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CMR Institute of Technology, Bengaluru
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Solutons of Internal Assesment Test – III
Subject: OPERATIONAL AMPLIFIERS AND LINEAR ICS (18EE46)
Semester: 4A

1. Design a non-inverting Schmitt trigger to have UTP= +3 V and LTP=-5 V. Use op-amp 741 with supply voltage of 15V.

Explain the working of non-inverting Zero Crossing Detector (ZCD)

Solution:

Solution : The circuit is shown in the Fig. 5.6.7.

UTP = 3 V, LTP = –5 V

The current I_2 through R_1 must be much higher than $I_{B(max)}$.

$$\therefore \quad I_2 = 500\ \mu A$$

$$R_2 = \frac{|V_{UT}|}{I_2} = \frac{3}{500\times 10^{-6}}$$

$$= 6\ k\Omega \text{ (Use } \mathbf{5.6\ k\Omega}\text{)}$$

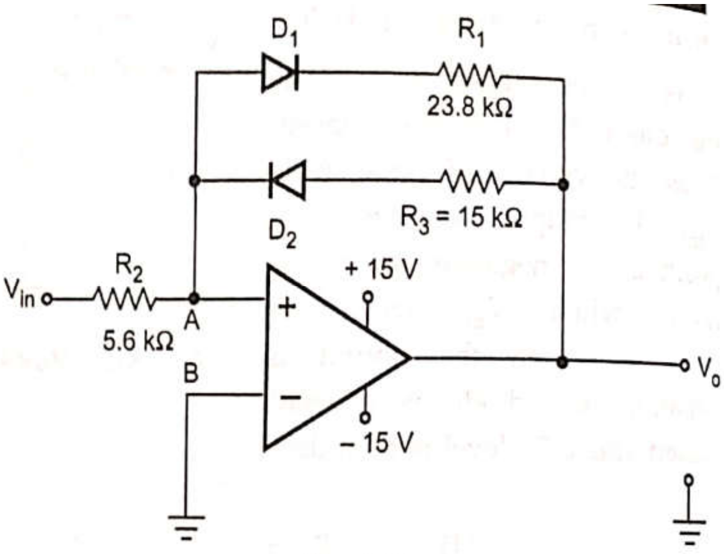


Fig. 5.6.7

For $V_{CC} = \pm 15$ V, output swings between ± 13.5 V

$$\therefore \quad UTP = \frac{|V_o|-V_F}{R_1}\times R_2 \quad \text{i.e.} \quad 3 = \frac{13.5-0.7}{R_1}\times 5.6\times 10^3$$

$$\therefore \quad R_1 = 23.89\ k\Omega \text{ (Use } \mathbf{22\ k\Omega} \text{ and } \mathbf{1.8\ k\Omega} \text{ in series)}$$

For LTP design, $R_2 = 5.6\ k\Omega$ remains same.

$$I_3 = \text{Current through } R_3 = \frac{|V_{LT}|}{R_2} = \frac{5}{5.6\times 10^3} = 0.8928\ mA$$

$$\therefore \quad R_3 = \frac{|V_o|-V_F}{I_3} = \frac{13.5-0.7}{0.8928\times 10^{-3}} = 14.33\ k\Omega \text{ (Use } \mathbf{15\ k\Omega}\text{) PIV of diodes} > \mathbf{15\ V}$$

Mon-inverting Zero Crossing Detector (ZCD):

In a Non-inverting zero crossing detector, the op-amp is used in open loop mode. Inverting terminal of the op-amp is grounded and input is applied to the non-inverting terminal. The circuit is shown in the Fig. 5.3.1.

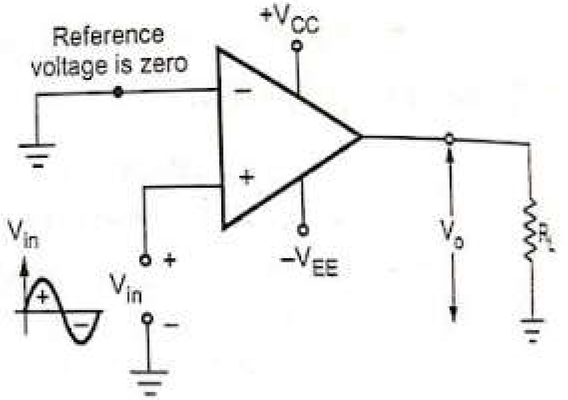
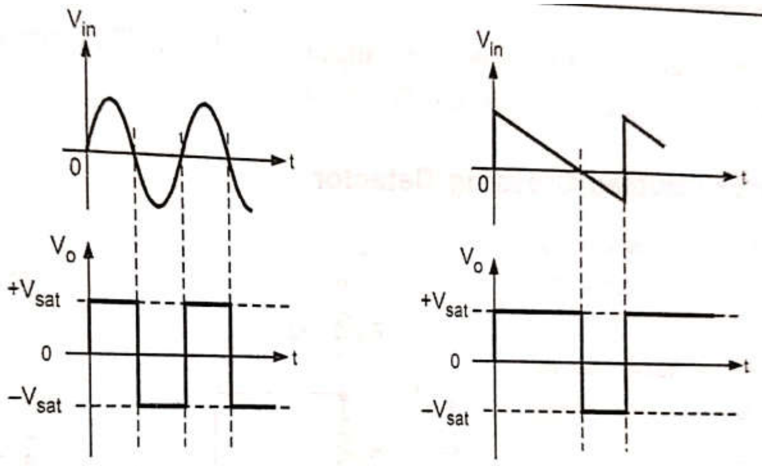


Fig. 5.3.1 Non-inverting zero crossing detector

During the positive half cycle, the input voltage is positive i.e. above the reference voltage. Hence the output voltage is $+V_{sat}$. During negative half cycle, the input voltage V_{in} is negative, i.e. below the reference voltage. The output voltage is then $-V_{sat}$. Thus the output voltage switches between $+V_{sat}$ and $-V_{sat}$ whenever the input signal crosses the zero level. This is illustrated in Fig. 5.3.2.



(a) Input is sinusoidal

(b) Input is triangular

Fig. 5.3.2 Waveforms of non-inverting zero crossing detector

Key Point *From the waveforms of non-inverting zero crossing detector it can be seen that the circuit can be used as a square wave generator.*

2. With a neat circuit diagram and waveforms, explain the operation of inverting Schmitt trigger with different UTP and LTP. Draw its transfer characteristics and hysteresis curve.

