UNIT-4

OP-AMP Applications-2

Comparator:

To obtain for better performance, we shall also look at integrated designed specifically as comparators and converters. A comparator as its name implies, compares a signal voltage on one input of an op-amp with a known voltage called a reference voltage on the other input. Comparators are used in circuits such as,

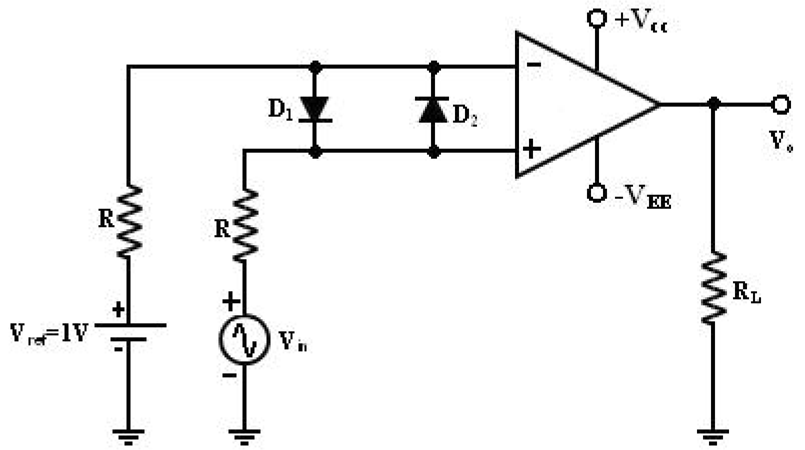
Digital Interfacing

Schmitt Trigger

Discriminator

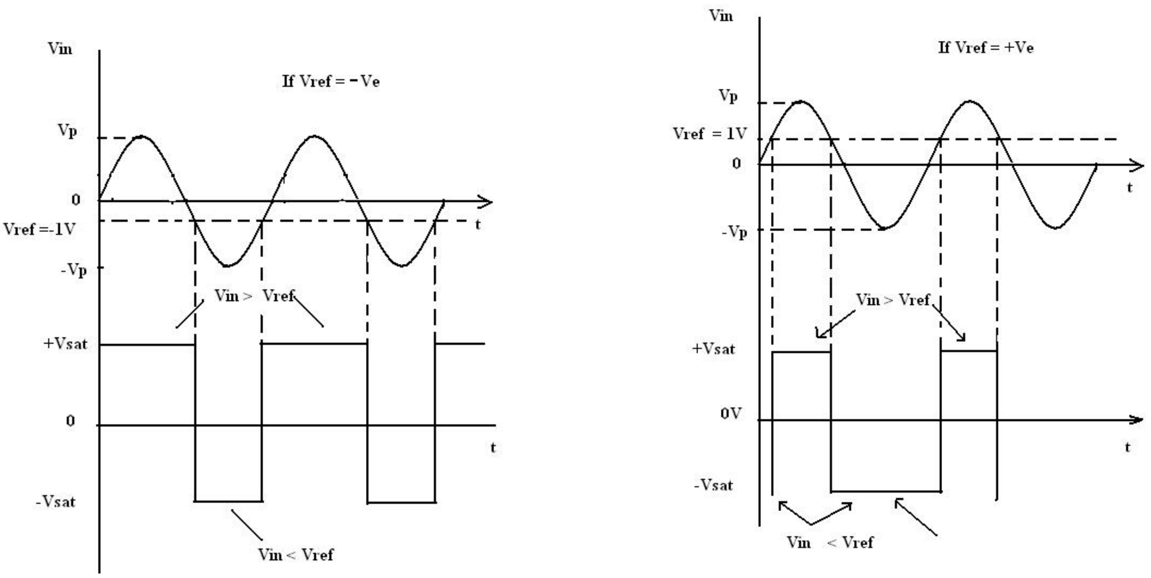
Voltage level detector and oscillators

1. Non-inverting Comparator:

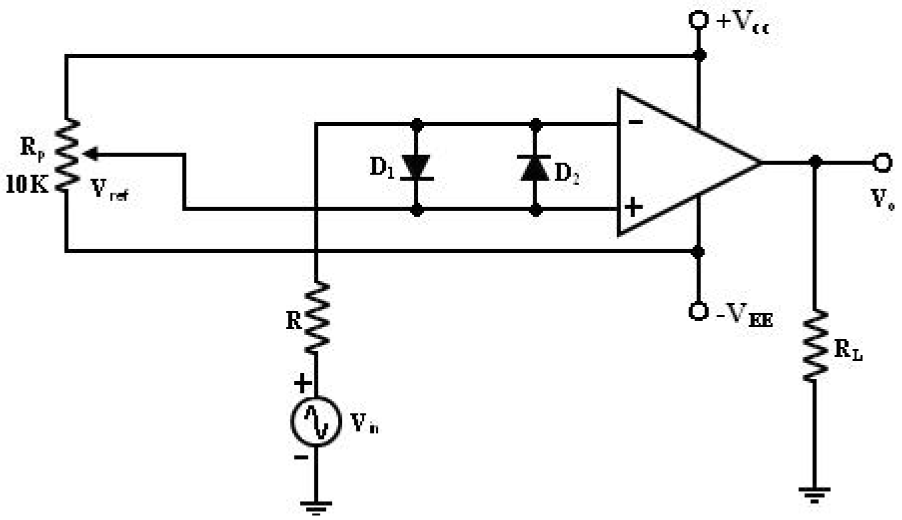


A fixed reference voltage Vref of 1 V is applied to the negative terminal and time varying signal voltage Vin is applied tot the positive terminal. When Vin is less than Vref the output becomes V_0 at –Vsat [Vin < Vref => V_0 (-Vsat)]. When Vin is greater than Vref, the (+) input becomes positive, the V_0 goes to +Vsat. [Vin > Vref => V_0 (+Vsat)]. Thus the V_0 changes from one saturation level to another. The diodes D_1 and D_2 protects the op-amp from damage due to the excessive input voltage Vin. Because of these diodes, the difference input voltage Vid of the op-amp diodes are called clamp diodes. The resistance R in series with Vin is used to limit the current through D_1 and D_2 . To reduce offset problems, a resistance Rcomp = R is connected between the (-ve) input and Vref.

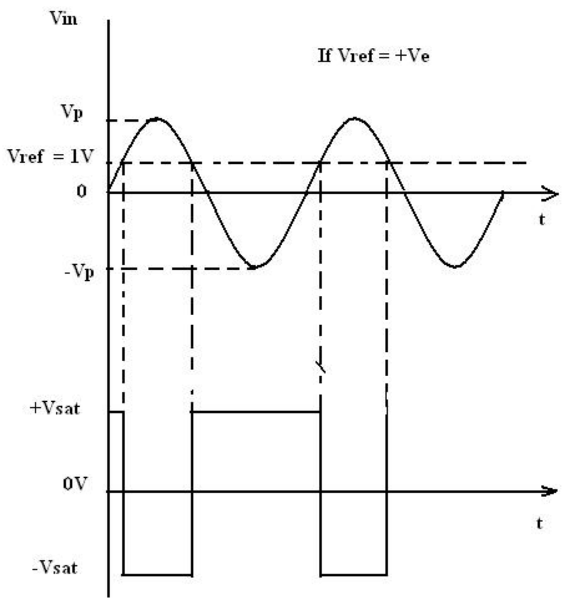
Input and Output Waveforms:

