LICA

tutorialspoint

SIMPLY EASY LEARNING

001 ▶

About the Tutorial

Linear Integrated Circuits are solid state analog devices that can operate over a continuous range of input signals. Theoretically, they are characterized by an infinite number of operating states. Linear Integrated Circuits are widely used in amplifier circuits.

Audience

This tutorial is designed for readers who are aspiring to learn the concepts of Linear Integrated Circuits and their applications. It covers Linear Integrated Circuits such as op-amp, timer, phase locked loop and voltage regulator ICs.

After completing this tutorial, you will be able to know the functionality of various Linear Integrated Circuits and how to utilize them for a specific application, by combining with few additional electronic components.

Prerequisites

As a learner of this tutorial, you are expected to have a basic understanding of Electronic Circuits. If you are not familiar with these, we suggest you to refer to tutorials on Electronic Circuits first. That knowledge will be useful for understanding the concepts discussed in this tutorial.

Copyright & Disclaimer

Table of Contents

1. LICA – Basics of Integrated Circuits

An **electronic circuit** is a group of electronic components connected for a specific purpose.

A simple electronic circuit can be designed easily because it requires few discrete electronic components and connections. However, designing a complex electronic circuit is difficult, as it requires more number of discrete electronic components and their connections. It is also time taking to build such complex circuits and their reliability is also less. These difficulties can be overcome with Integrated Circuits.

Integrated Circuit (IC)

If multiple electronic components are interconnected on a single chip of semiconductor material, then that chip is called as an **Integrated Circuit (IC)**. It consists of both active and passive components.

This chapter discusses the advantages and types of ICs.

Advantages of Integrated Circuits

Integrated circuits offer many advantages. They are discussed below:

- **Compact size:** For a given functionality, you can obtain a circuit of smaller size using ICs, compared to that built using a discrete circuit.

- **Lesser weight:** A circuit built with ICs weighs lesser when compared to the weight of a discrete circuit that is used for implementing the same function of IC.

- **Low power consumption:** ICs consume lower power than a traditional circuit, because of their smaller size and construction.

- **Reduced cost:** ICs are available at much reduced cost than discrete circuits because of their fabrication technologies and usage of lesser material than discrete circuits.

- **Increased reliability:** Since they employ lesser connections, ICs offer increased reliability compared to digital circuits.

- **Improved operating speeds:** ICs operate at improved speeds because of their switching speeds and lesser power consumption.

Types of Integrated Circuits

Integrated circuits are of two types: **Analog Integrated Circuits** and **Digital Integrated Circuits**.

Analog Integrated Circuits

Integrated circuits that operate over an entire range of continuous values of the signal amplitude are called as **Analog Integrated Circuits**. These are further classified into the two types as discussed here:

- **Linear Integrated Circuits**: An analog IC is said to be Linear, if there exists a linear relation between its voltage and current. IC 741, an 8-pin Dual In-line Package (DIP)op-amp, is an example of Linear IC.

- **Radio Frequency Integrated Circuits**: An analog IC is said to be Non-Linear, if there exists a non-linear relation between its voltage and current. A Non-Linear IC is also called as Radio Frequency IC.

Digital Integrated Circuits

If the integrated circuits operate only at a few pre-defined levels instead of operating for an entire range of continuous values of the signal amplitude, then those are called as **Digital Integrated Circuits**.

In the coming chapters, we will discuss about various Linear Integrated Circuits and their applications.

2. LICA – Basics of Operational Amplifier

Operational Amplifier, also called as an Op-Amp, is an integrated circuit, which can be used to perform various linear, non-linear, and mathematical operations. An op-amp is a **direct coupled high gain amplifier**. You can operate op-amp both with AC and DC signals. This chapter discusses the characteristics and types of op-amps.

Construction of Operational Amplifier

An op-amp consists of differential amplifier(s), a level translator and an output stage. A differential amplifier is present at the input stage of an op-amp and hence an op-amp consists of **two input terminals**. One of those terminals is called as the **inverting terminal** and the other one is called as the **non-inverting terminal**. The terminals are named based on the phase relationship between their respective inputs and outputs.

Characteristics of Operational Amplifier

The important characteristics or parameters of an operational amplifier are as follows:

- Open loop voltage gain

- Output offset voltage

- Common Mode Rejection Ratio

- Slew Rate

This section discusses these characteristics in detail as given below:

Open loop voltage gain

The open loop voltage gain of an op-amp is its differential gain without any feedback path.

Mathematically, the open loop voltage gain of an op-amp is represented as:

$$A_V = \frac{V_0}{V_1 - V_2}$$

Output offset voltage

The voltage present at the output of an op-amp when its differential input voltage is zero is called as **output offset voltage**.

Common Mode Rejection Ratio

Common Mode Rejection Ratio (**CMRR**) of an op-amp is defined as the ratio of the closed loop differential gain, A_d and the common mode gain, A_c.

Mathematically, CMRR can be represented as:

$$CMRR = \frac{A_d}{A_c}$$

Note that the common mode gain, A_c of an op-amp is the ratio of the common mode output voltage and the common mode input voltage.

Slew Rate

Slew rate of an op-amp is defined as the maximum rate of change of the output voltage due to a step input voltage.

Mathematically, slew rate (SR) can be represented as:

$$SR = Maximum\ of\ \frac{dV_0}{dt}$$

where, V_0 is the output voltage. In general, slew rate is measured in either $V/\mu\ Sec$ or $V/m\ Sec$.

Types of Operational Amplifiers

An op-amp is represented with a triangle symbol having two inputs and one output.

Op-amps are of two types**: Ideal Op-Amp** and **Practical Op-Amp**.

They are discussed in detail as given below:

Ideal Op-Amp

An ideal op-amp exists only in theory, and does not exist practically. The **equivalent circuit** of an ideal op-amp is shown in the figure given below:
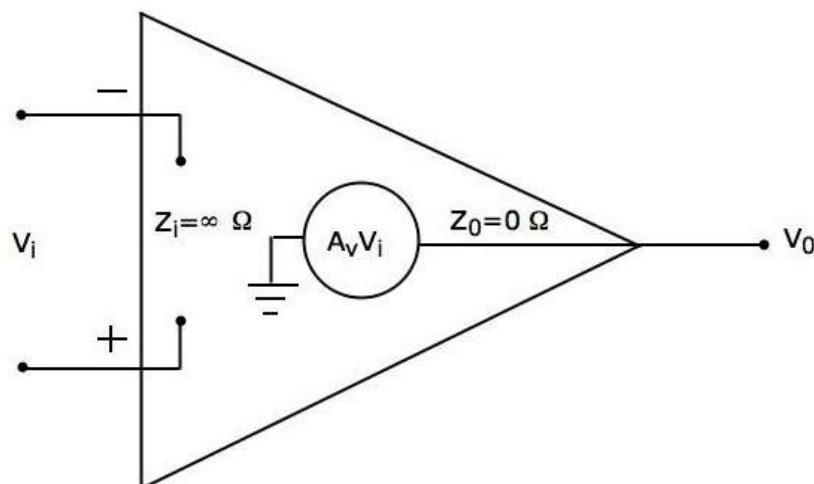
An **ideal op-amp** exhibits the following characteristics:

- Input impedance $Z_i = \infty \, \Omega$

- Output impedance $Z_0 = 0 \, \Omega$

- Open loop voltage gain $A_v = \infty$

- If (the differential) input voltage $V_i = 0 \, V$, then the output voltage will be $V_0 = 0 \, V$

- Bandwidth is **infinity**. It means, an ideal op-amp will amplify the signals of any frequency without any attenuation.

- Common Mode Rejection Ratio (**CMRR**) is **infinity**.

- Slew Rate (**SR**) is **infinity**. It means, the ideal op-amp will produce a change in the output instantly in response to an input step voltage.

Practical Op-Amp

Practically, op-amps are not ideal and deviate from their ideal characteristics because of some imperfections during manufacturing. The **equivalent circuit** of a practical op-amp is shown in the following figure:
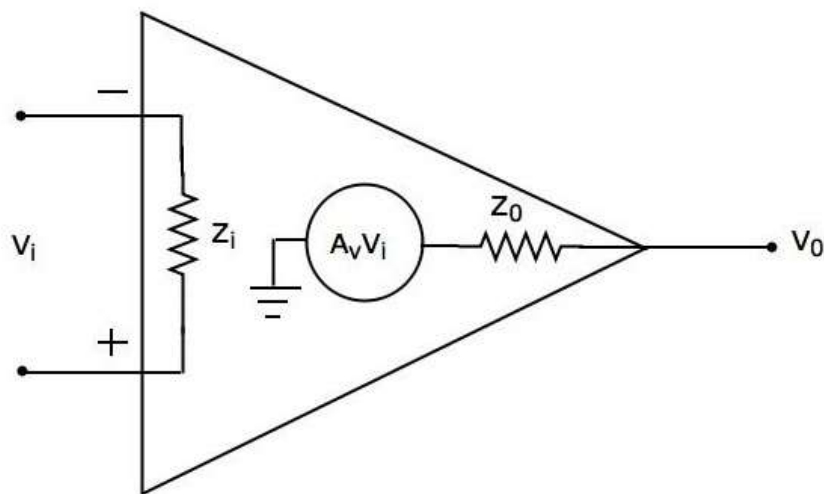
A **practical op-amp** exhibits the following characteristics:

- Input impedance, Z_i in the order of **Mega ohms**.

- Output impedance, Z_0 in the order of **few ohms**.

- Open loop voltage gain, A_v will be **high**.

When you choose a practical op-amp, you should check whether it satisfies the following conditions:

- Input impedance, Z_i should be as high as possible.

- Output impedance, Z_0 should be as low as possible.

- Open loop voltage gain, A_v should be as high as possible.

- Output offset voltage should be as low as possible.

- The operating Bandwidth should be as high as possible.

- CMRR should be as high as possible.

- Slew rate should be as high as possible.

Note: IC 741 op-amp is the most popular and practical op-amp.

A circuit is said to be **linear**, if there exists a linear relationship between its input and the output. Similarly, a circuit is said to be **non-linear**, if there exists a non-linear relationship between its input and output.

Op-amps can be used in both linear and non-linear applications. The following are the basic applications of op-amp:

- Inverting Amplifier

- Non-inverting Amplifier

- Voltage follower

This chapter discusses these basic applications in detail.

Inverting Amplifier

An inverting amplifier takes the input through its inverting terminal through a resistor R_1, and produces its amplified version as the output. This amplifier not only amplifies the input but also inverts it (changes its sign).

The **circuit diagram** of an inverting amplifier is shown in the following figure:
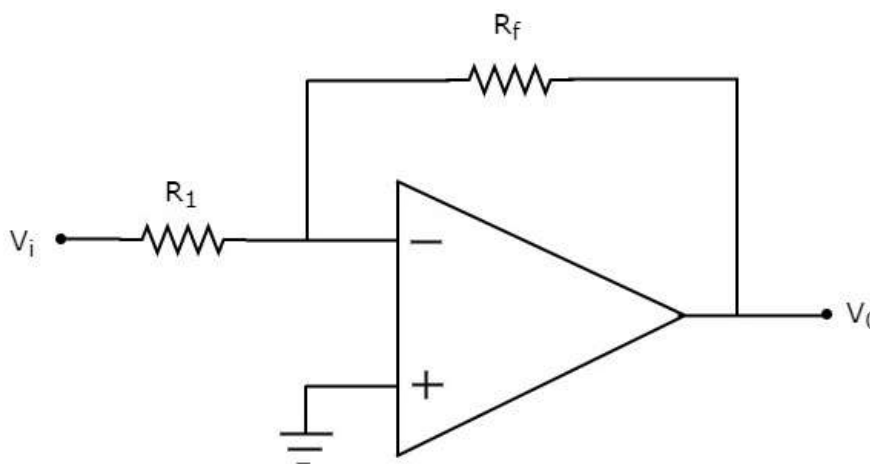
Note that for an op-amp, the voltage at the inverting input terminal is equal to the voltage at its non-inverting input terminal. Physically, there is no short between those two terminals but **virtually**, they are in **short** with each other.

In the circuit shown above, the non-inverting input terminal 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 zero volts.

11

The **nodal equation** at this terminal's node is as shown below:

$$\frac{0 - V_i}{R_1} + \frac{0 - V_0}{R_f} = 0$$

$$=> \frac{-V_i}{R_1} = \frac{V_0}{R_f}$$

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

$$=> \frac{V_0}{V_i} = -\frac{R_f}{R_1}$$

The ratio of the output voltage V_0 and the input voltage V_i is the voltage-gain or gain of the amplifier. Therefore, the **gain of inverting amplifier** is equal to $-\frac{R_f}{R_1}$.

Note that the gain of the inverting amplifier is having a **negative sign**. It indicates that there exists a 180^0 phase difference between the input and the output.

Non-Inverting Amplifier

A non-inverting amplifier takes the input through its non-inverting terminal, and produces its amplified version as the output. As the name suggests, this amplifier just amplifies the input, without inverting or changing the sign of the output.

The **circuit diagram** of a non-inverting amplifier is shown in the following figure:
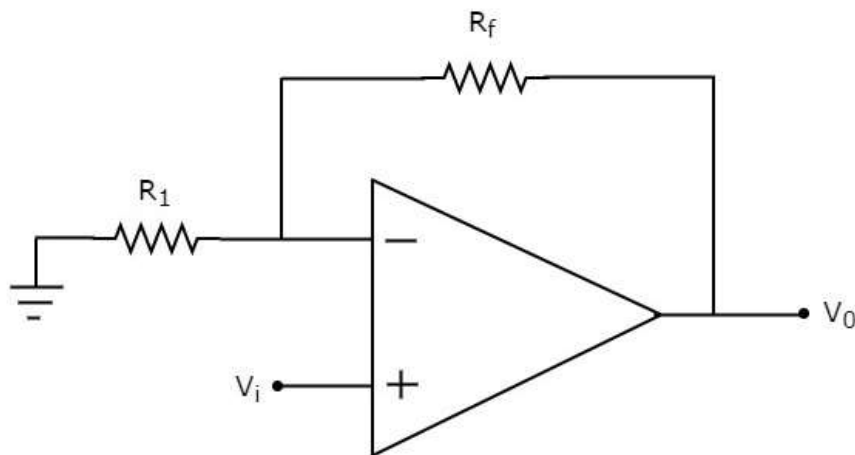
In the above circuit, the input voltage V_i is directly applied to the non-inverting input terminal of op-amp. So, the voltage at the non-inverting input terminal of the op-amp will be V_i.

By using **voltage division principle**, we can calculate the voltage at the inverting input terminal of the op-amp as shown below:

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

According to the **virtual short concept**, the voltage at the inverting input terminal of an op-amp is same as that of the voltage at its non-inverting input terminal.

12

$$=> V_1 = V_i$$

$$=> V_0 \left(\frac{R_1}{R_1 + R_f} \right) = V_i$$

$$=> \frac{V_0}{V_i} = \frac{R_1 + R_f}{R_1}$$

$$=> \frac{V_0}{V_i} = 1 + \frac{R_f}{R_1}$$

Now, the ratio of output voltage V_0 and input voltage V_i or the voltage-gain or **gain of the non-inverting amplifier** is equal to $1 + \frac{R_f}{R_1}$.

Note that the gain of the non-inverting amplifier is having a **positive sign**. It indicates that there is no phase difference between the input and the output.

Voltage follower

A **voltage follower** is an electronic circuit, which produces an output that follows the input voltage. It is a special case of non-inverting amplifier.

If we consider the value of feedback resistor, R_f as zero ohms and (or) the value of resistor, R_1 as infinity ohms, then a non-inverting amplifier becomes a voltage follower. The **circuit diagram** of a voltage follower is shown in the following figure:
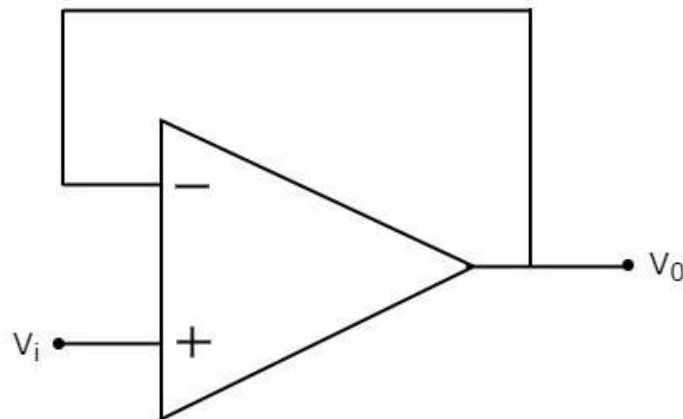
In the above circuit, the input voltage V_i is directly applied to the non-inverting input terminal of the op-amp. So, the voltage at the non-inverting input terminal of op-amp is equal to V_i. Here, the output is directly connected to the inverting input terminal of op-amp. Hence, the voltage at the inverting input terminal of op-amp is equal to V_0.

According to the **virtual short concept**, the voltage at the inverting input terminal of the op-amp is same as that of the voltage at its non-inverting input terminal.

$$=> V_0 = V_i$$

So, the output voltage V_0 of a voltage follower is equal to its input voltage V_i.

Thus, the **gain of a voltage follower** is equal to one since, both output voltage V_0 and input voltage V_i of voltage follower are same.

4. LICA – Arithmetic Circuits

In the previous chapter, we discussed about the basic applications of op-amp. Note that they come under the linear operations of an op-amp. In this chapter, let us discuss about arithmetic circuits, which are also linear applications of op-amp.

The electronic circuits, which perform arithmetic operations are called as **arithmetic circuits**. Using op-amps, you can build basic arithmetic circuits such as an **adder** and a **subtractor**. In this chapter, you will learn about each of them in detail.

Adder

An adder is an electronic circuit that produces an output, which is equal to the sum of the applied inputs. This section discusses about the op-amp based adder circuit.

An op-amp based adder produces an output equal to the sum of the input voltages applied at its inverting terminal. It is also called as a **summing amplifier**, since the output is an amplified one.

The **circuit diagram** of an op-amp based adder is shown in the following figure:
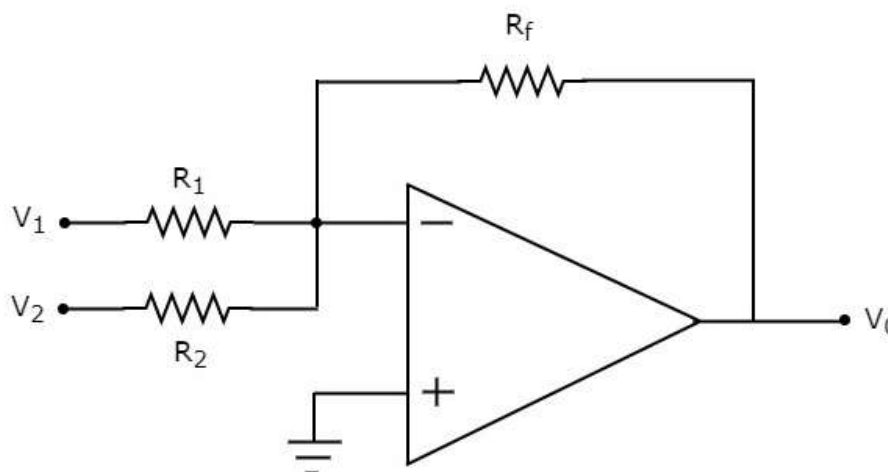
In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied at its non-inverting input terminal.

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

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

$$\frac{0 - V_1}{R_1} + \frac{0 - V_2}{R_2} + \frac{0 - V_0}{R_f} = 0$$

$$=> -\frac{V_1}{R_1} - \frac{V_2}{R_2} = \frac{V_0}{R_f}$$

tutorialspoint
SIMPLYEASYLEARNING

$$=> V_0 = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} \right)$$

If $R_f = R_1 = R_2 = R$, then the output voltage V_0 will be:

$$V_0 = -R \left(\frac{V_1}{R} + \frac{V_2}{R} \right)$$

$$=> V_0 = -(V_1 + V_2)$$

Therefore, the op-amp based adder circuit discussed above will produce the sum of the two input voltages V_1 and V_2, as the output, when all the resistors present in the circuit are of same value. Note that the output voltage V_0 of an adder circuit is having a **negative sign**, which indicates that there exists a 180^0 phase difference between the input and the output.

Subtractor

A subtractor is an electronic circuit that produces an output, which is equal to the difference of the applied inputs. This section discusses about the op-amp based subtractor circuit.

An op-amp based subtractor produces an output equal to the difference of the input voltages applied at its inverting and non-inverting terminals. It is also called as a **difference amplifier**, since the output is an amplified one.

