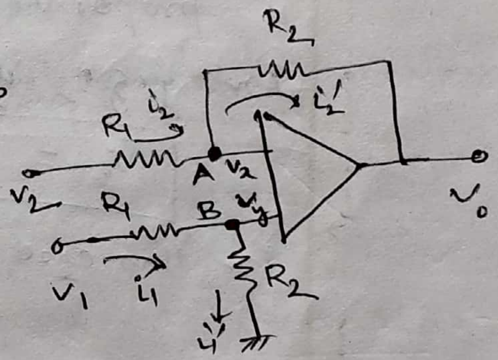


Fig. 9

Let, V_x and V_y are the potential at the points A and B respectively and are equal. Also almost same current will flow through R_1 and R_2.

Let, i_1 and i_1' currents flows through R_1 and R_2 which are connected to the non-inverting terminal. Then,

According to KCL, $i_1 = i_1'$

$$\Rightarrow \frac{V_1 - V_y}{R_1} = \frac{V_y - 0}{R_2} \longrightarrow (1)$$

Again, let i_2 and i_2' currents flow through R_1 and R_2 connected at the inverting terminal. Then, $i_2 = i_2'$

$$\Rightarrow \frac{V_2 - V_x}{R_1} = \frac{V_x - V_0}{R_2} \longrightarrow (2)$$

Subtracting eq^{n} ② from eq^{n} ① we have,

$$\frac{v_1 - v_y - v_2 + v_x}{R_1} = \frac{v_y - v_x + v_0}{R_2}$$

$$\Rightarrow \frac{v_1 - v_2}{R_1} = \frac{v_0}{R_2} \quad [\text{since, } v_x = v_y]$$

$$\Rightarrow \boxed{V_0 = \frac{R_2}{R_1}(v_1 - v_2)} \longrightarrow ③$$

Thus the ckt amplifies the difference of two input voltages.

Subtractor:

A substractor produces an output voltage which is proportional to the difference of two input voltages.
In fig 9, if $R_1 = R_2$, then eq^{n} ③ reduces to,

$$\boxed{V_0 = V_1 - V_2} \longrightarrow ④$$

In this case, OPAMP acts as a subtractor.

INTEGRATOR:

An OPAMP can be used to implement an integrator whose output voltage is proportional to the integral of the input voltage.

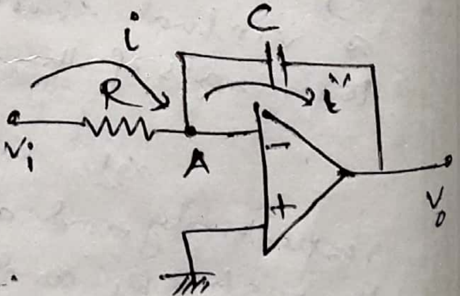


fig.10

The basic ckt diagram of an integrator is depicted in fig.10. It is nothing but an inverting amplier where the feed back resistance is replaced by a capacitor C. Let the input voltage V_i is applied to the inverting terminal of the amplifier through a resistance R. Since the input impedance and gain of the OPAMP is infinite, ~~here~~ the point A will act as virtual ground

Let i and i' currents flows through R and C respectively. Applying KCL, at A, we have $i = i'$.

$$\text{Now } i = \frac{V_i - 0}{R_1} = \frac{V_i}{R} \longrightarrow (1)$$

Also i' = current flowing through C $= \frac{dq}{dt}$

dq = charge accumulated on the capacitor in time dt

Also, $q = C(0 - V_0) = -CV_0$ C = capacitance, V_0 = P.d. across the capacitor = output voltage

$$\therefore i' = \frac{dq}{dt} = -C\frac{dV_0}{dt} = \frac{V_i}{R} \Rightarrow dV_0 = (V_i\,dt) \times -\frac{1}{CR}$$

$$\Rightarrow V_0 = -\frac{1}{CR}\int V_i\,dt + K \longrightarrow (2)$$

where K = integration constant whose value depends on the initial condition i.e. the initial capacitor voltage.

~~Here at t = 0, the capacitor voltage~~ $V_i \neq 0$

The ckt thus provides an output voltage which is proportional to the ~~rate~~ time integral of the input voltage.

For example, if the input voltage is a sine wave, the output will be a cosine wave; if the input voltage is a square wave, the output will be a triangular wave.

DISCUSSIONS

The basic integrator ckt of fig 10 has the problem of dc stability. Since the capacitor is open to d.c. signals, the d.c. gain of the amplifier is infinite, because

the capacitive reactance $X_C = \frac{1}{j\omega C} = \frac{1}{0} = \infty$

and thus gain $= A = \frac{X_C}{R} = \infty$.

As a result, any offset voltage may ~~derive~~ drive the OPAMP output to a saturation.

A wayout of this difficulty is to decrease the d.c. gain by inserting a resistance (R_1) parallel with C as shown in fig. 11. The value of R_1 is so chosen that the time constant CR_1 becomes large compared to to period of the input voltage.

Also to minimise Page No. 18 the error due to offset a resistance R_2 (ANSWER SHEET) $= R \| R_1$ may be added between the non-inverting terminal and the ground.