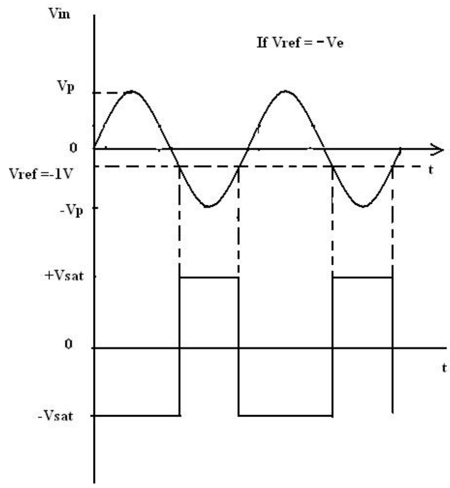


2. Inverting Comparator:



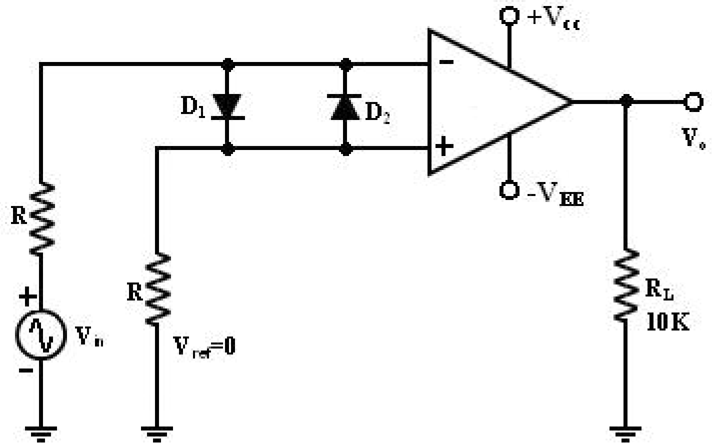
This fig shows an inverting comparator in which the reference voltage Vref is applied to the (+) input terminal and Vin is applied to the (-) input terminal. In this circuit Vref is obtained by using a 10K potentiometer that forms a voltage divider with dc supply volt +Vcc and -1 and the wiper connected to the input. As the wiper is moved towards +Vcc, Vref becomes more positive. Thus a Vref of a desired amplitude and polarity can be obtained by simply adjusting the 10k potentiometer.



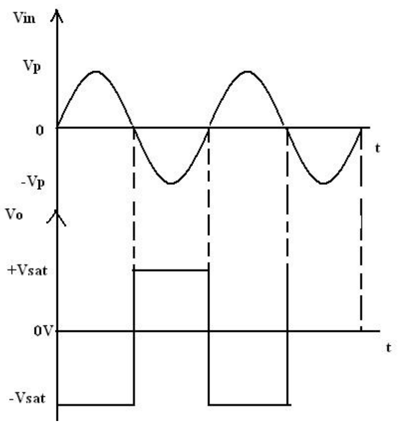


APPLICATIONS OF COMPARATORS:

Zero Crossing Detector: [Sine wave to Square wave converter]



One of the application of comparator is the zero crossing detector or ―sine wave to Square wave Converter‖. The basic comparator can be used as a zero crossing detector by setting Vref is set to Zero. (Vref =0V). This Fig shows when in what direction an input signal Vin crosses zero volts. (i.e) the o/p V_0 is driven into negative saturation when the input the signal Vin passes through zero in positive direction. Similarly, when Vin passes through Zero in negative direction the output V_0 switches and saturates positively.

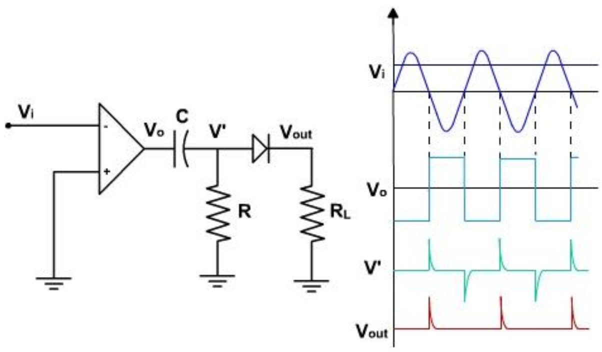


Drawbacks of Zero- crossing detector:

In some applications, the input Vin may be a slowly changing waveform, (i.e) a low frequency signal. It will take Vin more time to cross 0V, therefore V_0 may not switch quickly from one saturation voltage to the other. Because of the noise at the op-amp's input terminals the output V_0 may fluctuate between 2 saturations voltages +Vsat and –Vsat. Both of these problems can be cured with the use of regenerative or positive feedback that cause the output V_0 to change faster and eliminate any false output transitions due to noise signals at the input. Inverting comparator with positive feedback . This is known as ―Schmitt Trigger‖.

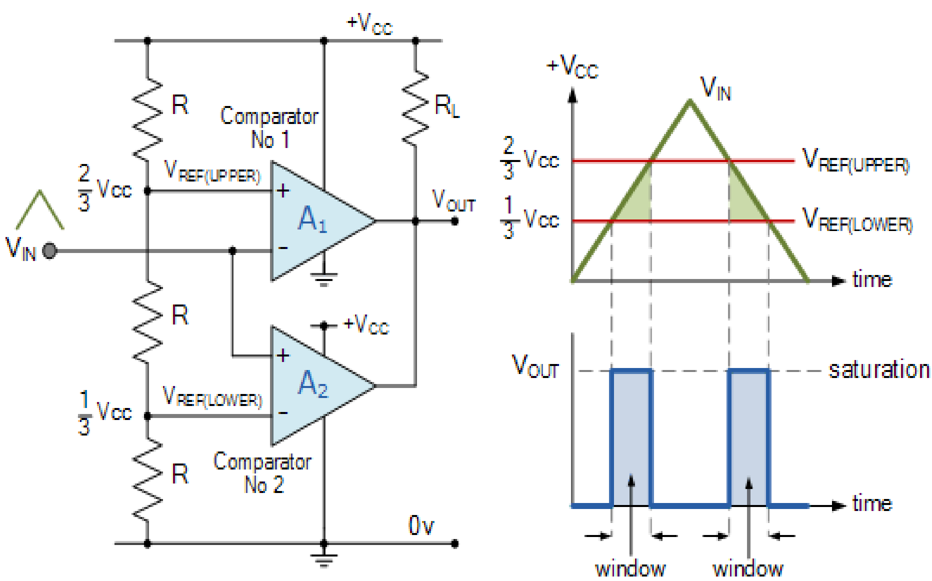
TIME MARKER GENERATOR:

The resistance is chosen so that the zener operates in zener region. When V_R= 0 then the output changes rapidly from one state to other very rapidly every time that the input passes through zero as shown in fig.



Such a configuration is called zero crossing detector. If we want pulses at zero crossing then a differentiator and a series diode is connected at the output. It produces single pulses at the zero crossing point in every cycle.