Solution:

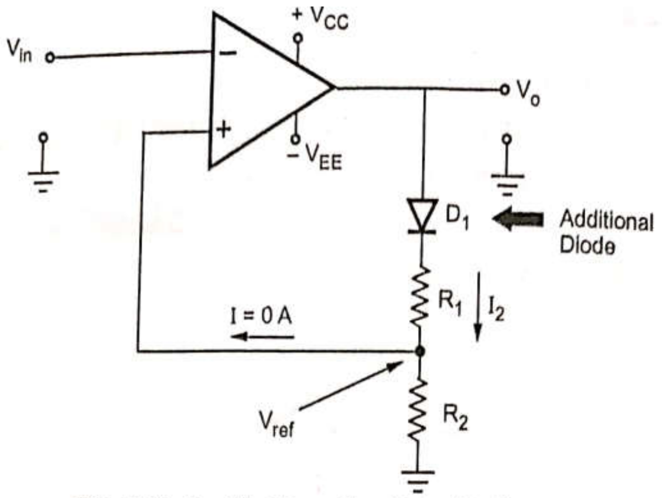


Fig. 5.6.1 Modified inverting Schmitt trigger

When the output is negative saturation voltage ($-V_{sat}$), the diode D_1 is reverse biased and current I_2 is almost zero. Thus the drop across R_2 which decides V_{ref} is zero. This gives,

$$V_{LT} = LTP = 0\ V$$

When the output is positive saturation voltage ($+V_{sat}$), the diode D_1 is forward biased.

Then the drop across R_2 due to I_2 decides the V_{ref} i.e. UTP level of the circuit.

Let V_F = The drop across forward biased diode ≈ 0.7 V.

$$I_2 = \frac{V_0 - V_F}{R_1 + R_2}$$

$$\therefore \quad \boxed{UTP = V_{UT} = \frac{|V_0| - V_F}{R_1 + R_2} \times R_2} \quad \text{Where } V_o = +V_{sat}$$

The diode D_1 must have peak inverse voltage rating more than the supply voltage.

PIV of D_1 > Supply voltage

The maximum reverse recovery time (t_{rr}) of the diode must be very much smaller than the minimum pulse width of the input signal.

$$\therefore \quad \boxed{t_{rr} \leq \frac{\text{Minimum pulse width}}{10}}$$

Key Point *By reversing the direction of the diode D_1, any negative level of LTP with zero UTP level can be achieved.*

By using two diodes, in series with two different resistances, two different UTP and LTP levels can be achieved. This is shown in the Fig. 5.6.2.

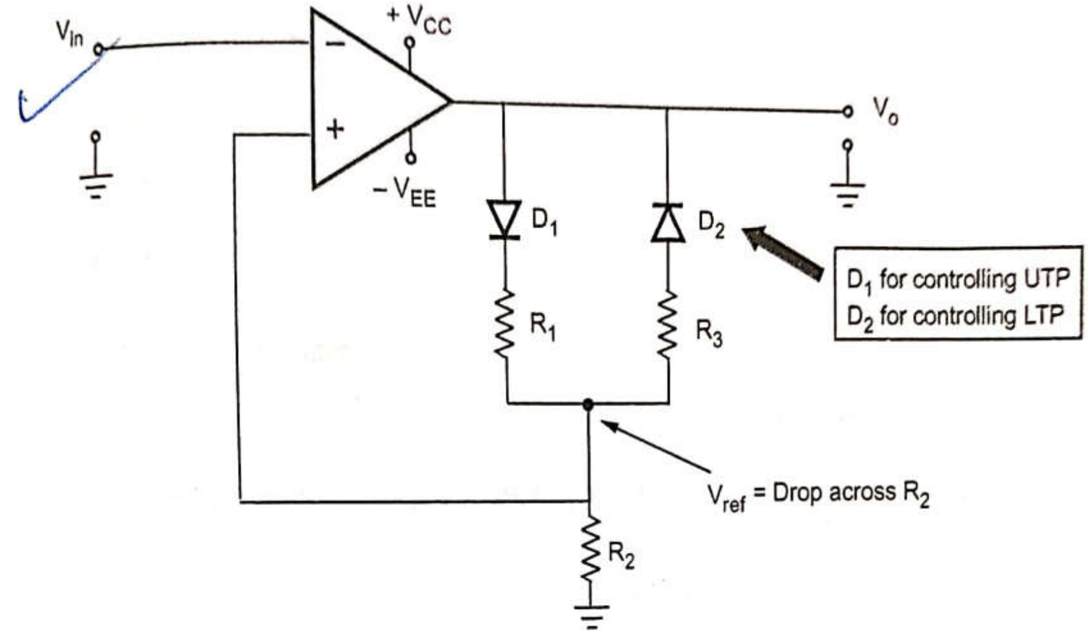


Fig. 5.6.2 Achieving different UTP and LTP levels in an inverting Schmitt trigger

When the output is positive , D_1 is forward biased and drop across R_2 decides UTP levels.

$$\boxed{\text{UTP} = \frac{|V_o| - V_F}{R_1 + R_2} \times R_2}$$

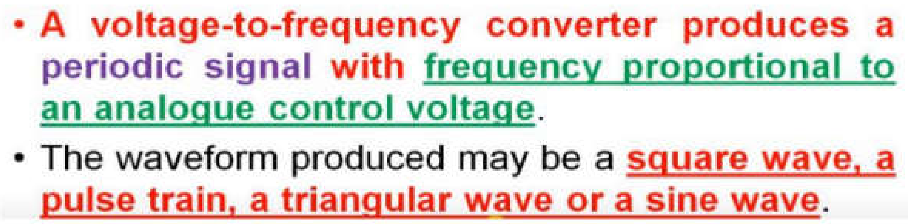
When the output is negative , D_2 is forward biased and drop across R_2 decides LTP levels,

$$\boxed{\text{LTP} = \frac{|V_o| - V_F}{R_2 + R_3} \times R_2}$$

By varying the values of R_1 and R_3 , any desired UTP and LTP levels can be achieved.

3. Write short notes on the following:
Voltage to frequency converter.
Voltage to current (V/I) converter with grounded load.

Solution:
Voltage to frequency converter.