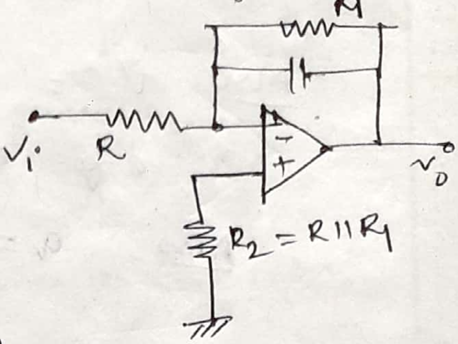


Fig 11

Applications:

The integrator ckts are widely used in digital voltmeters, in sweep or ramp (i.e. voltage varying linearly with time) generators and simulation studies in analog computers.

DIFFERETIATOR

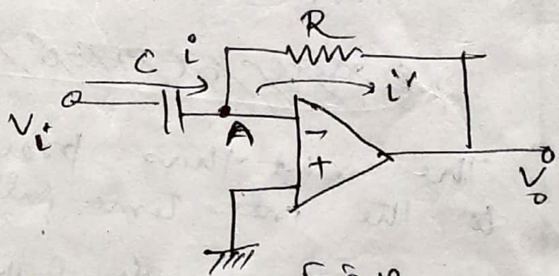


Fig 12

A differentiator provides an output voltage proportional to the time derivative of the input voltage. The basic ckt. diagram of a differentiator using an OPAMP is shown in fig. 12. Here, the differentiator ckt is nothing but an inverting amplifier where the input resistance is replaced by a capacitor c.

Since the input impedance and gain of an ideal OPAMP is infinite, the point A will act as a virtual ground.

Let i and i' are currents flow through the capacitor and the feedback resistance R. V_i and V_0 are the input and output voltages.

Now, according to KCL at A, $i = i'$.

here $i = \frac{dq}{dt}$ with $q = cV_i$.

$\therefore i = c\frac{dV_i}{dt} \longrightarrow (1)$

also, $i' = \frac{0 - V_0}{R} = -\frac{V_0}{R} \longrightarrow (2)$

From (1) and (2) $-\frac{V_0}{R} = c\frac{dV_i}{dt} \Rightarrow \boxed{V_0 = -CR\frac{dV_i}{dt}} \rightarrow (3)$

Thus, from eq ③, it is clear that the output voltage of the ckt is proportional to the time derivative of the input voltage. The constant of proportionality (i.e. scale factor) being $-CR$.

For example, if the input voltage is a sine wave the output will be a ~~b~~ cosine wave and if the input is a square wave the output will be a triangular wave.

DISCUSSIONS

If the input signal is $V_i = V_0 \sin\omega t$ then the output voltage will be,

$$v_0 = -V_0 \omega CR \cos\omega t \longrightarrow ④$$

i.e. the output voltage $v_0 \propto \omega$

That means that the differentiator behaves as a simple frequency-to-voltage converter, and the magnitude of the output voltage changes linearly with the frequency of the input voltage.

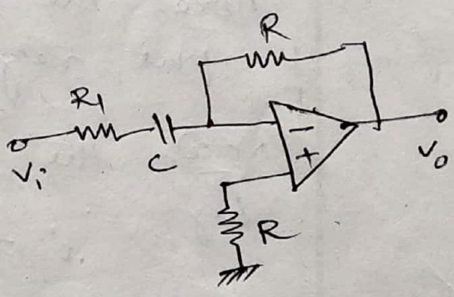


Fig. 13

The ckt has high gain at high frequencies and thus it amplifies high frequency noise and switching spikes. The ckt is found to be very much unstable. To avoid this difficulty, a resistor R_1 having magnitude $\frac{R}{10}$ to $\frac{R}{100}$ is connected in series with C. The resistor R_1 limits the high frequency gain and makes the practical differentiator useful only for frequency ~~at~~ well below the limiting frequency given by $1/2\pi CR_1$.

Applications:

The differentiator is used in wave-shaping ckts to detect high frequency components. It is also used as a rate-of-change detector in FM modulators.

LOGARITHMIC AMPLIFIER

If the feedback resistor of an inverting amplifier is replaced by a p-n junction diode, we obtained a logarithmic amplifier which gives an output voltage proportional to the logarithmic of the input voltage. The ckt. of a logarithmic amplifier is shown in fig.13.

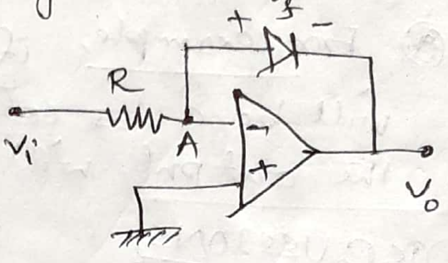


Fig 13.

Here, the input voltage is V_i, input resistance is R and the output voltage is V_o.

Now, the volt-ampere characteristics of a diode is given by,

$$i = I_s\left(e^{\frac{eV_f}{\eta KT}} - 1\right) \longrightarrow (1)$$

where, i = instantaneous current passing through the diode for forward voltage V_f.

