UNIT II

→ Instrumentation amplifier :-

→ In a number of industrial and consumer applications, one is required to measure and control physical quantities.

→ Some typical examples are measurement and control of temperature, humidity, light intensity, water flow etc.

→ These are measured with the help of transducers.

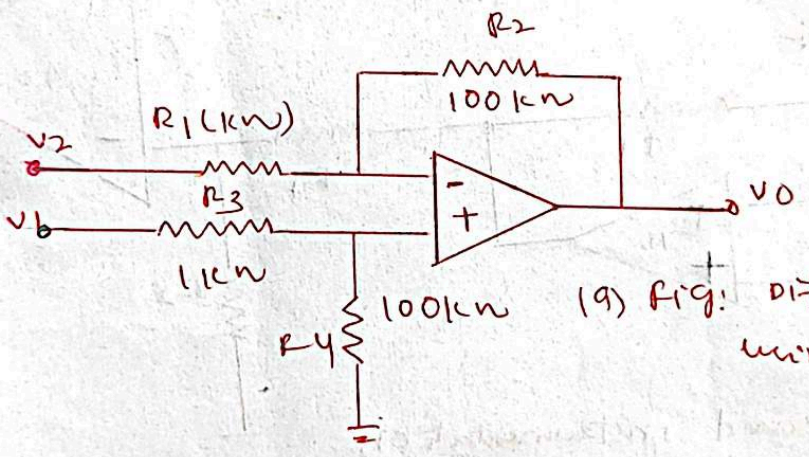
→ The output of transducer has to be amplified so that it can drive the indicator or display system.

→ This function is performed by an instrumentation amplifier.

→ The important features are :

(i) high gain accuracy
(ii) high CMRR
(iii) high gain stability with low temperature co-efficient
(iv) low dc offset
(v) low output impedance.

→ consider a basic differential amplifier shown in fig.



(9) Fig: Differential Amplifier using single op-amp.

The output voltage V_0 is given by

$$V_0 = \left(-\frac{R_2}{R_1}\right) V_2 + \left(\frac{R_4}{R_3+R_4}\right) V_1 \left(1+\frac{R_2}{R_1}\right)$$

$$V_0 = \left(-\frac{R_2}{R_1}\right) V_2 + \left(\frac{1}{1+\frac{R_3}{R_4}}\right) V_1 \left(1+\frac{R_2}{R_1}\right)$$

$$= \left(-\frac{R_2}{R_1}\right) V_2 + \frac{R_2}{R_1}\left(1+\frac{R_1}{R_2}\right)\left(\frac{1}{1+\frac{R_3}{R_4}}\right) V_1$$

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$$V_0 = -\frac{R_2}{R_1}\left[V_2 - \frac{1}{\left(1+\frac{R_3}{R_4}\right)}\left(1+\frac{R_1}{R_2}\right)V_1\right]$$

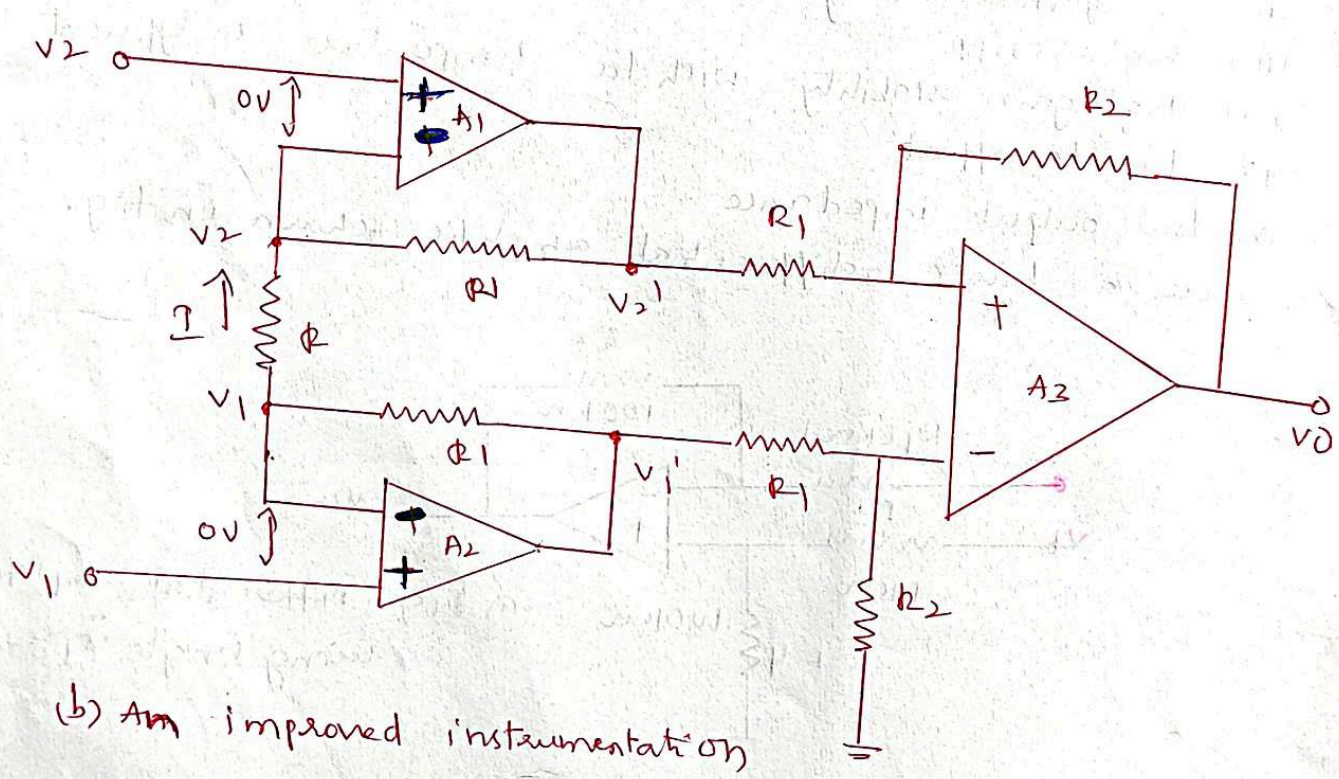
for $R_1 | R_2 = R_3 | R_4$, we obtain $V_0 = -\frac{R_2}{R_1}\left[V_2 - \frac{1}{\left(1+\frac{R_1}{R_2}\right)}\left(1+\frac{R_1}{R_2}\right)V_1\right]$

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

→ In the circuit of fig (a), source V_1 sees an input impedance $=(R_3+R_4)$ $(=101\,k\Omega)$ and the impedance seen by source V_2 is only R_1 $(1\,k\Omega)$.

→ This low impedance may load the signal source heavily.

→ Therefore, high resistance buffer is used proceeding each input to avoid this loading effect as shown in fig (b).



(b) An improved instrumentation Amplifier.

→ The op-amps A_1 and A_2 have differential input voltage as zero.

→ for $V_1 = V_2$, that is, under common mode condition, the voltage across R will be zero.

→ As no current flows through R and R' the non-inverting amplifier A_1 acts as voltage follower, so its output is $V_2' = V_2$.

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→ Similarly op-amp A_2 acts as voltage follower having output $v_1' = v_1$.

→ However, if $v_1 \neq v_2$, current flows in R and R', and $(v_2' - v_1') > (v_2 - v_1)$.

→ Therefore, this circuit has differential gain and CMRR more compared to the single op-amp circuit of fig (4).

→ The voltage v_0 can be calculated as

The voltage at the (+) input terminal of op-amp A_3 is

$$\frac{R_2 v_1'}{R_1 + R_2}$$

Using superposition theorem, we have,

$$v_0 = -\frac{R_2}{R_1} v_2' + \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_2 v_1'}{R_1 + R_2}\right)$$

$$= -\frac{R_2}{R_1} v_2' + \frac{R_2}{R_1}\left(1 + \cancel{\frac{R_1}{R_2}}\right) \frac{v_1'}{\left(1 + \cancel{\frac{R_1}{R_2}}\right)}$$

$$= \frac{R_2}{R_1}\left(v_1' - v_2'\right)$$

→ Since no current flows into op-amp, the current I flowing (upwards) in R is $I = \frac{v_1 - v_2}{R}$ and passes through the resistor R'. $v_1' - v_1 = I R'$

$$v_1' = R' I + v_1$$

Similarly $v_2 - v_2' = I R'$

$$v_2' = -I R' + v_2$$

Sub $I = \frac{v_1 - v_2}{R}$ in above two expressions

$$v_1' = R'\left(\frac{v_1 - v_2}{R}\right) + v_1 = \frac{R'}{R}(v_1 - v_2) + v_1$$

$$v_2' = -R'\left(\frac{v_1 - v_2}{R}\right) + v_2 = \frac{R'}{R}(v_1 - v_2) + v_2$$

$$\therefore v_0 = \frac{R_2}{R_1}\left(v_1' - v_2'\right) = \frac{R_2}{R_1}\left(\frac{R'}{R}(v_1 - v_2) + v_1 - \left(\frac{R'}{R}(v_1 - v_2) - v_2\right)\right)$$

$$= \frac{R_2}{R_1}\left(2\frac{R'}{R_1}(v_1 - v_2) + (v_1 - v_2)\right) = \frac{R_2}{R_1}\left[(v_1 - v_2)\left(2\frac{R'}{R} + 1\right)\right]$$

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$$V_0 = \frac{R_2}{R_1}\left(1 + \frac{2R'}{R}\right)(V_1 - V_2)$$

→ The difference gain of this instrumentation amplifier can be varied by using a variable resistance R.