The **circuit diagram** of an op-amp based subtractor is shown in the following figure:
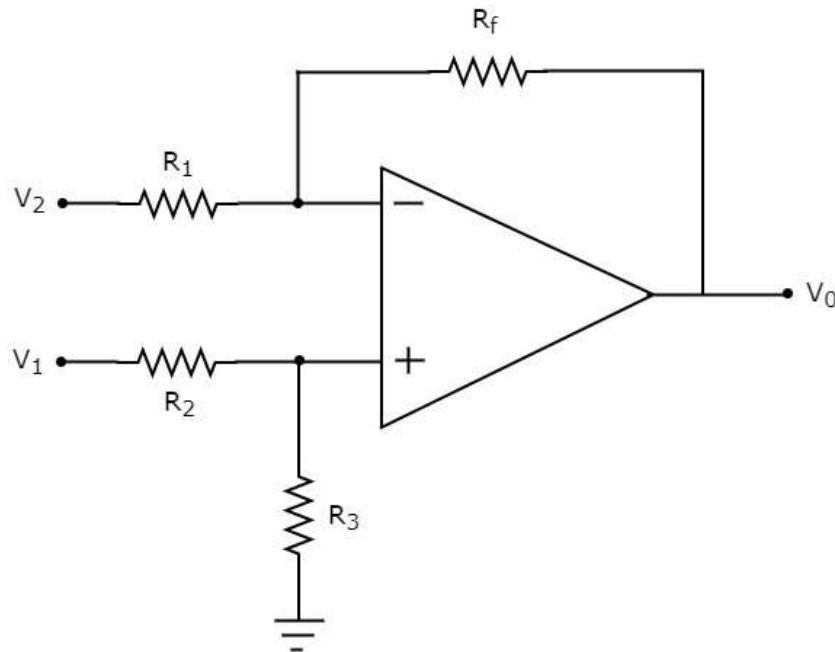
Now, let us find the expression for output voltage V_0 of the above circuit using **superposition theorem** using the following steps:

Step1

Firstly, let us calculate the output voltage V_{01} by considering only V_1.

For this, eliminate V_2 by making it short circuit. Then we obtain the **modified circuit diagram** as shown in the following figure:

tutorialspoint
SIMPLYEASYLEARNING
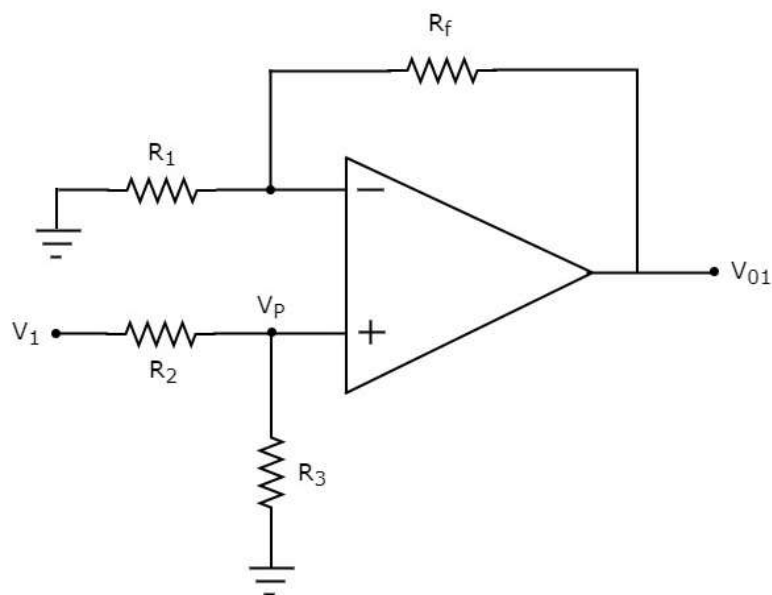
Now, using the **voltage division principle**, calculate the voltage at the non-inverting input terminal of the op-amp.

$$=> V_P = V_1 \left(\frac{R_3}{R_2 + R_3} \right)$$

Now, the above circuit looks like a non-inverting amplifier having input voltage V_P. Therefore, the output voltage V_{01} of above circuit will be

$$V_{01} = V_P \left(1 + \frac{R_f}{R_1} \right)$$

Substitute, the value of V_P in above equation, we obtain the output voltage V_{01} by considering only V_1, as:

$$V_{01} = V_1 \left(\frac{R_3}{R_2 + R_3} \right) \left(1 + \frac{R_f}{R_1} \right)$$

Step2

In this step, let us find the output voltage, V_{02} by considering only V_2. Similar to that in the above step, eliminate V_1 by making it short circuit. The **modified circuit diagram** is shown in the following figure.
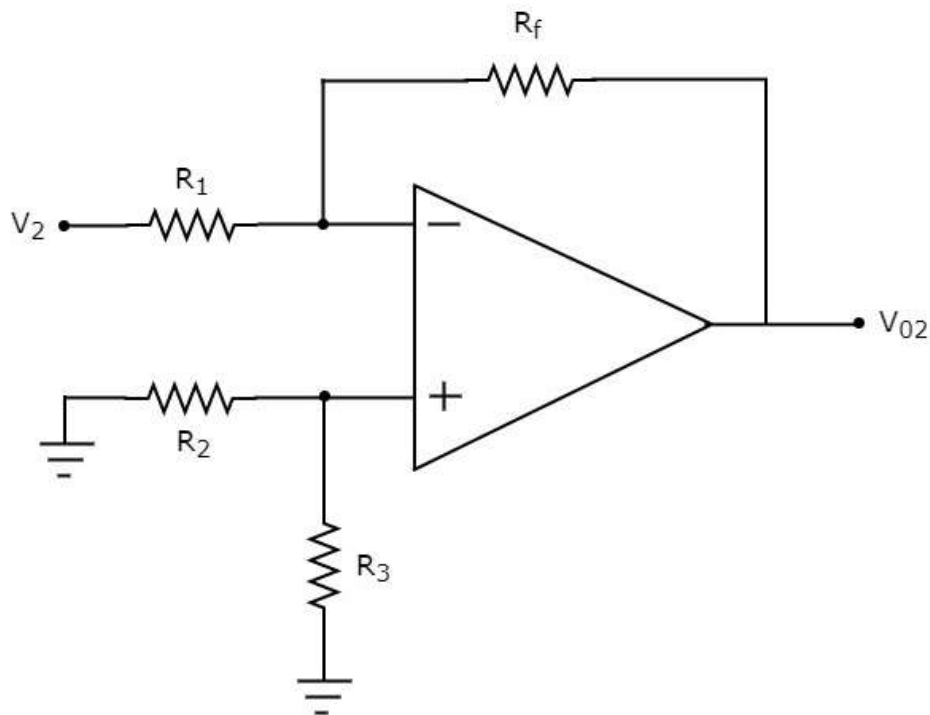
You can observe that the voltage at the non-inverting input terminal of the op-amp will be zero volts. It means, the above circuit is simply an **inverting op-amp**. Therefore, the output voltage V_{02} of above circuit will be:

$$V_{02} = \left(-\frac{R_f}{R_1} \right) V_2$$

Step3

In this step, we will obtain the output voltage V_0 of the subtractor circuit by **adding the output voltages** obtained in Step1 and Step2. Mathematically, it can be written as:

$$V_0 = V_{01} + V_{02}$$

Substituting the values of V_{01} and V_{02} in the above equation, we get:

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

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

If $R_f = R_1 = R_2 = R_3 = R$, then the output voltage V_0 will be:

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

$$=> V_0 = V_1 \left(\frac{R}{2R} \right) (2) - (1) V_2$$

$$=> V_0 = V_1 - V_2$$

Thus, the op-amp based subtractor circuit discussed above will produce an output, which is the difference of two input voltages V_1 and V_2, when all the resistors present in the circuit are of same value.

5. LICA – Differentiator and Integrator

The electronic circuits which perform the mathematical operations such as differentiation and integration are called as differentiator and integrator, respectively.

This chapter discusses in detail about op-amp based **differentiator** and **integrator**. Please note that these also come under linear applications of op-amp.

Differentiator

A **differentiator** is an electronic circuit that produces an output equal to the first derivative of its input. This section discusses about the op-amp based differentiator in detail.

An op-amp based differentiator produces an output, which is equal to the differential of input voltage that is applied to its inverting terminal. The **circuit diagram** of an op-amp based differentiator is shown in the following figure:
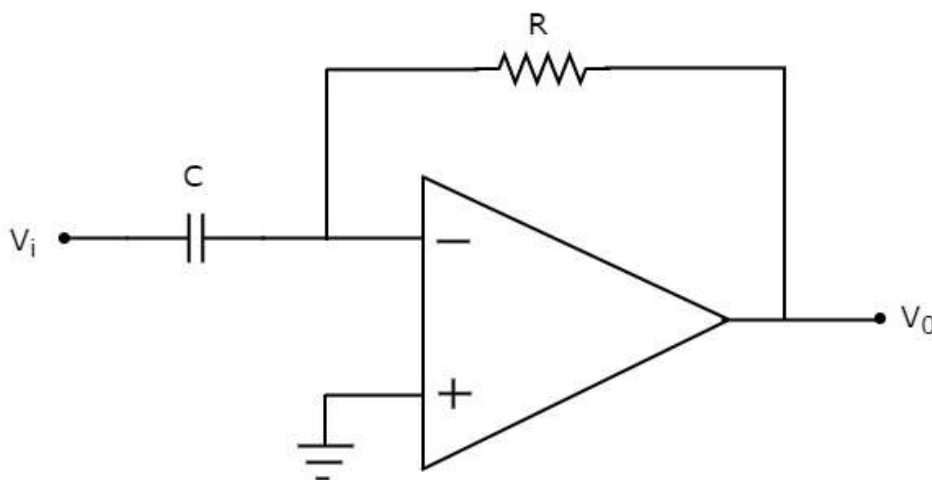
In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal.

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 the inverting input terminal of op-amp will be zero volts.

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

$$C\frac{d(0 - V_i)}{dt} + \frac{0 - V_0}{R} = 0$$

$$=> -C\frac{dV_i}{dt} = \frac{V_0}{R}$$

$$=> V_0 = -RC\frac{dV_i}{dt}$$

If $RC = 1\ sec$, then the output voltage V_0 will be:

$$V_0 = -\frac{dV_i}{dt}$$

Thus, the op-amp based differentiator circuit shown above will produce an output, which is the differential of input voltage V_i, when the magnitudes of impedances of resistor and capacitor are reciprocal to each other.

Note 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.

Integrator

An **integrator** is an electronic circuit that produces an output that is the integration of the applied input. This section discusses about the op-amp based integrator.

An op-amp based integrator produces an output, which is an integral of the input voltage applied to its inverting terminal. The **circuit diagram** of an op-amp based integrator is shown in the following figure:
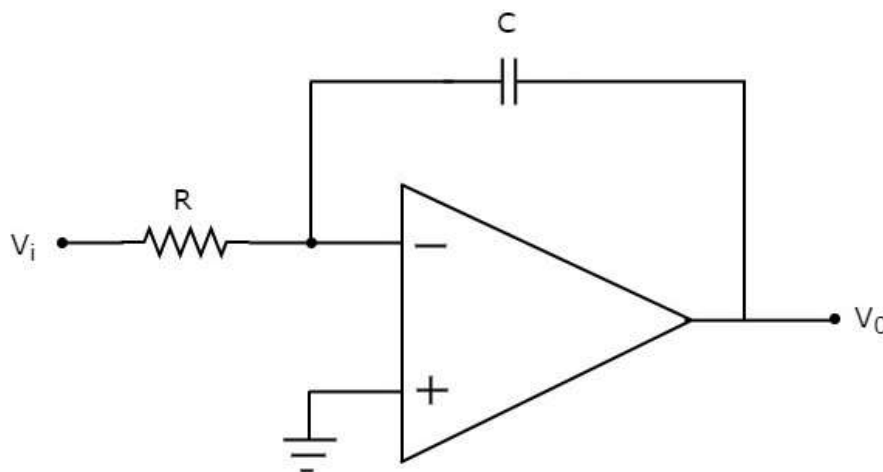
In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal.

According to **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 the inverting input terminal of op-amp will be zero volts.

The **nodal equation** at the inverting input terminal is:

$$\frac{0 - V_i}{R} + C\frac{d(0 - V_0)}{dt} = 0$$

$$=> -\frac{V_i}{R} = C\frac{dV_0}{dt}$$

$$=> \frac{dV_0}{dt} = -\frac{V_i}{RC}$$

$$=> dV_0 = \left(-\frac{V_i}{RC}\right) dt$$

Integrating both sides of the equation shown above, we get:

$$\int dV_0 = \int \left(-\frac{V_i}{RC}\right) dt$$

$$=> V_0 = -\frac{1}{RC} \int V_i \, dt$$

If $RC = 1 \, sec$, then the output voltage, V_0 will be:

$$V_0 = -\int V_i \, dt$$

So, the op-amp based integrator circuit discussed above will produce an output, which is the integral of input voltage V_i, when the magnitude of impedances of resistor and capacitor are reciprocal to each other.

Note: The output voltage, V_0 is having a **negative sign**, which indicates that there exists 180^0 phase difference between the input and the output.

Voltage and current are the basic electrical quantities. They can be converted into one another depending on the requirement. **Voltage to Current Converter** and **Current to Voltage Converter** are the two circuits that help in such conversion. These are also linear applications of op-amps. This chapter discusses them in detail.

Voltage to Current Converter

A **voltage to current converter** or **V to I converter,** is an electronic circuit that takes current as the input and produces voltage as the output. This section discusses about the op-amp based voltage to current converter.

An op-amp based voltage to current converter produces an output current when a voltage is applied to its non-inverting terminal. The **circuit diagram** of an op-amp based voltage to current converter is shown in the following figure.
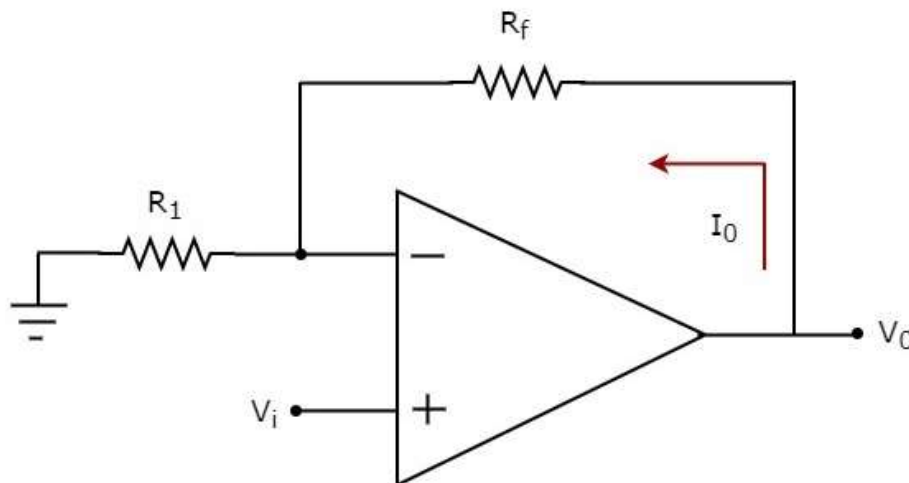
In the circuit shown above, an input voltage V_i is applied at the non-inverting input terminal of the op-amp. According to the **virtual short concept**, the voltage at the inverting input terminal of an op-amp will be equal to the voltage at its non-inverting input terminal . So, the voltage at the inverting input terminal of the op-amp will be V_i.

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

$$\frac{V_i}{R_1} - I_0 = 0$$

$$=> I_0 = \frac{V_i}{R_1}$$

Thus, the **output current** I_0 of a voltage to current converter is the ratio of its input voltage V_i and resistance R_1.

We can re-write the above equation as:

$$\frac{I_0}{V_i} = \frac{1}{R_1}$$

The above equation represents the ratio of the output current I_0 and the input voltage V_i & it is equal to the reciprocal of resistance R_1. The ratio of the output current I_0 and the input voltage V_i is called as **Transconductance**.

We know that the ratio of the output and the input of a circuit is called as **gain**. So, the gain of an voltage to current converter is the Transconductance and it is equal to the reciprocal of resistance R_1.

Current to Voltage Converter

A **current to voltage converter** or **I to V converter** is an electronic circuit that takes current as the input and produces voltage as the output. This section discusses about the op-amp based current to voltage converter.

An op-amp based current to voltage converter produces an output voltage when current is applied to its inverting terminal. The **circuit diagram** of an op-amp based current to voltage converter is shown in the following figure.
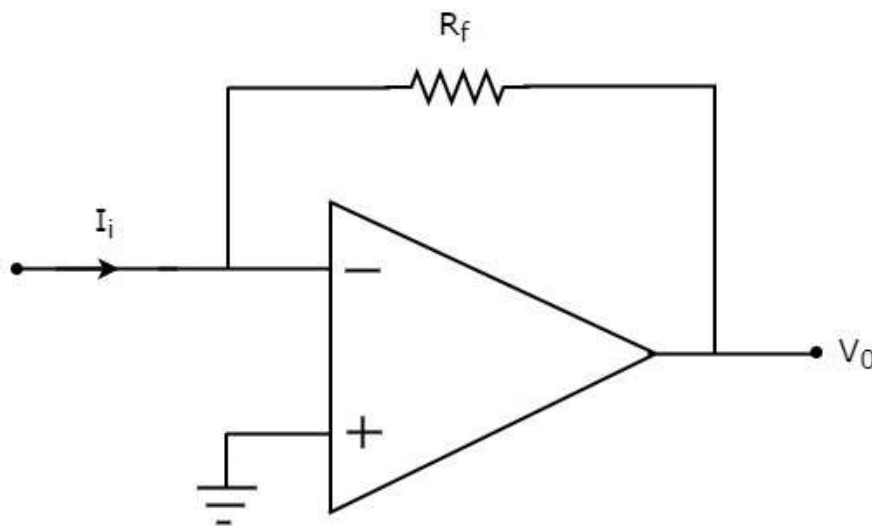
In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied at its non-inverting input terminal.

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 of the op-amp will be zero volts.

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

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

$$-I_i = \frac{V_0}{R_f}$$

$$V_0 = -R_f I_i$$

Thus, the **output voltage, V_0** of current to voltage converter is the (negative) product of the feedback resistance, R_f and the input current, I_i. 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 current and output voltage.

We can re-write the above equation as:

$$\frac{V_0}{I_i} = -R_f$$

The above equation represents the ratio of the output voltage V_0 and the input current I_i, and it is equal to the negative of feedback resistance, R_f. The ratio of output voltage V_0 and input current I_i is called as **Transresistance**.

We know that the ratio of output and input of a circuit is called as **gain**. So, the gain of a current to voltage converter is its trans resistance and it is equal to the (negative) feedback resistance R_f.

7. LICA – Comparators

A **comparator** is an electronic circuit, which compares the two inputs that are applied to it and produces an output. The output value of the comparator indicates which of the inputs is greater or lesser. Please note that comparator falls under non-linear applications of ICs.

An op-amp consists of two input terminals and hence an op-amp based comparator compares the two inputs that are applied to it and produces the result of comparison as the output. This chapter discusses about **op-amp based comparators**.

Types of Comparators

Comparators are of two types: **Inverting** and **Non-inverting.** This section discusses about these two types in detail.

Inverting Comparator

An **inverting comparator** is an op-amp based comparator for which a reference voltage is applied to its non-inverting terminal and the input voltage is applied to its inverting terminal. This comparator is called as **inverting** comparator because the input voltage, which has to be compared is applied to the inverting terminal of op-amp.

The **circuit diagram** of an inverting comparator is shown in the following figure.
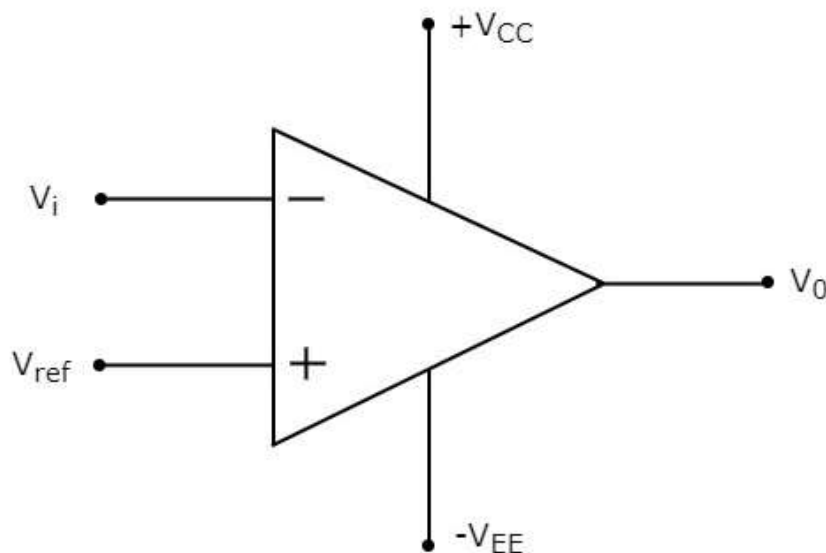
The **operation** of an inverting comparator is very simple. It produces one of the two values, $+V_{Sat}$ and $-V_{Sat}$ at the output based on the values of its input voltage V_i and the reference voltage V_{ref}.