I_s = reverse saturation current

K = Boltzmann constant $= 1.3807\times10^{-23}\ J/K$

T = Absolute temp. of the diode

η = constant $= 1$ for Ge diodes and 2 for Si diods

If $e^{eV_f/\eta KT} \gg 1$ then,

$$i \simeq I_s e^{eV_f/\eta KT} \Rightarrow \frac{i}{I_s} = e^{eV_f/\eta KT}$$

$$\Rightarrow \ln\left(\frac{i}{I_s}\right) = \frac{eV_f}{\eta KT} \Rightarrow V_f = \frac{\eta KT}{e}\ln\left(\frac{i}{I_s}\right) \longrightarrow (2)$$

Since, the input impedance and gain of the OPAMP is infinite hence, the point A is a virtual ground.

hence, $$i = \frac{V_i - 0}{R} = \frac{V_i}{R} \longrightarrow (3)$$

Thus from eq (2) $$V_f = \frac{\eta KT}{e}\ln\left(\frac{i}{I_s}\right)$$

$$= \frac{\eta KT}{e}\ln\left(\frac{V_i}{I_s R}\right) = -V_o$$

i.e. $$V_o = -\frac{\eta KT}{e}\ln\left(\frac{V_i}{I_s R}\right)$$

So, V_o is proportional to the logarithm of input voltage V_i.

FREQUENCY RESPONSE OF OPAMP

Fig. 14 represents the small-signal frequency response characteristics of a typical IC OPAMP. The OPAMP can show gain instability. For this internal compensating capacitors are used which make the open loop bandwidth or upper cut off frequency $f_2(OL)$ i.e. the frequency at which the gain drops to $\frac{1}{\sqrt{2}}$ of the d.c. gain, very low.

For IC OPAMP 741 the cutoff frequency $f_2(OL)$ is of the order of 10 Hz. For this an open loop OPAMP is not suitable for linear applications.

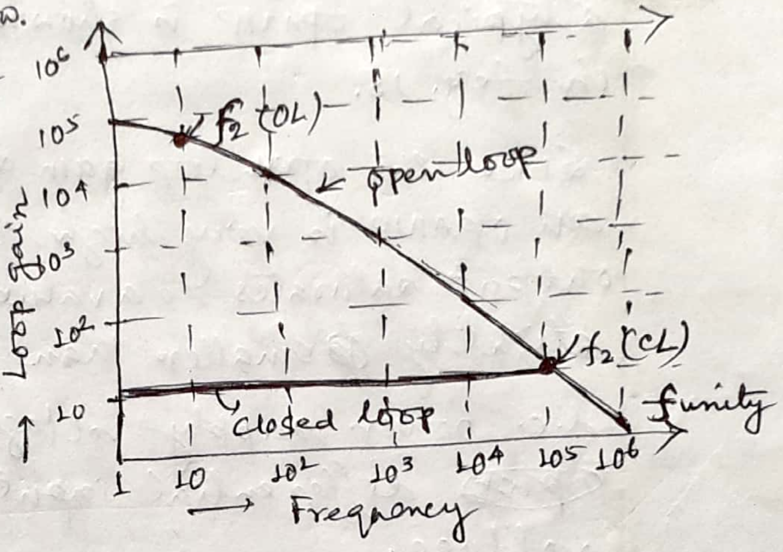


Fig.14

For an ideal OPAMP the band width is infinity, but for practical OPAMP the open loop gain is only 10 Hz. Thus the frequency response of the OPAMP is considered under closed loop condition.

SLEW RATE:

The maximum rate at which OPAMP's output can change is called the slew rate. It is usually expressed in V/μs. For IC741 OPAMP, the slew rate is about 0.5 V/μs.

- The speed limit on how fast the output of the OPAMP can change arises due to the fact that the internal compensating capacitor must be charged or discharged before the output voltage can change to different levels.

- If one tries to drive the output at a rate of voltage change greater than the slew rate the output becomes distorted.

INPUT– OUTPUT CHARACTERESTICS OF OPAMP

The basic nature of the input-output open-loop characteristics of a typical OPAMP is shown in fig. 15.

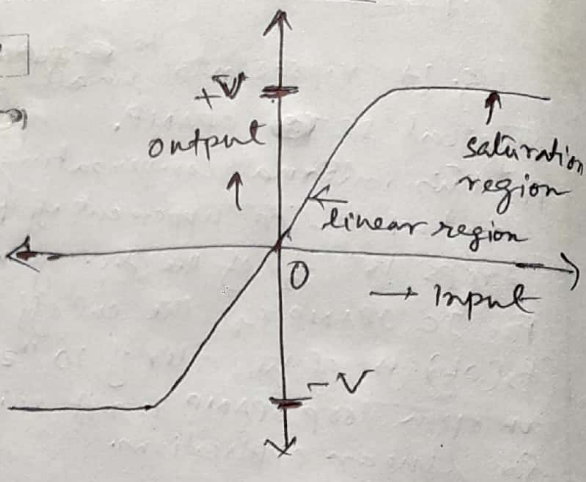


Fig. 15

Since the open loop gain of an OPAMP is very high, the output saturates to a value slightly smaller than the d.c power supply voltage ($\pm V$) as the magnitude of the differential input voltage exceeds only a very small voltage.

For the saturation region, the output of the OPAMP does not change with the input but remains constant at the supply voltages.

- For, IC 741 OPAMP, this voltage is usually $\pm 15\,V$ or $\pm 12\,V$. Thus the linear region of operation is limited to a small region around the origin.

- For practical OPAMP the curve may not pass through the origin due to the presence of offset voltage.

However, the minimum input voltage V_{min} that causes saturation is given by, $V_{min} = \frac{\pm V_{sat}}{A}$, where A is the open loop gain.