Window Detector:



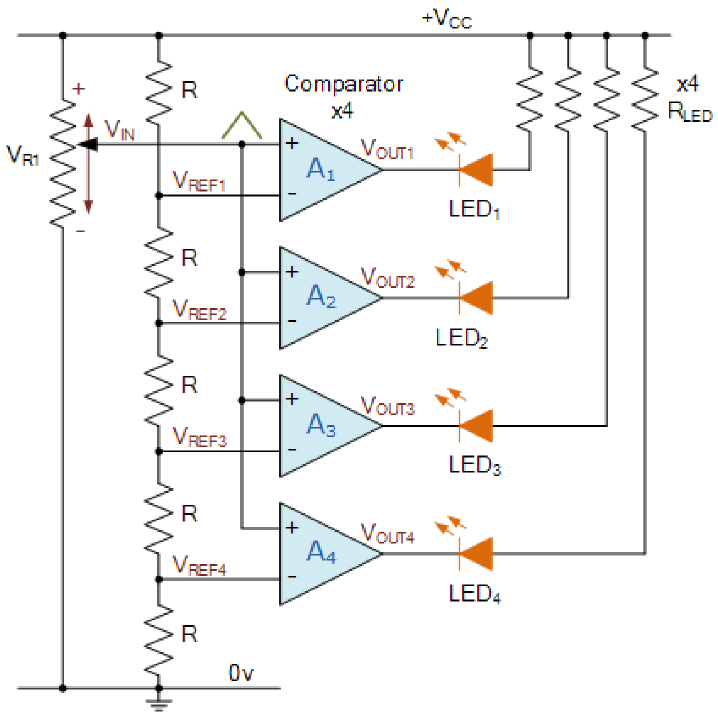
- The window detector circuit detects when an unknown voltage falls within a specified voltage band or window.
- It is also called window comparator.

- The initial switching condition of the circuit is the open-collector output of op-amp A_1 “OFF” with the open-collector output of op-amp A_2, “ON” (sinking current) so V_{OUT} is equal to 0V.
- When V_{IN} is below the lower voltage level, $V_{REF(LOWER)}$ which equates to 1/3Vcc, V_{OUT} will be LOW.
- When V_{IN} exceeds this 1/3Vcc lower voltage level, the first op-amp comparator detects this and switches its open-collector output HIGH. This means that both op-amps have their outputs HIGH at the same time. No current flows through the pull-up resistor R_L so V_{OUT} is equal to Vcc.
- As V_{IN} continues to increase it passes the upper voltage level, $V_{REF(UPPER)}$ at 2/3Vcc. At this point the second op-amp comparator detects this and switches its output LOW and V_{OUT} becomes equal to 0V.
- Then the difference between $V_{REF(UPPER)}$ and $V_{REF(LOWER)}$ (which is 2/3Vccc – 1/3Vcc in this example) creates the switching window for the positive going signal.
- Lets now assume that V_{IN} is at its maximum value and equal to Vcc. As V_{IN} decreases it passes the upper voltage level $V_{REF(UPPER)}$ of the second op-amp comparator which switches the output HIGH. As V_{IN} continues to decrease it passes the lower voltage level, $V_{REF(LOWER)}$ of the first op-amp comparator once again switching the output LOW.
- Then the difference between $V_{REF(UPPER)}$ and $V_{REF(LOWER)}$ creates the window for the negative going signal. So we can see that as V_{IN} passes above or passes below the upper and lower reference levels set by the two op-amp comparators, the output signal V_{OUT} will be HIGH or LOW.
- In this simple example we have set the upper trip level at 2/3Vcc and the lower trip level at 1/3Vcc (because we used three equal value resistors), but can be any values we choose by adjusting the input thresholds. As a result, the window width can be customized for a given application.
- If we used a dual power supply and set the upper and lower trip levels to say ±10 volts and V_{IN} was a sinusoidal waveform, then we could use this window comparator circuit as a zero crossing detector of the sine wave which would produce an output, HIGH or LOW every time the sine wave crossed the zero volts line from positive to negative or negative to positive.

Level Detector:

- Level detector circuit is used to detect the input voltage level when it crosses certain voltage level (ref level). A LED or some indicator is used as a output level indicator.
- As above, the voltage divider network provides a set of reference voltages for the individual op-amp comparator circuits. To produce the four reference voltages will require five resistors.
- The junction at the bottom pair of resistors will produce a reference voltage that is one-fifth the supply voltage, 1/5Vcc using equal value resistors. The second pair 2/5Vcc, a third pair 3/5Vcc and so on, with these reference voltages increasing by a fixed amount of one-fifth (1/5) towards 5/5Vcc which is actually Vcc.
- As the common input voltage increases, the output of each op-amp comparator circuit switches in turn thereby turning OFF the connected LED starting with the lower comparator, A_4 and upwards towards A_1 as the input voltage increases. So by setting the

values of the resistors in the voltage divider network, the comparators can be configured to detect any voltage level. One good example of the use of voltage level detection and indication would be for a battery condition monitor by reversing the LED's and connecting them to 0V (ground) instead of V_{CC}.



- Also by increasing the number of op-amp comparators in the set, more trigger points can be created. So for example, if we had eight op-amp comparators in the chain and fed the output of each comparator to an 8-to-3 line Digital Encoder, we could make a very simple analogue-to-digital converter, (ADC) that would convert the analogue input signal into a 3-bit binary code (0-to-7).

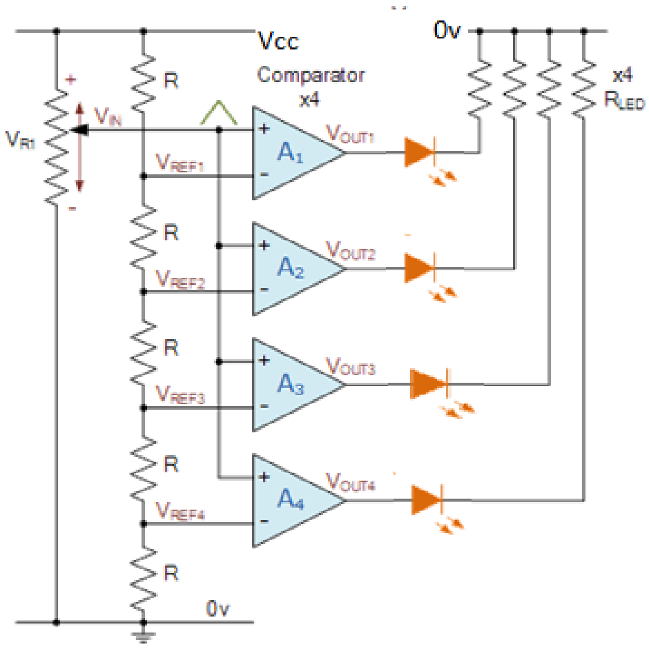


Fig: Battery level Indicator using level detector circuit.

Rectifiers:

AC and **DC** are two frequent terms that you encounter while studying the flow of electrical charge. **Alternating Current (AC)** has the property to change its state continuously. For example, if we consider a sine wave, the current flows in one direction for positive half cycle and in the opposite direction for negative half cycle. On the other hand, **Direct Current (DC)** flows only in one direction.

An electronic circuit, which produces either DC signal or a pulsated DC signal, when an AC signal is applied to it is called as a **rectifier**. This chapter discusses about op-amp based rectifiers in detail.