- The output value of an inverting comparator will be $-V_{Sat}$, for which the input voltage V_i is greater than the reference voltage V_{ref}.

- The output value of an inverting comparator will be $+V_{Sat}$, for which the input voltage V_i is less than the reference voltage V_{ref}.

Example

Let us draw the **output wave form** of an inverting comparator, when a sinusoidal input signal and a reference voltage of zero volts are applied to its inverting and non-inverting terminals respectively.

The **operation** of the inverting comparator shown above is discussed below:

- During the **positive half cycle** of the sinusoidal input signal, the voltage present at the inverting terminal of op-amp is greater than zero volts. Hence, the output value of the inverting comparator will be equal to $-V_{Sat}$ during positive half cycle of the sinusoidal input signal.

- Similarly, during the **negative half cycle** of the sinusoidal input signal, the voltage present at the inverting terminal of the op-amp is less than zero volts. Hence, the output value of the inverting comparator will be equal to $+V_{Sat}$ during negative half cycle of the sinusoidal input signal.

The following figure shows the **input and output waveforms** of an inverting comparator, when the reference voltage is zero volts.
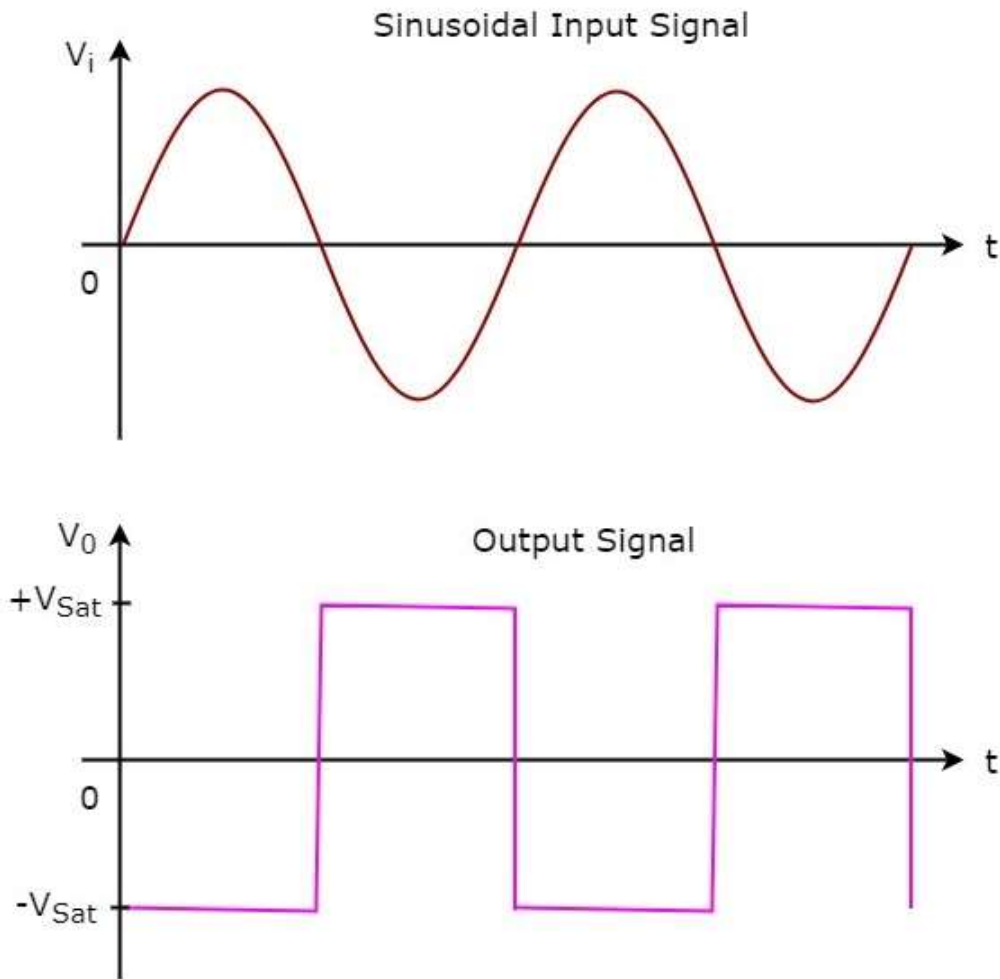
In the figure shown above, we can observe that the output transitions either from $-V_{Sat}$ to $+V_{Sat}$ or from $+V_{Sat}$ to $-V_{Sat}$ whenever the sinusoidal input signal is crossing zero volts. In other words, output changes its value when the input is crossing zero volts. Hence, the above circuit is also called as **inverting zero crossing detector**.

Non-Inverting Comparator

A non-inverting comparator is an op-amp based comparator for which a reference voltage is applied to its inverting terminal and the input voltage is applied to its non-inverting terminal. This op-amp based comparator is called as **non-inverting** comparator because the input voltage, which has to be compared is applied to the non-inverting terminal of the op-amp.

The **circuit diagram** of a non-inverting comparator is shown in the following figure:
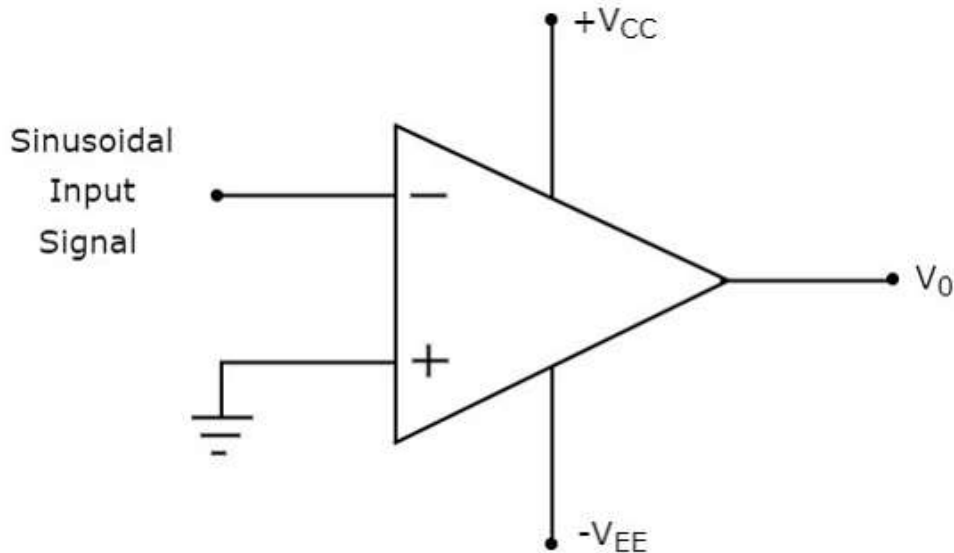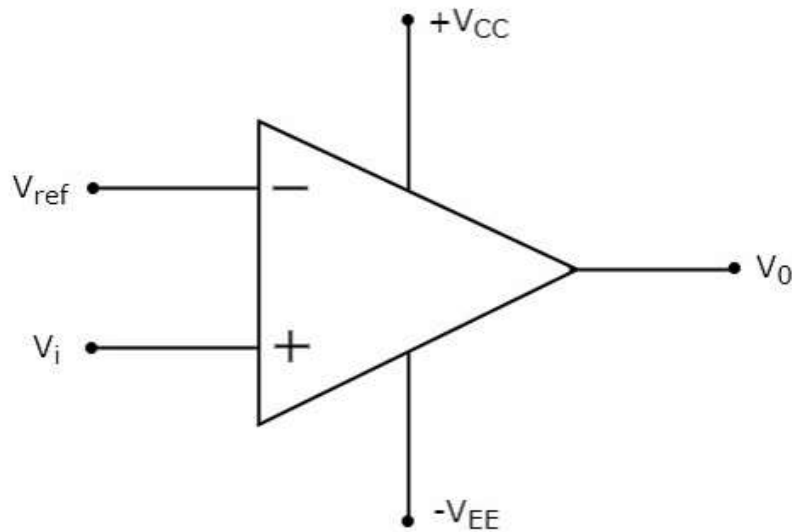

The **operation** of a non-inverting comparator is very simple. It produces one of the two values, $+V_{Sat}$ and $-V_{Sat}$ at the output based on the values of input voltage V_i and the reference voltage V_{ref}.

- The output value of a non-inverting comparator will be $+V_{Sat}$, for which the input voltage V_i is greater than the reference voltage V_{ref}.

- The output value of a non-inverting comparator will be $-V_{Sat}$, for which the input voltage V_i is less than the reference voltage, V_{ref}.

Example

Let us draw the **output wave form** of a non-inverting comparator, when a sinusoidal input signal and reference voltage of zero volts are applied to the non-inverting and inverting terminals of the op-amp respectively.
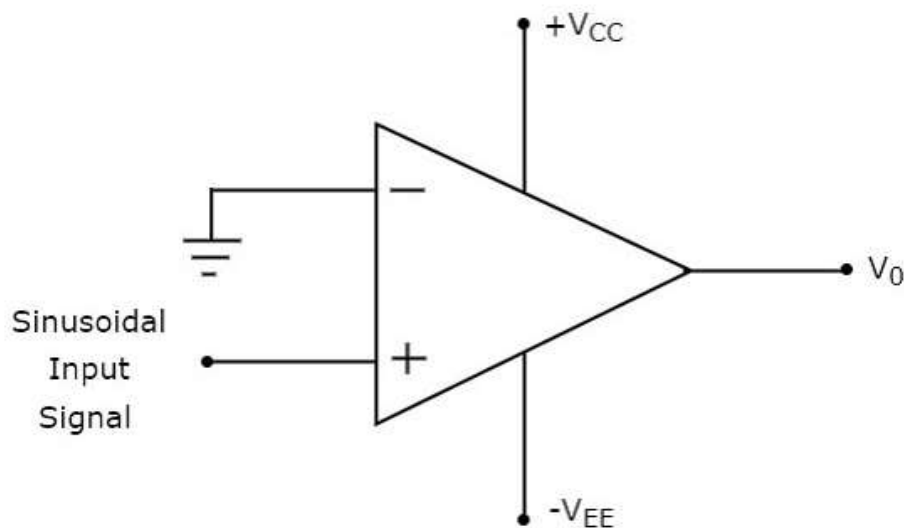
The **operation** of a non-inverting comparator is explained below:

- During the **positive half cycle** of the sinusoidal input signal, the voltage present at the non-inverting terminal of op-amp is greater than zero volts. Hence, the output value of a non-inverting comparator will be equal to $+V_{Sat}$ during the positive half cycle of the sinusoidal input signal.

- Similarly, during the **negative half cycle** of the sinusoidal input signal, the voltage present at the non-inverting terminal of op-amp is less than zero volts. Hence, the output value of non-inverting comparator will be equal to $-V_{Sat}$ during the negative half cycle of the sinusoidal input signal.

The following figure shows the **input and output waveforms** of a non-inverting comparator, when the reference voltage is zero volts.
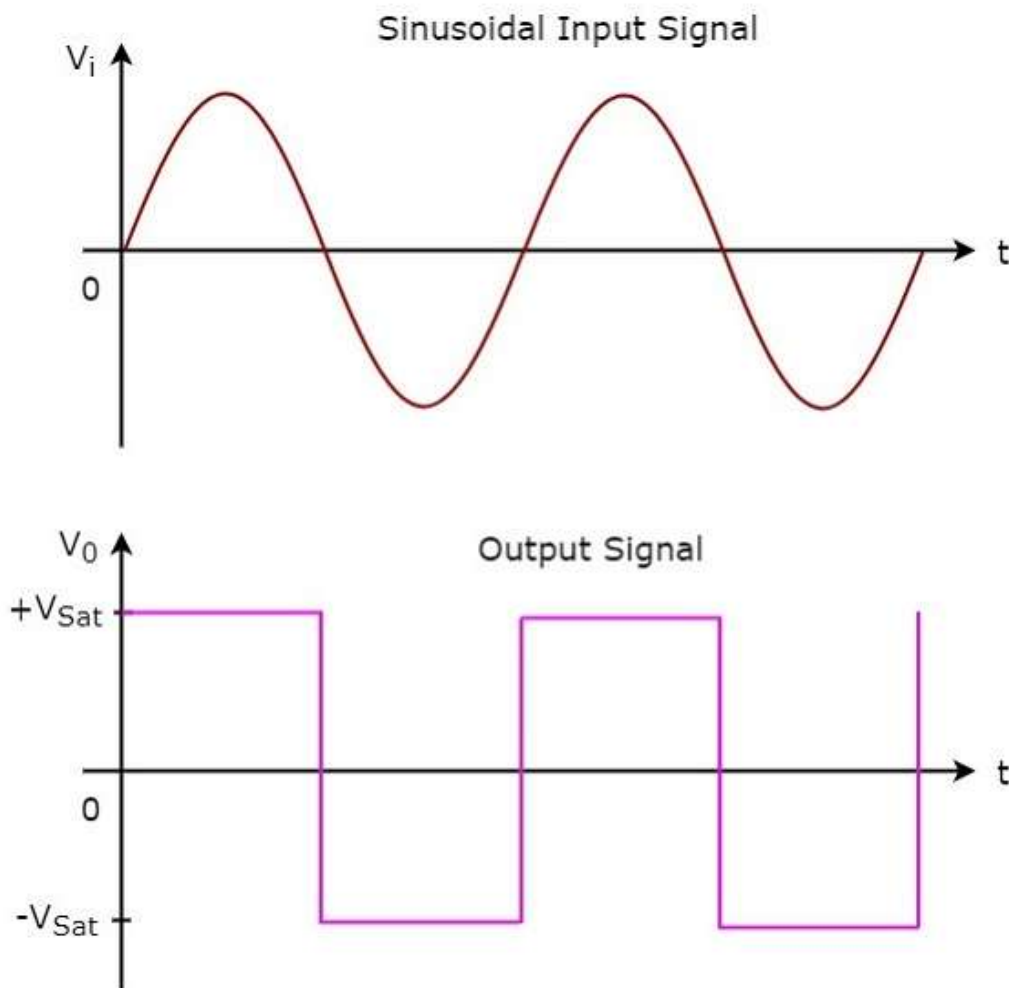

From the figure shown above, we can observe that the output transitions either from $+V_{Sat}$ to $-V_{Sat}$ or from $-V_{Sat}$ to $+V_{Sat}$ whenever the sinusoidal input signal crosses zero volts. That means, the output changes its value when the input is crossing zero volts. Hence, the above circuit is also called as **non-inverting zero crossing detector**.

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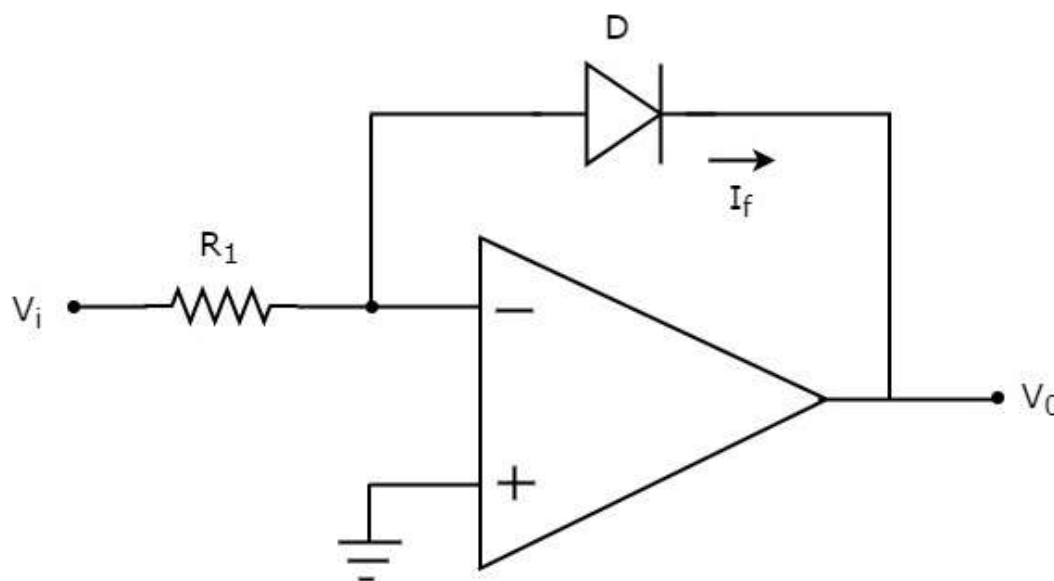
In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied at the non-inverting input terminal of the op-amp.

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:

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

$$=> I_f = \frac{V_i}{R_1} \quad \text{------- Equation 1}$$

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

$$I_f = I_s \, e^{\left(\frac{V_f}{\eta V_T}\right)} \quad \text{------- Equation 2}$$

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:

$$I_f = I_s \, e^{\left(\frac{-V_0}{\eta V_T}\right)} \quad \text{------- Equation 3}$$

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:

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

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

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

$$\ln\left(\frac{V_i}{R_1 I_s}\right) = \frac{-V_0}{\eta V_T}$$

$$=> V_0 = -\eta V_T \ln\left(\frac{V_i}{R_1 I_s}\right)$$

Note that in the above equation, the parameters η, 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:
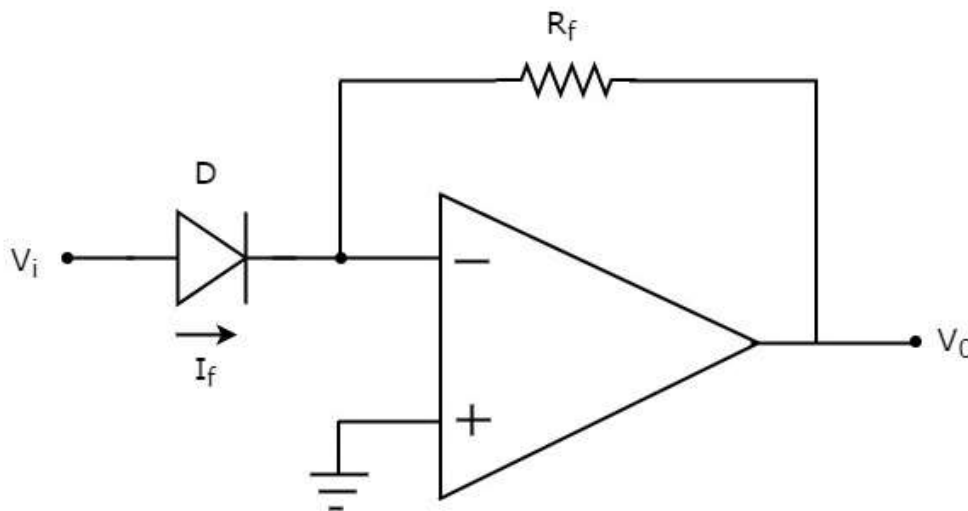
In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. It means zero volts is applied to its non-inverting input terminal.

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:

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

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

$$=> V_0 = -R_f\, I_f \quad \text{------- Equation 4}$$

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

$$I_f = I_s\, e^{\left(\frac{V_f}{\eta V_T}\right)}$$

Substituting the value of I_f in Equation 4, we get:

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

$$\Rightarrow V_0 = -R_f \, I_s \, e^{\left(\frac{V_f}{\eta V_T}\right)} \text{-------Equation 5}$$

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

$$V_i - V_f = 0$$

$$\Rightarrow V_f = V_i$$

Substituting, the value of V_f in the Equation 5, we get:

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

Note that, in the above equation the parameters η, 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, $R_f \, I_s = 1 \, V$. 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.

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.