- For example, If $\pm V_{sat} = \pm 12\,V$ and $A = 10^5$ then

$$V_{min} = \frac{\pm 12}{10^5} = \pm 0.12\ mV$$

This means that that the input voltage more positive than $+0.12\,V$ will give positive saturation and input voltage more that $-0.12\,V$ will drive negative saturation voltage. So linear operation the input of OPAMP should be restricted to very small values. This makes an open loop OPAMP unsuitable for linear operation.

Voltage to current converter

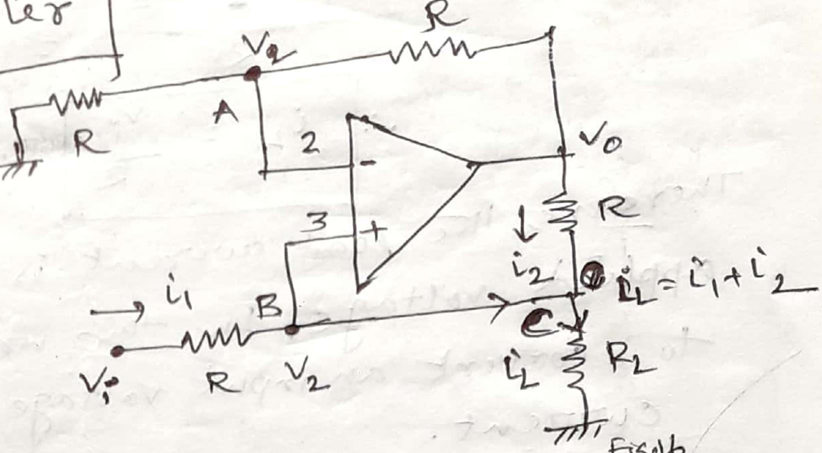


Fig 16

Very often it becomes necessary to convert a voltage signal to proportional output current. An OPAMP can be successfully applied in this purpose. A voltage to current converter using an OPAMP is shown in the figure. The input voltage is usually applied to the non-inverting terminal of an OPAMP. The input voltage V_i is applied to the non inverting terminal through a resistance R, whereas the inverting input terminal is grounded through another resistance R. The feedback resistance is also taken as R. The output terminal is connected to R_L through R, where R_L (load resistance) is grounded. Let the potentials at the point A and B are V_1 and V_2 respectively. The input current is i_1, output current is i_2 and the load current is i_L.

Then, according to KCL at C, $i_L = i_1 + i_2 \longrightarrow (1)$

Now, $i_1 = \dfrac{V_i - V_2}{R}$ and $i_2 = \dfrac{V_0 - V_2}{R}$ [V_0 = output voltage]

$\therefore$ $i_L = \dfrac{V_i - V_2}{R} + \dfrac{V_0 - V_2}{R}$

$$I_L = \frac{V_i + V_0 - 2V_2}{R} \longrightarrow (2)$$

Since the input voltage is applied to the non-inverting amplifier, the gain of the amplifier is $= \left(1 + \frac{R}{R}\right) = 2$

Further, the effective voltage treated as the input voltage is $= V_2$

$\therefore$ Gain $= \dfrac{V_0}{V_2} = 2 \Rightarrow V_0 = 2V_2$

Substituting the value of V_0 in eq^n (2) we have,

$$i_L = \frac{V_i + 2V_2 - 2V_2}{R} = \frac{V_i}{R}$$

$$\therefore \boxed{i_L = \frac{V_i}{R}} \longrightarrow (3)$$

i.e. $\left(i_L \propto V_i \text{ when } R = \text{const.} \right)$

Therefore, the load current is directly proportional to the applied voltage. In this way an OPAMP can be employed to convert an input voltage to its proportional output current.

Current to voltage converter

Very often we need to convert a current to its proportional voltage. In this purpose OPAMP is used widely. For example, as we know that the output voltage of a sensor can not be sent to a large distance due to creation of noise. In that case, that voltage is first converted into current and send it to a distant place. Then using a current to voltage converter we can easily convert the current into voltage.

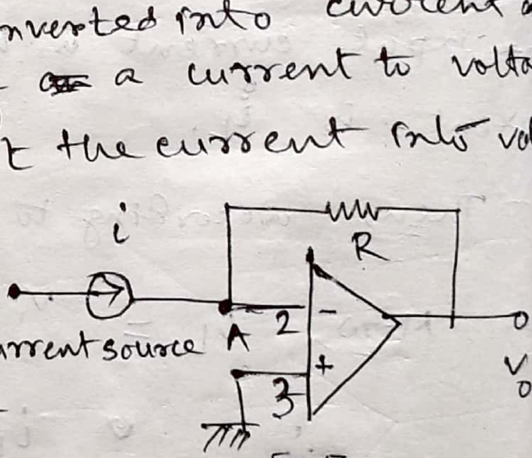


Fig-17

The ckt. diagram of a current to voltage converter using an OPAMP is shown in the figure. The current source is connected directly to the inverting input terminal and the non-inverting terminal is grounded. The feedback resistance used is R. According to the concept of virtual ground, the point A will act as virtual ground. As a result, the input current i will flow through R.

The ~~voltage~~ output voltage V_0 = voltage across the feedback resistance

$\Rightarrow$ $V_0 = -Ri$ [$-$ve sign arises due to application of input current to the inverting terminal i.e. $\boxed{v_o \propto i}$

Obviously, the output voltage is proportional to the input current.