→

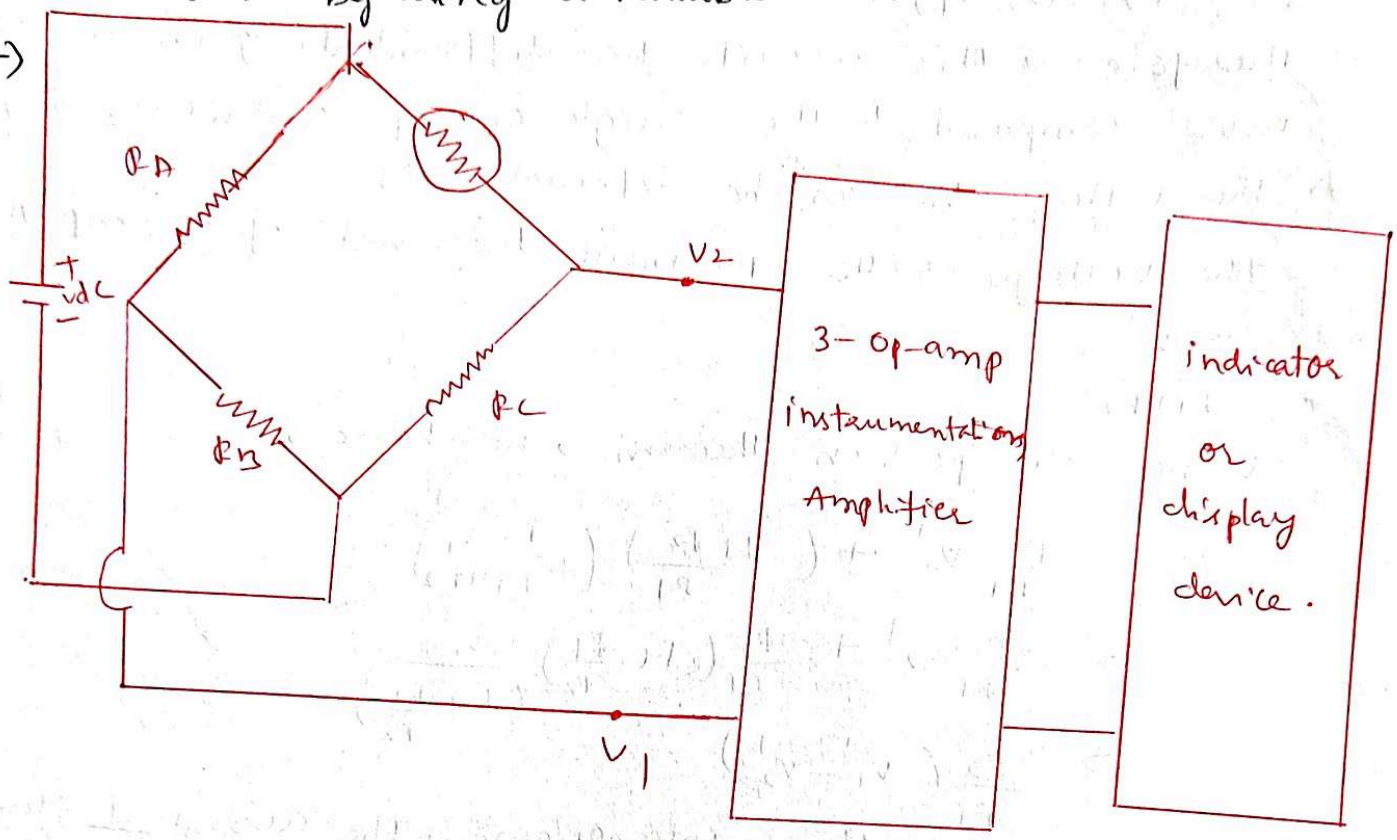

Fig: (c) Instrumentation amplifier using transducer bridge.

→ Fig(c) shows a differential instrumentation amplifier using transducer bridge.

→ The circuit uses a resistive transducer whose resistance changes as a function of the physical quantity to be measured.

→ The bridge is initially balanced by a dc supply voltage Vdc so that $V_1 = V_2$.

→ As the physical quantity changes, the resistance R_T of the transducer also changes, causing an unbalance in the bridge ($V_1 \neq V_2$).

→ This differential voltage now gets amplified by the three op-amp differential instrumentation amplifier.

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→ Comparators and Applications:-

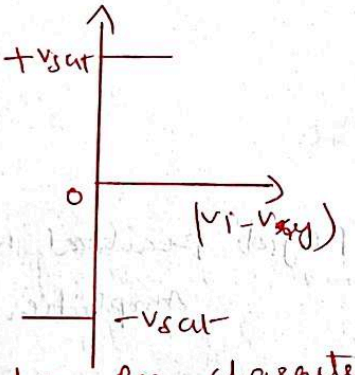
→ An operational amplifier in the open-loop configuration operates in a non-linear manner.

→ There are a number of applications of op-amp in this mode, such as comparators, detectors, limiters and digital interfacing devices.

→ 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.

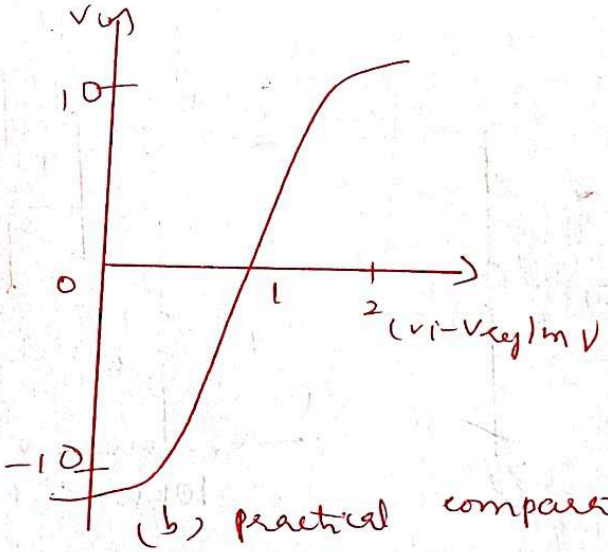
→ It is basically an open-loop op-amp with output $\pm V_{sat} (= V_{cc})$ as shown (a) in the ideal transfer characteristics.

→ However, a commercial op-amp has the transfer characteristics of fig (b).



The transfer characteristics

fig(a) ideal comparator



(b) practical comparator.

→ There are basically two types of comparators:

(i) Non-inverting comparator

(ii) Inverting comparator

→ **Non-inverting comparator:-**

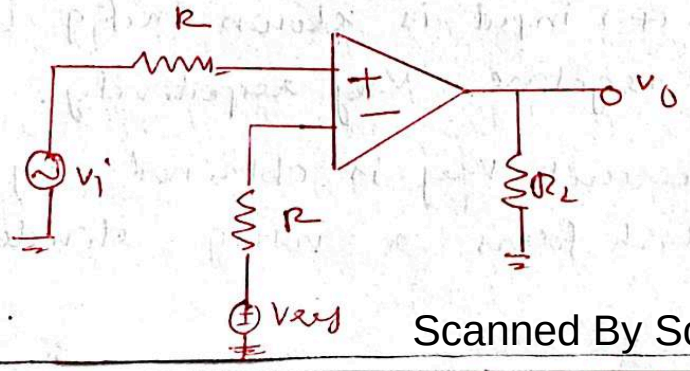


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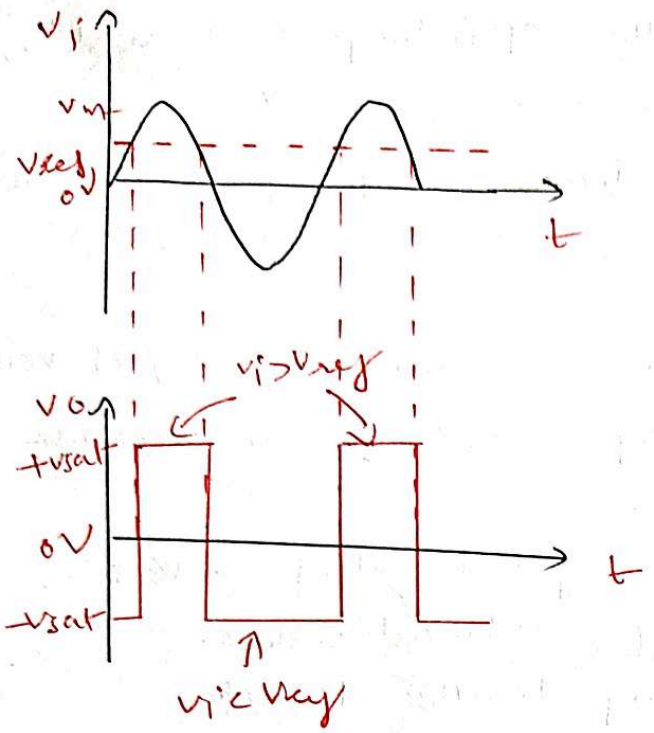
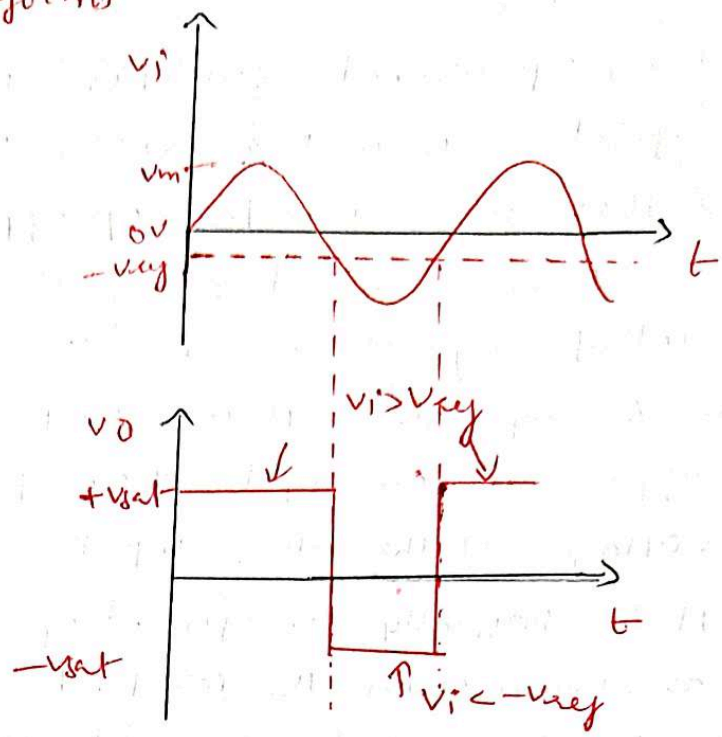
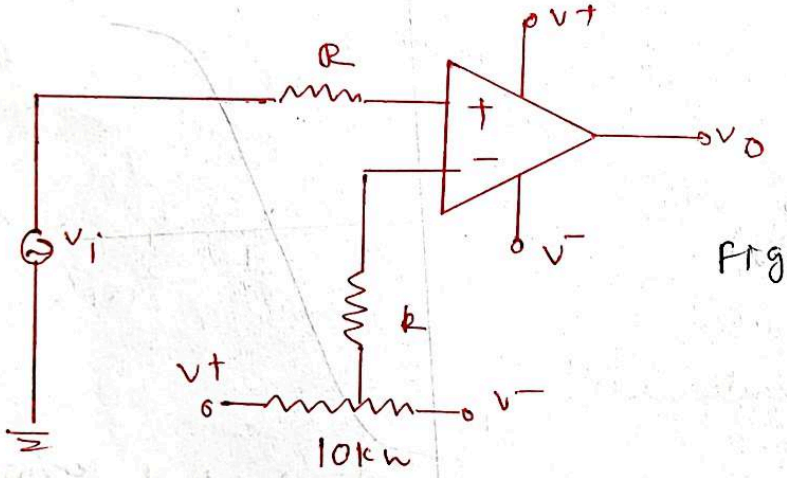
fig.(b) Input & output waveforms





