Jaipur Engineering College & Research Centre, Jaipur

Lecture Notes

3EE4-06: Analog Electronics

ACADEMIC SESSION 2020-21

Prepared By:
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VISION OF ELECTRICAL ENGINEERING DEPARTMENT

Electrical Engineering Department strives to be recognized globally for outcome based knowledge and to develop human potential to practice advance technology which contribute to society.

MISSION OF ELECTRICAL ENGINEERING DEPARTMENT

M1. To impart quality technical knowledge to the learners to make them globally competitive Electrical Engineers.

M2. To provide the learners ethical guidelines along with excellent academic environment for a long productive career.

M3. To promote industry-institute relationship.

PROGRAM OUTCOMES

1. **Engineering knowledge:** Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems in Electrical Engineering.
2. **Problem analysis:** Identify, formulate, research literature, and analyze complex engineering problems reaching substantial conclusions using first principles of mathematics, natural sciences, and engineering sciences in Electrical Engineering.
3. **Design/development of solutions:** Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations using Electrical Engineering.
4. **Conduct investigations of complex problems:** Use research based knowledge and research methods including design of experiments, analysis and interpretation of data and synthesis of the information to provide valid conclusions using Electrical Engineering.
5. **Modern tool usage:** Create, select and apply appropriate techniques, resources, and modern engineering and EE tools including prediction and modeling to complex engineering activities with an understanding of the limitations in EE.
6. **The engineer and society:** Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice using EE.
7. **Environment and sustainability:** Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of EE and need for sustainable development in EE.
8. **Ethics:** Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice using EE.
9. **Individual and team work:** Function effectively as an individual and as a member or leader in diverse teams, and multi-disciplinary settings in EE.
10. **Communication:** Communicate effectively on complex engineering activities with the engineering community and society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations and give and receive clear instructions.
11. **Project management and finance:** Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, to manage EE projects and in multi-disciplinary environments.
12. **Life-long learning:** Recognize the need for and have the preparation and ability to engage in independent and lifelong learning in the broadest context of technological changes needed in EE.

COURSE OUTCOMES:

On successful completion of the course, the students will be able to: -

CO1	Understand the characteristics of Diodes, concepts behind the Clippers, and Clampers. Design and analysis of various rectifier and amplifier circuits
CO2	Analyze the characteristics of current flow in a bipolar junction transistor and MOSFET & different electronic devices such as Amplifiers
CO3	Understand the dynamics of Linear & Non Linear Devices

Syllabus

RAJASTHAN TECHNICAL UNIVERSITY, KOTA

SYLLABUS

2nd Year - III Semester: B.Tech. (Electrical Engineering)

3EE4-06: Analog Electronics

Credit: 3 | **Max. Marks: 150 (IA:30, ETE:120)**
3L+0T+0P | **End Term Exam: 3 Hours**

SN		Hours
1.	**Diode circuits** P-N junction diode, I-V characteristics of a diode; review of half-wave and full-wave rectifiers, Zener diodes, clamping and clipping circuits.	4
2.	**BJT circuits** Structure and I-V characteristics of a BJT; BJT as a switch. BJT as an amplifier: small-signal model, biasing circuits, current mirror; common-emitter, common-base and common collector amplifiers; Small signal equivalent circuits, high-frequency equivalent circuits.	8
3.	**MOSFET circuits** MOSFET structure and I-V characteristics. MOSFET as a switch. MOSFET as an amplifier: small-signal model and biasing circuits, common-source, common-gate and common-drain amplifiers; small signal equivalent circuits - gain, input and output impedances, transconductance, high frequency equivalent circuit.	8
4.	**Differential, multi-stage and operational amplifiers** Differential amplifier; power amplifier; direct coupled multi-stage amplifier; internal structure of an operational amplifier, ideal op-amp, non-idealities in an op-amp (Output offset voltage, input bias current, input offset current, slew rate, gain bandwidth product)	8
5.	**Linear applications of op-amp** Idealized analysis of op-amp circuits. Inverting and non-inverting amplifier, differential amplifier, instrumentation amplifier, integrator, active filter, P, PI and PID controllers and lead/lag compensator using an op-amp, voltage regulator, oscillators (Wein bridge and phase shift). Analog to Digital Conversion.	8
6.	**Nonlinear applications of op-amp** Hysteretic Comparator, Zero Crossing Detector, Square-wave and triangular-wave generators, Precision rectifier, peak detector. Monoshot	6
	TOTAL	**42**

Office of Dean Academic Affairs
Rajasthan Technical University, Kota

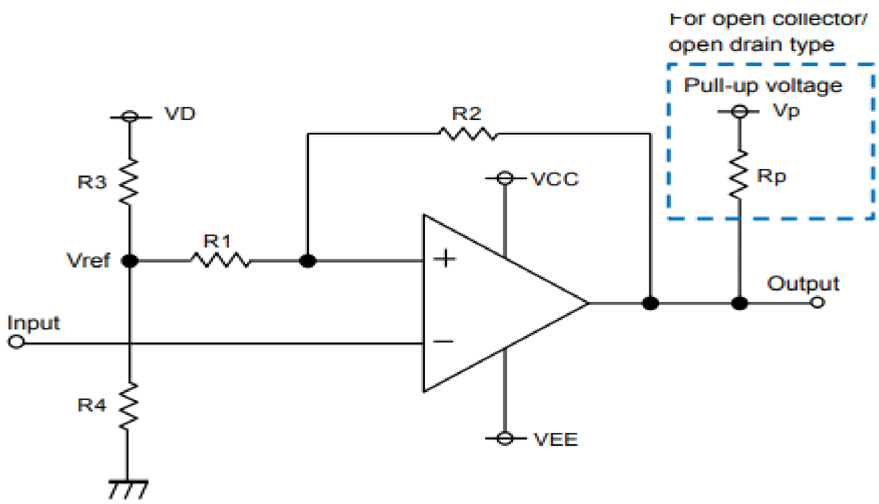
Unit: 6

Chapter: Nonlinear Applications of OP-AMP

Hysteresis comparator:

A hysteresis comparator is operated by applying a positive feedback* to the comparator. The potential difference between the High and Low output voltages and the feedback resistor are adjusted to change the voltage that is taken as a comparison reference to the input voltage for the +IN terminal. The width of variation in the reference voltage is the hysteresis width. In this circuits the signal is input to the-IN terminal , the output is inverted.

Note: A comparator cannot be operated as a hysteresis comparator when a negative feedback is applied.