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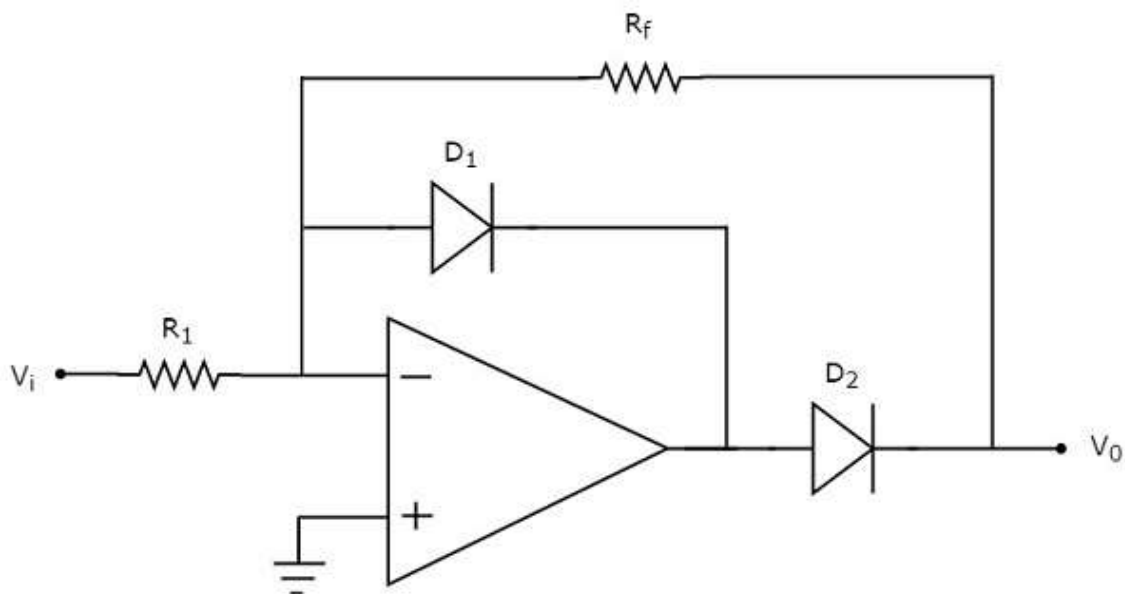
Observe that the circuit diagram of a half wave rectifier shown above looks like an inverting amplifier, with two diodes D_1 and D_2 in addition.

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:

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

- 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.

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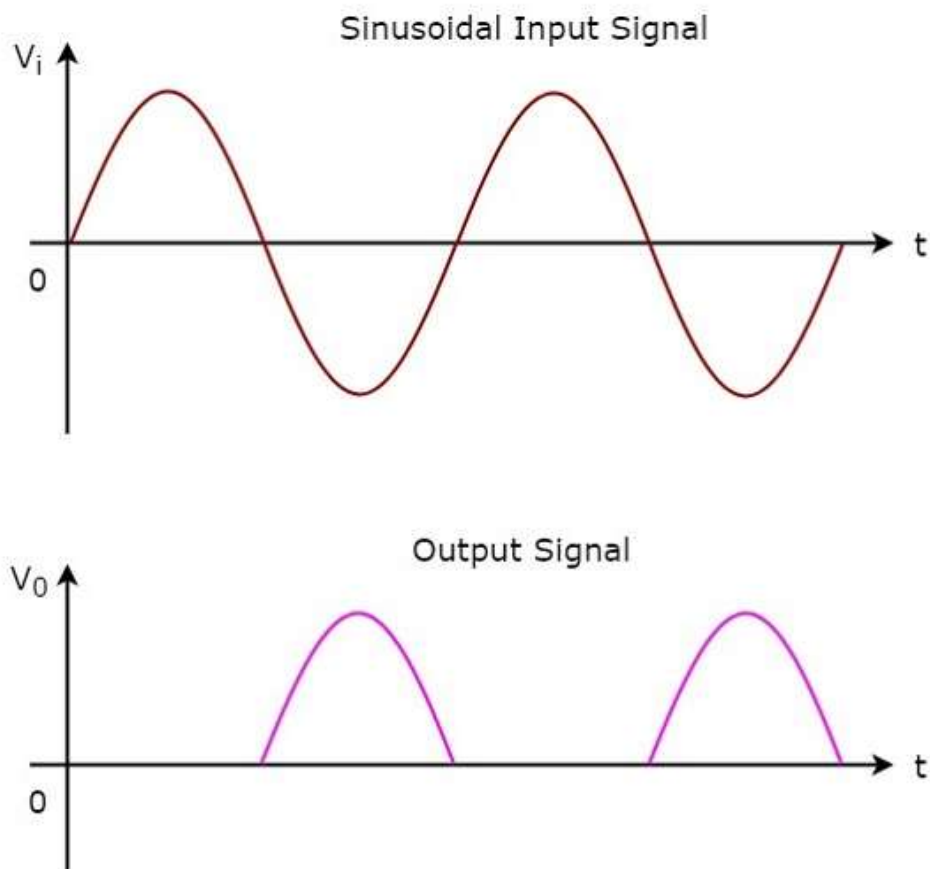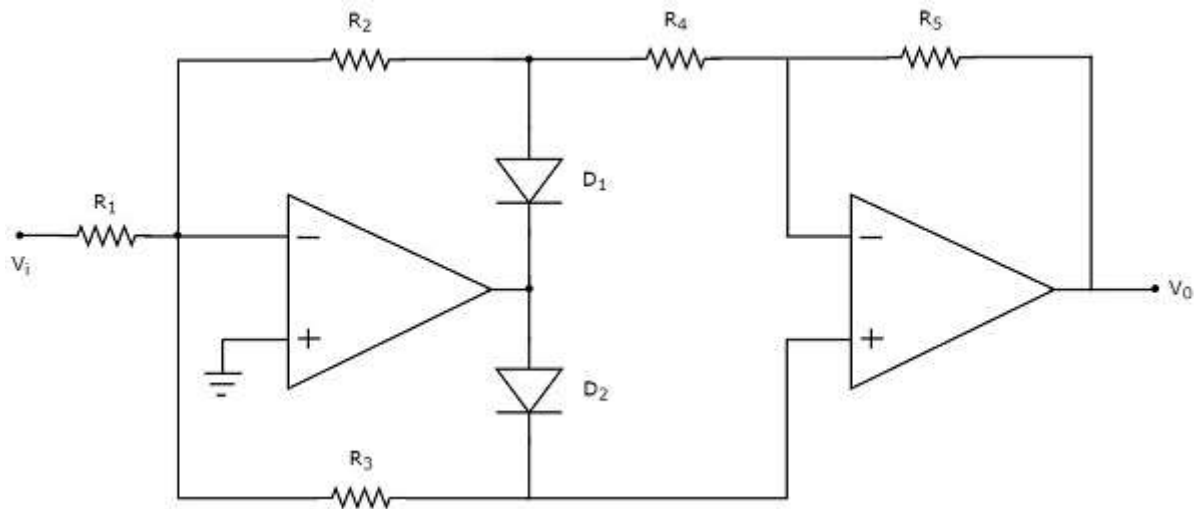
- For the **positive half cycle** of a sinusoidal input, the output of the first op-amp will be negative. Hence, diodes D_1 and D_2 will be forward biased and reverse biased respectively.

- 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 $R_1 = R_2 = R_4 = R_5 = R$, 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 $R_1 = 2R_3 = R_4 = R_5 = R$, 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:

Sinusoidal Input Signal

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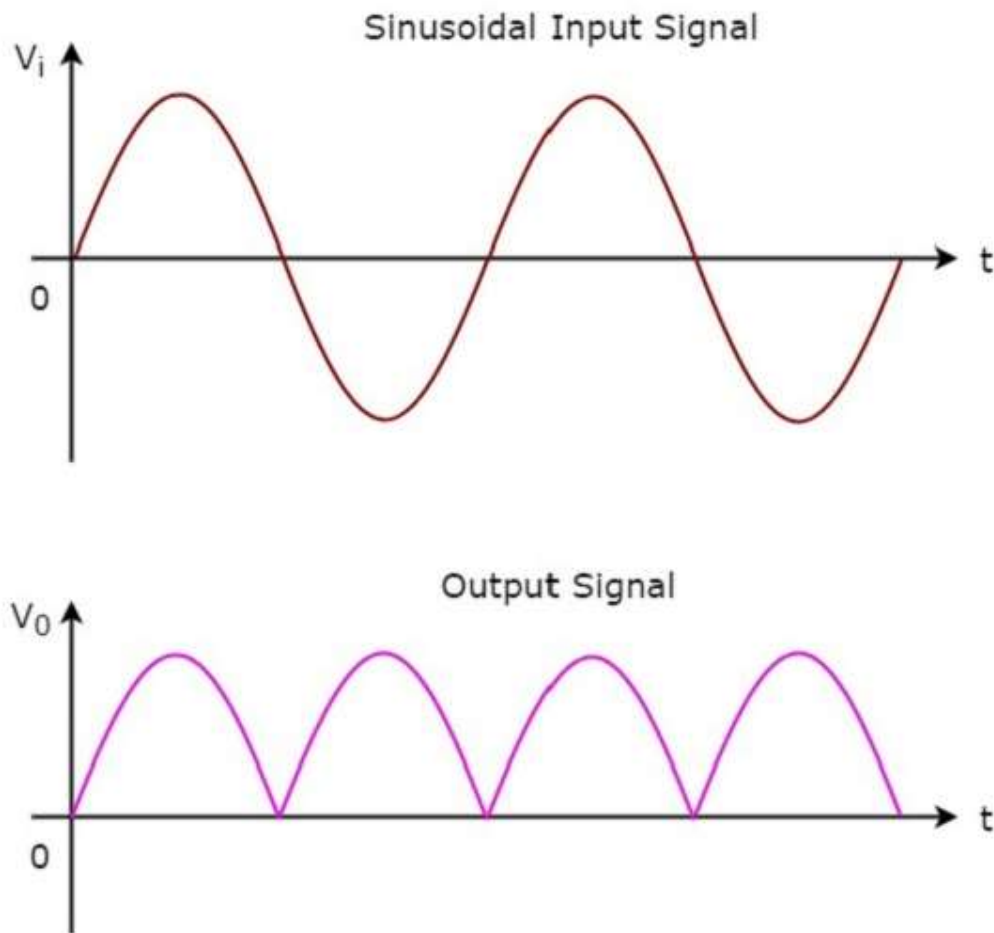
As you can see in the above figure, the full wave rectifier circuit diagram that we considered will produce only **positive half cycles** for both positive and negative half cycles of a sinusoidal input.

10. LICA – Clippers

Wave shaping circuits are the electronic circuits, which produce the desired shape at the output from the applied input wave form. These circuits perform two functions:

- Attenuate the applied wave

- Alter the dc level of the applied wave.

There are two types of wave shaping circuits: **Clippers** and **Clampers**. In this chapter, you will learn in detail about clippers.

Op-amp based Clippers

A **clipper** is an electronic circuit that produces an output by removing a part of the input above or below a reference value. That means, the output of a clipper will be same as that of the input for other than the clipped part. Due to this, the peak to peak amplitude of the output of a clipper will be always less than that of the input.

The main advantage of clippers is that they eliminate the unwanted noise present in the amplitude of an ac signal.

Clippers can be classified into the following two types based on the clipping portion of the input.
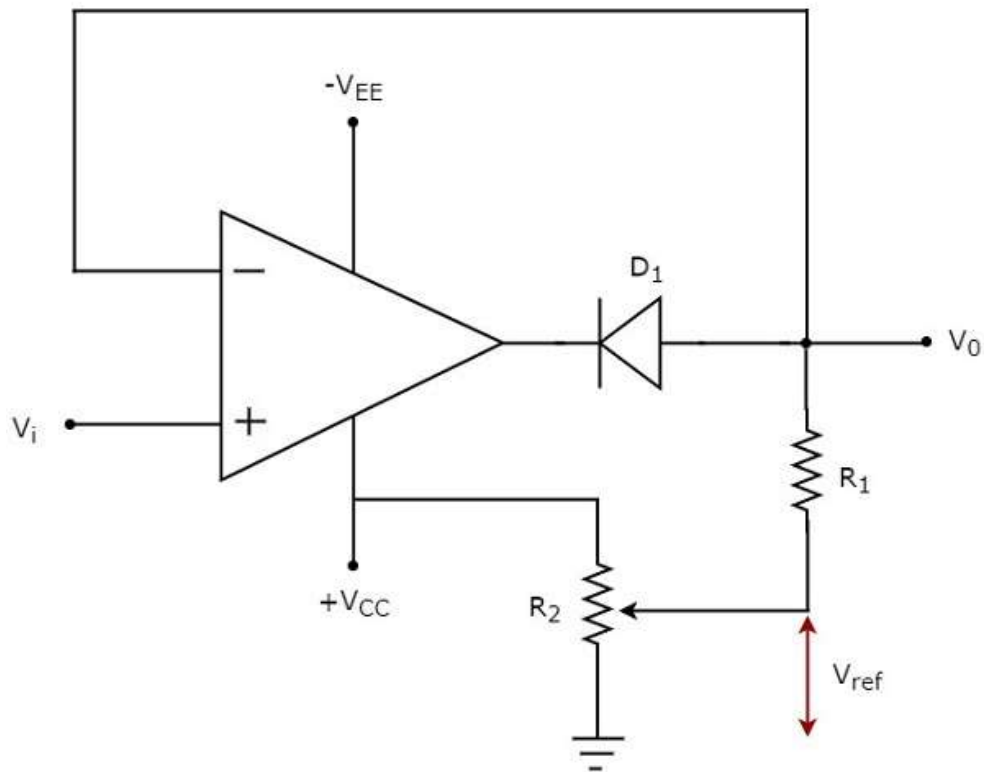
- Positive Clipper

- Negative Clipper

These are discussed in detail as given below:

Positive Clipper

A **positive clipper** is a clipper that clips only the positive portion(s) of the input signal.

The **circuit diagram** of positive clipper is shown in the following figure:

In the circuit shown above, a sinusoidal voltage signal V_i is applied to the non-inverting terminal of the op-amp. The value of the reference voltage V_{ref} can be chosen by varying the resistor R_2.

The **operation** of the circuit shown above is explained below:

- If the value of the input voltage V_i is less than the value of the reference voltage V_{ref}, then the diode D_1 conducts. Then, the circuit given above behaves as a **voltage follower**. Therefore, the output voltage V_0 of the above circuit will be same as that of the input voltage V_i, for $V_i < V_{ref}$.

- If the value of the input voltage V_i is greater than the value of reference voltage V_{ref}, then the diode D_1 will be off. Now, the op-amp operates in an open loop since the feedback path was open. Therefore, the output voltage V_0 of the above circuit will be equal to the value of the reference voltage V_{ref}, for $V_i > V_{ref}$.

The **input wave form** and the corresponding **output wave form** of a positive clipper for a positive reference voltage V_{ref}, are shown in the following figure:

Negative Clipper

A **negative clipper** is a clipper that clips only the negative portion(s) of the input signal. You can obtain the circuit of the negative clipper just by reversing the diode and taking the reverse polarity of the reference voltage, in the circuit that you have seen for a positive clipper.

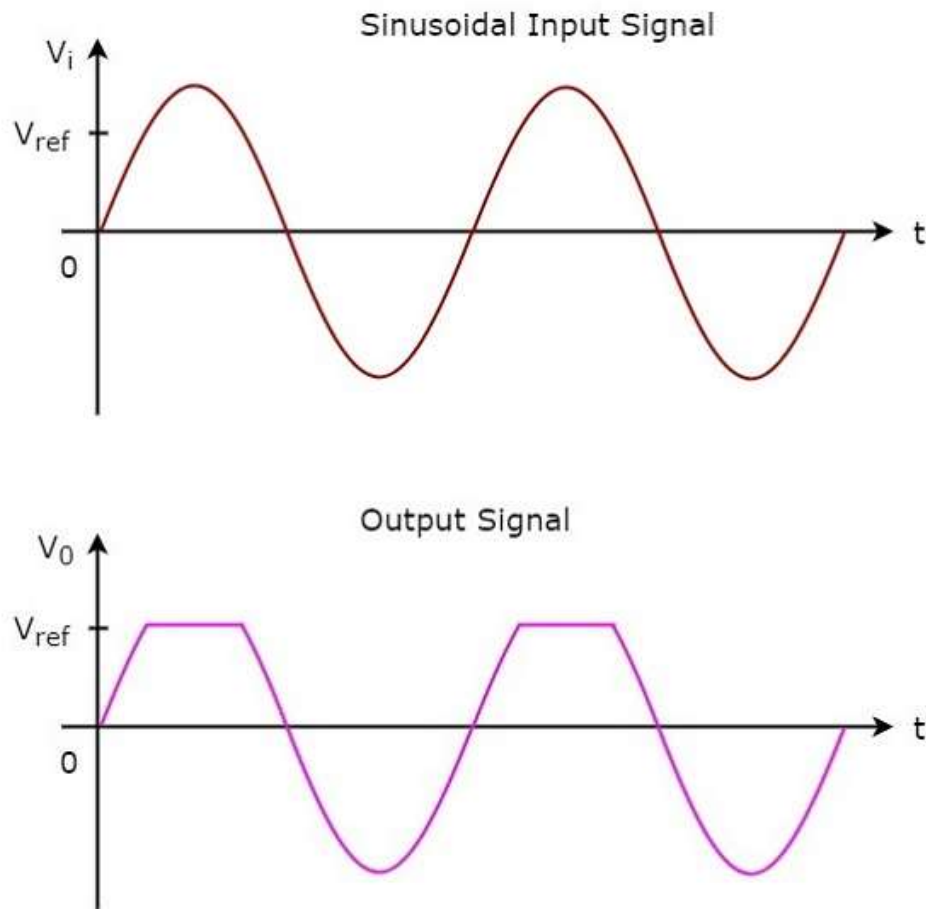The **circuit diagram** of a negative clipper is shown in the following figure:
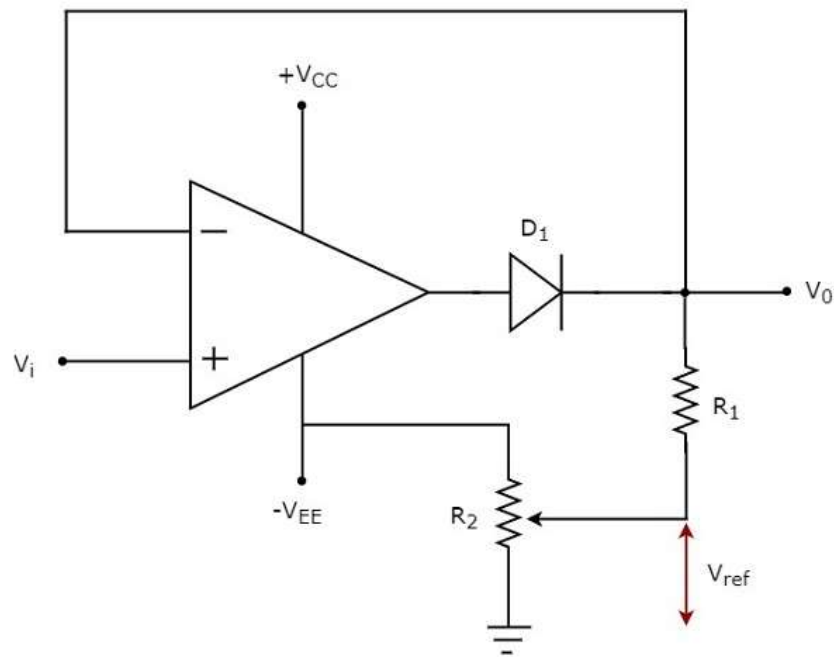
In the above circuit, a sinusoidal voltage signal V_i is applied to the non-inverting terminal of the op-amp. The value of the reference voltage V_{ref} can be chosen by varying the resistor R_2.

The **operation** of a negative clipper circuit is explained below:

- If the value of the input voltage V_i is greater than the value of reference voltage V_{ref}, then the diode D_1 conducts. Then, the above circuit behaves as a **voltage follower**. Therefore, the output voltage V_0 of the above circuit will be same as that of the input voltage V_i for $V_i > V_{ref}$.

- If the value of the input voltage V_i is less than the value of reference voltage V_{ref}, then the diode D_1 will be off. Now, the op-amp operates in an open loop since the feedback path is open. Therefore, the output voltage V_0 of the above circuit will be equal to the value of reference voltage V_{ref}, for $V_i < V_{ref}$.