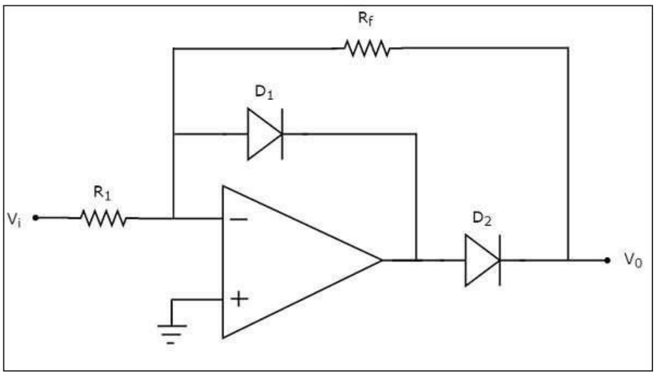
Types of Rectifiers

Rectifiers are classified into two types: **Half wave rectifier** and **Full wave rectifier**. This section discusses about these two types in detail.

Precision Half wave Rectifier

A **half wave rectifier** is a rectifier that produces positive half cycles at the output for one half cycle of the input and zero output for the other half cycle of the input.

The **circuit diagram** of a half wave rectifier is shown in the following figure.



Observe that the circuit diagram of a half wave rectifier shown above looks like an inverting amplifier, with two diodes D_1 and D_2 in addition.

The **working** of the half wave rectifier circuit shown above is explained below

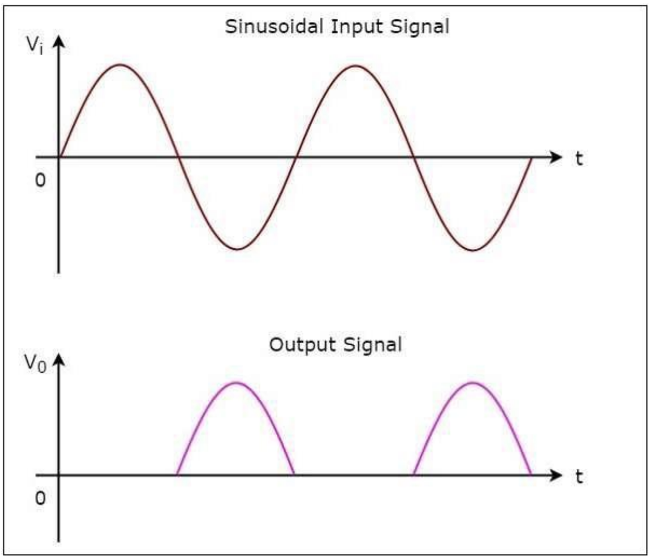
- For the **positive half cycle** of the sinusoidal input, the output of the op-amp will be negative. Hence, diode D_1 will be forward biased.
- When diode D_1 is in forward bias, output voltage of the op-amp will be -0.7 V. So, diode D_2 will be reverse biased. Hence, the **output voltage** of the above circuit is **zero** volts.
- Therefore, there is **no (zero) output** of half wave rectifier for the positive half cycle of a sinusoidal input.
- For the **negative half cycle** of sinusoidal input, the output of the op-amp will be positive. Hence, the diodes D_1 and D_2 will be reverse biased and forward biased respectively. So, the output voltage of above circuit will be –

$$V_0 = -\left(\frac{R_f}{R_1}\right) V_1$$

- Therefore, the output of a half wave rectifier will be a **positive half cycle** for a negative half cycle of the sinusoidal input.

Wave forms

The **input** and **output waveforms** of a half wave rectifier are shown in the following figure

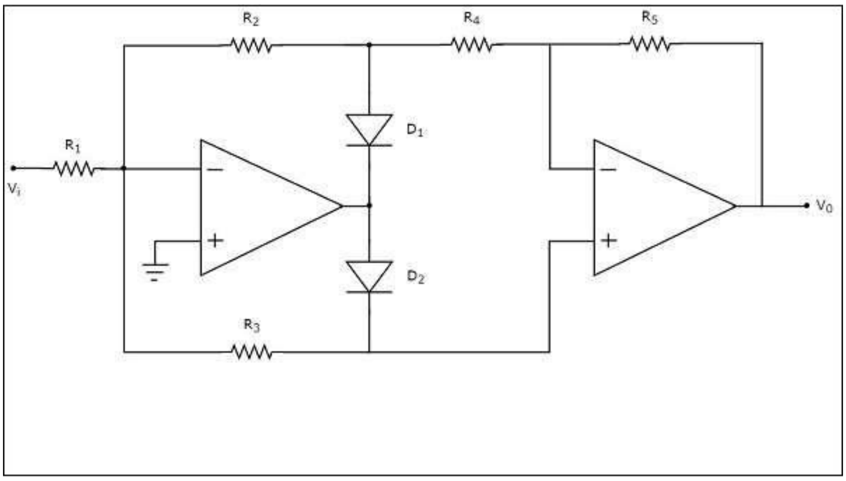


As you can see from the above graph, the half wave rectifier circuit diagram that we discussed will produce **positive half cycles** for negative half cycles of sinusoidal input and zero output for positive half cycles of sinusoidal input.

Precision Full wave Rectifier:

A **full wave rectifier** produces positive half cycles at the output for both half cycles of the input.

The **circuit diagram** of a full wave rectifier is shown in the following figure −



The above circuit diagram consists of two op-amps, two diodes, D_1 & D_2 and five resistors, R_1 to R_5**.** The **working** of the full wave rectifier circuit shown above is explained below −

- For the **positive half cycle** of a sinusoidal input, the output of the first op-amp will be negative. Hence, diodes D_1 and D_2 will be forward biased and reverse biased respectively.

- Then, the output voltage of the first op-amp will be −

$$V_{01} = -\left(\frac{R_2}{R_1}\right) V_i$$

- Observe that the output of the first op-amp is connected to a resistor R_4, which is connected to the inverting terminal of the second op-amp. The voltage present at the non-inverting terminal of second op-amp is 0 V. So, the second op-amp with resistors, R_4 and R_5 acts as an **inverting amplifier**.
- The output voltage of the second op-amp will be

$$V_0 = -\left(\frac{R_5}{R_4}\right) V_{01}$$

Substituting the value of V_{01} in the above equation, we get –

$$=> V_0 = -\left(\frac{R_5}{R_4}\right)\left\{-\left(\frac{R_2}{R_1}\right) V_i\right\}$$

$$=> V_0 = \left(\frac{R_2 R_5}{R_1 R_4}\right) V_i$$

- Therefore, the output of a full wave rectifier will be a positive half cycle for the **positive half cycle** of a sinusoidal input. In this case, the gain of the output is $\frac{R_2 R_5}{R_1 R_4}$.
- If we consider R1 =R2= R4 = R5 =R, then the gain of the output will be one.
- For the **negative half cycle** of a sinusoidal input, the output of the first op-amp will be positive. Hence, diodes D_1 and D_2 will be reverse biased and forward biased respectively.
- The output voltage of the first op-amp will be −

$$V_{01} = -\left(\frac{R_3}{R_1}\right) V_i$$

The output of the first op-amp is directly connected to the non-inverting terminal of the second op-amp. Now, the second op-amp with resistors, R_4 and R_5 acts as a **non-inverting amplifier**.