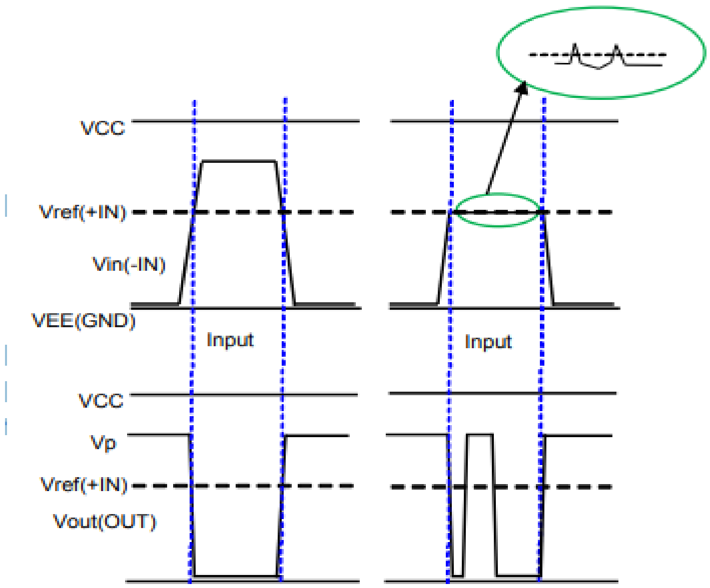


Hysteresis comparator circuit

• **Operation without hysteresis** : When the input signal and Vref (reference voltage) are nearly equal, exceeding the threshold value due to noise or other causes will destabilize the output. (Chattering occurs)

(1) When the input signal (-IN) is applied at a voltage sufficiently higher than Vref(+IN), the output is varied according to Vref as a threshold.

(2) When the input signal (-IN) is applied at a voltage equivalent to Vref(+IN), the input signal may or may not exceed the threshold at Vref due to noise or other causes, resulting in an instability (chattering)

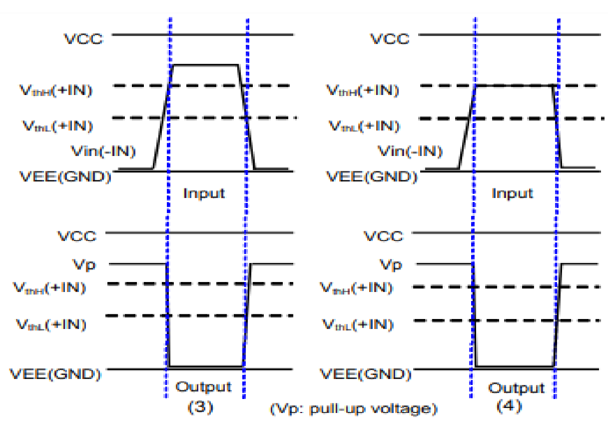


Response waveforms of non-hysteresis comparator.

• **Operation with hysteresis** Since a margin is provided between the High-to-Low and Low-to-High thresholds, no chattering occurs in the output even when a signal is input at a voltage near the threshold voltages..

(3) When the input signal (-IN) is applied at a voltage sufficiently higher than V_{thH}(+IN) and V_{thL}(+IN), the output is varied according to Vref as a threshold.

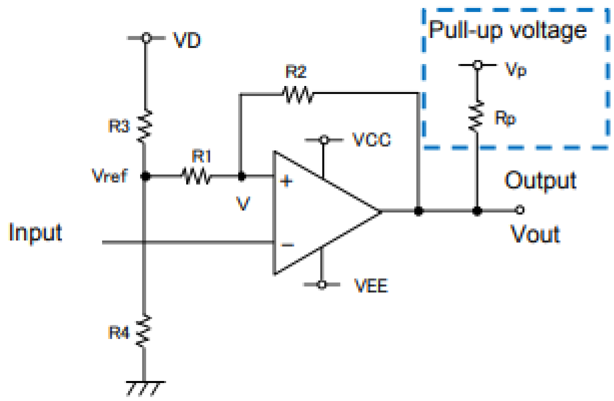
(4) When the input signal (-IN) is applied at a voltage equivalent to VthH(+IN) or above, no chattering occurs since the output will not respond unless the input falls below the threshold at VthL(+IN). VthL is the voltage switching from Low to High. VthH is the voltage switching from High to Low.



Response waveforms of hysteresis comparator

Calculation of threshold voltage (resistance division type)

Derivation of threshold voltage for hysteresis comparator



In the circuit configuration shown here, the threshold voltages and the hysteresis width are expressed as follows.

- Threshold voltages

$$V_{thH} = \frac{V_{OH} + \frac{R_2 a}{R_1 R_3} V_D}{\frac{1}{R_1}(R_1 + R_2 - \frac{R_2 a}{R_1})} \quad V_{thL} = \frac{V_{OL} + \frac{R_2 a}{R_1 R_3} V_D}{\frac{1}{R_1}(R_1 + R_2 - \frac{R_2 a}{R_1})}$$

- Hysteresis width

$$\Delta V_{th} = V_{thH} - V_{thL} \quad \text{where} \quad a = \frac{1}{(\frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_4})}$$

Calculation process Form a current equation for Vref and V_D

$$\frac{V_D - V_{ref}}{R_3} + \frac{V - V_{ref}}{R_1} = \frac{V_{ref}}{R_4} \quad \text{...(1)}$$

$$\frac{V - V_{ref}}{R_1} = \frac{V_{out} - V}{R_2} \quad \text{...(2)}$$

Solve equation (2) for Vout

$$\frac{R_2}{R_1} V - \frac{R_2}{R_1} V_{ref} = V_{out} - V$$

$$V_{out} = (\frac{R_2}{R_1} + 1)V - \frac{R_2}{R_1} V_{ref} \quad \text{...(3)}$$

Solve equation (1) for Vref

$$\frac{V_D}{R_3}-\frac{V_{ref}}{R_3}+\frac{V}{R_1}-\frac{V_{ref}}{R_1}=\frac{V_{ref}}{R_4}$$

$$(\frac{1}{R_1}+\frac{1}{R_3}+\frac{1}{R_4})V_{ref}=\frac{V_D}{R_3}+\frac{V}{R_1}$$

$$V_{ref}=\frac{1}{(\frac{1}{R_1}+\frac{1}{R_3}+\frac{1}{R_4})}\cdot\frac{V_D}{R_3}+\frac{1}{(\frac{1}{R_1}+\frac{1}{R_3}+\frac{1}{R_4})}\cdot\frac{V}{R_1}$$

$$V_{ref}=\frac{a}{R_3}V_D+\frac{a}{R_1}V \quad ...(4) \qquad \text{where} \quad a=\frac{1}{(\frac{1}{R_1}+\frac{1}{R_3}+\frac{1}{R_4})}$$

Solving equations (3) and (4) for V allows equation (5) to be obtained.