Voltage comparator

To compare two voltages, the comparator ckt. is used. The figure shown aside represents a comparator using OPAMP to compare an input voltage V_i (given to the inverting terminal of the OPAMP) with a reference voltage V_R (given to the non-inverting terminal of the OPAMP).

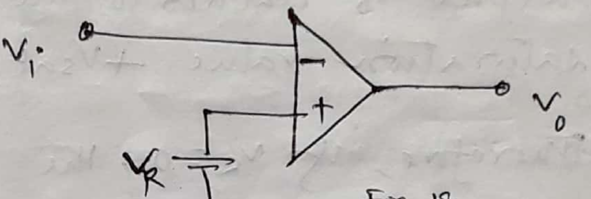


Fig-18

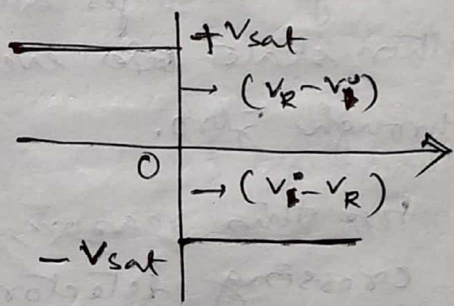


Fig.19

As long as $V_i < V_R$ the output voltage V_o goes to a maximum positive saturation voltage $+V_{sat}$ (say). As the input voltage crosses V_R and goes towards the region $V_i > V_R$, the output voltage switches to the negative saturation voltage $-V_{sat}$ (say). Therefore, looking at the output voltage profile, one can easily identify whether the voltage V_i is greater than or less than V_R.

The comparator can be used to generate a systematic square wave from a sine wave, by just taking $V_R = 0$ and choosing V_i as a sinusoidal voltage.

when v_i passes through zero towards positive values, the output v_o is driven into negative saturation voltage $-V_{sat}$. On the other hand, when v_i passes through zero towards negative values, the output v_o reaches to the positive saturation value $+V_{sat}$.

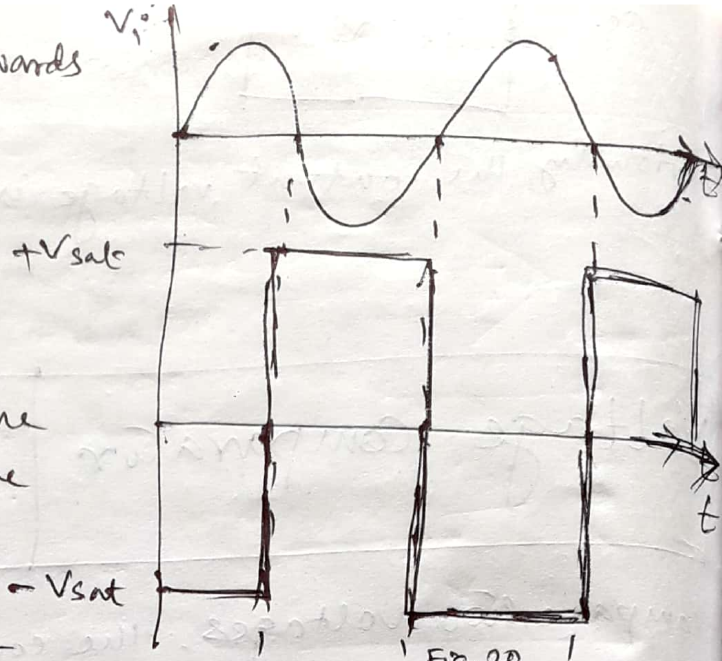


Fig. 20

Therefore, if $v_R = 0$, the output voltage changes almost discontinuously from one state to the other state ~~ate~~ every time when the input voltage passes through zero.

For this reason, such a configaration is called a zero-crossing detector. This type of ckt. is often used to convert a sinusoidal waveform into square waveform.

Half-wave rectifier

An OPAMP can be used as half-wave rectifier. The ckt diagram of a half-wave rectifier using an OPAM is shown in the figure. Here, the sinusoidal input voltage v_i is given to the inverting ~~and~~ input-terminal through the resistance R_1. The non-inverting terminal is grounded. The feedback resistance R_2 is used in this ckt. diagram. The diodes D_1 and D_2 are connected as shown in the figure.

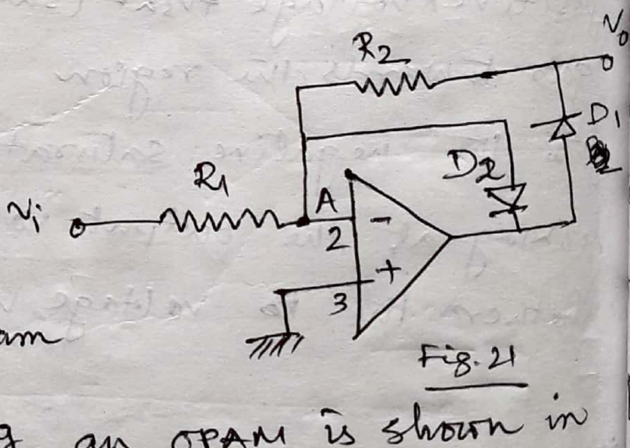


Fig. 21

he output voltage profile of
a half-wave rectifier is shown
in the figure beside. For the positive
half-cycle of the applied input ac
voltage, the diode D_2 become active and
the diode D_1 is off, since D_2 then
becomes forward biased so current
will pass through the diode D_2.