The output voltage of the second op-amp will be −

$$V_0 = \left(1 + \frac{R_5}{R_4}\right) V_{01}$$

Substituting the value of V_{01} in the above equation, we get

$$=> V_0 = \left(1+\frac{R_5}{R_4}\right)\left\{-\left(\frac{R_3}{R_1}\right)V_i\right\}$$

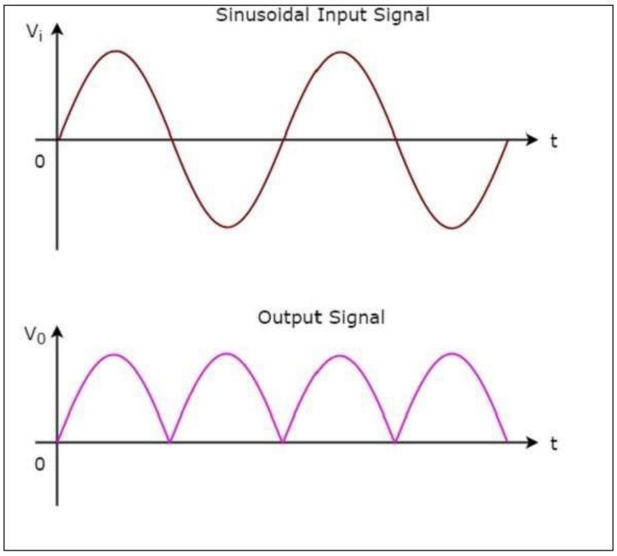
$$=> V_0 = -\left(\frac{R_3}{R_1}\right)\left(1+\frac{R_5}{R_4}\right)V_i$$

Therefore, the output of a full wave rectifier will be a **positive half cycle** for the negative half cycle of sinusoidal input also. In this case, the magnitude of the gain of the output is

$$\left(\frac{R_3}{R_1}\right)\left(1+\frac{R_5}{R_4}\right)$$

- If we consider R1 = R2 = R3 = R4 = R5 = R then the gain of the output will be **one**.

The **input** and **output waveforms** of a full wave rectifier are shown in the following figure



As you can see in the above figure, the full wave rectifier circuit diagram that we considered will produce only **positive half cycles** for both positive and negative half cycles of a sinusoidal input.

Log And Anti Log Amplifiers:

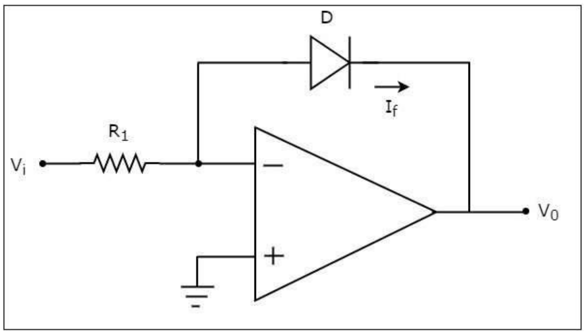
The electronic circuits which perform the mathematical operations such as logarithm and anti-logarithm (exponential) with an amplification are called as **Logarithmic amplifier** and **Anti-Logarithmic amplifier** respectively.

This chapter discusses about the **Logarithmic amplifier** and **Anti-Logarithmic amplifier** in detail. Please note that these amplifiers fall under non-linear applications.

Logarithmic Amplifier

A **logarithmic amplifier**, or a **log amplifier**, is an electronic circuit that produces an output that is proportional to the logarithm of the applied input. This section discusses about the op-amp based logarithmic amplifier in detail.

An op-amp based logarithmic amplifier produces a voltage at the output, which is proportional to the logarithm of the voltage applied to the resistor connected to its inverting terminal. The **circuit diagram** of an op-amp based logarithmic amplifier is shown in the following figure −



In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied at the non-inverting input terminal of the op-amp.

According to the **virtual short concept**, the voltage at the inverting input terminal of an op-amp will be equal to the voltage at its non-inverting input terminal. So, the voltage at the inverting input terminal will be zero volts.

The **nodal equation** at the inverting input terminal's node is −

$$\frac{0 - V_i}{R_1} + I_f = 0$$

$$=> I_f = \frac{V_i}{R_1} \ldots\ldots Equation1$$

The following is the **equation for current** flowing through a diode, when it is in forward bias

$$I_f = I_s e^{\left(\frac{V_f}{nV_T}\right)} \ldots\ldots Equation2$$

where,

I_s is the saturation current of the diode,
V_f is the voltage drop across diode, when it is in forward bias,
V_T is the diode's thermal equivalent voltage.

The **KVL equation** around the feedback loop of the op amp will be −

$$0 - V_f - V_0 = 0$$

$$=> V_f = -V_0$$

Substituting the value of V_f in Equation 2, we get –

$$I_f = I_s e^{\left(\frac{-V_0}{nV_T}\right)} \ldots\ldots Equation 3$$

Observe that the left hand side terms of both equation 1 and equation 3 are same. Hence, equate the right hand side term of those two equations as shown below –

$$\frac{V_i}{R_1} = I_s e^{\left(\frac{-V_0}{nV_T}\right)}$$

$$\frac{V_i}{R_1 I_s} = e^{\left(\frac{-V_0}{nV_T}\right)}$$

Applying **natural logarithm** on both sides, we get –

$$In\left(\frac{V_i}{R_1 I_s}\right) = \frac{-V_0}{nV_T}$$

$$V_0 = -nV_T In\left(\frac{V_i}{R_1 I_s}\right)$$

Note that in the above equation, the parameters n, V_T and I_s are constants. So, the output voltage V_0 will be proportional to the **natural logarithm** of the input voltage V_i for a fixed value of resistance R_1.

Therefore, the op-amp based logarithmic amplifier circuit discussed above will produce an output, which is proportional to the natural logarithm of the input voltage

V_i, when $R_1 I_s = 1V$.

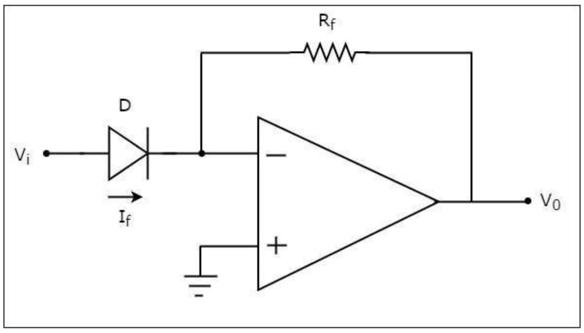
Observe that the output voltage V_0 has a **negative sign**, which indicates that there exists a 180^0 phase difference between the input and the output.

Anti-Logarithmic Amplifier

An **anti-logarithmic amplifier**, or an **anti-log amplifier**, is an electronic circuit that produces an output that is proportional to the anti-logarithm of the applied input. This section discusses about the op-amp based anti-logarithmic amplifier in detail.

An op-amp based anti-logarithmic amplifier produces a voltage at the output, which is proportional to the anti-logarithm of the voltage that is applied to the diode connected to its inverting terminal.

The **circuit diagram** of an op-amp based anti-logarithmic amplifier is shown in the following figure −



In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. It means zero volts is applied to its non-inverting input terminal.

According to the **virtual short concept**, the voltage at the inverting input terminal of op-amp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at its inverting input terminal will be zero volts.