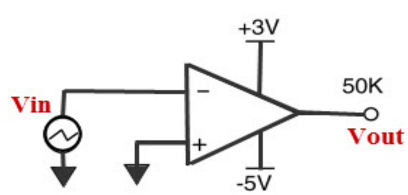
$$V=\frac{V_{out}+\frac{R_2 a}{R_1 R_3}V_D}{\frac{1}{R_1}(R_1+R_2-\frac{R_2 a}{R_1})} \qquad ...(5)$$

V provides two threshold voltages for the hysteresis comparator: V_{thL} is the voltage switching from Low to High and V_{thH} is the voltage switching from High to Low. Vout is the output voltage of the comparator providing two values: V_{OH} is the High output voltage and V_{OL} is the Low output voltage.

Zero crossing detector:

A zero-crossing detector or ZCD is one type of voltage comparator, used to detect a sine waveform transition from positive and negative, that coincides when the i/p crosses the zero voltage condition.

Zero-Crossing Detector Circuit: Zero crossing detector is a voltage comparator that changes the o/p between +Vsat & –Vsat when the i/p crosses zero reference voltage. In simple words, the comparator is a basic operational amplifier used to compare two voltages simultaneously and changes the o/p according to the comparison. In the same way, we can say ZCD is a comparator.



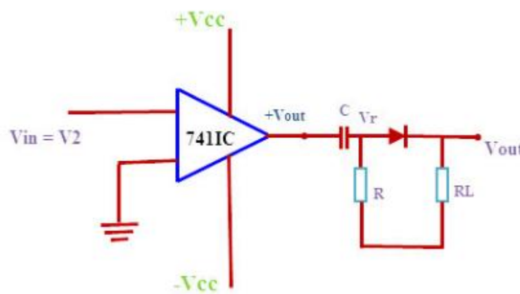
Zero-Crossing Detector Circuit

741 IC-based Zero Crossing Detector:

741 IC-based Zero Crossing Detector:

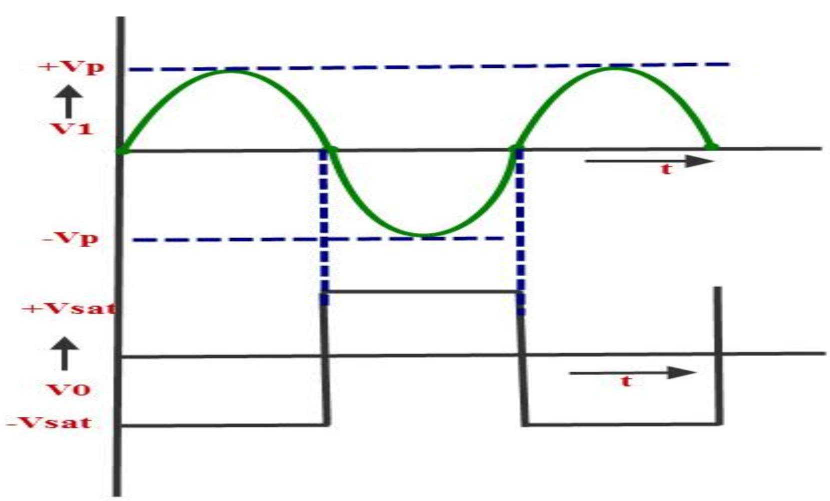
The zero-crossing detector circuit is a main application of the comparator circuit. It can also be named as the sine to square wave converter. For this, any one of the inverting/ noninverting comparators can be used as a zero crossing detector.

The only variation to be brought in is the Vref (reference voltage) with which the i/p voltage is to be compared, must be made reference voltage zero (Vref = 0V). An i/p sine wave is given as Vin. These are shown in the following inverting comparator circuit diagram and also i/p and o/p waveforms with a 0V reference voltage.



ZCD as Time Marker Generator

As shown in the below waveform, for a reference voltage (Vref), when the input sine wave permits through zero voltage and goes in the direction of positive. The o/p voltage is driven into negative saturation. In the same way, when the Vin permits through zero and goes in the direction of the negative, the Vout is driven to positive saturation. The diodes in the above circuit are called as clamp diodes. These diodes are used to guard the operational amplifier against damage due to an increase in Vin.



Applications of Zero Crossing Detector

Zero crossing detector circuits can be used to check the condition of an operational amplifier. And also used as a frequency counter and for switching purposes in power electronics circuits.

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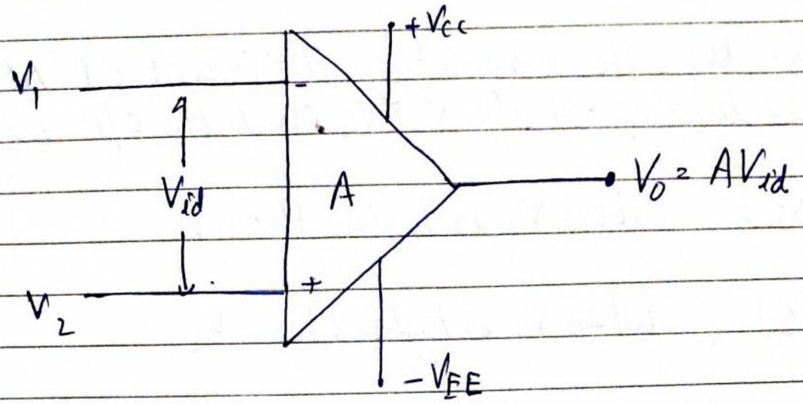
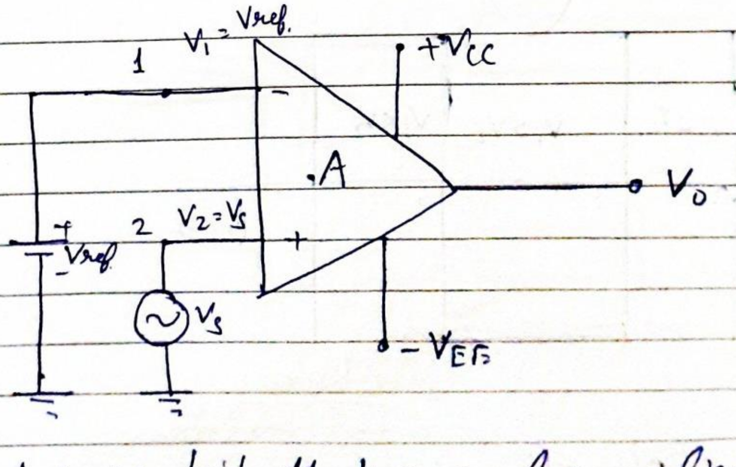
Comparator :- (Zero crossing Detector)



Compares a signal voltage on one i/p terminal with a reference voltage on the other i/p terminal. ~~with a reference voltage on the other i/p~~

OP-AMP which has a very high open loop gain (A).