fig(c)



fig(d) Practical non-inverting Amplifier.

→ A fixed reference voltage V_{ref} is applied to (−) input and a time varying signal V_i is applied to (+) input.

→ The output voltage is at $-V_{sat}$ for $V_i < V_{ref}$.

→ And V_o goes to $+V_{sat}$ for $V_i > V_{ref}$.

→ The output waveform for a sinusoidal input signal applied to the (+) input is shown in fig (b). and fig (c) for positive and negative V_{ref} respectively.

→ In a practical circuit V_{ref} is obtained by using a 10kΩ potentiometer which forms a voltage divider with the

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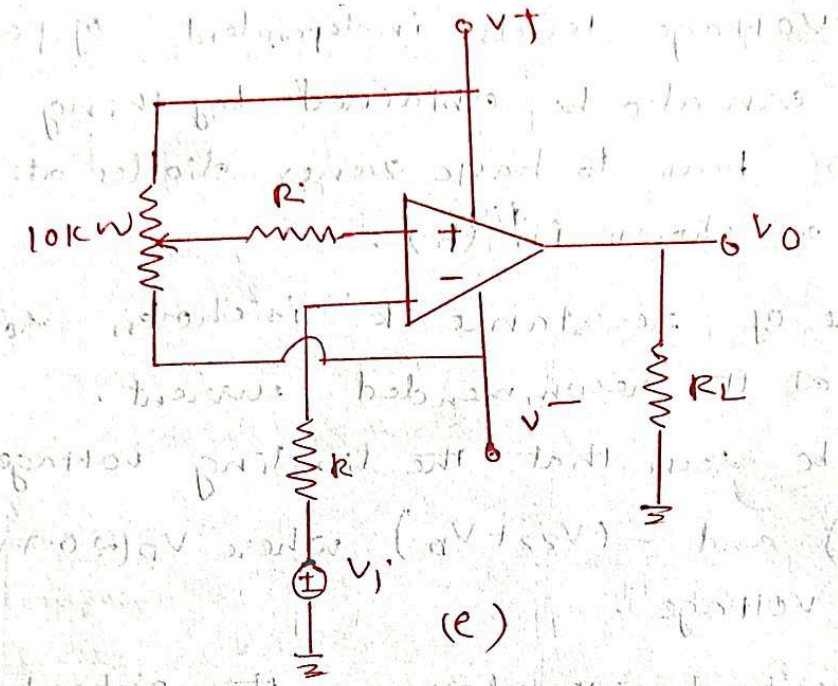
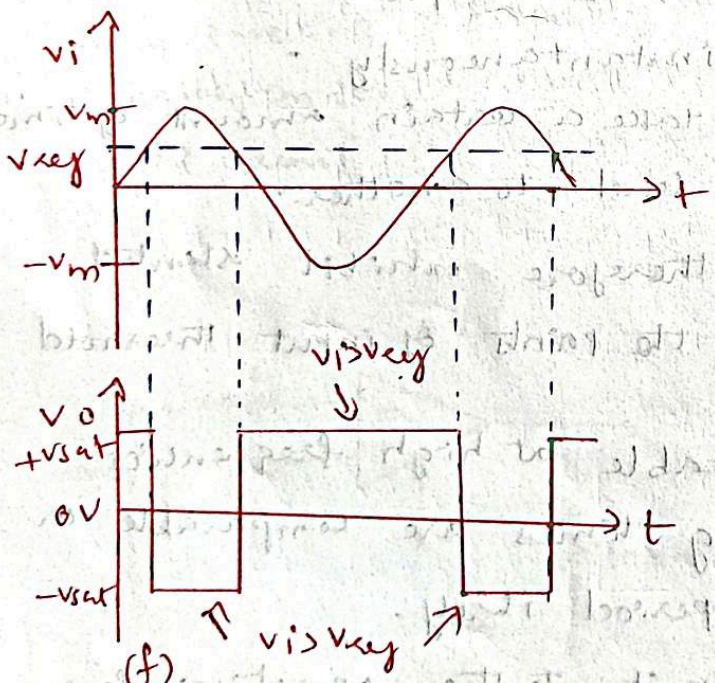
supply voltages V+ and V− with the wiper connected to (−) input terminal as shown in (d).

→ Thus a V_{ref} of desired amplitude and polarity can be obtained by simply adjusting the 10kΩ potentiometer.

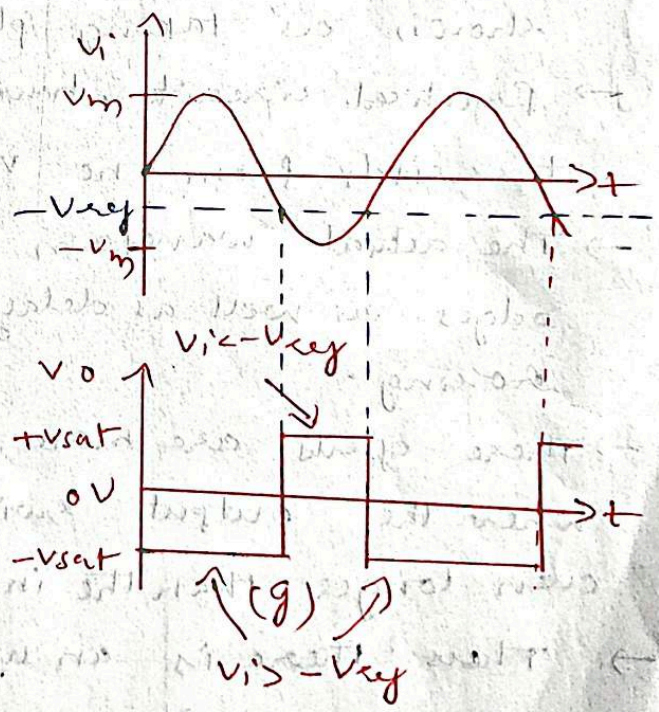
→ Fig (e) shows a practical <u>inverting comparator</u> :-



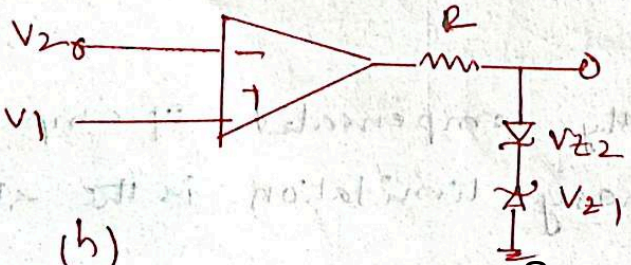
(e)



(f)



(g)



(h)

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→ In fig(e) Vref voltage reference Vref is applied to the (+) input and Vi is applied to (−) input.

→ For a sinusoidal input signal, the output waveform is shown in (f) and (g) for Vref positive and negative respectively.

→ Output voltage levels independent of power supply voltages can also be obtained by using a resistor R and two back to back zener diodes at the output of op-amp as shown in fig (h).

→ The value of resistance 'R' is chosen so the zener diodes operate at the recommended current.

→ It can be seen that the limiting voltages of Vo are $(V_{Z1}+V_D)$ and $-(V_{Z2}+V_D)$ where $V_D(\approx 0.7V)$ is the diode forward voltage.

→ In the output waveforms, the output transitions are shown as taking place instantaneously.

→ Practical circuits, however, take a certain amount of time to switch from one voltage level to another.

→ The actual waveform will therefore exhibit slanted edges as well as delays at the points of input threshold crossing.

→ These effects are more noticeable at high frequencies where the output switching times are comparable or even longer than the input period itself.

→ Thus there is an upper limit to the operating frequency of any comparator.

→ In 741, the internally compensated op-amp is used as comparator, the primary limitation is the slew rate.

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→ Since 741C has slew rate equal to 0.5 V/μs, it takes $\frac{2\times13}{0.5} \simeq 50\,\mu s$ ($V_{sat} = \pm 13$ V for 741) to swing from one saturation level to the other.

→ In many applications, this is too long. To increase the response time, it is possible to use uncompensated op-amps such as 301, for comparator applications.

→ **Applications of comparator:-**

(i) Zero crossing detector
(ii) Window detector
(iii) Time marker generator
(iv) phase detector or meter.

→ **Zero crossing detector:-**

The basic comparators can be used as a zero crossing detector provided that V_{ref} is set to zero.

→ An inverting zero crossing detector is shown (a) and the output waveform for a sinusoidal input signal is also shown (b).

→ The circuit is also called a sine to square wave generator.