The **nodal equation** at the inverting input terminal's node is −

$$-I_f + \frac{0 - V_0}{R_f} = 0$$

$$=> -\frac{V_0}{R_f} = I_f$$

$$=> V_0 = -R_f I_f \ldots\ldots\ldots Equation 4$$

We know that the equation for the current flowing through a diode, when it is in forward bias, is as given below –

$$I_f = I_s e^{\left(\frac{V_f}{nV_T}\right)}$$

Substituting the value of I_f in Equation 4, we get

$$V_0 = -R_f \left\{ I_s e^{\left(\frac{V_f}{nV_T}\right)} \right\}$$

$$V_0 = -R_f I_s e^{\left(\frac{V_f}{nV_T}\right)} \ldots\ldots Equation 5$$

The KVL equation at the input side of the inverting terminal of the op amp will be

$$V_i - V_f = 0$$

$$V_f = V_i$$

Substituting, the value of Vf in the Equation 5, we get –

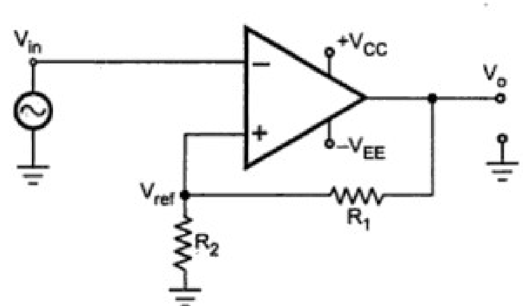
$$V_0 = -R_f I_s e^{\left(\frac{V_i}{nV_T}\right)}$$

Note that, in the above equation the parameters n, V_T and I_s are constants. So, the output voltage V_0 will be proportional to the **anti-natural logarithm** (exponential) of the input voltage V_i, for a fixed value of feedback resistance R_f.
Therefore, the op-amp based anti-logarithmic amplifier circuit discussed above will produce an output, which is proportional to the anti-natural logarithm (exponential) of the input voltage V_i when, $R_f I_s = 1V$. Observe that the output voltage V_0 is having a **negative sign**, which indicates that there exists a 180^0 phase difference between the input and the output.

Schmitt Trigger:

- A **Schmitt trigger** is a special type of comparator circuit with hysteresis implemented , used to avoid unwanted triggering.
- It is also called **Regenerative Comparator**.
- The op-amp Schmitt Triggers are two types
  - Inverting Schmitt Trigger
  - Non-inverting Schmitt Trigger.

Inverting Schmitt Trigger:



- $V_{in} > V_{ref} \rightarrow V_0 = -V_{sat}$
- $V_{in} < V_{ref} \rightarrow V_0 = +V_{sat}$
- Ref . Voltage Controlled by the R1 & R2 Resistors.

Contd..

$$+V_{ref} = \frac{V_0}{R_1+R_2} \times R_2 = \frac{+V_{sat}}{R_1+R_2} \times R_2 \text{ .... positive saturation}$$

$$-V_{ref} = \frac{V_0}{R_1+R_2} \times R_2 = \frac{-V_{sat}}{R_1+R_2} \times R_2 \text{ .... negative saturation}$$

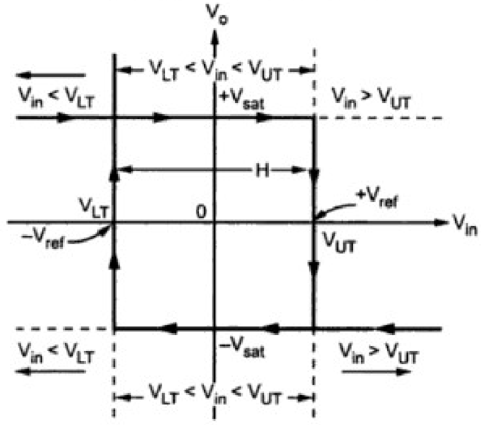
- $+V_{ref}$ is for positive saturation when $V_0 = +V_{sat}$ and is called **Upper Threshold Voltage (V_{UT})**
- $-V_{ref}$ is negative saturation when $V_o = -V_{sat}$ and is called **Lower Threshold Voltage (V_{LT})**

Contd..

- $V_{in} > V_{UT} \rightarrow V = -V_{sat}$
- $V_{in} < V_{LT} \rightarrow V_0 = +V_{sat}$
- $V_{LT} < V_{in} < V_{UT} \rightarrow V_0$ = Previous state
- The difference between V_{UT} & V_{LT} is called width of hysteresis. Denoted as **H**
- Hysteresis is also called **dead band** or **dead zone.**

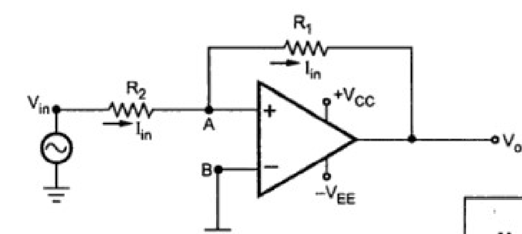
Contd..

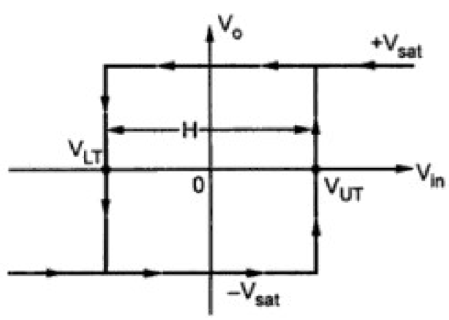
$$H = \frac{2\ V_{sat}\ R_2}{R_1 + R_2}$$



- Hysteresis Transfer characteristics.

Non-Inverting Schmitt Trigger





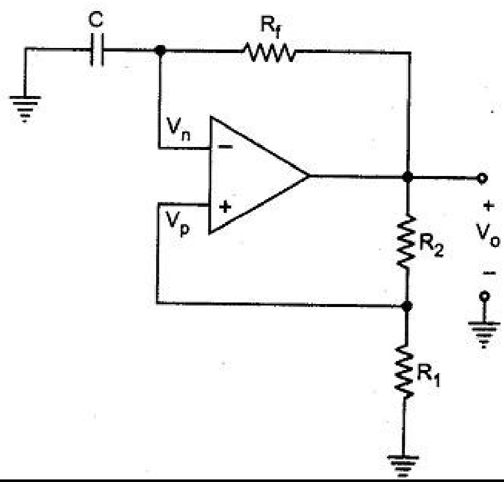
$$V_{UT} = I_{in}\ R_2 = \frac{R_2}{R_1}(+V_{sat}) = V_{sat}\ \frac{R_2}{R_1}$$

$$V_{LT} = \frac{R_2}{R_1}(-V_{sat}) = -V_{sat}\ \frac{R_2}{R_1}$$

$$H = V_{UT} - V_{LT} = 2\ V_{sat}\ \frac{R_2}{R_1}$$

SQUAREWAVE GENERATOR:

- The square wave generator using op amp means the astable multivibrator circuit using op-amp.