Gain A is so high that even for negligible value of i/p voltage V_{id} the OP-Amp saturates to $\pm V_{sat}$ ~~the sig~~ +ve or -ve sign being decided by the sign of V_{id}.

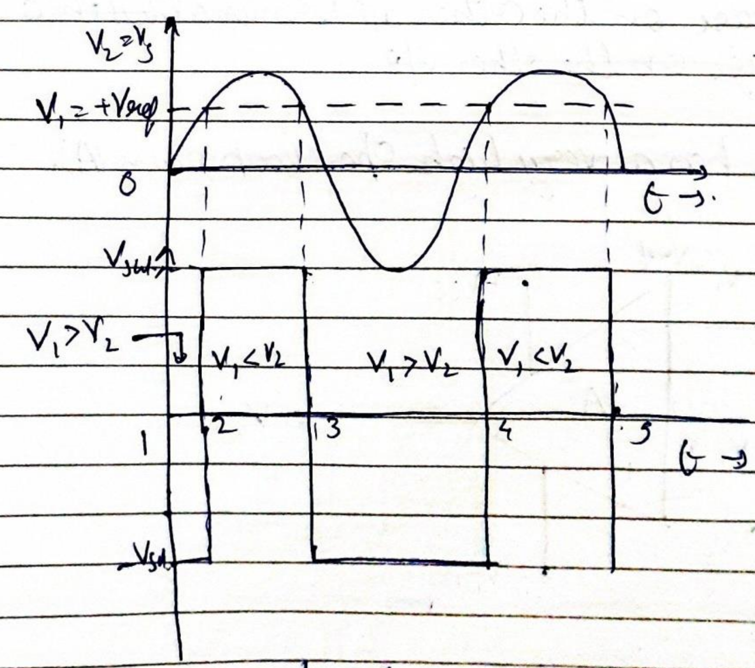
If $V_2 > V_1 \Rightarrow V_0 = A(V_{id}) = A(V_2 - V_1) = +V_{sat}$.
$V_2 < V_1 \Rightarrow V_0 = AV_{id} = A(V_2 - V_1) = -V_{sat}$.

Thus for the above mentioned circuit OP-AMP compares two of its i/p V_1 & V_2 and the o/p is obtained as

$+V_{sat}$, when V_2 is higher than V_1

$-V_{sat}$, when V_1 is higher than V_2.

Let $V_1 = V_{ref}$ & $V_2 = V_s$.



O/P when V_{ref} is +ve

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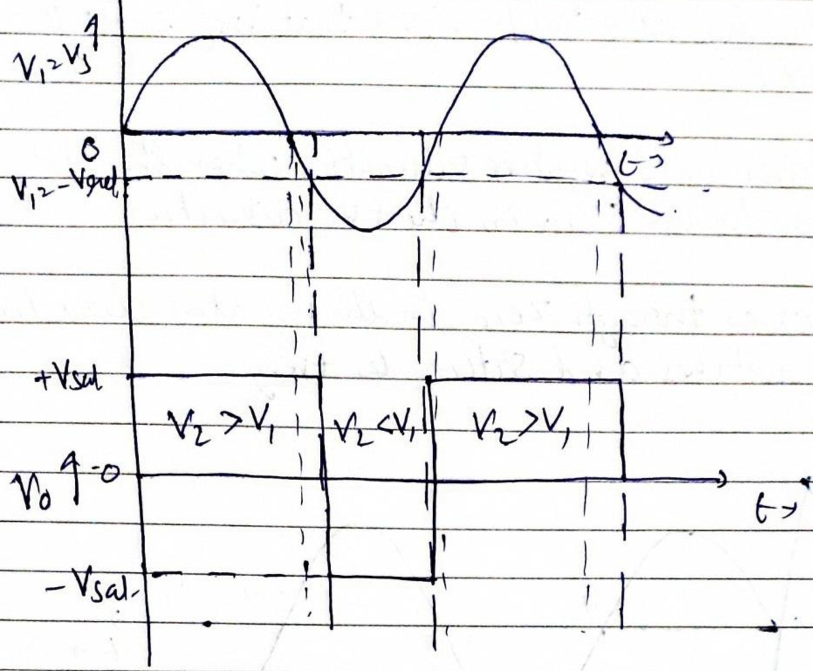
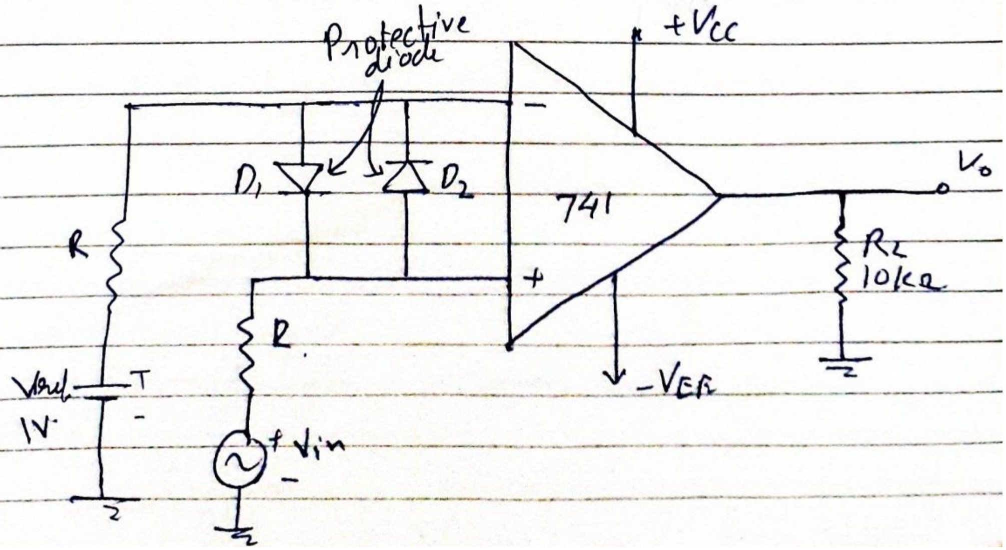


I/P & O/P when Vref is negative

Zero crossing detector / Sine wave to square wave converter.