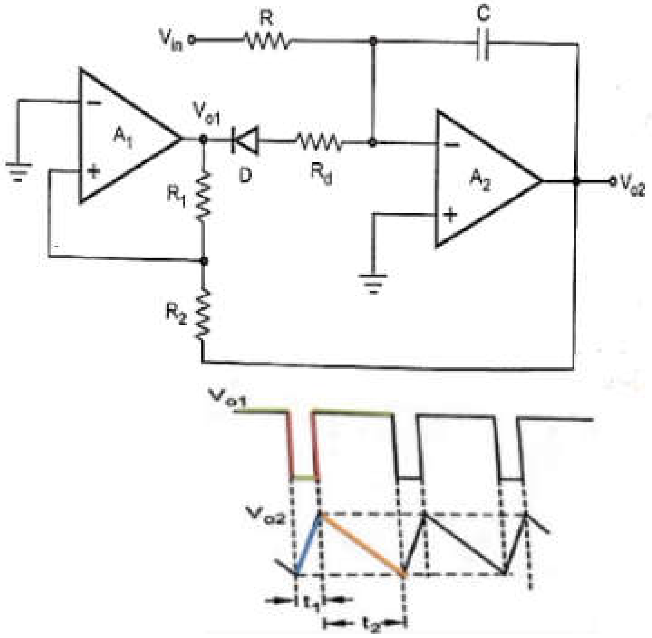
- A voltage-to-frequency converter produces a periodic signal with frequency proportional to an analogue control voltage.
- The waveform produced may be a square wave, a pulse train, a triangular wave or a sine wave.

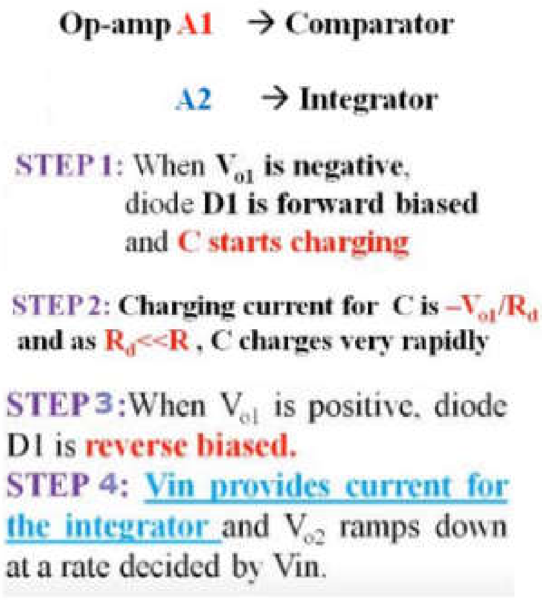
V-F Converter accepts an analog input Vin and generates a pulse train with frequency f

Mathematically expressed as:

f=kVin

Where **k**= sensitivity of V-F Converter is Hz/V





Op-amp A1 → Comparator

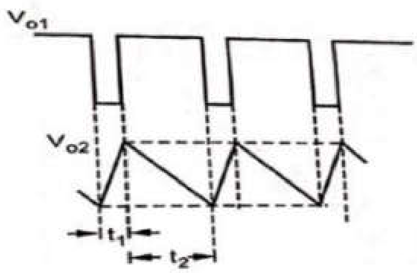
A2 → Integrator

STEP 1: When V_{o1} is negative, diode D1 is forward biased and C starts charging

STEP 2: Charging current for C is $-V_{o1}/R_d$ and as $R_d << R$, C charges very rapidly

STEP 3: When V_{o1} is positive, diode D1 is reverse biased.

STEP 4: Vin provides current for the integrator and V_{o2} ramps down at a rate decided by Vin.



Time period t_1 is less than t_2

Output frequency is decided by t_2 i.e Vin

Hence it acts like a frequency to Voltage converter.

The frequency of oscillation is given by:

$$\boxed{f = \frac{R_1}{2R_2RC\,V_{sat}}\,V_{in} = k\,V_{in}}$$

- V-F CONVERTERS
  - Wide SweepMultivibrator
  - Charge Balancing

Voltage to current (V/I) converter with grounded load

When one of end of the load is grounded, it is no longer possible to place the load within feedback loop of the op-amp.

Fig. 5.7.2 shows a voltage to current converter in which one end of load resistor R_L is grounded. It is also known as 'Howland Current Converter' from the name of its inventor.

The analysis of the circuit is accomplished by first determining the voltage V_1 at the noninverting input terminal and then establishing the relationship between V_1 and the load current.

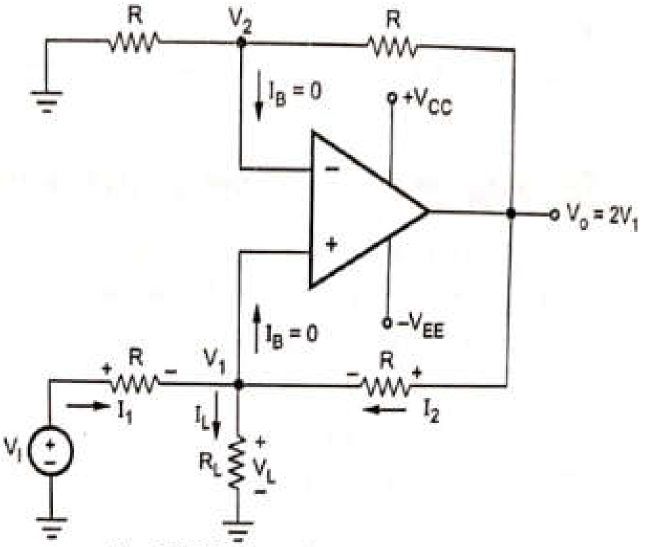


Fig. 5.7.2 Voltage to current converter with grounded load

Applying KCL at node V_1 we get,

$$I_1 + I_2 = I_L \quad \text{i.e.} \quad \frac{V_i - V_1}{R} + \frac{V_o - V_1}{R} = I_L$$

$$V_i + V_o - 2V_1 = I_L R \quad \text{i.e.} \quad V_1 = \frac{V_i + V_o - I_L R}{2} \qquad \dots (5.7.3)$$

The gain of op-amp in noninverting mode is given as $A = 1 + R_f/R_1$. For this circuit it is $1 + R/R = 2$. Hence, output voltage can be written as

$$V_o = 2V_1 = V_i + V_o - I_L R \quad \text{... (5.7.4)}$$

$$0 = V_i - I_L R \quad \text{i.e.} \quad V_i = I_L R$$

$$\therefore \quad \boxed{I_L = \frac{V_i}{R}} \quad \text{... (5.7.5)}$$

From the above equation we can say that the load current depends on the input voltage V_i and resistor R.