SQUAREWAVE GENERATOR:

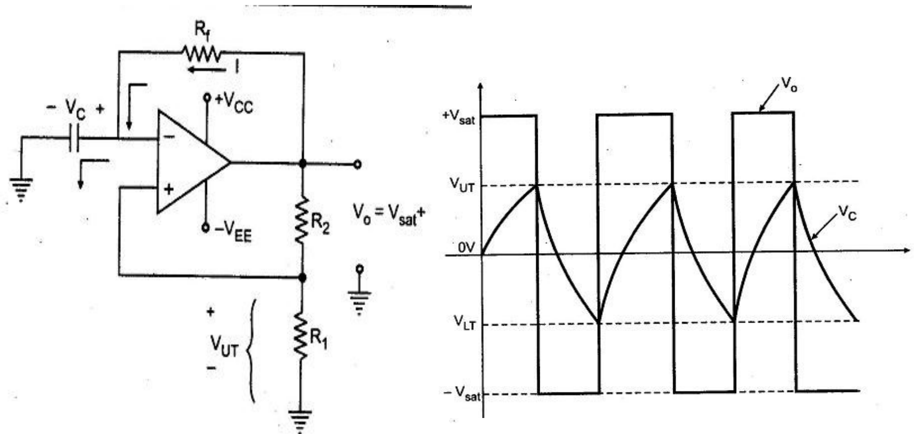
When V_o is at $+V_{sat}$, the feedback voltage is called the upper threshold voltage V_{UT} and is given as

$$V_{UT} = \frac{R_1 \cdot +V_{sat}}{R_1 + R_2} \quad \text{... (1)}$$

When V_o is at $-V_{sat}$, the feedback voltage is called the lower-threshold voltage V_{LT} and is given as

$$V_{LT} = \frac{R_1 \cdot -V_{sat}}{R_1 + R_2} \quad \text{... (2)}$$

Contd..



Frequency of Oscillation:

- The voltage across the capacitor as a function of time is given as

$$V_C(t) = V_{max} + (V_{initial} - V_{max})e^{(-t/T)} \quad \ldots (3)$$

Where,

$V_C(t)$ is the instantaneous voltage across the capacitor.

$V_{initial}$ is the initial voltage

V_{max} is the voltage toward which the capacitor is charging.

Contd..

- Let us consider the charging of capacitor from V_{LT} to V_{UT}, where V_{LT} is the initial voltage, V_{UT} is the instantaneous voltage and $+V_{sat}$ is the maximum voltage.
- At $t = T_1$, voltage across capacitor reaches V_{UT} and therefore equation (3) becomes

$$V_{UT} = +V_{sat} + (V_{LT} - +V_{sat})e^{(-T_1/R_f C)} \quad \ldots (4)$$

$$\therefore -(V_{LT} - +V_{sat})e^{(-T_1/R_f C)} = +V_{sat} - V_{UT}$$

Contd..

$$e^{(-T_1/R_f C)} = \frac{(+V_{sat} - V_{UT})}{(+V_{sat} - V_{LT})}$$

$$\frac{-T_1}{R_f C} = ln\left(\frac{+V_{sat} - V_{UT}}{+V_{sat} - V_{LT}}\right)$$

$$T_1 = -R_f C\, ln\left(\frac{+V_{sat} - V_{UT}}{+V_{sat} - V_{LT}}\right)$$

$$= R_f C\, ln\left(\frac{+V_{sat} - V_{LT}}{+V_{sat} - V_{UT}}\right) \quad \ldots (5)$$

- The time taken by capacitor to charge from V_{UT} to V_{LT} is same as time required for charging capacitor from V_{LT} to V_{UT} . Therefore, total time required for one oscillation is given as

Contd..

$$T = 2T_1 \quad \dots (6)$$

$$= 2R_f\, C\, ln\left(\frac{+V_{sat} - V_{LT}}{+V_{sat} - V_{UT}}\right) \quad \dots (7)$$

- The frequency of oscillation can be determined as $f_o = 1/T$, where T represents the time required for one oscillation.
- Substituting the value of T we get,

$$f_0 = \frac{1}{2R_f\, C\, ln\left(\frac{+V_{sat} - V_{LT}}{+V_{sat} - V_{UT}}\right)} \quad \dots (8)$$

Contd..

Substituting the values of V_{UT} and V_{LT} we get,

$$T = 2R_f\, C\, ln\left[\frac{+V_{sat} - (R_1 \times - V_{sat})/R_1 + R_2}{+V_{sat} - (R_1 \times + V_{sat})/R_1 + R_2}\right]$$

If magnitudes of $+V_{sat}$ and $-V_{sat}$ are equal,

$$T = 2R_f\, C\, ln\left[\frac{+V_{sat}\left(1 + \frac{R_1}{R_1 + R_2}\right)}{+V_{sat}\left(1 - \frac{R_1}{R_1 + R_2}\right)}\right]$$

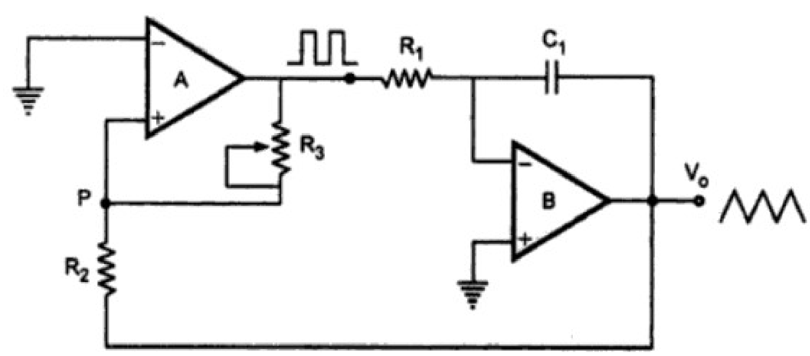
$$\boxed{T = 2R_f\, C\, ln\left(\frac{2R_1 + R_2}{R_2}\right)}$$

IC Applications

UNIT-III

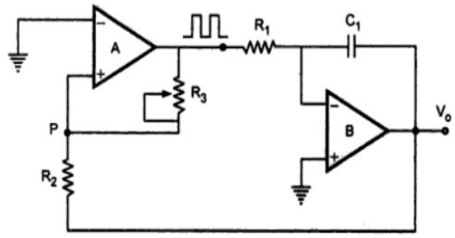
TOPIC: Triangular & Sawtooth wave Generator

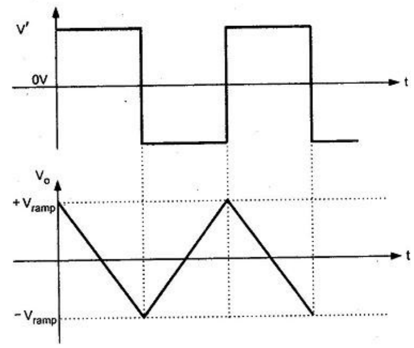
Triangular wave Generator



- It is the combination of Schmitt Trigger and integrator.
- A → Square wave (Schmitt Trigger)
- B → Triangular wave (Integrator)

Contd..





- Output wave forms of triangular wave generator

Amplitude & Frequency Calculation:

- When comparator output is at $+V_{sat}$, the effective voltage at point P is given by

$$-V_{ramp} + \frac{R_2}{R_2 + R_3}\left[+V_{sat} - (-V_{ramp})\right] \qquad \ldots (1)$$

When effective voltage at P becomes equal to zero, we can write above equation

$$-V_{ramp} + \frac{R_2}{R_2 + R_3}\left[+V_{sat} - (-V_{ramp})\right] = 0$$

$$-V_{ramp} + \frac{R_2}{R_2 + R_3}(V_{ramp}) + \frac{R_2}{R_2 + R_3}(+V_{sat}) = 0$$

Contd..