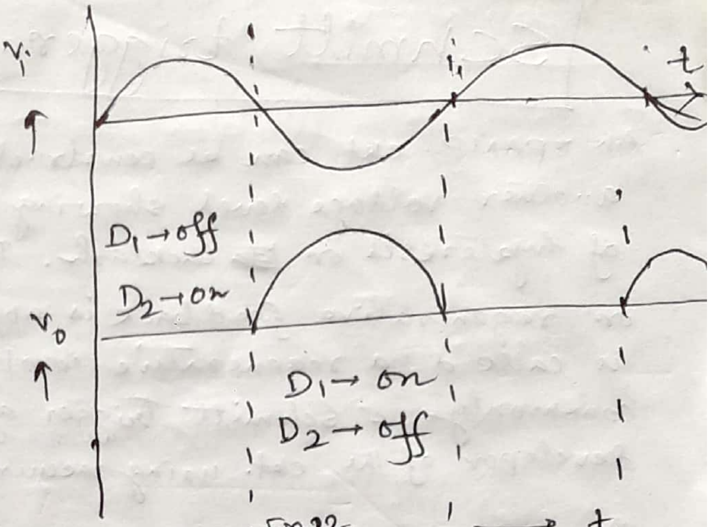


Fig.22

Neglecting the diode resistance, the output ~~volt~~ v_0 will be zero, because $v_0 = -\frac{\text{diode resistance}}{R_1} v_i$
i.e. $v_0 = 0$. However, in this case the diode is virtually grounded to the point A (since the diode resistance is neglected).
Therefore, the output voltage in the positive half cycle will be zero (as shown in the fig.).

Now, during the negative half-cycle of the input voltage, diode D_1 will be forward biased and hence will active (on), on the other hand the diode D_2 will be reversed biased and thus current will pass through D_2. Neglecting the diode resistance, the gain of the amplifier will be $-\frac{R_2}{R_1}$. Thus the output voltage is $v_0 = -\frac{R_2}{R_1} \times -v_i = \frac{R_2}{R_1} v_i$. Therefore, output voltage will be found for the negative half-cycle. In this way, OP-AMP can be used as a half-wave rectifier.

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Schmitt trigger or regenerative comparator

An OPAMP ckt can be constructed to switch from one voltage level to another voltage level showing the phenomenon of hysteresis or ~~eta~~ backlash. In this case positive or regenerative feedback is applied. Such a ckt. is called a regenerative comparator or more commonly a Schmitt trigger after the original developer of the ckt. using vacuum tubes.

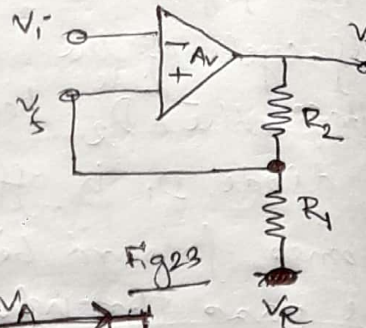
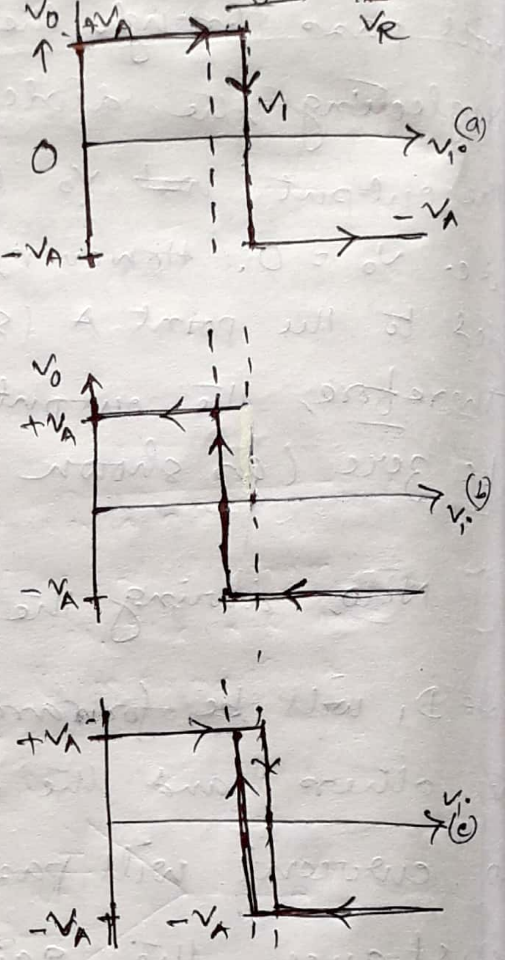


Fig 23

An OPAMP Schmitt trigger is shown in fig 23. The input voltage v_i is applied to the inverting terminal and the feedback voltage V_f is applied to the non-inverting terminal.



From the superposition theorem we get,

$$V_f = \frac{R_1 V_o}{R_1+R_2} + \frac{R_2 V_R}{R_1+R_2} \longrightarrow (1)$$

If, V_i is small or negative such that $V_i << V_f$, then the output of the amplifier will saturates to $V_o = +V_A$, where $+V_A$ is the +ve saturation voltage.