If R is constant, then $I_L \propto V_i$. If R is a precision resistor, then the output current will be precisely fixed.

4. With circuit and relevant waveform, explain the working of RC phase shift oscillator. Design a RC phase shift Oscillator using Op-amp. Assume C=0.1 μF, frequency of oscillation=200 Hz. Use the supply voltage as 15V.

Solution:

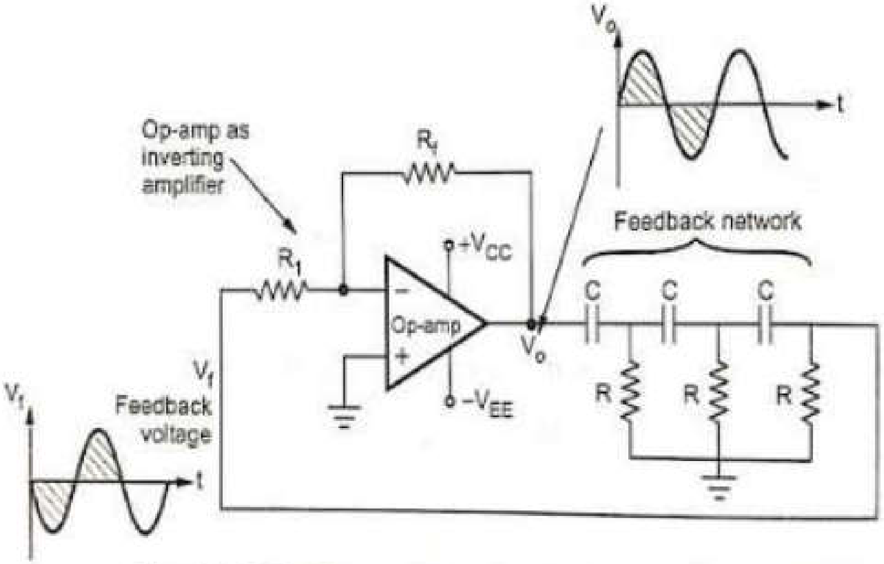


Fig. 4.6.3 R-C Phase shift oscillator using op-amp

R-C phase shift oscillator using op-amp uses op-amp in inverting amplifier mode. Thus it introduces the phase shift of 180° between input and output. The feedback network consists of 3 RC sections each producing 60° phase shift. Such a RC phase shift oscillator using op-amp is shown in the Fig. 4.6.3.

The output of amplifier is given to feedback network. The output of feedback network drives the amplifier. The total phase shift around a loop is 180° of amplifier and 180° due to 3 RC section, thus 360°. This satisfies the required condition for positive feedback and circuit works as an oscillator.

The frequency of sustained oscillations generated depends on the values of R and C and is given by,

$$\boxed{f = \frac{1}{2\pi\sqrt{6}\,RC}}$$ ... The frequency is measured in Hz.

At this frequency the gain of the op-amp must be atleast 29 to satisfy $A\beta = 1$.

Now gain of the op-amp inverting amplifier is given by,

$$\boxed{|A| \geq \frac{R_f}{R_1} \geq 29 \text{ for oscillations} \quad \text{i.e. } R_f \geq 29\,R_1}$$

Thus circuit will work as an oscillator which will produce a sinusoidal waveform if gain is 29 and total phase shift around a loop is 360°. This satisfies the Barkhausen criterion for the oscillator. These oscillators are used over the audio frequency range i.e. about 20 Hz upto 100 kHz.

Let $C = 0.1\ \mu F$. Then, from Equation (7–22a),

$$R = \frac{0.065}{(200)(10^{-7})} = 3.25\ \text{k}\Omega$$

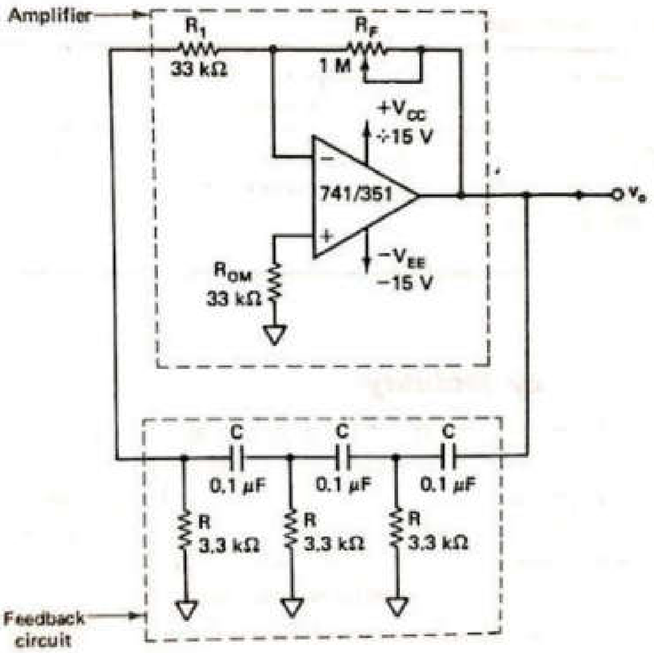
(Use $R = 3.3\ \text{k}\Omega$.) .

To prevent the loading of the amplifier because of RC networks, it is necessary that $R_1 \geq 10\,R$. Therefore, let $R_1 = 10R = 33\ \text{k}\Omega$. Then, from Equation (7–22b)

$$R_F = 29(33\ \text{k}\Omega) = 957\ \text{k}\Omega$$

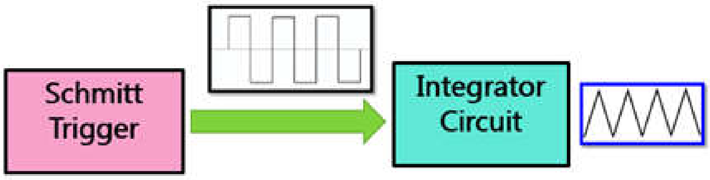
(Use R_F = 1-MΩ potentiometer.)