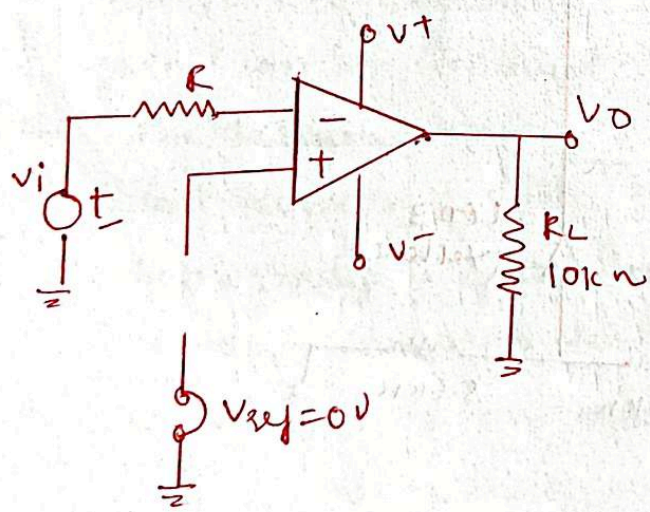

Fig (a) Zero crossing detector

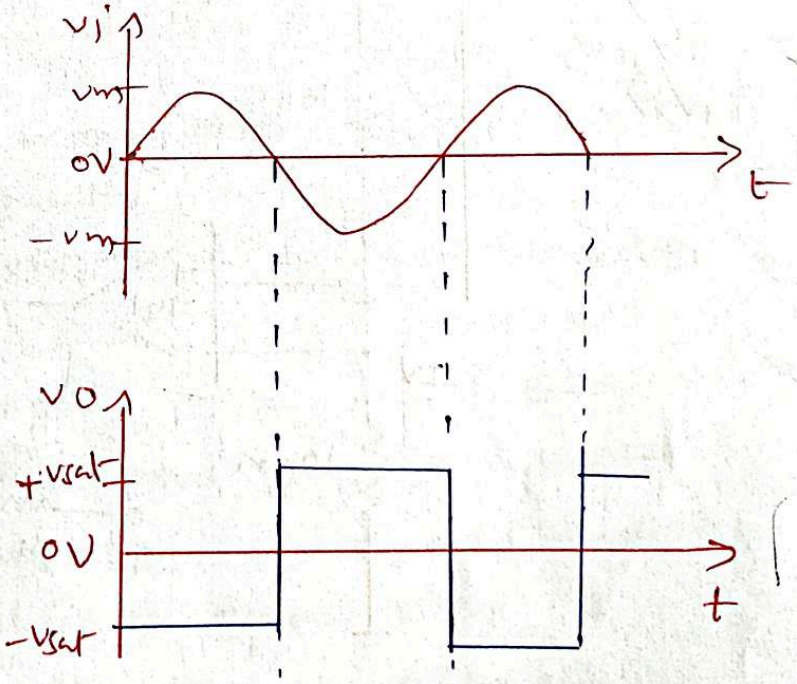

Fig (b) Input and output waveforms.

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→ Window detecting :-

→ Sometimes one may like to mark the instant at which an unknown input is between two threshold levels.

→ This can be achieved by a circuit called window detector.

→ The fig. shows a three level detector with indicator lights.

→ There are three indicators : yellow (LED3) for input too low (< 3V), Green (LED 2) for safe input (3-6V) and Red (LED 1) for high input (> 6V).

→ They are turned on and off as indicated in table 5.1.

Table : Three level comparator LED specifications

Input (volt)	Yellow LED3	Green LED 2	Red LED1
Less than 3V	On	Off	Off
Between 3V and 6V	Off	On	Off
Greater than 6V	Off	Off	On

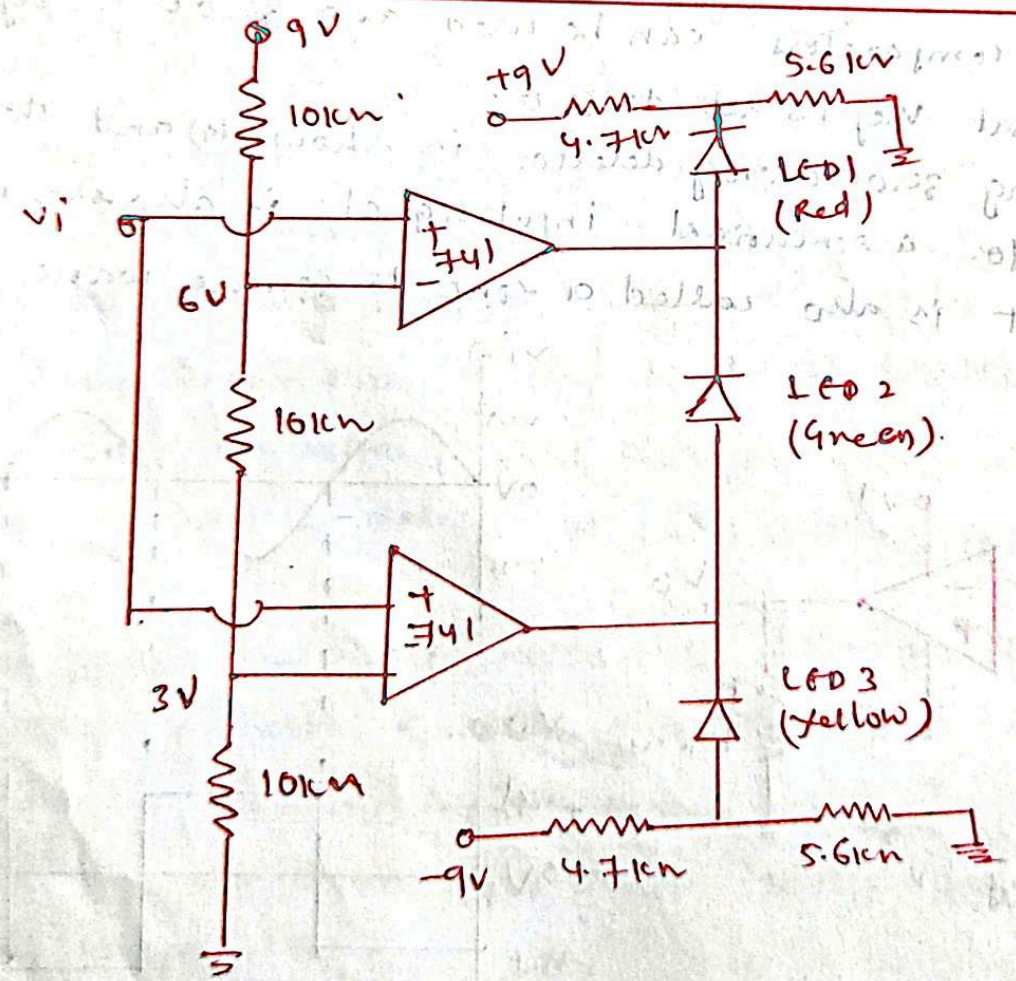

Fig. Three level comparator with LED indicator.

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→ Time marker Generator :-

→ The output of the zero-crossing detector is differentiated by an RC circuit (RC << T), so that the voltage v' is a series of positive and negative pulses as shown.

→ The negative portion is clipped off after passing through the diode D and the waveform V_L is as shown.

→ So, with the help of this circuit, the sinusoid has been converted into a train of positive pulses of spacing T and may be used for triggering the monoshots, SCR, sweep voltage of CRT etc.

→ Phase detector :-

→ The phase angle between two voltages can also be measured using the circuit for Time marker generator.

→ Both voltages are converted into spikes and the time interval between the pulse spikes of one input and that of the other is measured.

→ The time interval is proportional to the phase difference.

→ One can measure phase angles from 0° to 360° with such a circuit.

→ SCHMITT TRIGGER (Regenerative comparator).

→ If positive feedback is added to the comparator circuit, gain can be increased greatly.

→ The transfer curve of comparator becomes more close to ideal curve.

→ Theoretically, if the loop gain $-\beta A_{OL}$ is adjusted to unity, then the gain with feedback, A_{vf} becomes infinite.

→ This results in an abrupt (zero rise time) transition between the extreme values of output voltage.

→ In practical circuits, however, it may not be possible to maintain loop-gain exactly equal to unity for a long time

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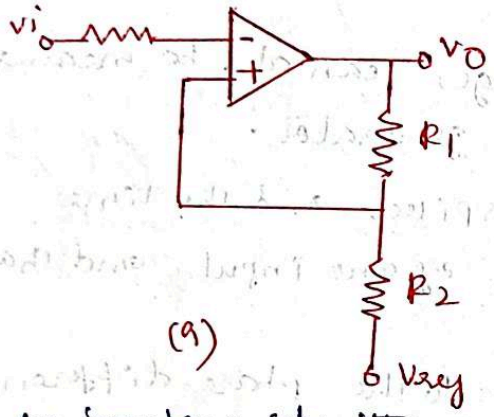
because of supply voltage and temperature variations.

→ So a value greater than unity is chosen. This also gives an output waveform virtually discontinuous at the comparision voltage.