Therefore, $$V_f = \frac{R_1 V_A}{R_1+R_2} + \frac{R_2 V_R}{R_1+R_2} = V_1 \text{ (say)} \longrightarrow (2)$$

Let now, V_i increase in the +ve direction. The value of V_o will remain unchanged to $+V_A$ till V_i attains ~~the~~ threshold, critical or trigger voltage V_1. At this trigger voltage, the output of the amplifier switches to $V_o = -V_A$, because in this case V_i just exceeds V_1 and thus V_o and V_f will decrease. Thus $(V_i - V_f)$ increases to decrease V_o further. This cumulative action takes place rapidly to bring V_o immediately to $-V_A$. The output voltage V_o is sticks to $-V_A$ as long as $V_i > V_1$.

Fig. 24

For $V_i > V_1$ we have,

$$V_f = \frac{R_2 V_R}{R_1+R_2} - \frac{V_A R_1}{R_1+R_2} = V_2 \text{ (say)} \longrightarrow (3)$$

The switching action occurs only if the amplification is sufficiently large so that small changes in V_f are amplified to the desired extent. The feedback factor is $\beta = \frac{R_1}{R_1+R_2}$. The ckt. will function satisfactorily provided the loop gain $-\beta A_v$ is much larger than unity.

Suppose that we now decrease V_i. Then the output will remain at $-V_A$ till $V_i = V_2$. A regenerative transition will occur at this point as shown in fig 24(b), so that V_o will switch to $+V_A$ instantaneously.

The overall transfer characteristics of the Schmitt trigger is shown in fig 24(c). This curve will be called a hysteresis curve because it has the form of a magnetic hysteresis loop.

The hysteresis curve shows that the ckt triggers at a higher voltage for increasing input signals than for decreasing input signals.

The width of the hysteresis loop is given by,

$$V_H = V_1 - V_2 = \frac{2R_1V_A}{R_1+R_2} \longrightarrow (4)$$

In order to reduce V_H, we have to make $\frac{R_1}{R_1+R_2}$ small. But it can not be reduced greatly, for otherwise the loop gain $-\beta A_v$ becomes small.

$\boxed{\text{Example}}$

Suppose we have to design a Schmitt trigger for which $V_R = 3V$, and $V_H = 0.03\,V$, using an OPAMP for which $V_A = 5V$ and $A_v = -20000$. Then,

$$V_H = \frac{2R_1V_A}{R_1+R_2} = \frac{5\times 2\,R_1}{R_1+R_2} = 0.03$$

$$\Rightarrow \frac{R_1}{R_1+R_2} = 0.003 = \beta$$

The loop gain is $\cancel{A_vf}$ $-\frac{A_vR_1}{R_1+R_2}$ $(-\beta A_v)$

$$= -20000\times 0.003 = -60$$

This is much larger than 1, and is therefore acceptable.

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Applications

An important application of the schmitt trigger is to transform a slowly varying input voltage into a square voltage at the output.

The schmitt trigger is a comparator because the ckt. compares an input voltage with the trigger levels V_1 and V_2 for the output voltage to swing between $-V_A$ and $+V_A$. It is a regenerative comparator because it employs positive or regenerative feedback.

WIEN BRIDGE OSCILLATOR

Wienbridge oscillator is an RC oscillator which is widely used in the laboratory as an AF signal generator. The ckt. diagram of a Wienbridge oscillator using OPAMP is depicted in fig 25. The R-C combination and the resistors R_1 and R_2 form the four arms of a Wien bridge. The simplified ckt. of fig 25 is shown in fig 26. The output v_i of the bridge (betn points A and B of fig 26) is amplified by the OPAMP, which has very large positive voltage gain, very high input impedance and negligible output impedance. The output V_0 of the amplifier becomes the input of the bridge supply voltage.

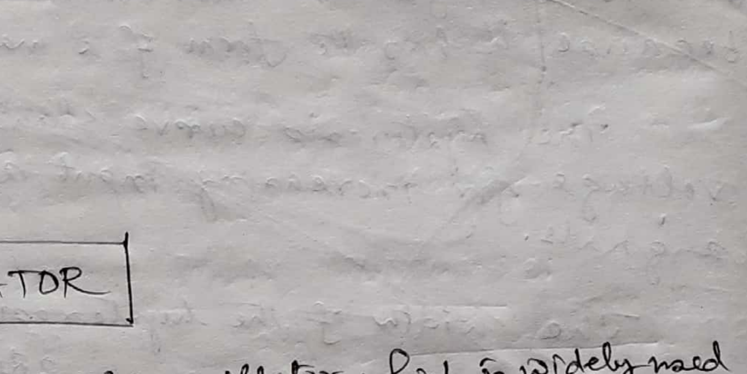

Fig. 25: Ckt. diagram of Wien bridge oscillator using OPAMP.

The oscillator operates with the bridge slightly unbalanced and sufficient amplification to establish a loop gain of unity. The ckt. uses positive feedback through RC combinations to the noninverting input terminal of the OPAMP. As the non-inverting ~~terminal of~~ OPAMP introduces no phase shift, the feedback voltage v_2 must be in phase with v_0 to satisfy Barkhausen criterion for oscillation.