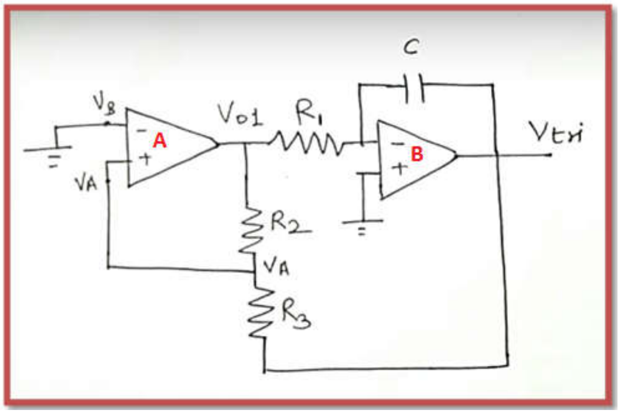
When choosing an op-amp, type 741 can be used at lower frequencies (<1 kHz); however, at higher frequencies, an op-amp such as the LM318 or LF351 is recommended because of its increased slew rate.

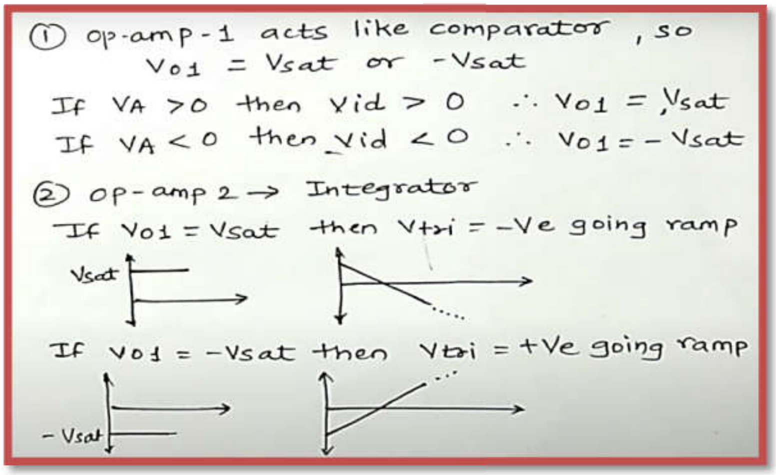


5. Draw and explain triangular wave generator using square wave generator and integrator method. Draw the required waveform.

Answer: It consists of a Schmitt trigger (A) and an integrator (B). The output of Schmitt trigger is a square wave of amplitude ± V_{sat} and is applied to the inverting (-) input terminal of the integrator. The output of integrator is a triangular wave and it is feedback as input to the Schmitt trigger, through a voltage divider R_2 and R_3. The circuit acts as free running waveform generator producing triangular and rectangular output waveforms simultaneously.







① op-amp-1 acts like comparator, so
$V_{o1} = V_{sat}$ or $-V_{sat}$
If $V_A > 0$ then $V_{id} > 0$ ∴ $V_{o1} = V_{sat}$
If $V_A < 0$ then $V_{id} < 0$ ∴ $V_{o1} = -V_{sat}$

② op-amp 2 → Integrator
If $V_{o1} = V_{sat}$ then V_{tri} = -Ve going ramp

If $V_{o1} = -V_{sat}$ then V_{tri} = +Ve going ramp

Case 1: To understand circuit operation, assume that the output of Schmitt trigger A (i.e V_{01}) is at $+V_{sat}$. This forces a constant current ($+V_{sat} / R_1$) through *C* to give a negative going ramp at the output of the integrator.

Case 2: Assume that the output of Schmitt trigger A (i.e V_{01}) is at $-V_{sat}$. This forces a reverse constant current (right to left) through *C*. Therefore, *C* discharges and recharges in the opposite direction. This produces a positive going ramp at the output of the integrator, as shown in the following Fig. The sequence then repeats to give triangular wave at the output of integrator B. The output waveform is shown below:

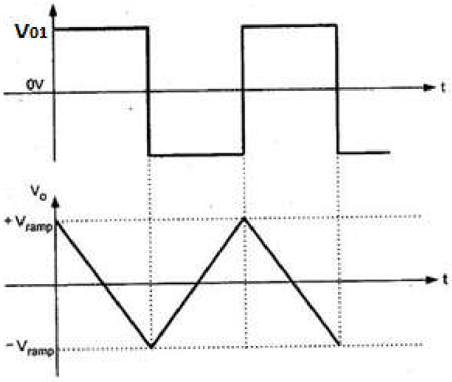
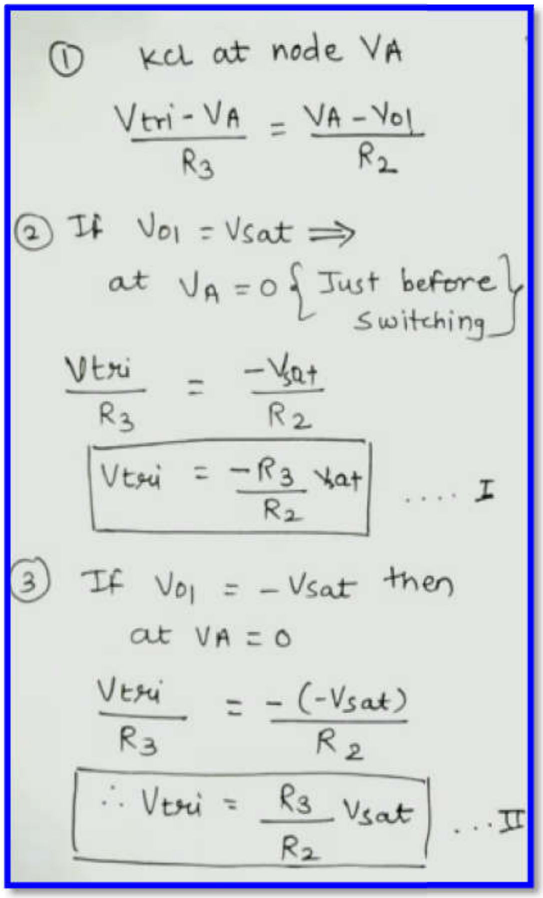


Fig: Output waveform

Peak-to-peak amplitude of triangular wave:



① KCL at node VA

$$\frac{V_{tri}-V_A}{R_3} = \frac{V_A - V_{o1}}{R_2}$$

② If $V_{o1} = V_{sat} \Rightarrow$

at $V_A = 0$ $\left\{\text{Just before switching}\right\}$

$$\frac{V_{tri}}{R_3} = \frac{-V_{sat}}{R_2}$$

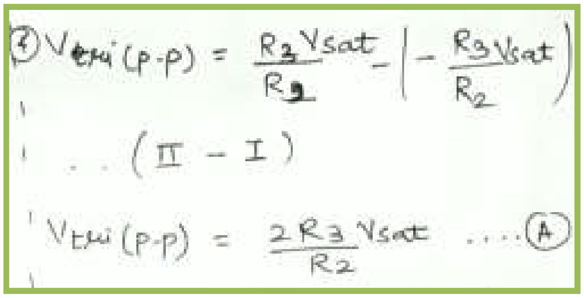
$$\boxed{V_{tri} = \frac{-R_3}{R_2}V_{sat}} \quad \ldots\ I$$