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

$$-V_{ramp} = \frac{-R_2}{R_3}(+V_{sat}) \quad \text{... (2)}$$

Similarly, when comparator output is at $-V_{sat}$ we can write,

$$V_{ramp} = \frac{-R_2}{R_3}(-V_{sat}) \quad \text{... (3)}$$

The peak to peak amplitude of the triangular wave can be given as

$$\begin{aligned} V_{o(pp)} &= +V_{ramp} - (-V_{ramp}) \\ &= \frac{-R_2}{R_3}(-V_{sat}) - \left(\frac{-R_2}{R_3}\right)(+V_{sat}) \end{aligned} \quad \text{... (4)}$$

Contd..

If $|+V_{sat}| = |-V_{sat}|$ then, we can write

$$V_{o(pp)} = \frac{R_2}{R_3}V_{sat} + \frac{R_2}{R_3}V_{sat} = \frac{2R_2}{R_3}V_{sat} \quad \text{... (5)}$$

•The time taken by the output to swing from – V_{ramp} to + V_{ramp} (or from + V_{ramp} to – V_{ramp}) is equal to half the time period T/2.

• This time can be calculated from the integrator output equation as follows :

$$V_{o(pp)} = -\frac{1}{R_1C_1}\int_0^{T/2}(-V_{sat})\,dt = \left(\frac{V_{sat}}{R_1C_1}\right)\frac{T}{2} \quad \text{... (6)}$$

Contd..

$$T = \frac{2R_1 C_1 V_{o(pp)}}{V_{sat}} \quad \text{.... (7)}$$

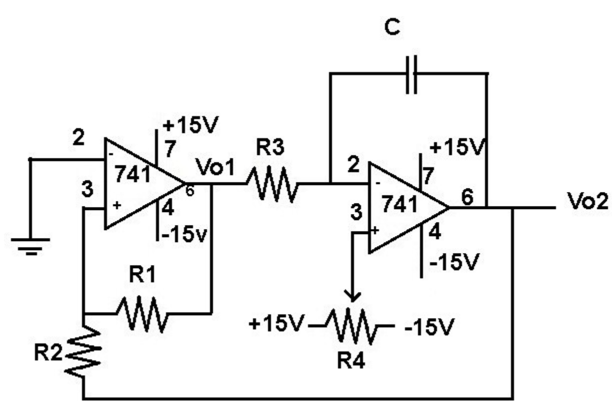
Substituting value of $V_{o(pp)}$ we get,

$$T = \frac{2R_1 C_1 \left(\frac{2R_2}{R_3} V_{sat}\right)}{V_{sat}} = \frac{4R_1 C_1 R_2}{R_3} \quad \text{... (8)}$$

Therefore, the frequency of oscillation can be given as,

$$\boxed{f_o = \frac{1}{T} = \frac{R_3}{4R_1 C_1 R_2}}$$

Sawtooth wave Generator:

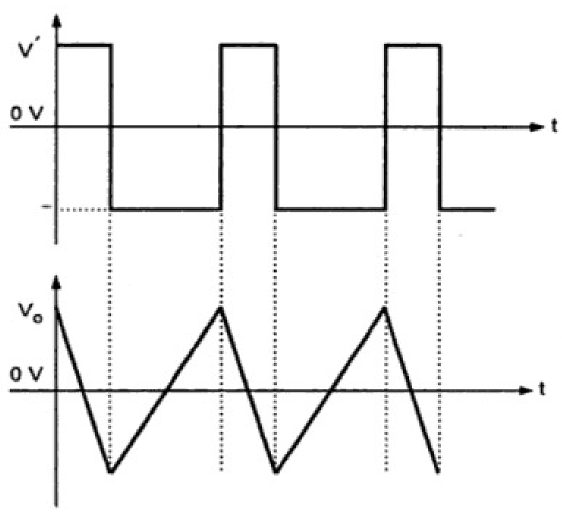


- Unlike the triangular wave, the sawtooth wave has unequal rise time & fall time.

Contd..

- The non inverting terminal of the integrator is driven by voltage set between +Vcc to –VEE by the potentiometer.
- Depending on R4 Setting, a certain DC level is added in the output of integrator.
- If the voltage at non-inverting terminal is
- Negative → <50% (DS) → Longer Rise time
- Positive → > 50% (DS) → Longer fall time.

Contd..



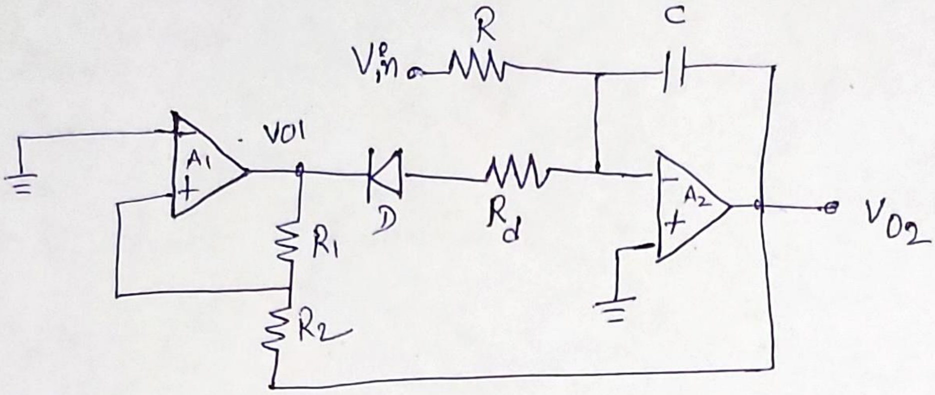
- Output waveforms of Swatooth wave generator.

Voltage to Frequency Converter (V-F)

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

→ Mathematically expressed as $f = K \cdot V_{in}$

where K = sensitivity of VF converter in Hz/V.



→ A_1 → Comparator

A_2 → Integrator

→ when V_{o1} is negative → 'D' diode forward biased & capacitor starts charging.

→ The charging current of C is $\frac{-V_{o1}}{R_d}$

as $R_d << R$; Capacitor charges very sharply

→ V_{o2} is a +ve ramp signal till it reaches to threshold value of comparator.

→ then V_{o1} becomes +ve & diode (D) will be reverse biased

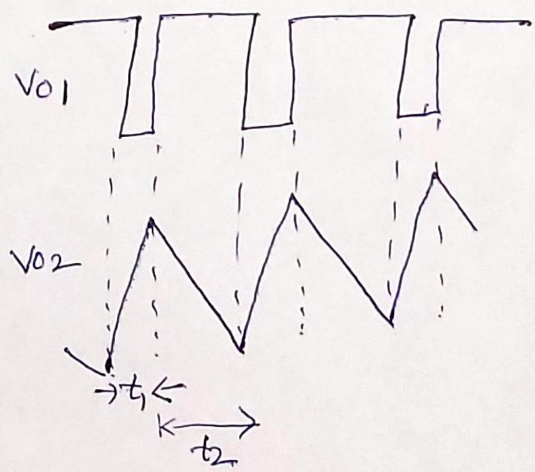
→ The voltage V_{in} produces current for integrator & V_{o2} is a -ve ramp signal decided by V_{in}.

→ when that ramp reaches to Lower threshold of comparator, V_{o1} becomes negative & cycle repeates

→ From the wave forms we can say,
$t_1 < t_2$

→ Hence o/p frequency is decided by t_2 i.e; V_{in}.

→ Here ckt acts as Voltage to frequency converter.



→ Frequency of oscillations is given by

$$f = \frac{R_1}{2R_2 RC\, V_{sat}} \times V_{in} = K . V_{in}$$

where, V_{sat} = saturation of op-amp.