When the bridge is balanced, we have,

$$\frac{R_1}{R_2} = \frac{R + \frac{1}{j\omega C}}{R \parallel j\omega C} \longrightarrow (1)$$

Here, $R \parallel j\omega C = \dfrac{1}{\frac{1}{R} + j\omega C} = \dfrac{R}{1 + j\omega CR}$

$$\therefore \frac{R_1}{R_2} = \frac{\cancel{R}\left(1 + \frac{1}{j\omega CR}\right)}{\cancel{R} \cdot \frac{1}{j\omega CR + 1}}$$

$$\Rightarrow \frac{R_1}{R_2} = \frac{(1 + j\omega CR)}{j\omega CR} \times (1 + j\omega CR) = \frac{(1 + j\omega CR)^2}{j\omega CR}$$

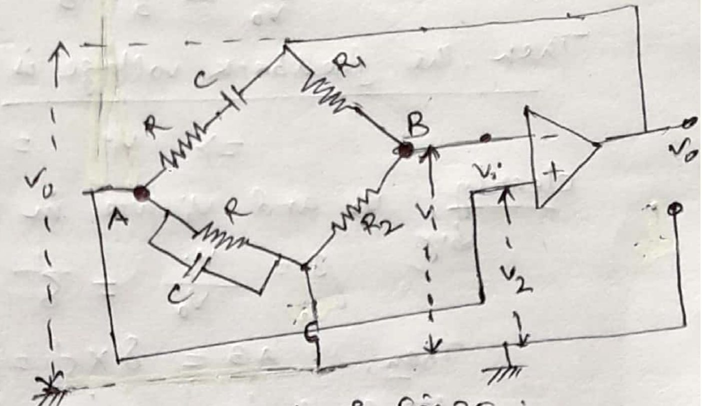

Fig 26: Equivalent ckt. of fig 25:

$$\frac{R_1}{R_2} = \frac{1 + 2j\omega CR - \omega^2 C^2 R^2}{j\omega CR} = 2 + \frac{1 - \omega^2 C^2 R^2}{j\omega CR} \longrightarrow (2)$$

Equating the real and imaginary parts on the both sides of eqⁿ (2), we have

$$\frac{R_1}{R_2} = 2 \Rightarrow \boxed{R_1 = 2R_2} \longrightarrow (3)$$

and, $\dfrac{1 - \omega^2 C^2 R^2}{j\omega CR} = 0 \Rightarrow \omega^2 C^2 R^2 = 1$

$\Rightarrow R = \dfrac{1}{\omega C}$ with $\omega = \dfrac{1}{CR}$

$\therefore$ The frequency of oscillation ω

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi RC} \longrightarrow (4)$$

When the bridge is balanced, then the voltage across the two lower arms (between A and B) must be equal, i.e.

$$v_1 = v_2 = \frac{R_2}{R_1 + R_2} v_0 = \frac{R_2}{3R_2} v_0 = \frac{1}{3} v_0 \quad [\text{from eq}^n (3)]$$

Therefore, at balanced condition, we get, $\dfrac{R_2}{R_1 + R_2} = \dfrac{1}{3} \longrightarrow (5)$

and, $\dfrac{v_1}{v_0} = \dfrac{v_2}{v_0} = \dfrac{1}{3} \longrightarrow (6)$

Since, $v_i \neq 0$ which nothing but $(v_1 - v_2)$ for oscillation to occur, the ratio $R_2/(R_1+R_2)$ is taken to be less than 1/3. If we let,

$$\frac{R_2}{R_1 + R_2} = \frac{1}{3} - \frac{1}{\delta} \longrightarrow (7)$$

where, δ is a number greater than 3, then the bridge is slightly-unbalanced and gives a feedback voltage v_i.

As the bridge is unbalanced by adjusting the ratio $\frac{R_1}{R_2}$, the ratio v_1/v_0 remains 1/3 but v_2/v_0 ratio changes which is given by

$$\frac{v_2}{v_0} = \frac{1}{3} - \frac{1}{\delta}$$

Then the feedback voltage is given by, $v_i = v_1 - v_2 = \left(\frac{1}{3} - \frac{1}{3} + \frac{1}{\delta}\right) v_0$

$$\Rightarrow v_i = \frac{v_0}{\delta}$$

clearly, v_0 and v_i are in phase, and the feedback fraction is given by, $\beta = \frac{v_i}{v_0} = \frac{1}{\delta}$ Further the gain(A) $= \frac{v_0}{v_i} = \delta = \frac{1}{\beta}$

Then, $A\beta = \delta \times \frac{1}{\delta} = 1$ i.e. the Barchausen criterion is satisfied by making $\delta > 3$.

Application: Like wise phase-shift oscillator, Wienbridge oscillator is used in the AF range. Continuous variation of frequency is acheived by varying the two capacitors. This is an advantage over phase-shift oscillator, where three capacitors are varied simultenously.

The Wien-bridge oscillator has the following advantages:

(i) The overall gain is very high since high ~~amplification~~ gained network (OPAMP) is used.

(ii) The ckt. gives a very good sine wave output.

(iii) The frequency stability is very good. The frequency of oscillation remains markedly constant over a fairly long time interval.

(iv) The frequency of oscillation can be easily varied.

Disadvantages: The disadvantages of this oscillator is;

very high frequency can not be generated with Wien bridge oscillator.