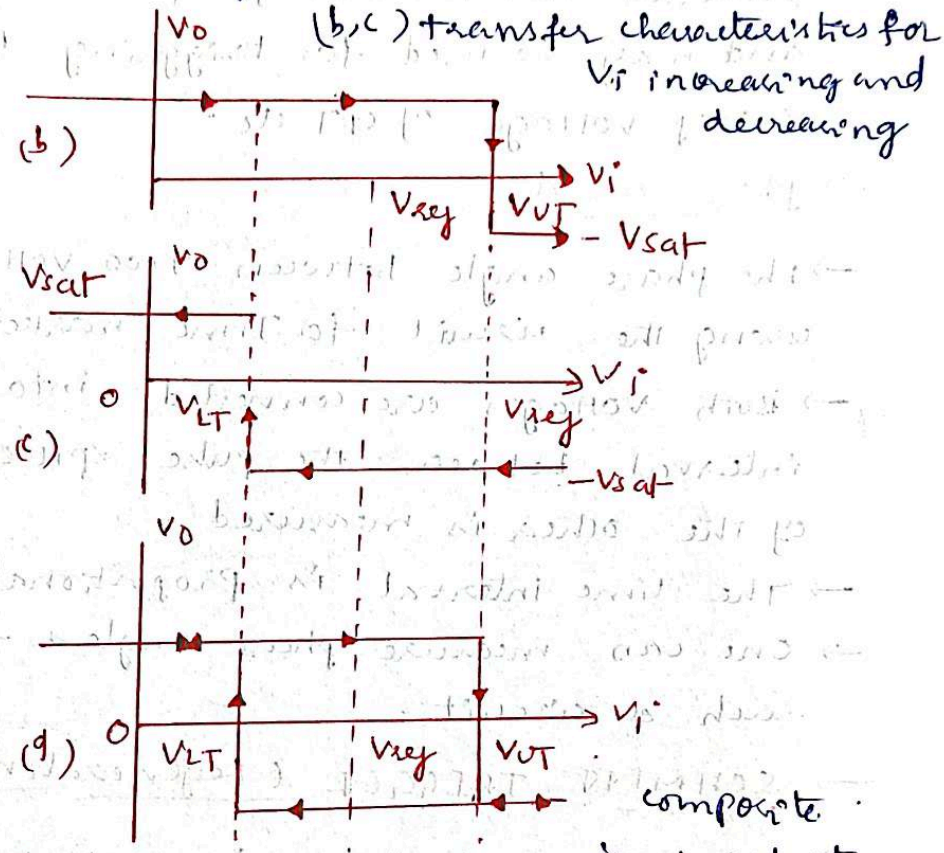
→ This circuit, however, now exhibits a phenomenon called hysteresis or backlash.

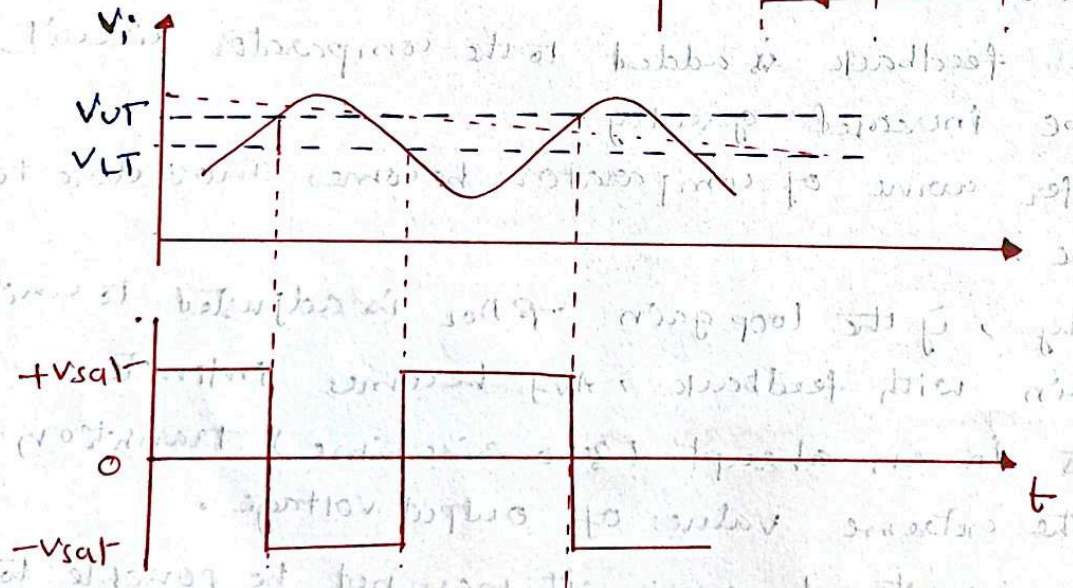
→ Fig-(a) shows such a regenerative comparator.



(a)

An inverting schmitter





(e) Schmitt trigger used as a squarer.

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→ The circuit is also known as schmitt trigger.
→ The input voltage is applied to the (−) input terminal and feedback voltage to the (+) input terminal.
→ The input voltage V_i triggers the output V_o everytime it exceeds certain voltage levels.
→ These voltage levels are called upper threshold voltage (V_{UT}) and lower threshold voltage (V_{LT}).
→ The hysteresis width is the difference between these two threshold voltages i.e, $V_{UT} - V_{LT}$.
→ These threshold voltages are calculated as follows.
→ Suppose the output $V_o = +V_{sat}$. The voltage at (+) input terminal will be

$$V_{ref} + \left(\frac{R_2}{R_1+R_2}\right)(V_{sat} - V_{ref}) = V_{UT}$$

→ This voltage is called upper threshold voltage V_{UT}.
→ As long as V_i is less than V_{UT}, the output V_o remains constant at $+V_{sat}$.
→ When V_i is just greater than V_{UT}, the output regeneratively switches to $-V_{sat}$ and remains at this level as long as $V_i > V_{UT}$ as shown in fig. (b)
For $V_o = -V_{sat}$, the voltage at the (+) input terminal is,

$$V_{ref} + \left(\frac{R_2}{R_1+R_2}\right)(-V_{sat} - V_{ref}) = V_{LT}$$

$$V_{ref} - \left(\frac{R_2}{R_1+R_2}\right)(V_{sat} + V_{ref}) = V_{LT}$$

→ This voltage is referred to as lower threshold voltage V_{LT}.
→ The input voltage V_i must become lesser than V_{LT} in order to cause V_o to switch from $-V_{sat}$ to $+V_{sat}$.
→ A regenerative transition takes place as shown in fig(c) and

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the output V_o returns from $-V_{sat}$ to V_{sat} almost instantaneously.

→ The complete transfer characteristics are shown in fig(d).

→ $V_{LT} < V_{UT}$ and the difference between these two voltages is the hysteresis width V_H and

$$V_H = V_{UT} - V_{LT} =$$

$$= V_{ref} + \left(\frac{R_2}{R_1+R_2}\right)(V_{sat} - V_{ref}) - \left[V_{ref} - \frac{R_2}{R_1+R_2}(V_{sat}+V_{ref})\right]$$

$$= \frac{2R_2}{R_1+R_2} V_{sat}.$$

→ Because of the hysteresis, the circuit triggers at a higher voltage for increasing signals than for decreasing ones.

→ Further, if peak-to-peak input signal v_i were smaller than V_H then the schmitt trigger circuit, having responded at a threshold voltage by a transition in one direction would never reset itself, that is, once the output has jumped to, say, $+V_{sat}$ it would remain at this level and never return to $-V_{sat}$.

→ The hysteresis width V_H is independent of V_{ref}.

→ The resistor R_3 in fig(a) is chosen equal to $R_1 \| R_2$ to compensate for the input bias current.

→ A non-inverting schmitt-trigger is obtained if v_i and V_{ref} are interchanged.

→ The most important application of schmitt trigger circuit is to convert a very slowly varying input voltage into a square wave output as shown in (e).

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→ If in the circuit, V_{ref} is chosen as zero volt, it follows that

$$V_{UT} = V_{ref} + \left(\frac{R_2}{R_1+R_2}\right)(V_{sat} + V_{ref})$$

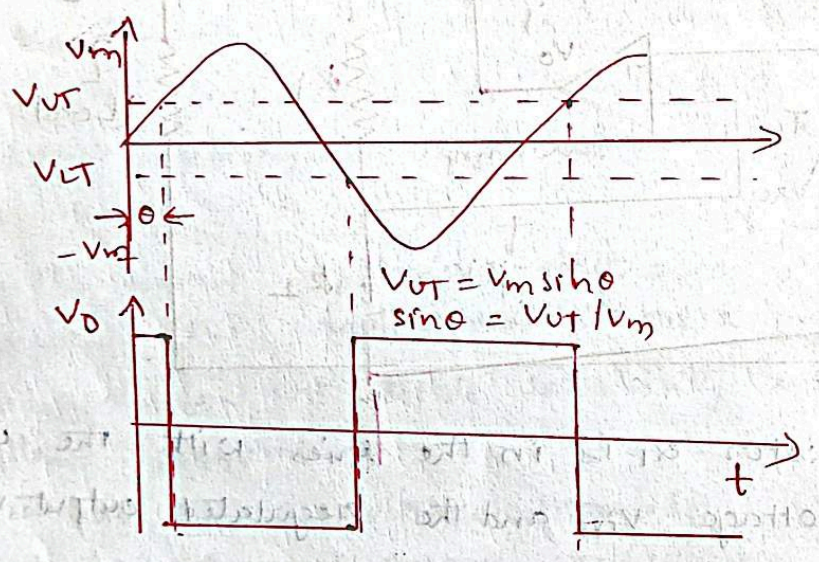
$$= 0 + \left(\frac{R_2}{R_1+R_2}\right)(V_{sat}+0) = \left(\frac{R_2}{R_1+R_2}\right)V_{sat}$$

$$V_{LT} = V_{ref} - \left(\frac{R_2}{R_1+R_2}\right)(V_{sat} + V_{ref})$$

$$= 0 - \left(\frac{R_2}{R_1+R_2}\right)(V_{sat}+0) = -\frac{R_2}{R_1+R_2}V_{sat}$$

$$\boxed{\therefore V_{UT} = -V_{LT} = \frac{R_2}{R_1+R_2}V_{sat}}$$

→



→ **Voltage Regulator :-**

→ The function of a voltage regulator is to provide a stable dc voltage for powering other electronic circuits.

→ A voltage regulator should be capable of providing substantial output current.

→ Voltage regulators are classified as series regulator and switching regulator.