③ If $V_{o1} = -V_{sat}$ then

at $V_A = 0$

$$\frac{V_{tri}}{R_3} = -\frac{(-V_{sat})}{R_2}$$

$$\boxed{\therefore V_{tri} = \frac{R_3}{R_2}V_{sat}} \quad \ldots\ II$$

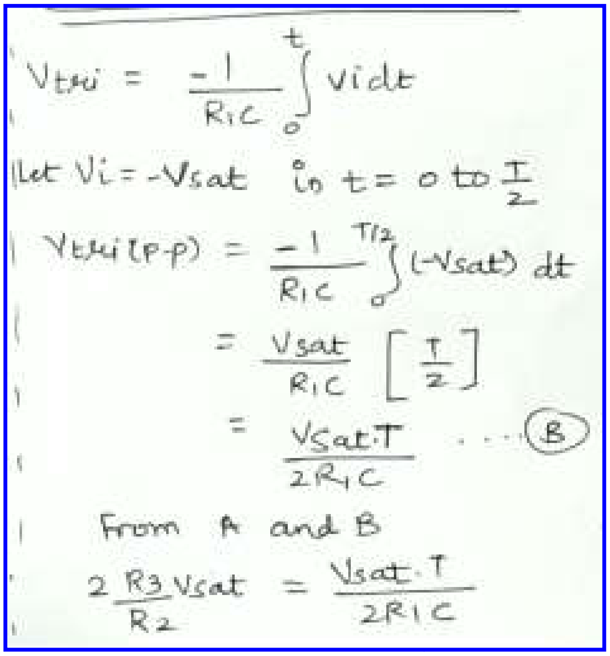


④ $V_{tri}(p\text{-}p) = \frac{R_3 V_{sat}}{R_2} - \left(-\frac{R_3 V_{sat}}{R_2}\right)$

$\ldots (II - I)$

$V_{tri}(p\text{-}p) = \frac{2R_3 V_{sat}}{R_2} \quad \ldots$ (A)

Frequency Calculation:



$$V_{tri} = \frac{-1}{R_1C}\int_0^t v_i\,dt$$

Let $V_i = -V_{sat}$ in $t = 0$ to $\frac{T}{2}$

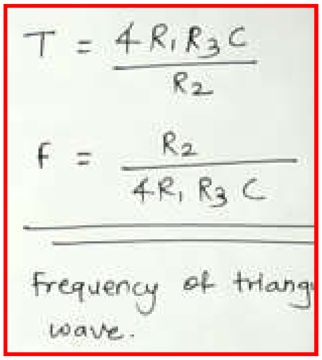
$$V_{tri}(p\text{-}p) = \frac{-1}{R_1C}\int_0^{T/2}(-V_{sat})\,dt$$

$$= \frac{V_{sat}}{R_1C}\left[\frac{T}{2}\right]$$

$$= \frac{V_{sat}T}{2R_1C} \quad \ldots\ (B)$$

From A and B

$$\frac{2R_3V_{sat}}{R_2} = \frac{V_{sat}\cdot T}{2R_1C}$$



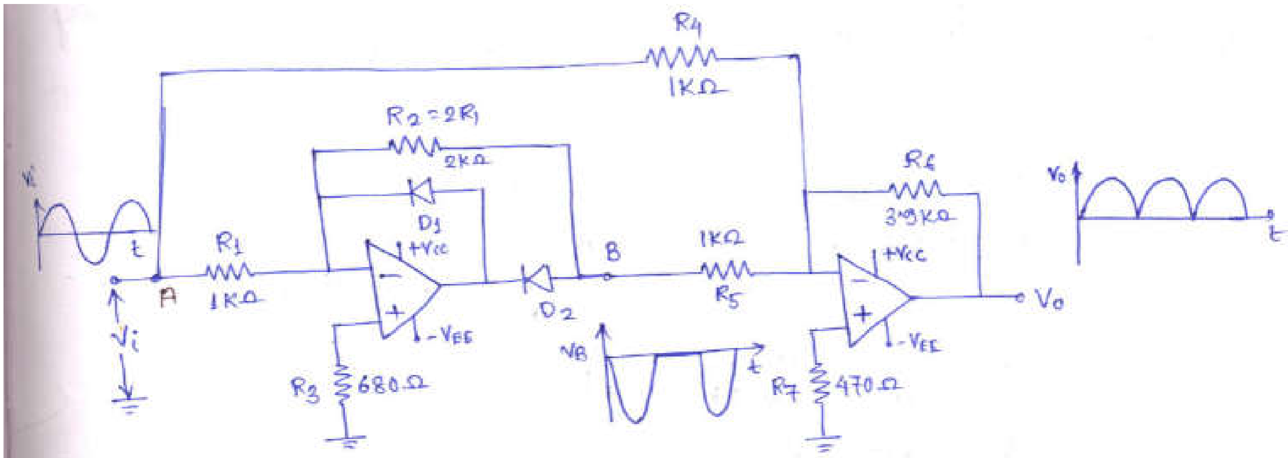
$$T = \frac{4R_1R_3C}{R_2}$$

$$f = \frac{R_2}{4R_1R_3C}$$

Frequency of triang
wave.

6. Explain the working of precision full wave rectifier with necessary circuit diagram and write the difference between ordinary rectifier and precision rectifier.

Solution:



The above circuit is a combination of half-wave rectifier with gain=2 and an inverting adder with gain=3.9

During +ve half-cycle

voltage at terminal A = +Vi

while that at terminal B is −2Vi.