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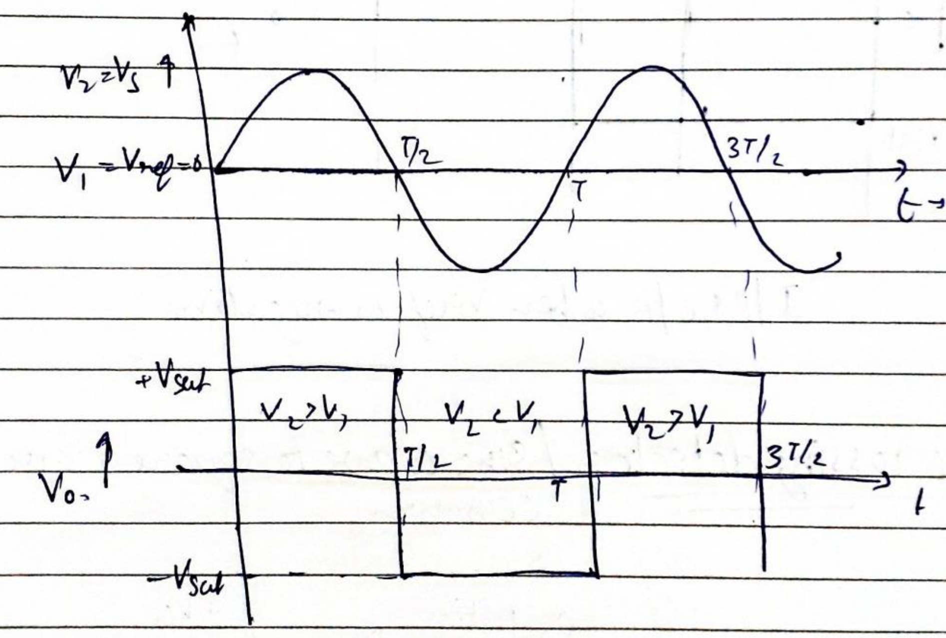
For zero crossing detector provided that V_{ref} is set to Zero. ($V_{ref} = 0V$)

O/P V_o is driven into negative saturation when the I/P S/g V_{in} passes through Zero in the +ve direction.

When V_{in} passes through zero in the negative direction the O/P V_o switches and saturates +vely.

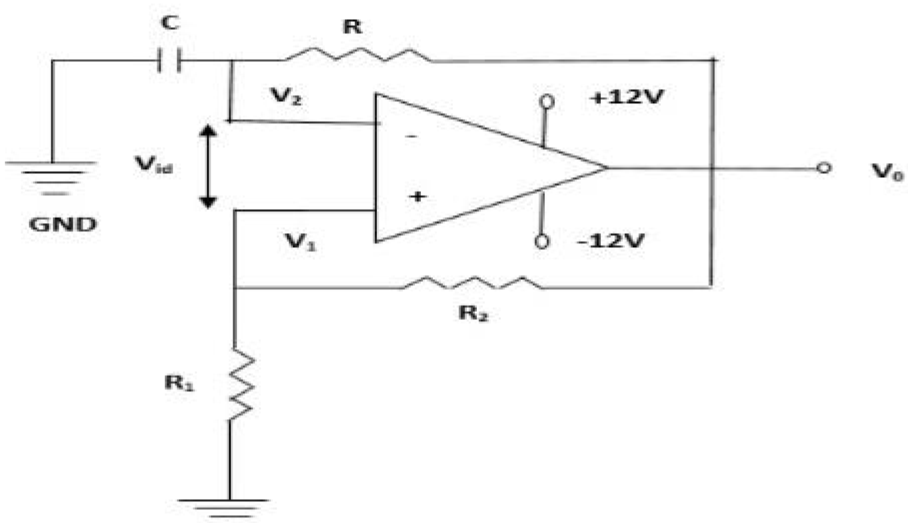


Square Wave Generator

The square wave generator is defined as an oscillator that gives the output without any input, without any input in the sense we should give input within zero seconds that means it must be an impulse input. This generator is used in digital signal processing and electronic applications. The square wave generator is also known as Astable Multivibrator or free-running and the frequency of the square wave generator is independent of the output voltage.

Square Wave Generator Circuit

To design the square wave generator, we need a capacitor, resistor, operational amplifier, and power supply. The capacitor and resistor are connected to the inverting terminal of the operational amplifier and the resistors R_1 and R_2 are connected to the non-inverting terminal of the operational amplifier. The circuit diagram of the square wave generator using an operational amplifier is shown below



Square Wave Generator Circuit using Op-Amp

If we force output to switch between the positive saturation voltage and the negative saturation voltage at the output of an operational amplifier we can achieve square wave as an output wave. Ideally without any input applied the output should be zero, it is expressed as

$$V_{out} \text{ (output voltage)} = 0 \text{ V} \quad \text{when } V_{in} \text{ (input voltage)} = 0 \text{ V}$$

The Resistors R_1 and R_2 form a voltage divider network. If the initial output voltage is non-zero we get voltage across V_b. Thus we get a positive input at the non-inverting terminal and the inverting terminal, then the output gets amplified by its gain and reaches the maximum output voltage thus we get the half of the square wave as shown in figure (a).

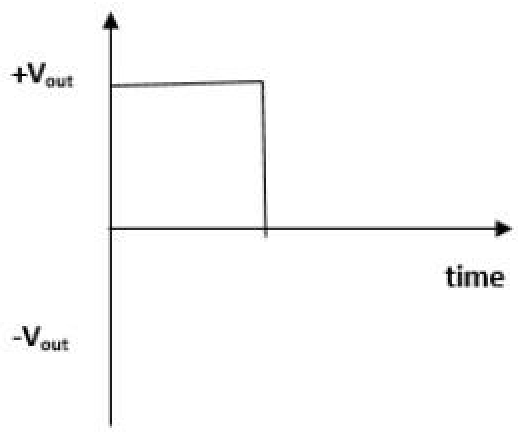


Figure (a)

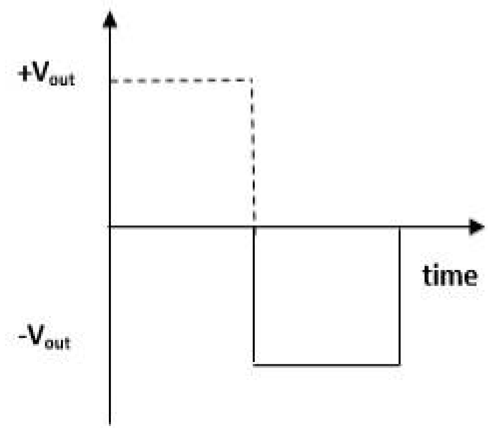


Figure (b)

The capacitor starts charging when we have a non-zero input at the inverting terminal. It will charge continuously until its voltage become greater than V_b. As soon as V_c is greater than the V_b ($V_c > V_b$). The inverting input becomes greater than the non-inverting input and hence op-amp output switches to negative voltage and gets amplified till $(-V_{out})_{max.}$ Thus will get the negative half of the square wave as shown in figure (b). This is the application of an op-amp as a square wave generator.