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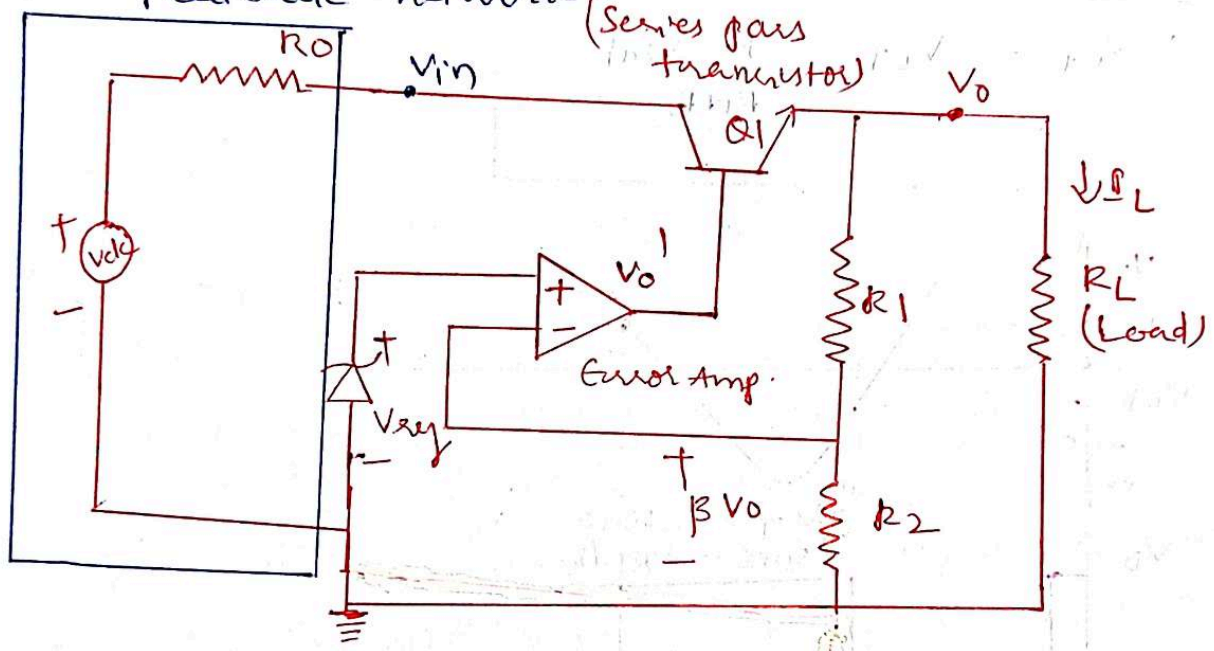
→ **Series op-amp regulator :-**

→ A voltage regulator is an electronic circuit that provides a stable dc voltage independent of the load current, temperature and ac line voltage variations.

→ The circuit consists of following four parts :

1. Reference voltage circuit
2. Error amplifier
3. series pass transistor
4. Feedback network



→ The power transistor Q_1 is in the series with the un-regulated dc voltage V_{in} and the regulated output voltage V_o

→ so it must absorb the difference between these two voltages whenever any fluctuation in output voltage V_o occurs

→ The transistor Q_1 is also connected as an emitter follower and therefore provides sufficient current gain to drive the load.

→ the output voltage is sampled by the R_1-R_2 divider and fed back to the (−) input terminal of the op-amp error amplifier.

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→ This sampled voltage is compared with the reference voltage V_{ref} (usually obtained by a Zener diode).

→ The output V_o' of the error amplifier drives the series transistor Q_1.

→ If the output voltage increases, due to variation in load current, the sampled voltage βV_o also increases where $\beta = \frac{R_2}{R_1+R_2}$.

→ This, in turn, reduces the output voltage V_o' of the diff-amp due to the 180° phase difference provided by the op-amp amplifier.

→ V_o' is applied to the base of Q_1, which is used as an emitter follower.

→ So V_o follows V_o', that is V_o also reduces.

→ Hence the increase in V_o is nullified. Similarly, reduction in output voltage also gets regulated.

→ **IC voltage regulator :-**

With the advent of micro-electronics, it is possible to incorporate the complete circuit on a monolithic silicon chip.

→ This gives low cost, high reliability, reduction in size and excellent performance.

→ Examples of monolithic regulators are 78xx | 79xx series and 723 general purpose regulators.

→ **Fixed voltage series regulator :-**

78xx series are three terminal, positive fixed voltage regulators.

→ There are seven output voltage options available such as 5, 6, 8, 12, 15, 18 and 24V.

→ In 78xx, the last two numbers (xx) indicate the output voltage.

→ Thus 7815 represents a 15V regulator.

→ There are also available 79xx series of fixed output, negative

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voltage regulators which are complements to the 78xx series devices.

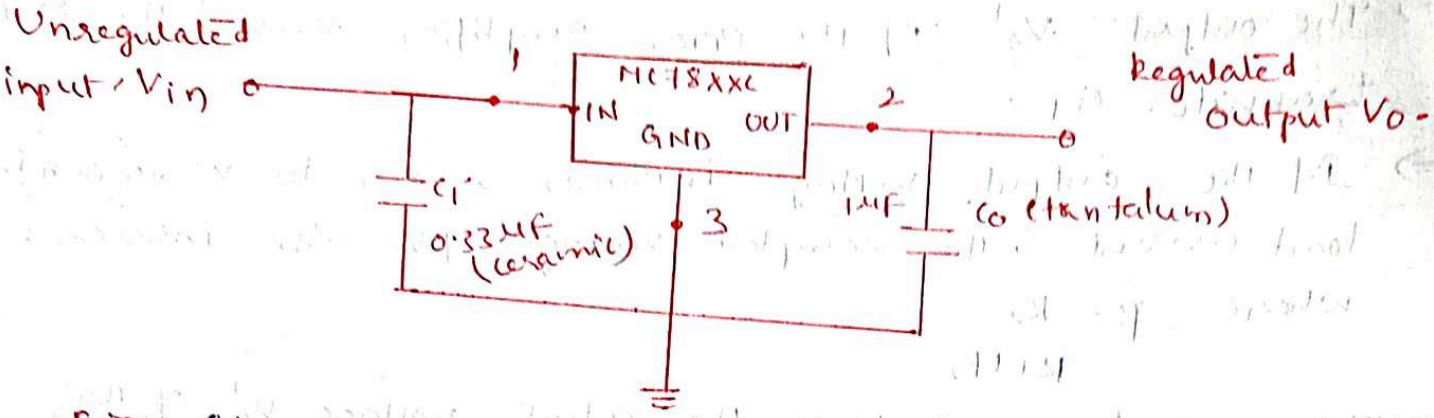

Fig: Standard representation of a three terminal positive monolithic regulator.

→ Characteristics:-

1. V_o: The regulated output voltage is fixed at a value as specified by the manufacturer.
   For 78xx series the output voltages are 5, 6, 8 etc.
2. $|V_{in}| \geq |V_o| + 2$ volts: The unregulated input voltage must be atleast 2V more than the regulated output voltage. For example, if $V_o = 5V$, then $V_{in} = 7V$.
3. $I_{o(max)}$: The load current may vary from 0 to rated maximum output current. The IC is usually provided with a heat sink, otherwise it may not provide the rated maximum output current.
4. Thermal shut down: The IC has a temperature sensor (built-in) which turns off the IC when it becomes too hot (usually 125°c to 150°c). The output current will drop and remain there until the IC has cooled significantly.

→ Performance parameters:-

Line / Input Regulation:- It is defined as the percentage change in the output voltage for a change in the input voltage. It is expressed in millivolts or as a percentage of the output voltage.

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→ Typical value of line regulation from the datasheet of 7805 is 3mV.

→ Load regulation:

→ It is defined as the change in output voltage for a change in load current and is also expressed in millivolts or as a percentage of V_o.

→ Typical value of load regulation for 7805 is 15mV for 5mA < I_o < 1.5A.

→ Ripple regulation:

→ The IC regulator not only keeps the output voltage constant but also reduces the amount of ripple voltage. Typical value for 7805 is 78 dB.

→ 723 General purpose Regulator:-

→ The limitations of three terminal regulators are

1. Not short circuit protection
2. Output voltage (positive or negative) is fixed.

→ These limitations have been overcome in the 723 general purpose regulator, which can be adjusted over a wide range of both positive or negative regulated voltage.

→ This IC is inherently low current device (150mA), but can be boosted to provide 5 amps or more current by connecting external components.

→ The limitation of 723 is that it has no in-built thermal protection.

→ 723 regulator IC has two separate sections.

→ The Zener diode, a constant current source and reference amplifier 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 the zener outputs a fixed voltage.

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→ The other section of the IC consists of an error amplifier, a series pass transistor Q_1 and a current limit transistor Q_2.

→ The error amplifier compares a sample of the output voltage applied at the 'INV' input terminal to the reference voltage V_{ref} applied at the 'NI' input terminal.

→ The error signal controls the conduction of Q_1.

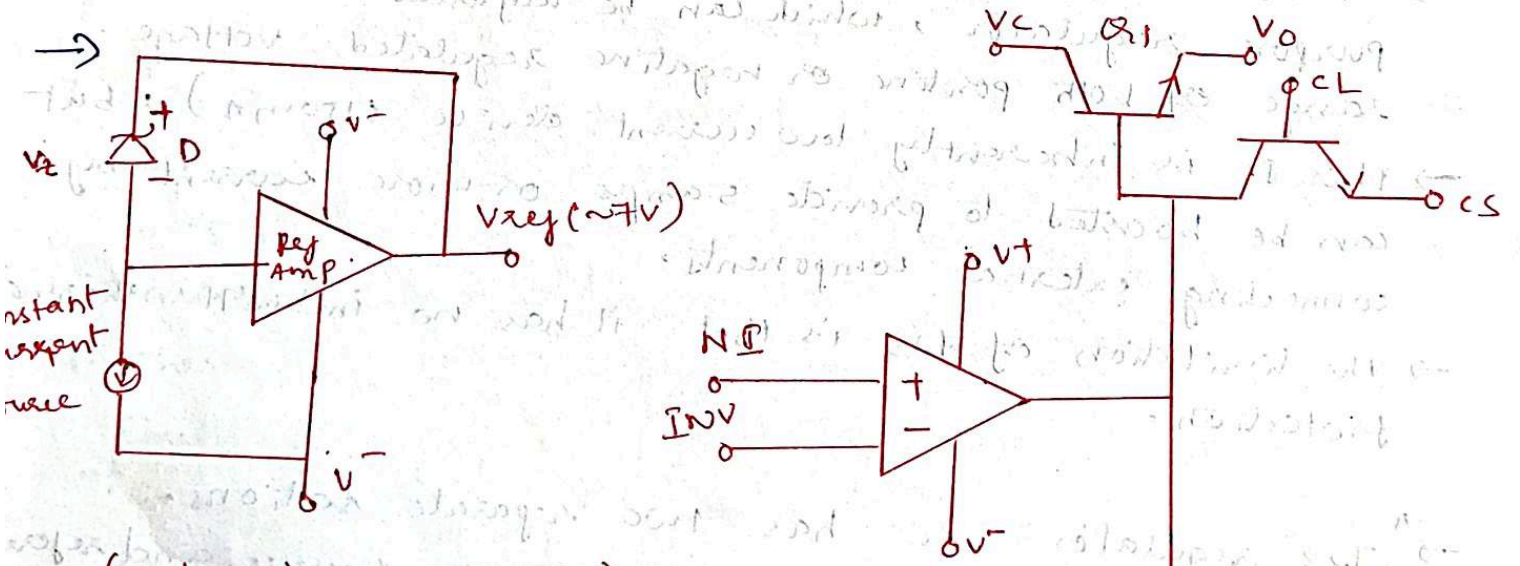
→ These two sections are not internally connected but the various points are brought out on the IC package.