The **input wave form** and the corresponding **output wave form** of a negative clipper, for a negative reference voltage V_{ref}, are shown in the following figure:
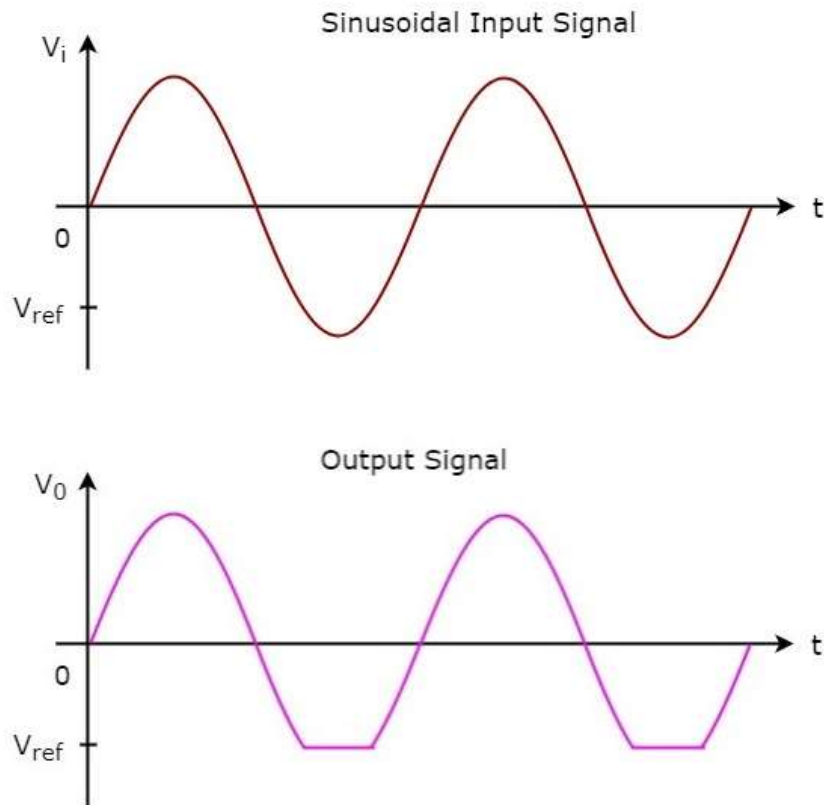
11. LICA – Clampers

In the previous chapter, we discussed about clippers. Now, let us discuss about other type of wave shaping circuits, namely clampers.

Op-amp based Clampers

A **clamper** is an electronic circuit that produces an output, which is similar to the input but with a shift in the DC level. In other words, the output of a clamper is an exact replica of the input. Hence, the peak to peak amplitude of the output of a clamper will be always equal to that of the input.

Clampers are used to introduce or restore the DC level of input signal at the output. There are **two types** of op-amp based clampers based on the DC shift of the input.

- Positive Clamper

- Negative Clamper

This section discusses about these two types of clampers in detail.

Positive Clamper

A positive clamper is a clamper circuit that produces an output in such a way that the input signal gets shifted vertically by a positive DC value.

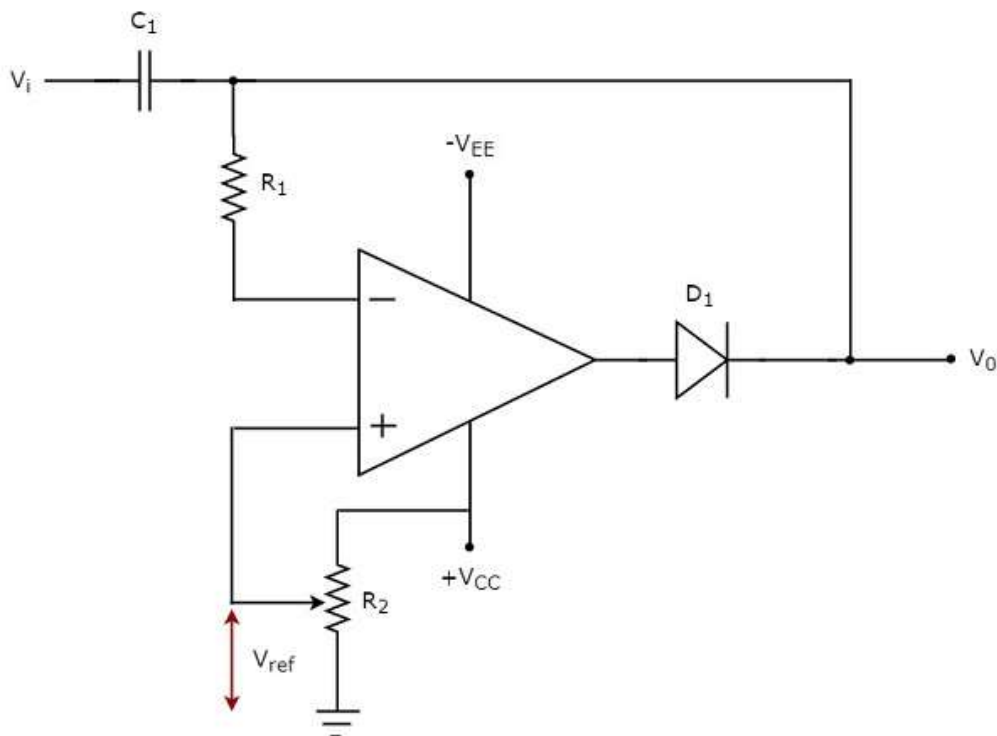The **circuit diagram** of a positive clamper is shown in the following figure:

tutorialspoint
SIMPLYEASYLEARNING

In the above circuit, a **sinusoidal voltage signal**, V_i is applied to the inverting terminal of op-amp through a network that consists of a capacitor C_1 and a resistor R_1. That means, AC voltage signal is applied to the inverting terminal of the op-amp.

The **DC reference voltage** V_{ref} is applied to the non-inverting terminal of the op-amp. The value of reference voltage V_{ref} can be chosen by varying the resistor R_2. In this case, we will get a reference voltage V_{ref} of a positive value.

The above circuit produces an **output**, which **is the combination (resultant sum)** of the sinusoidal voltage signal V_i and the reference voltage V_{ref}. That means, the clamper circuit produces an output in such a way that the sinusoidal voltage signal V_i gets shifted vertically upwards by the value of reference voltage V_{ref}.

The input wave form and the corresponding output wave form of positive clamper are shown in above figure:

From the figure above, you can observe that the positive clamper shifts the applied input waveform **vertically upward** at the output. The amount of shift will depend on the value of the DC reference voltage.

Negative Clamper

A **negative clamper** is a clamper circuit that produces an output in such a way that the input signal gets shifted vertically by a negative DC value.

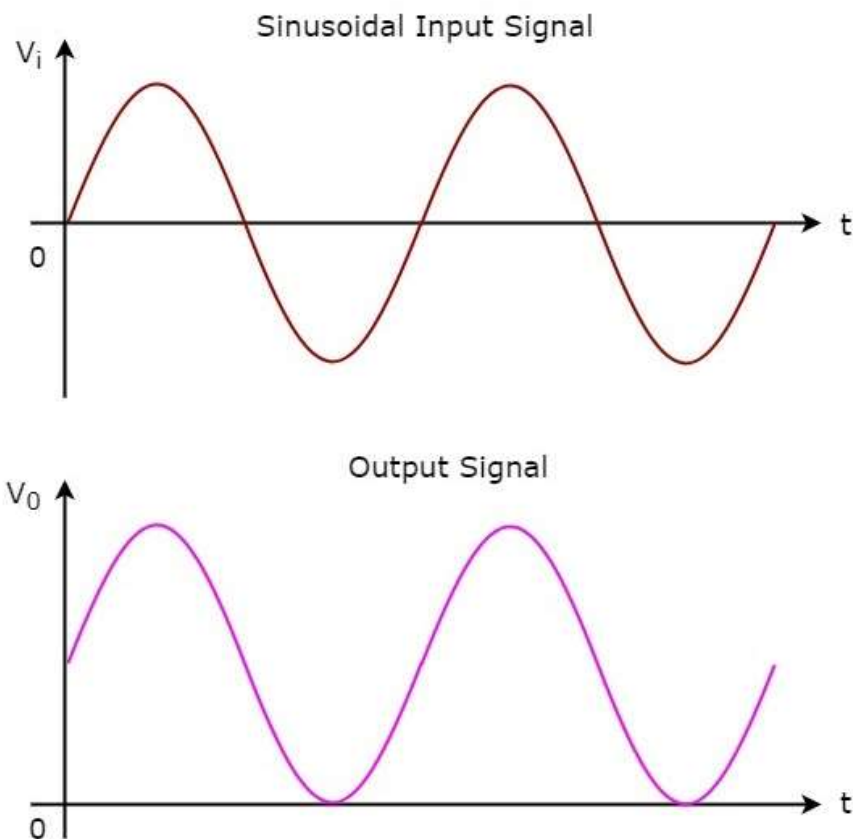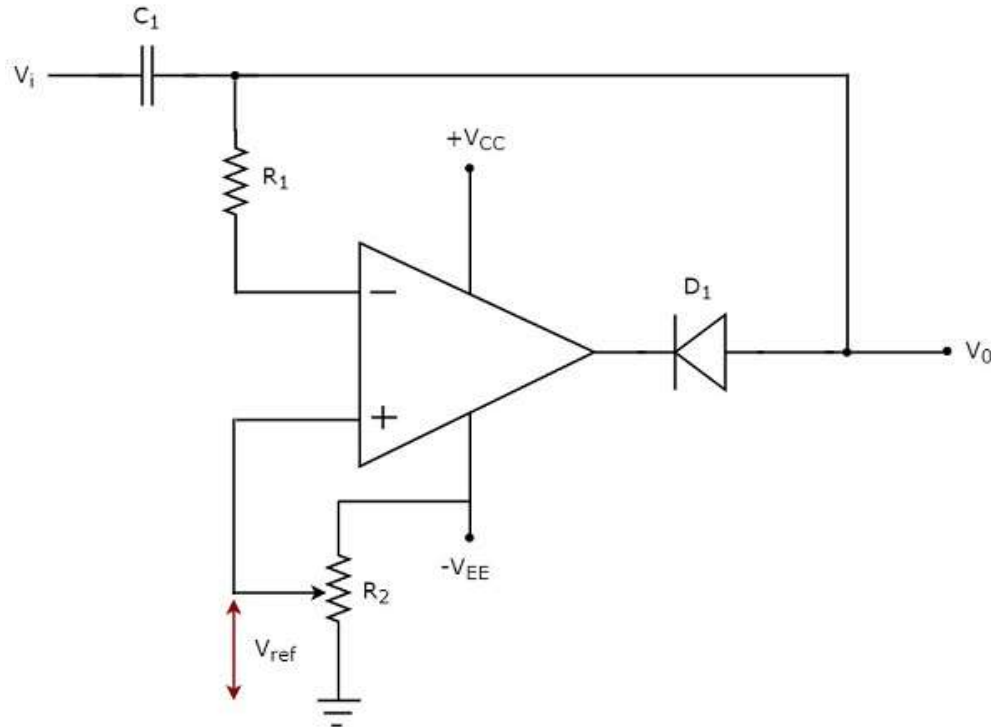The **circuit diagram** of negative clamper is shown in the following figure:

In the above circuit, a **sinusoidal voltage signal** V_i is applied to the inverting terminal of the op-amp through a network that consists of a capacitor C_1 and resistor R_1. That means, AC voltage signal is applied to the inverting terminal of the op-amp.

The **DC reference voltage** V_{ref} is applied to the non-inverting terminal of the op-amp. The value of reference voltage V_{ref} can be chosen by varying the resistor R_2. In this case, we will get reference voltage V_{ref} of a negative value.

The above circuit produces an output, which is the combination (resultant sum) of sinusoidal voltage signal V_i and reference voltage V_{ref}. That means, the clamper circuit produces an output in such a way that the sinusoidal voltage signal V_i gets shifted vertically downwards by the value of reference voltage V_{ref}.

The input wave form and the corresponding output wave form of a negative clamper are shown in the following figure:
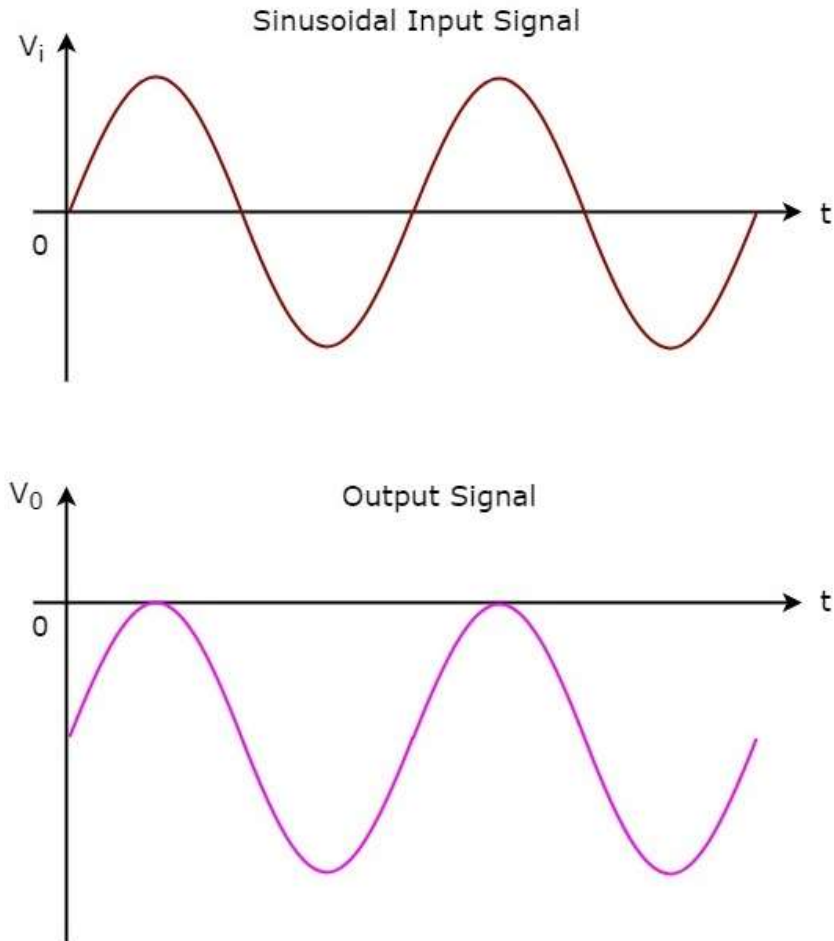
We can observe from the output that the negative clamper shifts the applied input waveform **vertically downward** at the output. The amount of shifting will depend on the value of DC reference voltage.

Filters are electronic circuits that allow certain frequency components and / or reject some other. You might have come across filters in network theory tutorial. They are passive and are the electric circuits or networks that consist of passive elements like resistor, capacitor, and (or) an inductor.

This chapter discusses about **active filters** in detail.

Types of Active Filters

Active filters are the electronic circuits, which consist of active element like op-amp(s) along with passive elements like resistor(s) and capacitor(s).

Active filters are mainly classified into the following **four types** based on the band of frequencies that they are allowing and / or rejecting:

- Active Low Pass Filter

- Active High Pass Filter

- Active Band Pass Filter

- Active Band Stop Filter

Active Low Pass Filter

If an active filter allows (passes) only **low frequency** components and rejects (blocks) all other high frequency components, then it is called as an **active low pass filter**.

The **circuit diagram** of an active low pass filter is shown in the following figure:
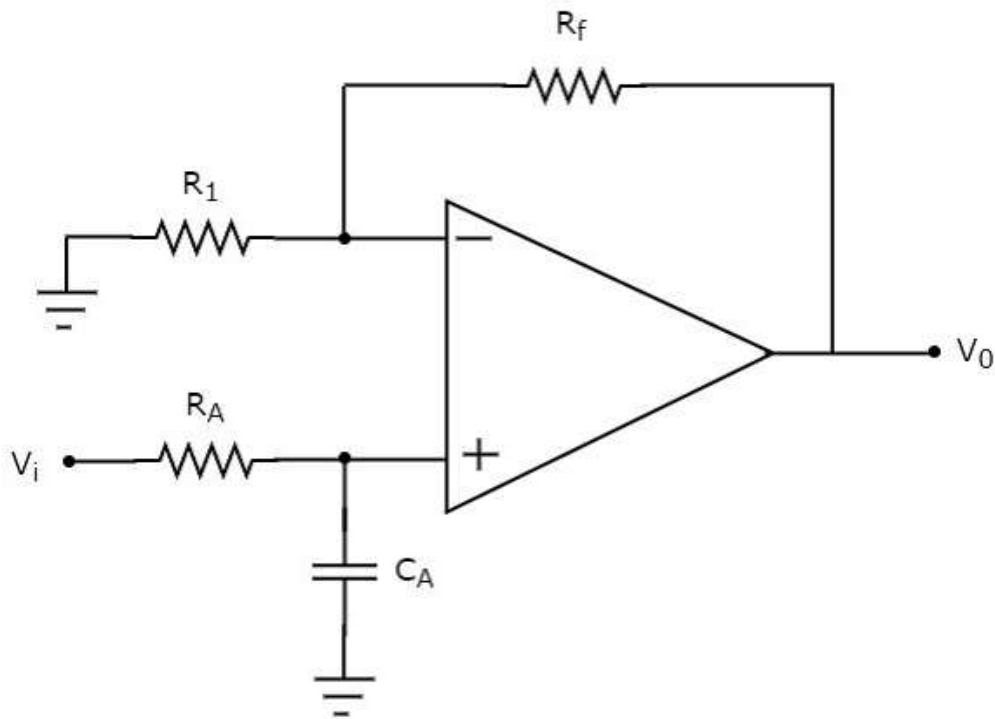
We know that the electric network, which is connected to the non-inverting terminal of an op-amp is a **passive low pass filter**. So, the input of a non-inverting terminal of an op-amp is the output of a passive low pass filter.

Observe that the above circuit resembles a **non-inverting amplifier**. It is having the output of a passive low pass filter as an input to the non-inverting terminal of op-amp. Hence, it produces an output, which is $\left(1 + \frac{R_f}{R_1}\right)$ times the input present at the non-inverting terminal.

We can choose the values of R_f and R_1 suitably in order to obtain the **desired gain** at the output. Suppose, if we consider the resistance values of R_f and R_1 as zero ohms and infinity ohms, then the above circuit will produce a **unity gain** low pass filter output.

Active High Pass Filter

If an active filter allows (passes) only **high frequency** components and rejects (blocks) all other low frequency components, then it is called an **active high pass filter**.

The **circuit diagram** of an active high pass filter is shown in the following figure:

We know that the electric network, which is connected to the non-inverting terminal of an op-amp is a **passive high pass filter**. So, the input of a non-inverting terminal of op-amp is the output of passive high pass filter.
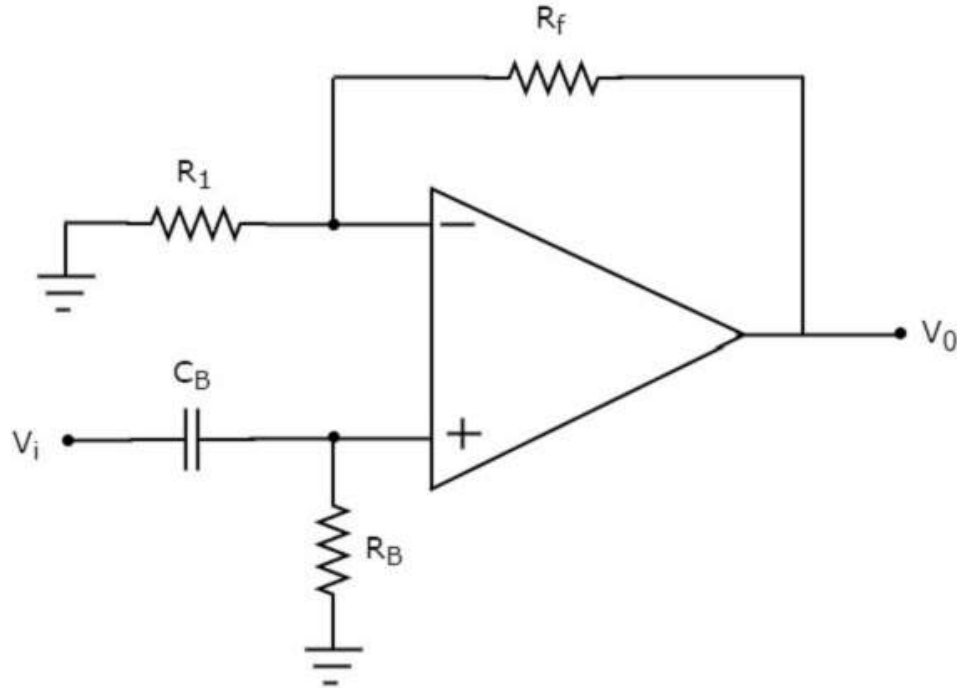
Now, the above circuit resembles a **non-inverting amplifier**. It is having the output of a passive high pass filter as an input to non-inverting terminal of op-amp. Hence, it produces an output, which is $\left(1 + \frac{R_f}{R_1}\right)$ times the input present at its non-inverting terminal.

We can choose the values of R_f and R_1 suitably in order to obtain the **desired gain** at the output. Suppose, if we consider the resistance values of R_f and R_1 as zero ohms and infinity ohms, then the above circuit will produce a **unity gain** high pass filter output.