Time Period and Frequency Derivation of Square Wave Generator

In the figure, Square Wave Generator Circuit V_2 is the voltage across the capacitor, and V_1 is the node voltage at the positive terminal. The current through op-amp is zero because of the ideal characteristics of an op-amp. Let us consider node equations from the circuit diagram.

$$V_1 - V_o / R_2 + V_1 / R_1 = 0$$

$$V_1 \, [1/R_2 + 1/ R_1] = V_o / R_2$$

$$V_1 \, [R_1 + R_2 / R_1 \, R_2] = V_o / R_2$$

$$V_1(\alpha) = V_o \, ... \, eq \, (1)$$

Let's take

$$\alpha = R_1 + R_2 / R_1 = 1 + R_2 / R_1 > 1$$

therefore, $\alpha > 1$ and $V_0 > 1$

When $V_0 = + V_{sat}$

$$V_1 = V_0 / \alpha = + V_{sat} / \alpha = + V_1$$

When $V_0 = -V_{sat}$

$$V_1 = - V_{sat} / \alpha = -V_1$$

The voltage V_1 have only two possibilities + V_1 and – V_1, so whenever V_0 changes V_1 also changes. Now let's see how V_2 is going to change. The voltage V_2 will be the charging and discharging if we form a node equation here current through a capacitor is equal to the current.

$$C\ d/dt\ (0 - V_2) = V_2 - V_0 / R$$

$$-C\ d V_2/dt = V_2 - V_0 / R$$

$$d V_2 / V_0 - V_2 = dt / RC$$

If we solve the above equation will get that

$$\int_0^{V2} d\ (V_2/V_0 - V_2\ ) = \int_0^{t} dt/RC$$

Initially, we have to assume the voltage across the capacitor is zero

$$-\log\ (V_0 - V_2) = t / RC + K$$

$$\log\ (V_0 - V_2) = -t / RC + K$$

$$V_0 - V_2 = K\ e^{-t/RC} \quad \ldots\ldots\ldots\ldots \quad eq\ (2)$$

Substituting t=0, V_2 = 0 in the above equation will get

$$K = V_0 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq (3)}$$

$$\text{Where } e^0 = 1$$

Substitute eq (3) in eq (2) will get

$$V_0 - V_2 = K\, e^{-t/RC}$$

$$V_2 = V_0 - V_0\, e^{-t/RC}$$

$$V_2 = V_0\, [1 - e^{-t/RC}]$$

Applying initial conditions to the above equation

Stage 1: Let $V_2 = 0$, $V_0 = +V_{sat}$

In stage-1 the voltage V_2 is charging up to $+V_1$

Stage 2: Let $V_2 = 0$, $V_0 = -V_{sat}$

In stage-2 the voltage V_2 is discharging up to $-V_1$

$$[\log (V0 + V1 / V0 - V1)] = 1/RC\ [T/2]$$
$$[\log (\alpha V_1 + V_2 / \alpha V_1 - V_1)] = 1/RC\ [T/2] \ldots\ldots\ldots\ldots \text{eq(4)}$$

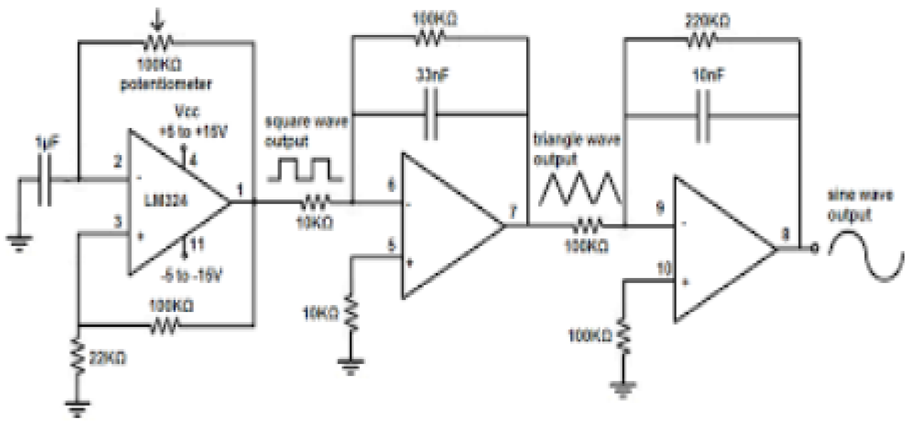
Substitute eq (1) in eq (4) will get

$$\log [V_1 (\alpha + 1) / V_1 (\alpha - 1)] = [T/2\ RC]$$
$$\log[((R_1+R_2/ R_1) +1)/((R_1+R_2/ R_1) -1)] = T/2\ RC$$
$$\log[R_1+R_2 + R_1/ R_1{}^{+} R_2 - R_1] = T/2\ RC$$
$$\log[2R_1+R_2 / R_2] = T/2\ RC$$
$$T = 2\ RC \log[2R_1+R_2 / R_2] \ldots\ldots\ldots \text{eq (5)}$$
$$f = 1 / T$$
$$= 1/ 2\ RC \log[2R_1+R_2 / R_2] \ldots\ldots\ldots \text{eq (6)}$$

An equation (5) and (6) are the time period and frequency of square wave generator

Function Generator Circuit

The function generator is a type of instrument which is used to generate the different type of waveforms like sinusoidal waveforms, triangular waveforms, rectangular waveforms, sawtooth waveforms, square waveforms and these different type of waveforms have different frequencies and they can have generated with the help of the instrument called function generator. The frequencies of these waveforms may be adjusted from a fraction of Hertz to several hundred kiloHertz and this generator have the capability to generate the different waveforms at the same time in different applications. The circuit diagram of the function generator using LM1458 is shown below



function-generator-circuit

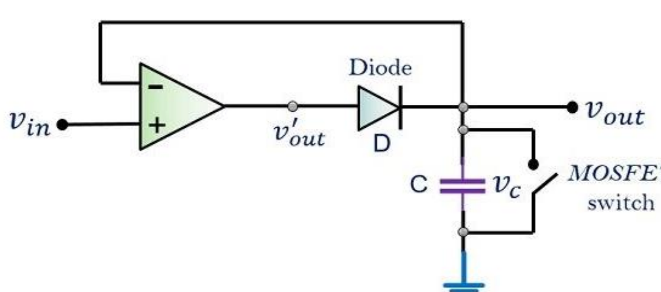
Advantages: The advantages of the square wave generator are

- Simple
- Easy to maintenance
- Cheap

Peak detector:

Peak detector circuits are used to determine the **peak** (maximum) value of an input signal. It stores the **peak** value of input voltages for infinite time duration until it comes to reset condition. The **peak detector** circuit utilizes its property of following the highest value of an input signal and storing it.