→ 723 regulated IC is available in a 14-pin dual-in-line package or 10-pin metal can.

→ The important features are –

* Input voltage 40 V max
* output voltage adjustable from 2V to 37V
* 150 mA output current without external pass transistor.
* output currents in excess of 10A possible by adding external transistors.
* can be used as either a linear or a switching regulator.

→



(Section 1) (Section 2)

fig (a) Functional diagram of 723 regulator.

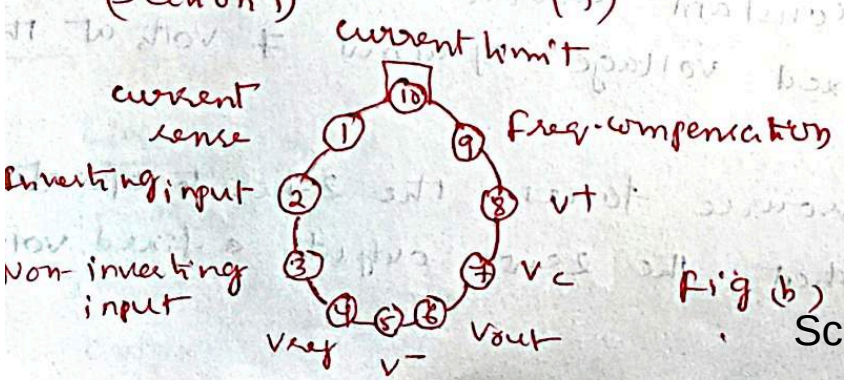


fig (b) 10-pin metal can

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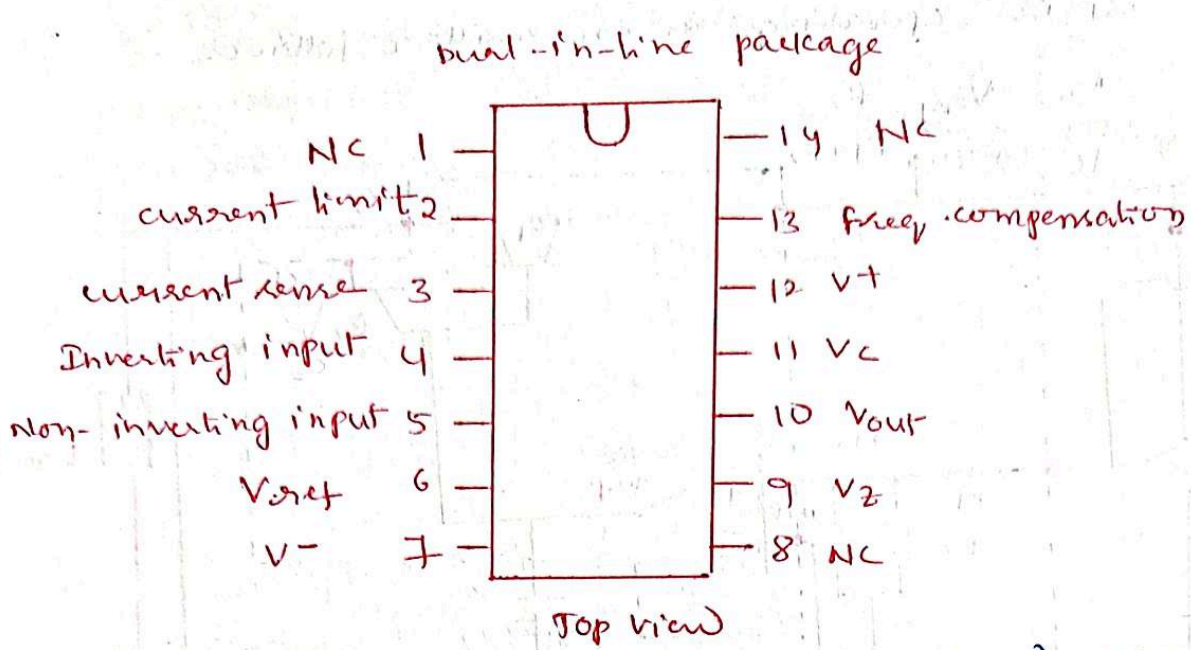

→ A simple positive low-voltage (2V to 7V) regulator can be made using 723 as shown in fig (c) below.

→ The detailed circuit is shown in (d).

→ The voltage at the NI terminal of the error amplifier due to R1R2 divider is, $V_{NI} = V_{ref} \frac{R_2}{R_1+R_2}$

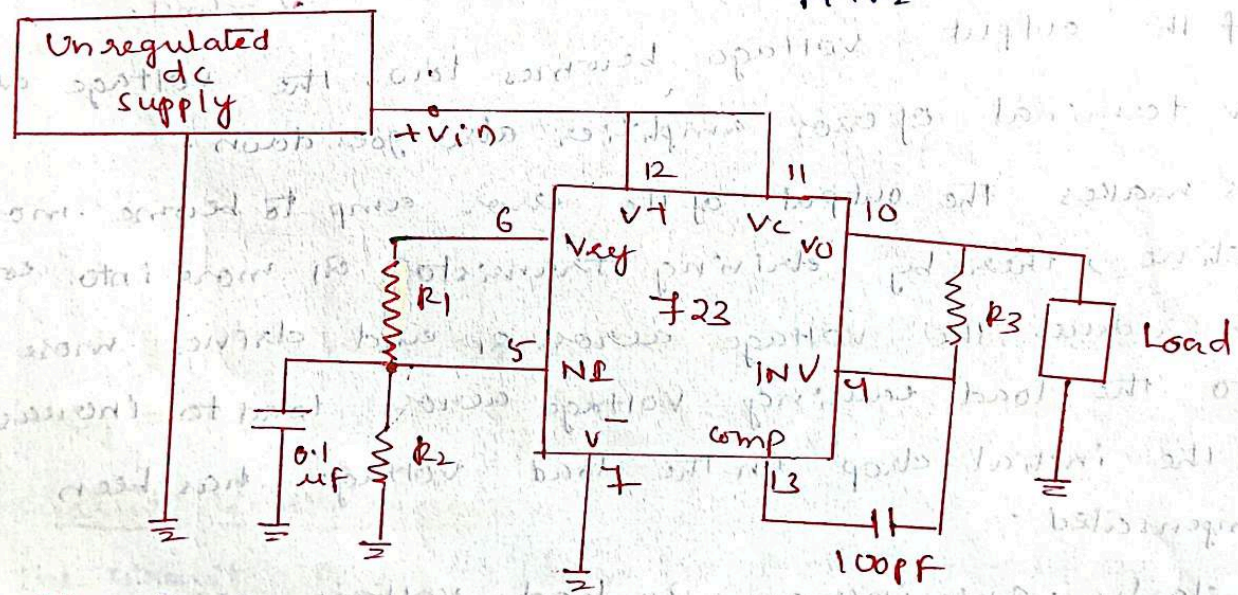

Fig (c) A low voltage regulator using 723 IC.

→ The difference between V_{NI} and the output voltage V_o which is directly fed back to the INV terminals is amplified by the error amplifier.

→ The output of the error amplifier drives the pass transistor Q_1 so as to minimize the difference between the NI and INV inputs of error amplifier.