Active Band Pass Filter

If an active filter allows (passes) only one band of frequencies, then it is called as an **active band pass filter**. In general, this frequency band lies between low frequency range and high frequency range. So, active band pass filter rejects (blocks) both low and high frequency components.

The **circuit diagram** of an active band pass filter is shown in the following figure:
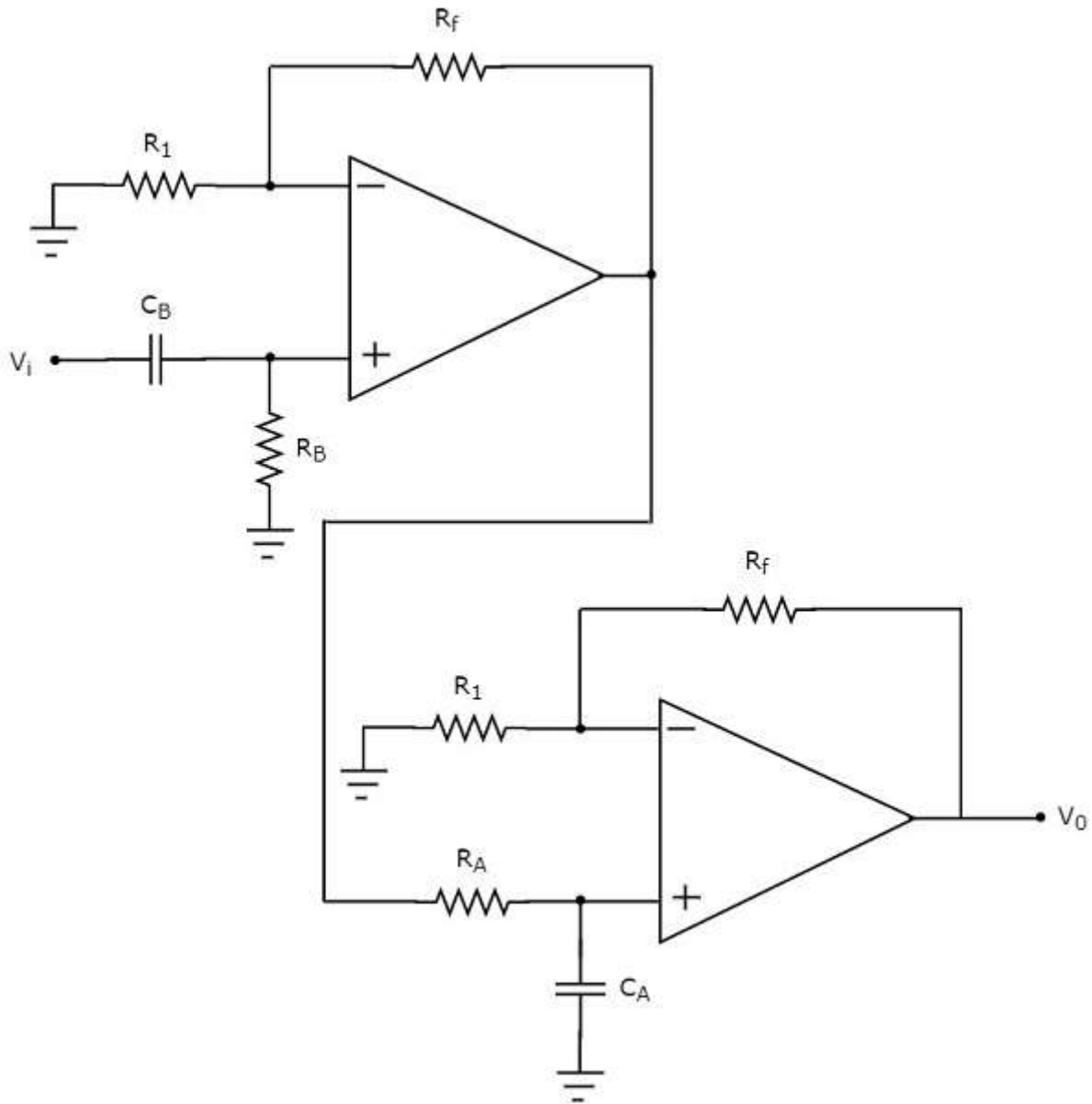
Observe that there are **two parts** in the circuit diagram of active band pass filter: The first part is an active high pass filter, while the second part is an active low pass filter.

The output of the active high pass filter is applied as an input of the active low pass filter. That means, both active high pass filter and active low pass filter are **cascaded** in order to obtain the output in such a way that it contains only a particular band of frequencies.

The **active high pass filter**, which is present at the first stage allows the frequencies that are greater than the lower cut-off frequency of the active band pass filter. So, we have to choose the values of R_B and C_B suitably, to obtain the desired **lower cut-off frequency** of the active band pass filter.

Similarly, the **active low pass filter**, which is present at the second stage allows the frequencies that are smaller than the higher cut-off frequency of the active band pass filter. So, we have to choose the values of R_A and C_A suitably in order to obtain the desired **higher cut-off frequency** of the active band pass filter.

Hence, the circuit in the diagram discussed above will produce an active band pass filter output.

Active Band Stop Filter

If an active filter rejects (blocks) a particular band of frequencies, then it is called as an **active band stop filter**. In general, this frequency band lies between low frequency range and high frequency range. So, active band stop filter allows (passes) both low and high frequency components.

The **block diagram** of an active band stop filter is shown in the following figure:
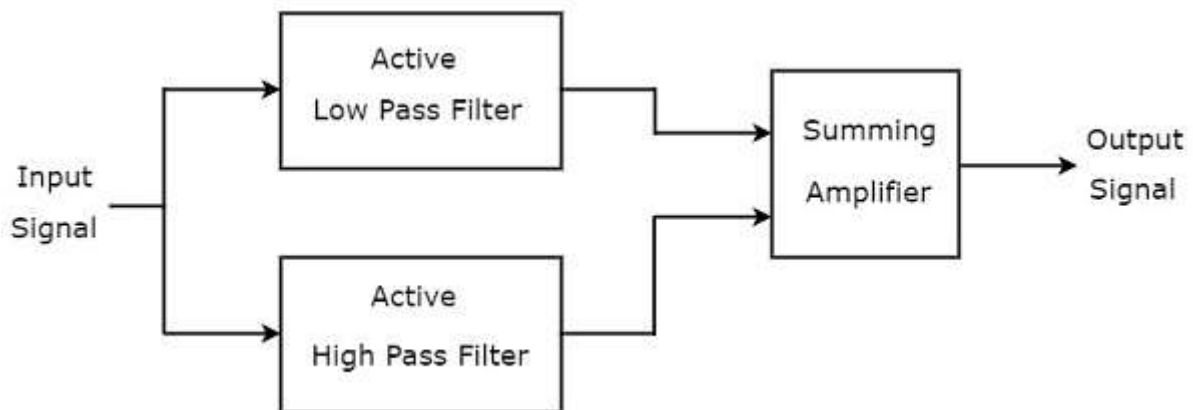
Observe that the block diagram of an active band stop filter consists of two blocks in its first stage: an active low pass filter and an active high pass filter. The outputs of these two blocks are applied as inputs to the block that is present in the second stage. So, the **summing amplifier** produces an output, which is the amplified version of sum of the outputs of the active low pass filter and the active high pass filter.

Therefore, the output of the above block diagram will be the **output of an active band stop filter**, when we choose the cut-off frequency of low pass filter to be smaller than cut-off frequency of a high pass filter.

The **circuit diagram** of an active band stop filter is shown in the following figure:
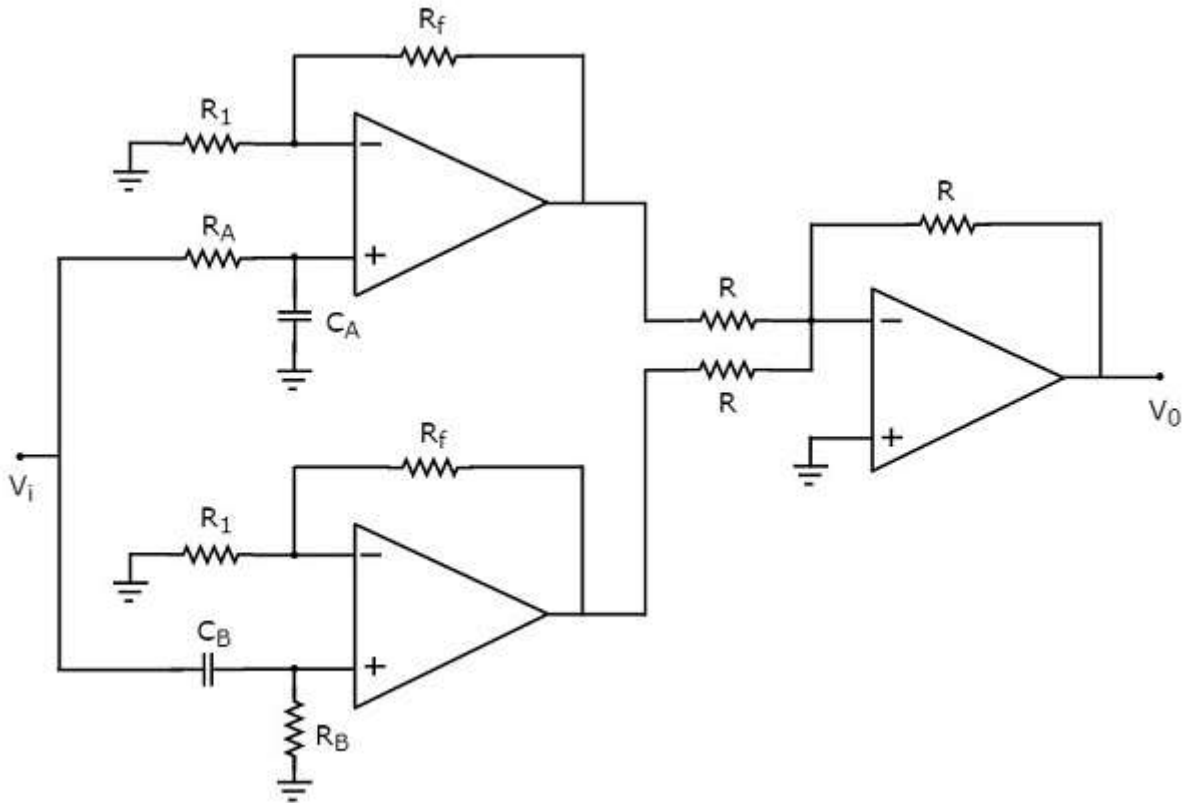
We have already seen the circuit diagrams of an active low pass filter, an active high pass filter and a summing amplifier. Observe that we got the above **circuit diagram** of active band stop filter by replacing the blocks with the respective circuit diagrams in the block diagram of an active band stop filter.

13. LICA – Sinusoidal Oscillators

An oscillator is an electronic circuit that produces a periodic signal. If the oscillator produces sinusoidal oscillations, it is called as a **sinusoidal oscillator**. It converts the input energy from a DC source into an AC output energy of a periodic signal. This periodic signal will be having a specific frequency and amplitude.

The **block diagram** of a sinusoidal oscillator is shown in the following figure:
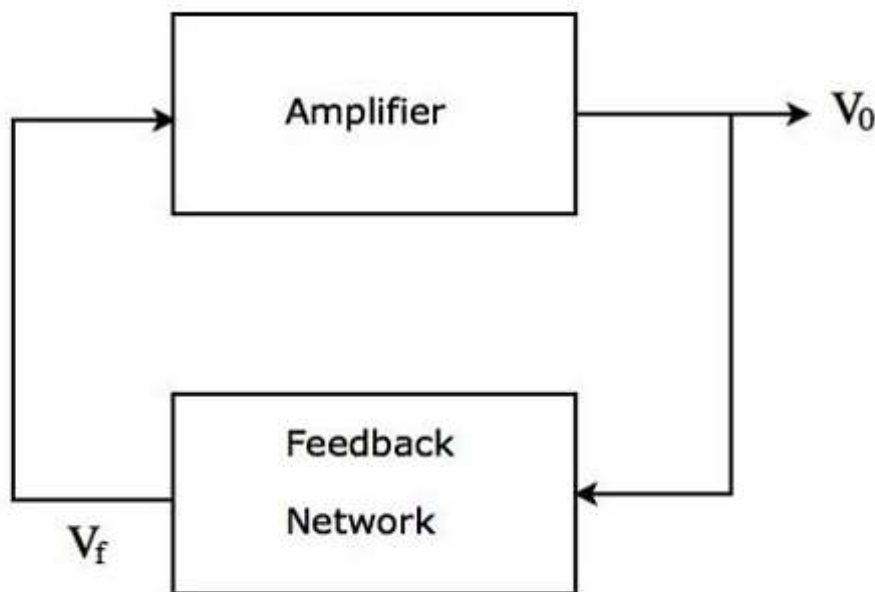
The above figure mainly consists of **two blocks**: an amplifier and a feedback network. The feedback network takes a part of the output of amplifier as an input to it and produces a voltage signal. This voltage signal is applied as an input to the amplifier.

The block diagram of a sinusoidal oscillator shown above produces sinusoidal oscillations, when the following **two conditions** are satisfied:

- The **loop gain** $A_v \beta$ of the above block diagram of sinusoidal oscillator must be greater than or equal to **unity**. Here, A_v and β are the gain of amplifier and gain of the feedback network, respectively.

- The total **phase shift** around the loop of the above block diagram of a sinusoidal oscillator must be either 0^0 or 360^0.

The above two conditions together are called as **Barkhausen criteria**.

Op-Amp Based Oscillators

There are **two** types of op-amp based oscillators.

- RC phase shift oscillator

- Wien bridge oscillator

This section discusses each of them in detail.
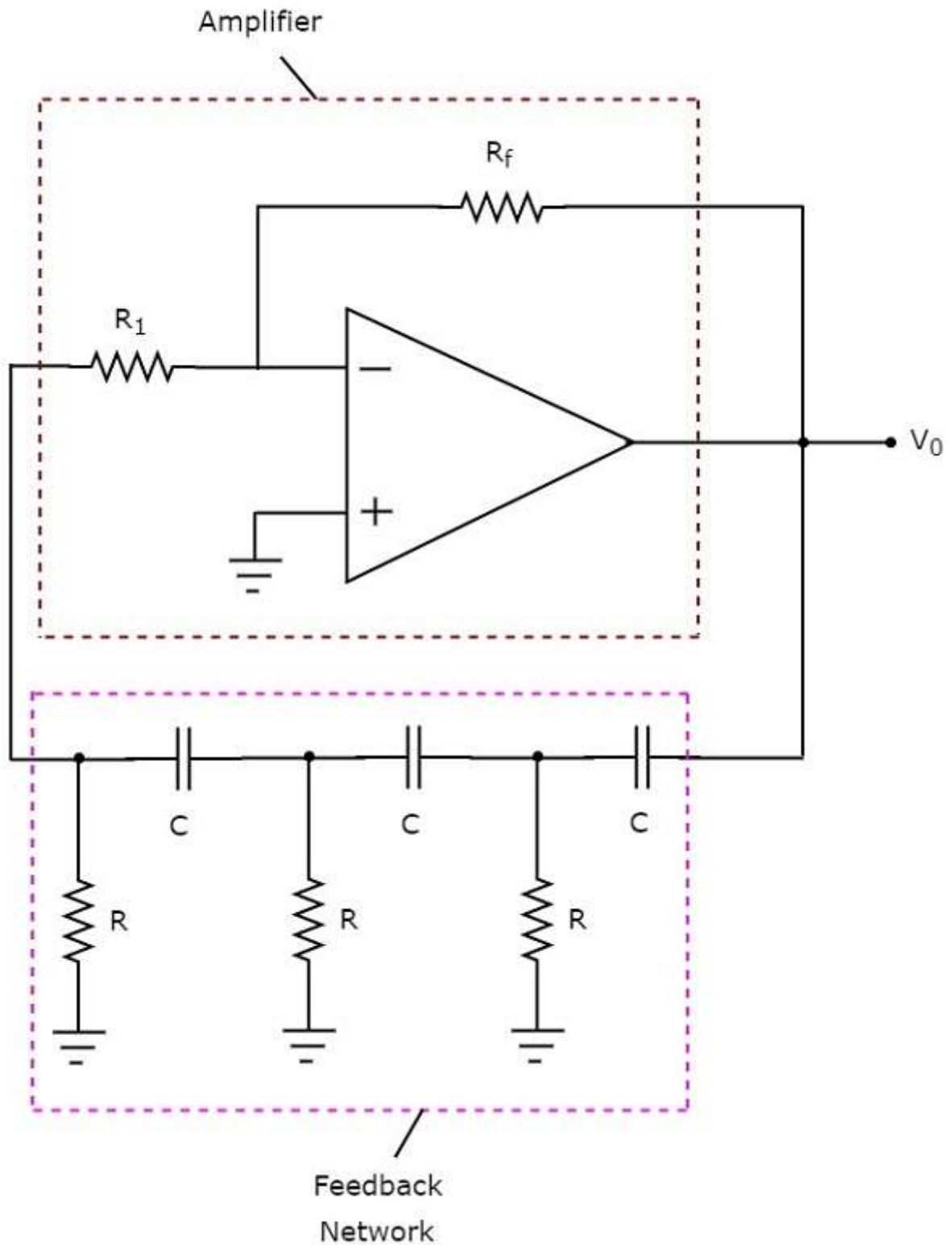
RC Phase Shift Oscillator

The op-amp based oscillator, which produces a sinusoidal voltage signal at the output with the help of an inverting amplifier and a feedback network is known as a **RC phase shift oscillator**. This feedback network consists of three cascaded RC sections.

The **circuit diagram** of a RC phase shift oscillator is shown in the following figure:

In the above circuit, the op-amp is operating in **inverting mode**. Hence, it provides a phase shift of 180^0. The feedback network present in the above circuit also provides a phase shift of 180^0, since each RC section provides a phase shift of 60^0. Therefore, the above circuit provides a total phase shift of **360^0** at some frequency.

- The **output frequency** of a RC phase shift oscillator is:

$$f = \frac{1}{2\Pi RC\sqrt{6}}$$

- The **gain** A_V of an inverting amplifier should be greater than or equal to -29,

$$i.e., -\frac{R_f}{R_1} \geq -29$$

$$=> \frac{R_f}{R_1} \geq 29$$

$$=> R_f \geq 29\ R_1$$

So, we should consider the value of feedback resistor R_f, as minimum of 29 times the value of resistor R_1, in order to produce sustained oscillations at the output of a RC phase shift oscillator.

Wien Bridge Oscillator

The op-amp based oscillator, which produces a sinusoidal voltage signal at the output with the help of a non-inverting amplifier and a feedback network is known as **Wien bridge oscillator**.