Circuit Working of Peak detector



It consists of a diode and capacitor along with an op-amp as shown above. The circuit does not require any complex component in order to determine the peak of the input waveform.

Working Principle

The working principle of the circuit is such that, the peak of the input waveform is followed and stored in terms of voltage in the capacitor.

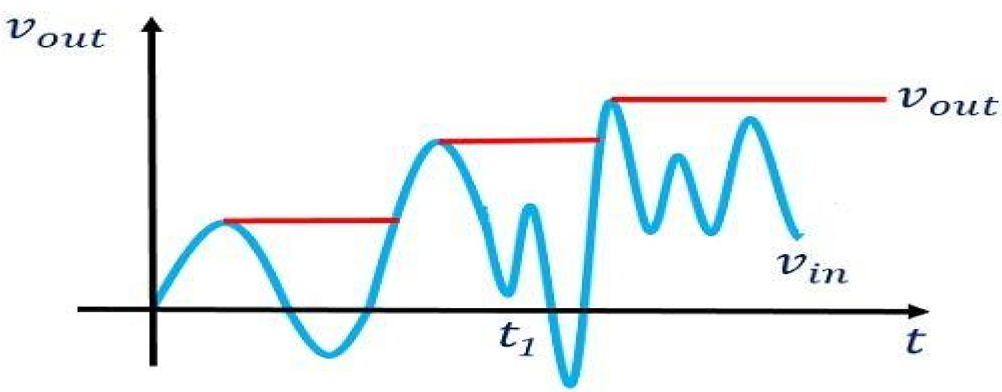
By the time on moving further, if the circuit detects a higher peak, the new peak value is stored in the capacitor until it is discharged.

The capacitor employed in the circuit is charged through the diode by the applied input signal. The small voltage drop across the diode is ignored and the capacitor is charged up to the highest peak of the applied input signal.

Let us consider initially the **capacitor** is charged to voltage $\mathbf{V_c}$. The diode employed in the circuit gets forward biased when the applied **input voltage** $\mathbf{V_{in}}$ exceeds the capacitor voltage $\mathbf{V_c}$. Thereby allowing the circuit to behave as a **voltage follower**. The output voltage follows the applied input voltage until V_{in} is more than V_c.

As the input voltage V_{in} reduces below the value of capacitive voltage V_c, it causes the diode to get reverse biased. In such condition, the capacitor retains the value until the input again exceeds the value stored in the capacitor.

The figure below shows the output voltage waveform for an applied input signal.



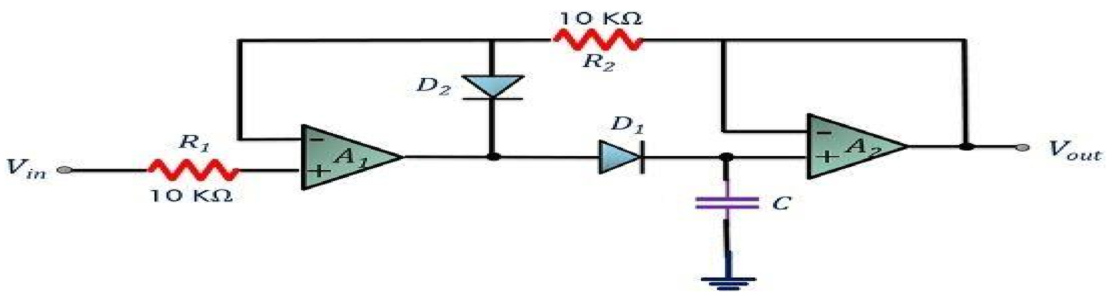
Output waveform for an applied input waveform

As we can see in the waveform shown above, at time t_1, the circuit misses the peak of the input signal as it is less than the previous peak of the input signal. Thereby allowing the capacitor to hold the value of the previously occurred peak.

As it is a positive peak detector, one can also construct a negative peak detector circuit, that will hold the lowest or most negative signal voltage. This is basically done by **reversing** the **polarities** of the diode in the circuit.

Improvement in peak detector circuit

The figure below shows the circuit of an improved peak detector. It is used to buffer the source of the signal from that of the capacitor.



Improved circuit of a Peak detector

Electronics Coach

As we can see the circuit is comprised of **2 Op-amps**. However, the basic circuit of the peak detector contains only one Op-amp. A high impedance load is offered by the **op-amp A_1** to the source. While **op-amp A_2** performs buffering action in between the load and capacitor.

The same basic principle is applied in this circuit also. The voltage at the output side is the similar as the peak of the input signal stored in the capacitor. Its working is such that, as the input voltage becomes higher than the charge stored on the capacitor, it charges itself with the new higher value of input signal.

However, for a smaller value of the input, the capacitor sticks to the previous higher value. The diode D_2 employed here restricts the output of op-amp A_1 from reaching negative saturation. This basically provides an improvement in the recovery time of op-amp A_1 at the condition of attaining a higher peak than the previous. The two resistances serve as the path for the bias current of input to A_1. To prevent the effect of the offset voltage, the value of the two resistances R_1 and R_2 are kept equal.

The **necessary frequency compensation** must be given to op-amp A_1 in order to have **stability against oscillations**.

Applications of Peak detector

1. It is used in the **analysis** of **spectral** and **mass spectrometer**.
2. Peak detector finds its application in destructive testing.

3. It is used for **instrumentation measurement**, mostly in amplitude modulated wave communication.
4. It widely finds applications in **sound measuring instruments**.