[Diode D_1 is off and D_2 is on]

~~During~~ The output of the summing circuit, with $R_4 = R_5$

$$V_o = -\frac{R_6}{R_4}(V_A + V_B)$$

$$= -\frac{R_6}{R_4}(V_i - 2V_i)$$

$$= -\frac{R_6}{R_4}(-V_i) = \frac{R_6}{R_4}V_i$$

During −ve half-cycle

$V_A = -V_i$

$V_B = 0$ as D_1 is on and D_2 is off.

consequently the output is,

$$V_o = -\frac{R_6}{R_4}(V_A + V_B) = -\frac{R_6}{R_4}(-V_i + 0)$$

$$\boxed{V_o = +\frac{R_6}{R_4}V_i}$$

So, it can be seen that the output voltage is positive for both the cycle of the input voltage. If $R_6 = R_4 = R_5$ then the gain of the circuit is 1. when R_6 is greater than R_4 then rectification and amplification both occurs.

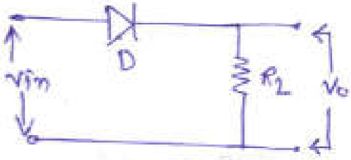
Precision Rectifiers

The figure shows a half wave rectifier using diode (which is not ideal).

The disadvantages of the circuits are -

(i) Cann't rectify voltage below 0·7 volt.

(ii) No amplification.



Half wave rectifier.

Precision rectifier provides solution to these drawbacks -

(i) No diode voltage drop b/w input and output.

(ii) Ability to rectify very small voltages (typically below 0·7 V)

(iii) Amplification if required.

(iv) Low output impedance.

7. Explain the working of R-2R ladder DAC. Assume that binary input is 001.

In this type, reference voltage is applied to one of the switch positions, and other switch position is connected to ground, as shown in the Fig. 7.3.4.

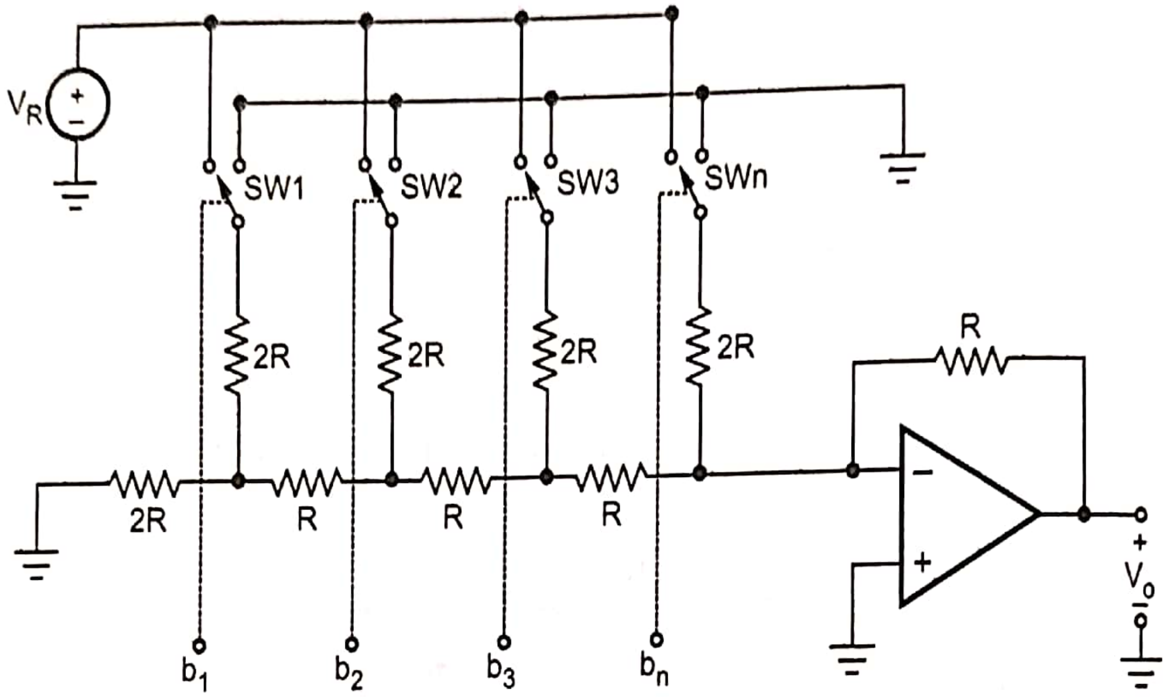


Fig. 7.3.4 R/2R ladder D/A converter

Let us consider 3-bit R/2R ladder DAC with binary input 001, as shown in the Fig. 7.3.5.