The **circuit diagram** of a Wien bridge oscillator is shown in the following figure:
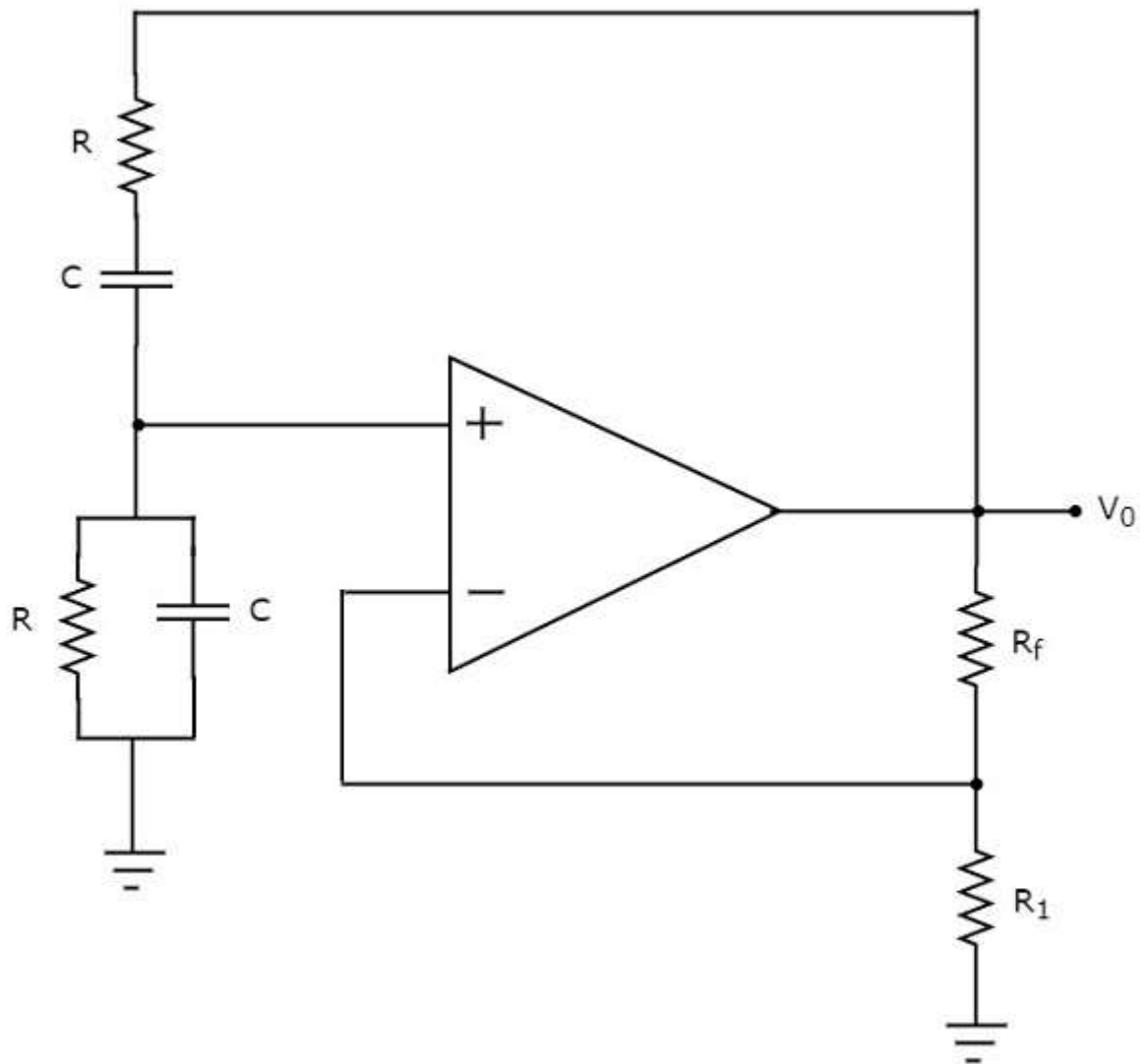
In the circuit shown above for Wein bridge oscillator, the op-amp is operating in **non-inverting mode**. Hence, it provides a phase shift of 0^0. So, the feedback network present in the above circuit should not provide any phase shift.

If the feedback network provides some phase shift, then we have to **balance the bridge** in such a way that there should not be any phase shift. So, the above circuit provides a total phase shift of 0^0 at some frequency.

- The **output frequency** of Wien bridge oscillator is

$$f = \frac{1}{2 \Pi RC}$$

- The **gain** A_V of the non-inverting amplifier should be greater than or equal to 3.

$$i.e., 1 + \frac{R_f}{R_1} \geq 3$$

$$=> \frac{R_f}{R_1} \geq 2$$

$$=> R_f \geq 2\,R_1$$

So, we should consider the value of feedback resistor R_f at least twice the value of resistor, R_1 in order to produce sustained oscillations at the output of Wien bridge oscillator.

14. LICA – Waveform Generators

A **waveform generator** is an electronic circuit, which generates a standard wave. There are two types of op-amp based waveform generators:

- Square wave generator

- Triangular wave generator

This chapter discusses each of these op-amp based waveform generators in detail.

Square Wave Generator

A **square wave generator** is an electronic circuit which generates square wave. This section discusses about op-amp based square wave generators.

The **circuit diagram** of a op-amp based square wave generator is shown in the following figure:
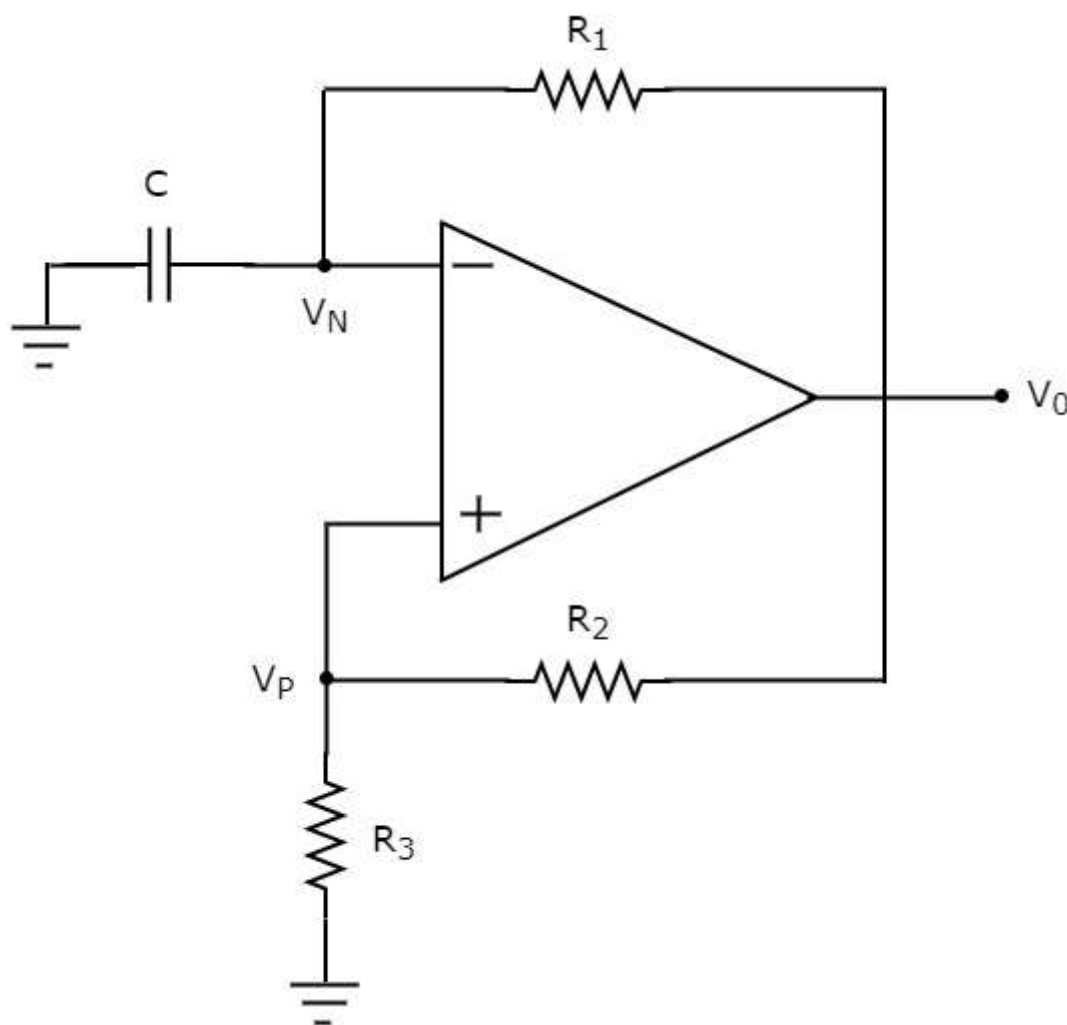
Observe that in the circuit diagram shown above, the resistor R_1 is connected between the inverting input terminal of the op-amp and its output of op-amp. So, the resistor R_1 is used in the **negative feedback** path. Similarly, the resistor R_2 is connected between the non-inverting input terminal of the op-amp and its output. So, the resistor R_2 is used in the **positive feedback** path.

A capacitor C is connected between the inverting input terminal of the op-amp and ground. So, the **voltage across capacitor C** will be the input voltage at this inverting terminal of op-amp. Similarly, a resistor R_3 is connected between the non-inverting input terminal of the op-amp and ground. So, the **voltage across resistor R_3** will be the input voltage at this non-inverting terminal of the op-amp.

The **operation** of a square wave generator is explained below:

- Assume, there is **no charge** stored in the capacitor initially. Then, the voltage present at the inverting terminal of the op-amp is zero volts. But, there is some offset voltage at non-inverting terminal of op-amp. Due to this, the value present at the output of above circuit will be $+V_{Sat}$.

- Now, the capacitor C starts **charging** through a resistor R_1. The value present at the output of the above circuit will change to $-V_{Sat}$, when the voltage across the capacitor C reaches just greater than the voltage (positive value) across resistor R_3.

- The capacitor C starts **discharging** through a resistor R_1, when the output of above circuit is $-V_{Sat}$. The value present at the output of above circuit will change to $+V_{Sat}$, when the voltage across capacitor C reaches just less than (more negative) the voltage (negative value) across resistor R_3.

Thus, the circuit shown in the above diagram will produce a **square wave** at the output as shown in the following figure:
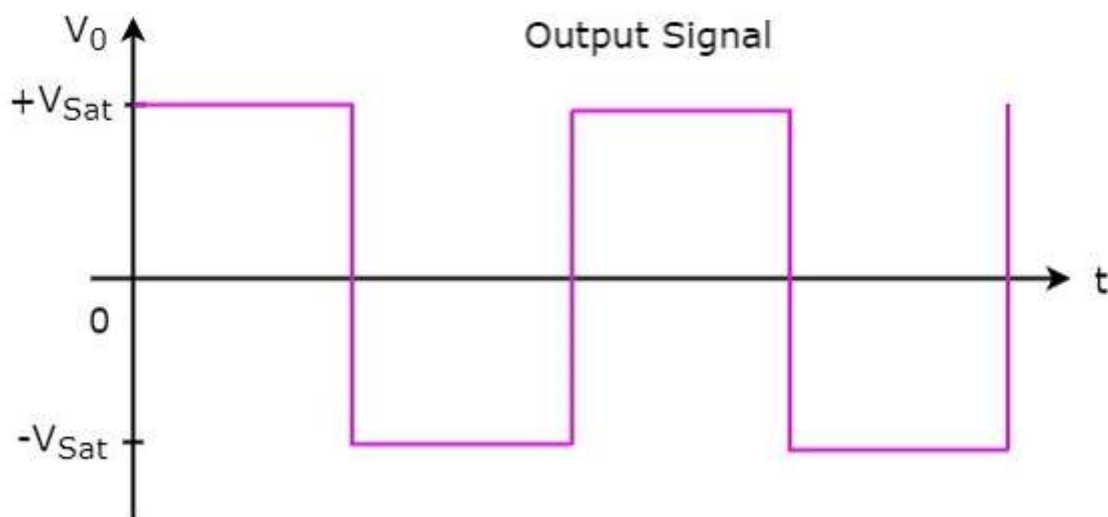
From the above figure we can observe that the output of square wave generator will have one of the two values: $+V_{Sat}$ and $-V_{Sat}$. So, the output remains at one value for some duration and then transitions to another value and remains there for some duration. In this way, it continues.

Triangular Wave Generator

A triangular wave generator is an electronic circuit, which generates a triangular wave. The **block diagram** of a triangular wave generator is shown in the following figure:
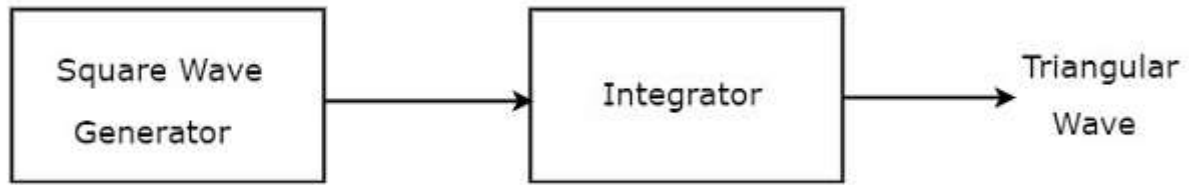
The block diagram of a triangular wave generator contains mainly two blocks: a square wave generator and an integrator. These two blocks are **cascaded**. That means, the output of square wave generator is applied as an input of integrator. Note that the integration of a square wave is nothing but a triangular wave.

The **circuit diagram** of an op-amp based triangular wave generator is shown in the following figure:
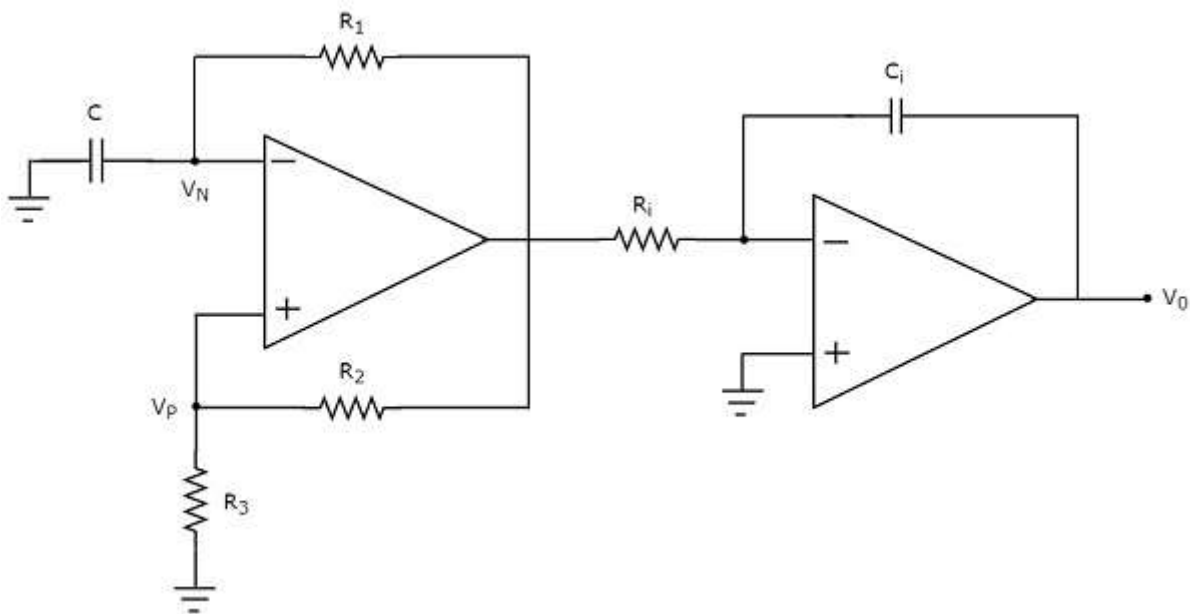
We have already seen the circuit diagrams of a square wave generator and an integrator. Observe that we got the above **circuit diagram** of an op-amp based triangular wave generator by replacing the blocks with the respective circuit diagrams in the block diagram of a triangular wave generator.

The **555 Timer** IC got its name from the three $5K\,\Omega$ resistors that are used in its voltage divider network. This IC is useful for generating accurate time delays and oscillations. This chapter explains about 555 Timer in detail.

Pin Diagram and Functional Diagram

In this section, first let us discuss about the pin diagram of 555 Timer IC and then its functional diagram.

Pin Diagram

The 555 Timer IC is an 8 pin mini Dual-Inline Package (DIP). The **pin diagram** of a 555 Timer IC is shown in the following figure:
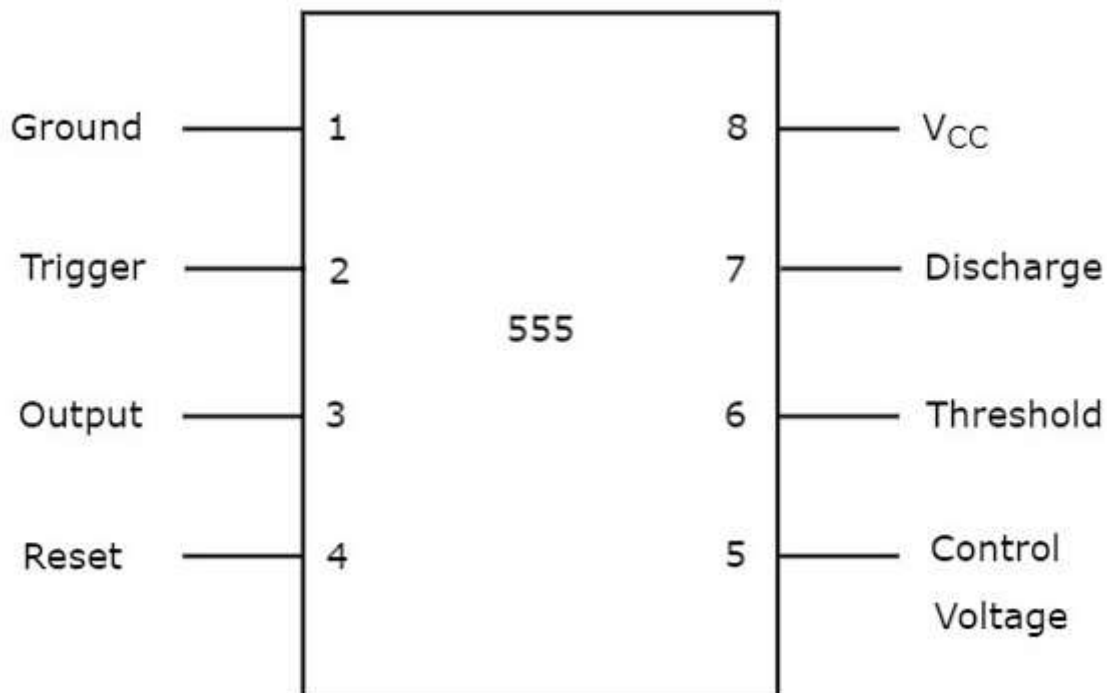
The significance of each pin is self-explanatory from the above diagram. This 555 Timer IC can be operated with a DC supply of +5V to +18V. It is mainly useful for generating **non-sinusoidal wave forms** like square, ramp, pulse & etc.

Functional Diagram

The pictorial representation showing the internal details of a 555 Timer is known as functional diagram.

The **functional diagram** of 555 Timer IC is shown in the following figure:

Observe that the functional diagram of 555 Timer contains a voltage divider network, two comparators, one SR flip-flop, two transistors and an inverter. This section discusses about the purpose of each block or component in detail:

Voltage Divider Network

- The **voltage divider network** consists of a three $5K\,\Omega$ resistors that are connected in series between the supply voltage V_{CC} and ground.

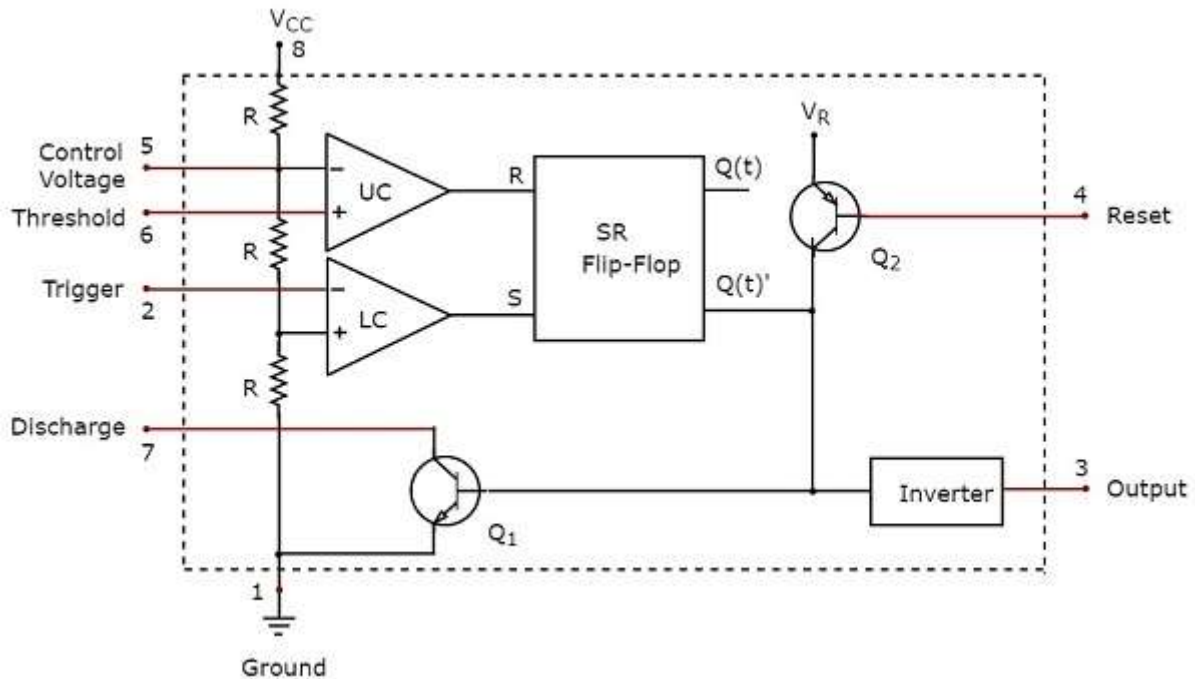- This network provides a voltage of $\frac{V_{CC}}{3}$ between a point and ground, if there exists only one $5K\,\Omega$ resistor. Similarly, it provides a voltage of $\frac{2\,V_{CC}}{3}$ between a point and ground, if there exists only two $5K\,\Omega$ resistors.