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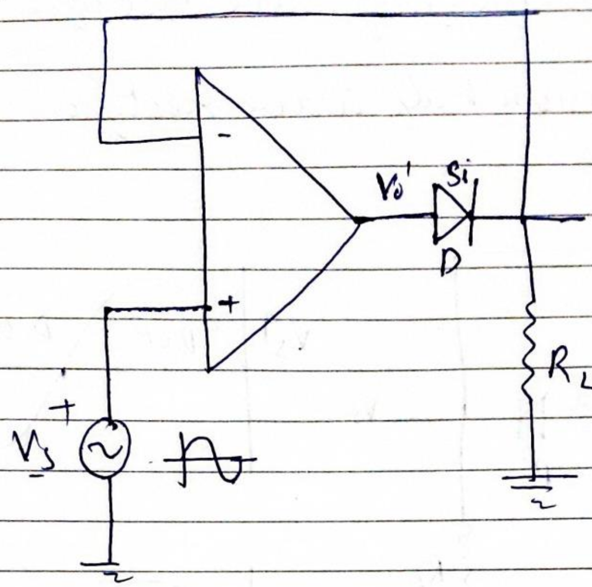
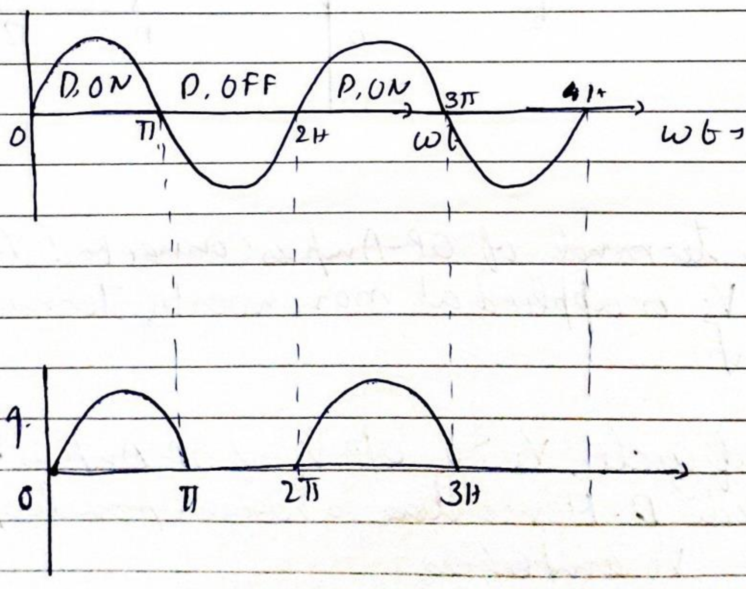
Precision Rectifier :-



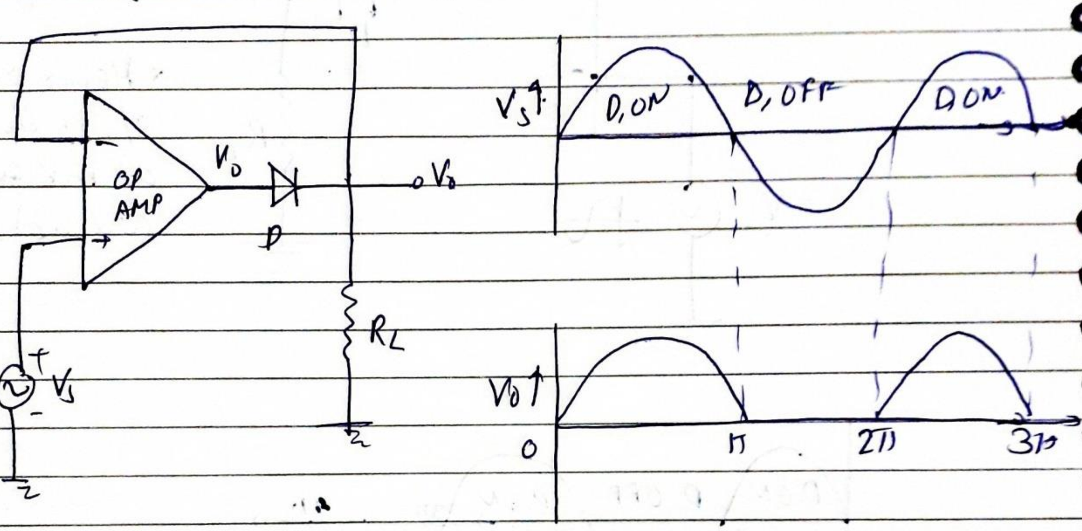
Problem of rect.
* If i/p voltage is below 0.7 diode is cutoff and o/p is zero
* Hence small s/g of the order of mV are not rectified



Hence small s/g of (mV) order can be rectified by precision rectifier.

Two types of precision half wave rectifier

① Positive Precision half wave rectifier.



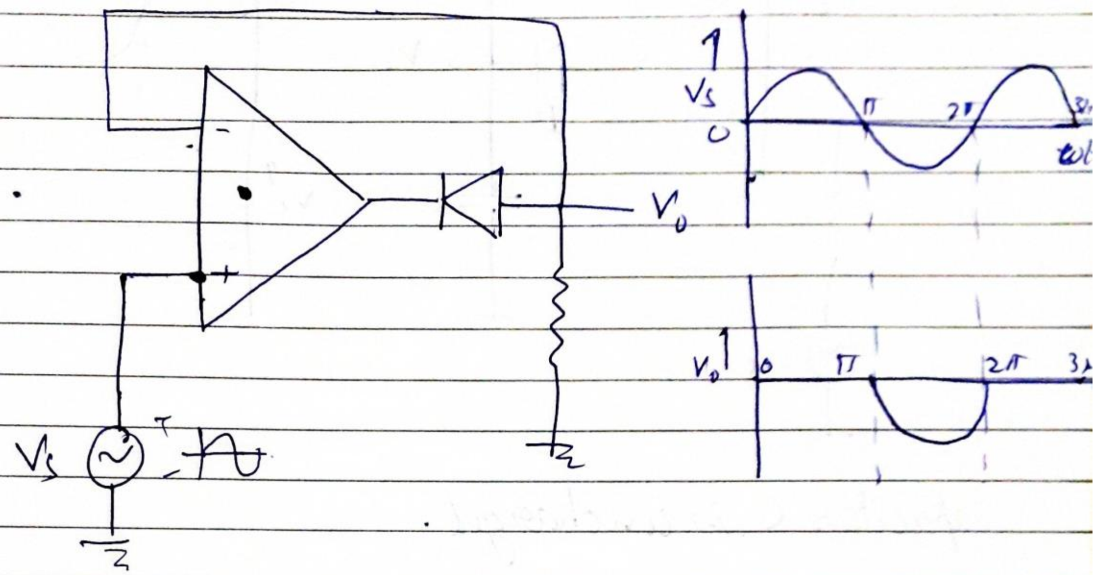
* Inverting terminal of OP-Amp is connected to o/p of diode. V_s is applied at non inverting terminal of OP-Amp.

For +ve half cycle, $V_s > 0$, O/P V_o' of OP-Amp is suff. to F-B diode D. Hence due to large open loop gain of OP-Amp, V_s amplifies

$$V_o' = V_s + 0.7V \rightarrow \text{diode is F.B.}$$

$$V_o = V_o' - 0.7V = (V_s + 0.7) - 0.7V = V_s$$

(i) Negative Precision Half Wave rectifier:-



For +ve half cycle:

$V_s > 0$, V_o' is +ve. Diode D is cut off and O/P voltage V_o is zero.

For -ve half cycle:

V_o' is negative and diode is FB and behaves like a short circuit, O/P is equal to V_s.