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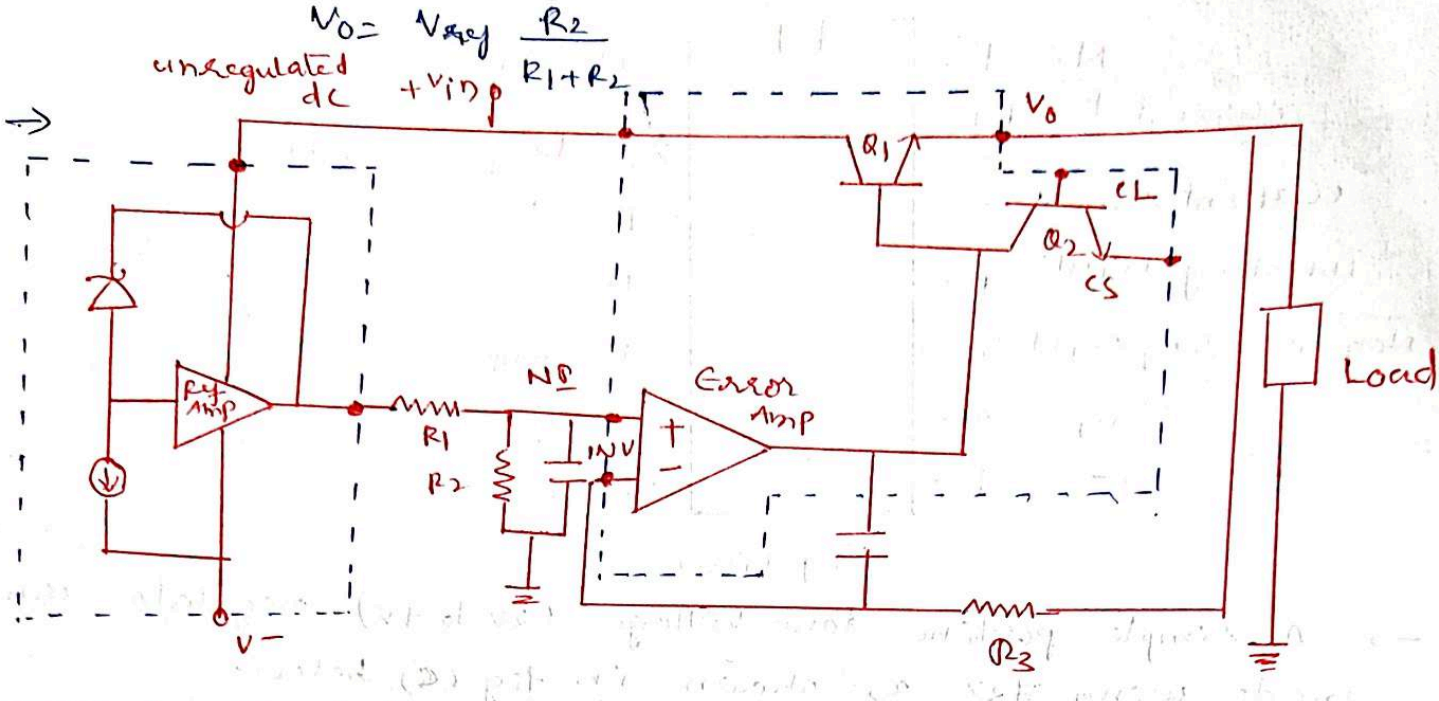
→ Since Q_1 is operating as an emitter follower

$$V_o = V_{reg} \frac{R_2}{R_1+R_2}$$



Fig(d) Functional diagram for a low voltage regulator.

$V_{reg} = 7V$, $V_o = V_{NI} = \frac{7R_2}{(R_1+R_2)}$, $V^+ = +V_{cc}$, $R_3 = R_1 \| R_2$

$V^- = \text{Gnd}$.

→ If the output voltage becomes low, the voltage at the INV terminal of error amplifier also goes down.

→ This makes the output of the error amp to become more positive, thereby driving transistor Q_1 more into conduction.

→ This reduces the voltage across Q_1 and drives more current into the load causing voltage across load to increase.

→ So the initial drop in the load voltage has been compensated.

→ Similarly, any increase in load voltage, or changes in the input voltage gets regulated.

→ The reference voltage is typically 7.15V. So, the output voltage V_o is $V_o = 7.15 \times \frac{R_2}{R_1+R_2}$

which will always be less than 7.15V. So, the circuit of fig (c) is used as low voltage (<7V) regulator.

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→ If it is desired to produce regulated output voltage greater than 7V, then the circuit fig.(e) is used.

→ The NI terminal is connected directly to V_{ref} through R_3.

→ so the voltage at the NI terminal is V_{ref}.

→ The error amplifier operates as a non-inverting amplifier with a voltage gain of $A_V = 1 + \frac{R_1}{R_2}$

so the output voltage for the circuit is

$$V_O = 7.15 \left[1 + \frac{R_1}{R_2}\right]$$

→

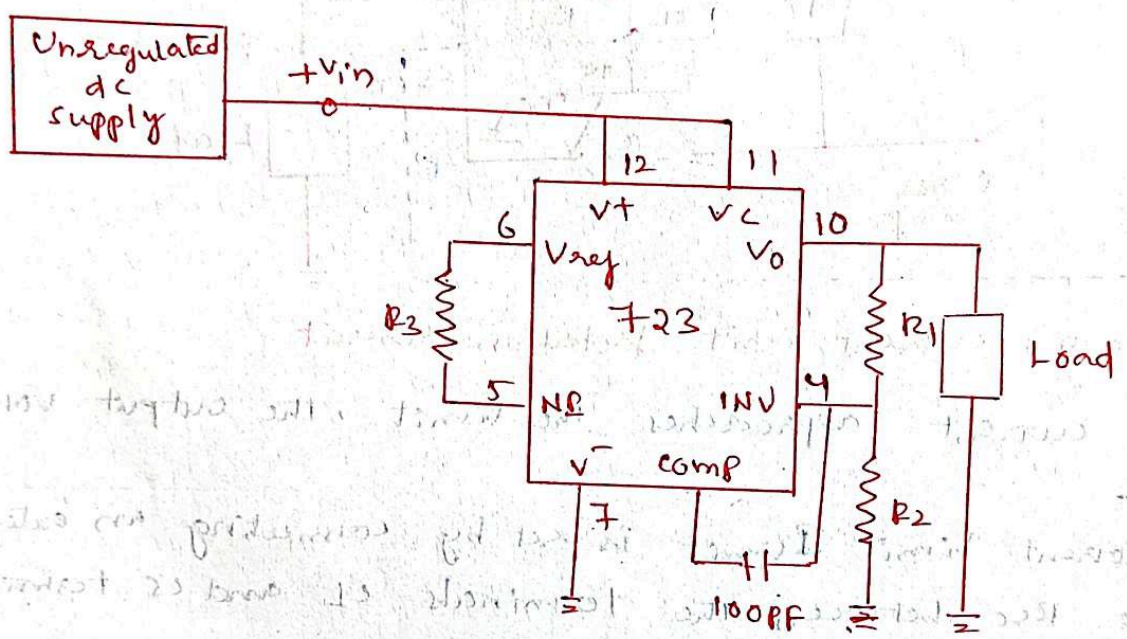

Fig.(e) Basic high voltage 723 regulator

$V_{ref} = 7V$, $V_o = 7(1 + \frac{R_1}{R_2})$, $R_3 = R_1 R_2$, $V^+ = +V_{cc}$, $V^- = Gnd$.

→ <u>current limit protection</u>:

→ The circuit of fig(c) have no protection. If the load demand more current e.g. under short circuit conditions, the IC tries to provide it at a constant output voltage getting hotter all the time. This may ultimately burn the IC.

→ The IC is, therefore, provided with a current limit facility.

→ current limiting refers to the ability of a regulator to prevent the load current from increasing above a present value.

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→ The characteristic curve of a current limited power supply is shown in fig (f).

→ The output voltage remains constant for load current below I_{limit}.

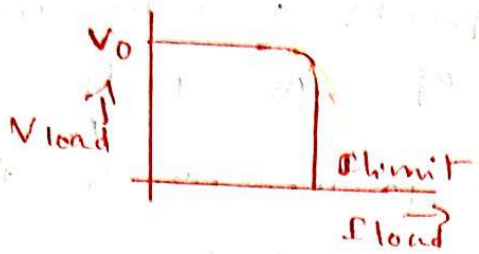

fig (f) characteristic curve for a current limited regulator.

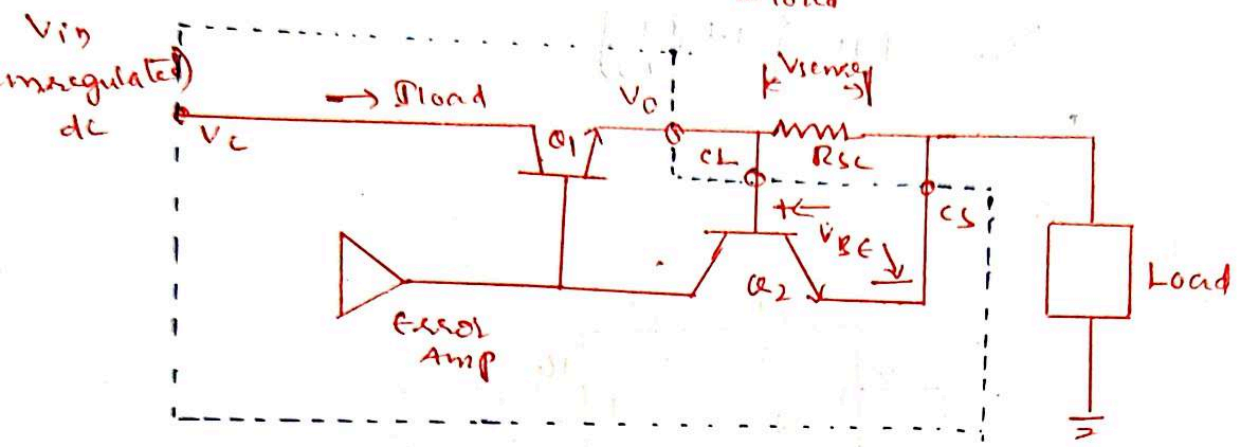

fig (g) current limit protection circuit

→ As the current approaches the limit, the output voltage drops.

→ The current limit I_{limit} is set by connecting an external resistor Rsc between the terminals CL and CS terminals as shown in fig (g).

→ The CL terminal is also connected to the output terminal V_o and CS terminal to the load.

→ The load current produces a small voltage drop V_{sense} across Rsc.

→ This voltage V_{sense} is applied directly across the base-emitter junction of Q_2.

→ When this voltage is approximately 0.5 volt, transistor Q_2 begins to turn ON.

→ Now a part of the current from error amplifier goes to the collector of Q_2, thereby decreasing the base current of Q_1.

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→ This in turn, reduces the emitter current of Q_1.

→ so, any increase in the load current will get nullified.

→ similarly, if the load current decreases, V_{BE} of Q_2 drops, repeating the cycle in such a manner that the load current is held constant to produce a voltage across R_{SC} sufficient to turn ON Q_2. This voltage is typically 0.5 V.

$$\text{so, } I_{limit} = \frac{V_{sense}}{R_{SC}} \approx \frac{0.5\,V}{R_{SC}}$$

→ This method of current limiting is also referred to as current sensing technique.

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