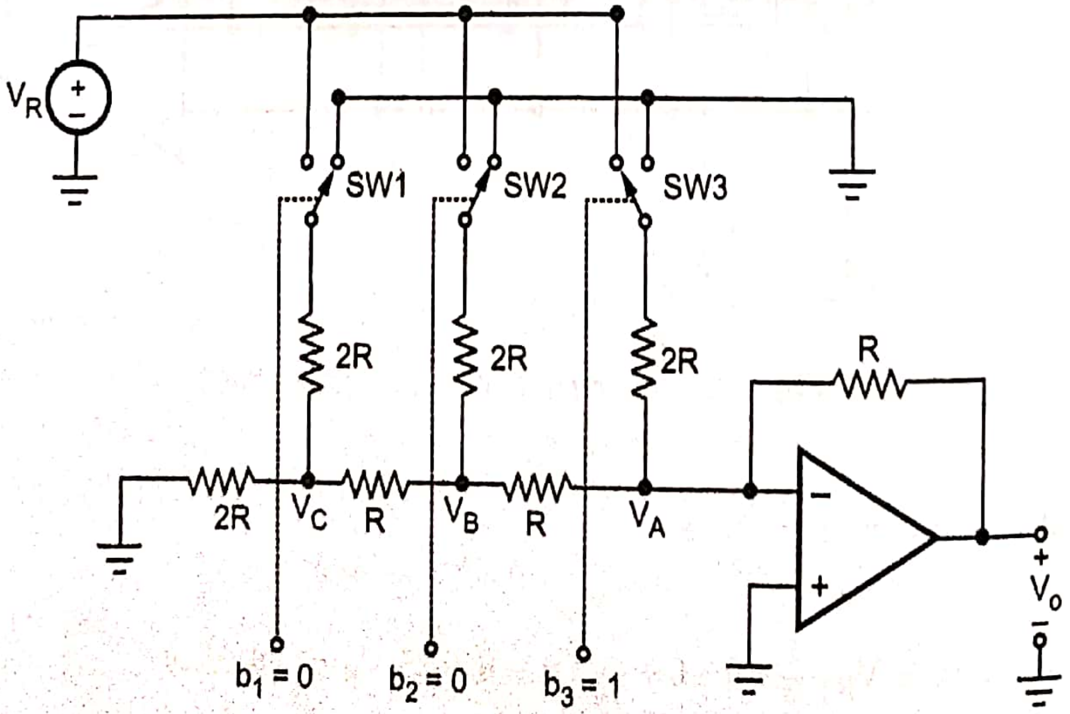


Fig. 7.3.5 3-bit R/2R ladder DAC

Reducing above network to the left by Thevenin's theorem we get,

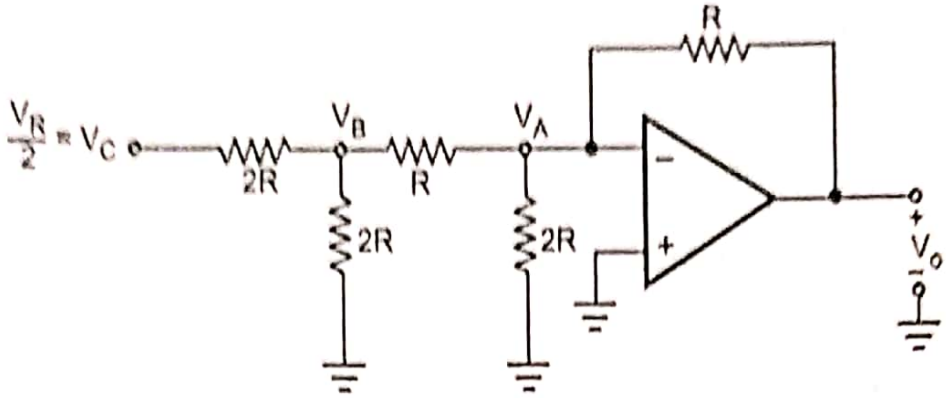


Fig. 7.3.6 (a)

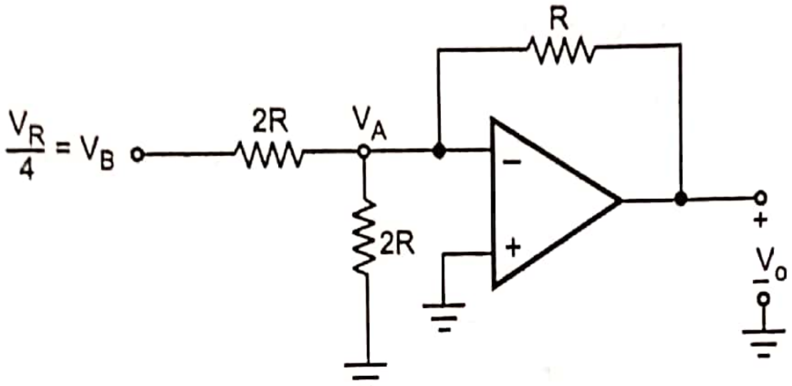


Fig. 7.3.6 (b)

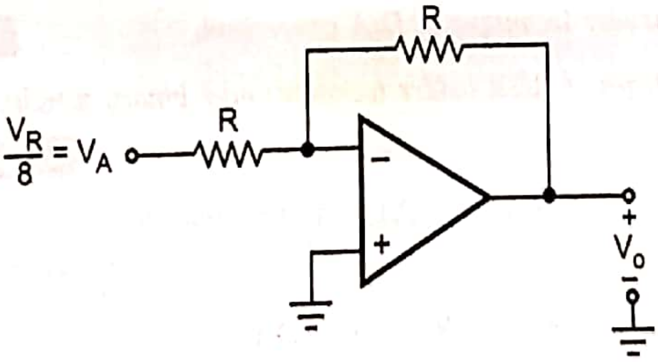


Fig. 7.3.6 (c)

Therefore, the output voltage is $V_R/8$ which is equivalent to binary input 001.

For binary input 100 the network can be reduced as follows :

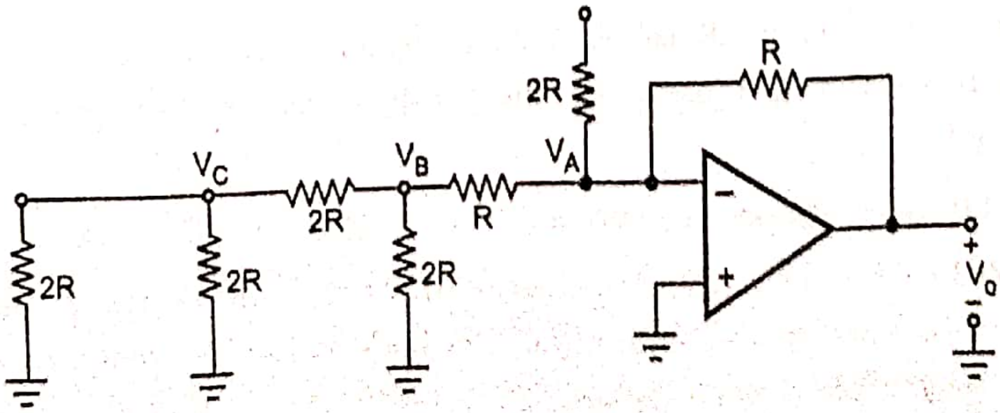


Fig. 7.3.7 (a)

Therefore, the output voltage is $V_R/2$, which is equivalent to binary input 100.

In general, the voltage is given by

$$V_0 = -V_R (b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + ... + b_n 2^{-n})$$

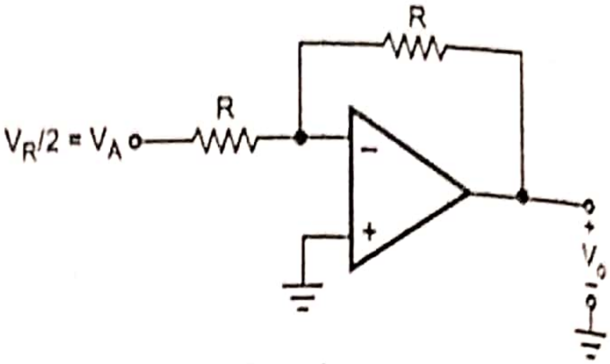


Fig. 7.3.7 (b)

Advantages of R/2R ladder DACs

1. Easier to build accurately as only two precision metal film resistors are required.
2. Number of bits can be expanded by adding more sections of same R/2R values.
3. In inverted R/2R ladder DAC, node voltages remain constant with changing input binary words. This avoids any slowdown effects by stray capacitances.