Comparator

- The functional diagram of a 555 Timer IC consists of two comparators: an Upper Comparator (UC) and a Lower Comparator (LC).

- Recall that a **comparator** compares the two inputs that are applied to it and produces an output.

- If the voltage present at the non-inverting terminal of an op-amp is greater than the voltage present at its inverting terminal, then the output of comparator will be $+V_{Sat}$. This can be considered as **Logic High** ('1') in digital representation.

- If the voltage present at the non-inverting terminal of op-amp is less than or equal to the voltage at its inverting terminal, then the output of comparator will be $-V_{Sat}$. This can be considered as **Logic Low** ('0') in digital representation.

SR Flip-Flop

- Recall that a **SR flip-flop** operates with either positive clock transitions or negative clock transitions. It has two inputs: S and R , and two outputs: Q(t) and Q(t)′. The outputs, Q(t) & Q(t)′ are complement to each other.

- The following table shows the **state table** of a SR flip-flop:

S	R	Q(t+1)
0	0	Q(t)
0	1	0
1	0	1
1	1	-

- Here, Q(t) & Q(t+1) are present state & next state respectively. So, SR flip-flop can be used for one of these three functions such as Hold, Reset & Set based on the input conditions, when positive (negative) transition of clock signal is applied.

- The outputs of Lower Comparator (LC) and Upper Comparator (UC) are applied as **inputs of SR flip-flop** as shown in the functional diagram of 555 Timer IC.

Transistors and Inverter

- The functional diagram of a 555 Timer IC consists of one npn transistor Q_1 and one pnp transistor Q_2. The npn transistor Q_1 will be turned ON if its base to emitter voltage is positive and greater than cut-in voltage. Otherwise, it will be turned-OFF.

- The pnp transistor Q_2 is used as **buffer** in order to isolate the reset input from SR flip-flop and npn transistor Q_1.

- The **inverter** used in the functional diagram of a 555 Timer IC not only performs the inverting action but also amplifies the power level.

The 555 Timer IC can be used in mono stable operation in order to produce a pulse at the output. Similarly, it can be used in astable operation in order to produce a square wave at the output.

Phase Locked Loop (**PLL**) is one of the vital blocks in linear systems. It is useful in communication systems such as radars, satellites, FMs, etc.
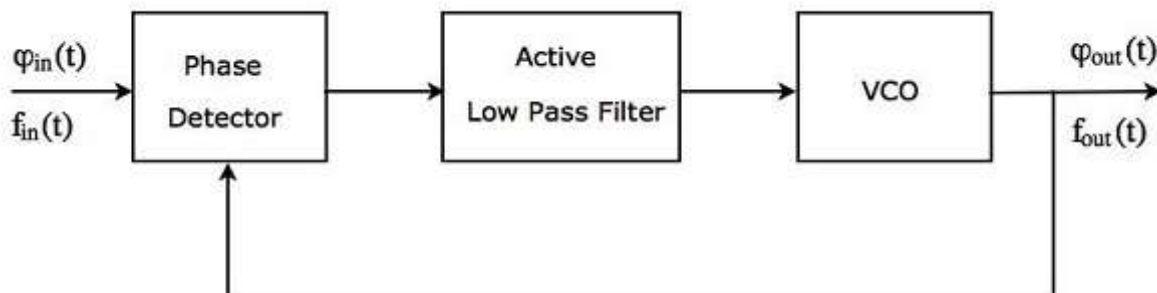
This chapter discusses about the block diagram of PLL and IC 565 in detail.

Block Diagram of PLL

A Phase Locked Loop (PLL) mainly consists of the following **three blocks**:

- Phase Detector

- Active Low Pass Filter

- Voltage Controlled Oscillator (VCO)

The **block diagram** of PLL is shown in the following figure:

The output of a phase detector is applied as an input of active low pass filter. Similarly, the output of active low pass filter is applied as an input of VCO.

The **working** of a PLL is as follows:

- **Phase detector** produces a DC voltage, which is proportional to the phase difference between the input signal having frequency of f_{in} and feedback (output) signal having frequency of f_{out}.

- A **phase detector** is a multiplier and it produces two frequency components at its output: sum of the frequencies f_{in} and f_{out} and difference of frequencies f_{in} & f_{out}.

- An **active low pass filter** produces a DC voltage at its output, after eliminating high frequency component present in the output of the phase detector. It also amplifies the signal.

- A **VCO** produces a signal having a certain frequency, when there is no input applied to it. This frequency can be shifted to either side by applying a DC voltage to it. Therefore, the frequency deviation is directly proportional to the DC voltage present at the output of a low pass filter.

The above operations take place until the VCO frequency equals to the input signal frequency. Based on the type of application, we can use either the output of active low pass filter or output of a VCO. PLLs are used in many **applications** such as FM demodulator, clock generator etc.

PLL operates in one of the following **three modes**:

- Free running mode

- Capture mode

- Lock mode

Initially, PLL operates in **free running mode** when no input is applied to it. When an input signal having some frequency is applied to PLL, then the output signal frequency of VCO will start change. At this stage, the PLL is said to be operating in the **capture mode**. The output signal frequency of VCO will change continuously until it is equal to the input signal frequency. Now, it is said to be PLL is operating in the **lock mode**.

IC 565

IC 565 is the most commonly used phase locked loop IC. It is a 14 pin Dual-Inline Package (DIP). The **pin diagram** of IC 565 is shown in the following figure:
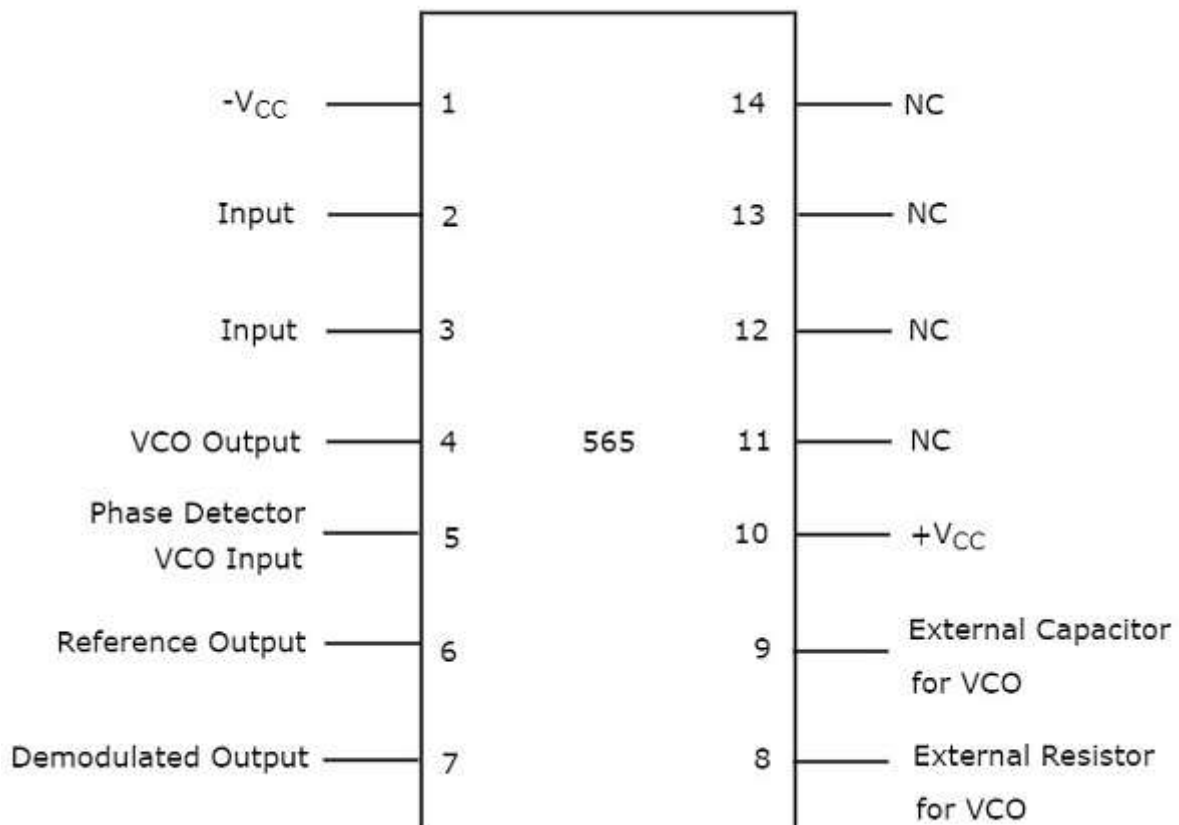
The purpose of each pin is self-explanatory from the above diagram. Out of 14 pins, only 10 pins (pin number 1 to 10) are utilized for the operation of PLL. So, the remaining 4 pins (pin number 11 to 14) are labelled with NC (No Connection).

The **VCO** produces an output at pin number 4 of IC 565, when the pin numbers 2 and 3 are grounded. Mathematically, we can write the output frequency, f_{out} of the VCO as

$$f_{out} = \frac{0.25}{R_V C_V}$$

where,

R_V is the external resistor that is connected to the pin number 8

C_V is the external capacitor that is connected to the pin number 9

- By choosing proper values of R_V and C_V, we can fix (determine) the output frequency, $\boldsymbol{f_{out}}$ of VCO.

- **Pin numbers 4 and 5** are to be shorted with an external wire so that the output of VCO can be applied as one of the inputs of phase detector.

- IC 565 has an internal resistance of $3.6\ K\Omega$. A capacitor, C has to be connected between pin numbers 7 and 10 in order to make a **low pass filter** with that internal resistance.

Note that as per the requirement, we have to properly configure the pins of IC 565.

The function of a **voltage regulator** is to maintain a constant DC voltage at the output irrespective of voltage fluctuations at the input and (or) variations in the load current. In other words, voltage regulator produces a regulated DC output voltage.

Voltage regulators are also available in Integrated Circuits (IC) forms. These are called as **voltage regulator ICs**.

Types of Voltage Regulators

There are **two types** of voltage regulators:

- Fixed voltage regulator

- Adjustable voltage regulator

This chapter discusses about these two types of voltage regulators one by one.

Fixed voltage regulator

A **fixed voltage regulator** produces a fixed DC output voltage, which is either positive or negative. In other words, some fixed voltage regulators produce positive fixed DC voltage values, while others produce negative fixed DC voltage values.

78xx voltage regulator ICs produce positive fixed DC voltage values, whereas, **79xx** voltage regulator ICs produce negative fixed DC voltage values.

The following points are to be noted while working with **78xx** and **79xx** voltage regulator ICs:

- "xx" corresponds to a two-digit number and represents the amount (magnitude) of voltage that voltage regulator IC produces.

- Both 78xx and 79xx voltage regulator ICs have **3 pins** each and the third pin is used for collecting the output from them.

- The purpose of the first and second pins of these two types of ICs is different:

  o The first and second pins of **78xx** voltage regulator ICs are used for connecting the input and ground respectively.

  o The first and second pins of **79xx** voltage regulator ICs are used for connecting the ground and input respectively.

Examples

- 7805 voltage regulator IC produces a DC voltage of +5 volts.

- 7905 voltage regulator IC produces a DC voltage of -5 volts.

The following figure shows how to produce a **fixed positive voltage** at the output by using a fixed positive voltage regulator with necessary connections.
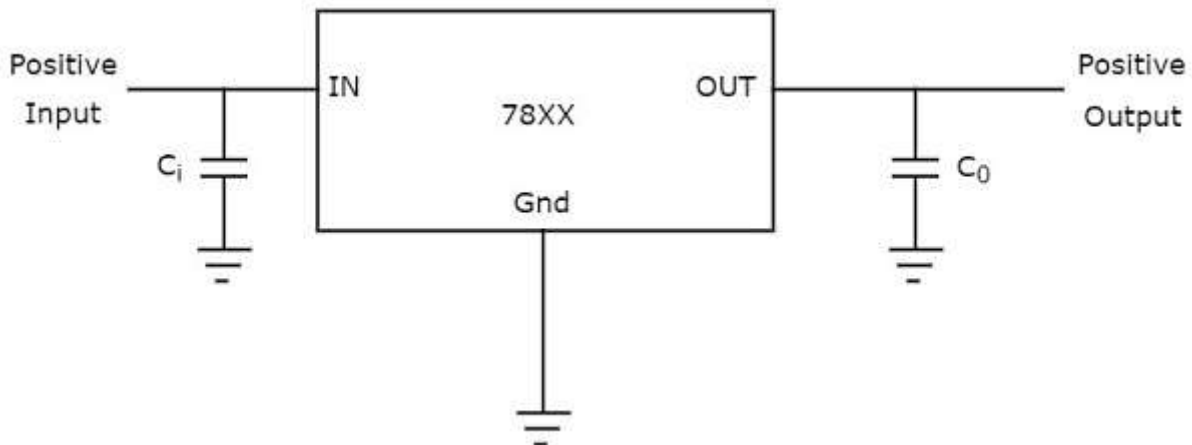
In the above figure that shows a fixed positive voltage regulator, the input capacitor C_i is used to prevent unwanted oscillations and the output capacitor, C_0 acts as a line filter to improve transient response.

Note: We can get a **fixed negative voltage** at the output by using a fixed negative voltage regulator with suitable connections.

Adjustable voltage regulator

An adjustable voltage regulator produces a DC output voltage, which can be adjusted to any other value of certain voltage range. Hence, adjustable voltage regulator is also called as a **variable voltage regulator**.

The DC output voltage value of an adjustable voltage regulator can be either positive or negative.

LM317 voltage regulator IC

LM317 voltage regulator IC can be used for producing a desired positive fixed DC voltage value of the available voltage range.

LM317 voltage regulator IC has 3 pins. The first pin is used for adjusting the output voltage, second pin is used for collecting the output and third pin is used for connecting the input.

The adjustable pin (terminal) is provided with a variable resistor which lets the output to vary between a wide range.
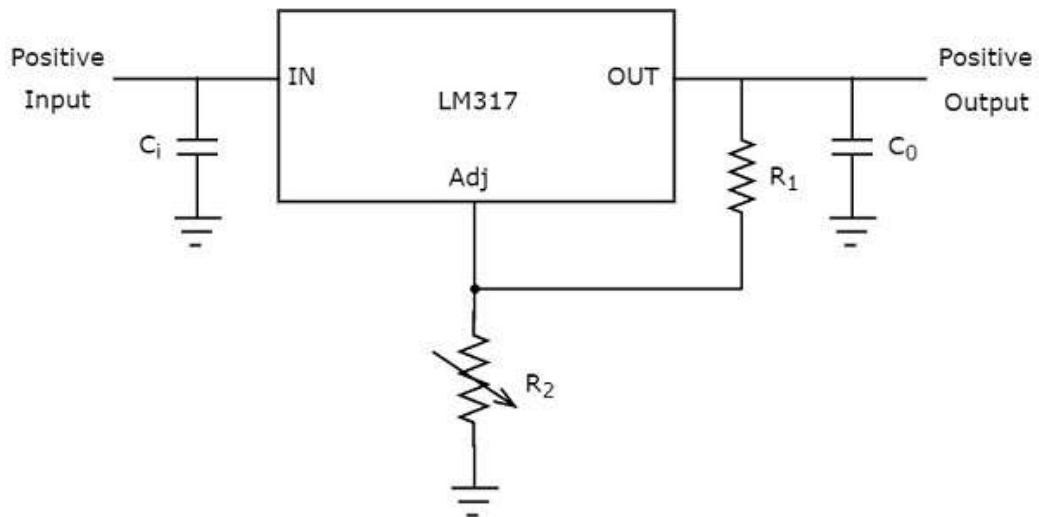
The above figure shows an unregulated power supply driving a LM 317 voltage regulator IC, which is commonly used. This IC can supply a load current of 1.5A over an adjustable output range of 1.25 V to 37 V.

18. LICA – Data Converters

All the real world quantities are analog in nature. We can represent these quantities electrically as analog signals. An **analog signal** is a time varying signal that has any number of values (variations) for a given time slot.

In contrast to this, a **digital signal** varies suddenly from one level to another level and will have only finite number of values (variations) for a given time slot.

This chapter discusses about the types of data converters and their specifications.

Types of Data Converters

The electronic circuits, which can be operated with analog signals are called as analog circuits. Similarly, the electronic circuits, which can be operated with digital signals are called as digital circuits. A data converter is an electronic circuit that converts data of one form to another.

There are two **types of data converters**:

- Analog to Digital Converter

- Digital to Analog Converter

If we want to connect the output of an analog circuit as an input of a digital circuit, then we have to place an interfacing circuit between them. This interfacing circuit that converts the analog signal into digital signal is called as **Analog to Digital Converter**.

Similarly, if we want to connect the output of a digital circuit as an input of an analog circuit, then we have to place an interfacing circuit between them. This interfacing circuit that converts the digital signal into an analog signal is called as **Digital to Analog Converter**.

Note that some Analog to Digital Converters may require Digital to Analog Converter as an internal block for their operation.

Specifications

The following are the **specifications** that are related to data conversions:

- Resolution

- Conversion Time

Resolution

- Resolution is the **minimum amount of change** needed in an analog input voltage for it to be represented in binary (digital) output. It depends on the number of bits that are used in the digital output.

  Mathematically, resolution can be represented as:

$$Resolution = \frac{1}{2^N}$$

where, 'N' is the number of bits that are present in the digital output.

From the above formula, we can observe that there exists an **inverse relationship** between the resolution and number of bits. Therefore, resolution decreases as the number of bits increases and vice-versa.

- **Resolution** can also be defined as the ratio of maximum analog input voltage that can be represented in binary and the equivalent binary number.

  Mathematically, resolution can be represented as

$$Resolution = \frac{V_{FS}}{2^N - 1}$$

where,

V_{FS} is the full scale input voltage or maximum analog input voltage,

'N' is the number of bits that are present in the digital output.

Conversion Time

The amount of time required for a data converter in order to convert the data (information) of one form into its equivalent data in other form is called as **conversion time**. Since we have two types of data converters, there are two types of conversion times as follows:

- Analog to Digital Conversion time
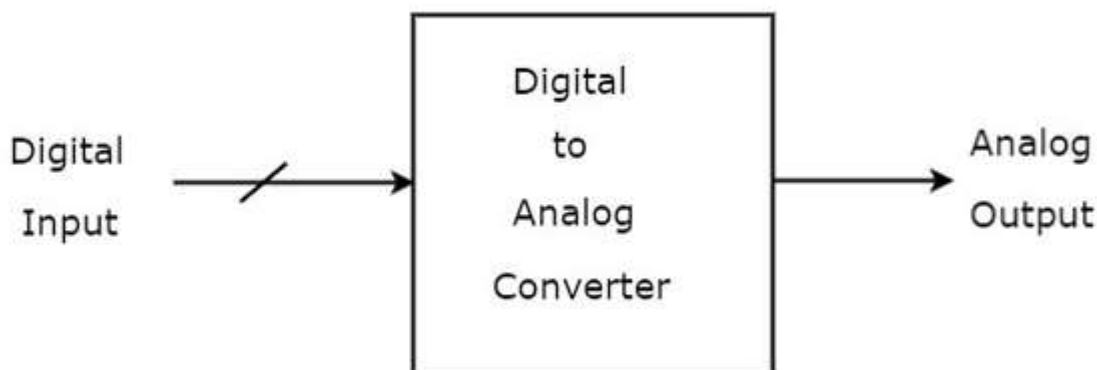
- Digital to Analog Conversion time

The amount of time required for an Analog to Digital Converter (ADC) to convert the analog input voltage into its equivalent binary (digital) output is called as **Analog to Digital conversion time**. It depends on the number of bits that are used in the digital output.

The amount of time required for a Digital to Analog Converter (DAC) to convert the binary (digital) input into its equivalent analog output voltage is called as **Digital to Analog conversion time**. It depends on the number of bits that are present in the binary (digital) input.

19. LICA – Digital to Analog Converters

A **Digital to Analog Converter (DAC)** converts a digital input signal into an analog output signal. The digital signal is represented with a binary code, which is a combination of bits 0 and 1. This chapter deals with Digital to Analog Converters in detail.

The **block diagram** of DAC is shown in the following figure:

A Digital to Analog Converter (DAC) consists of a number of binary inputs and a single output. In general, the **number of binary inputs** of a DAC will be a power of two.

Types of DACs

There are **two types** of DACs:

- Weighted Resistor DAC

- R-2R Ladder DAC

This section discusses about these two types of DACs in detail:

Weighted Resistor DAC

A weighted resistor DAC produces an analog output, which is almost equal to the digital (binary) input by using **binary weighted resistors** in the inverting adder circuit. In short, a binary weighted resistor DAC is called as weighted resistor DAC.

The **circuit diagram** of a 3-bit binary weighted resistor DAC is shown in the following figure:
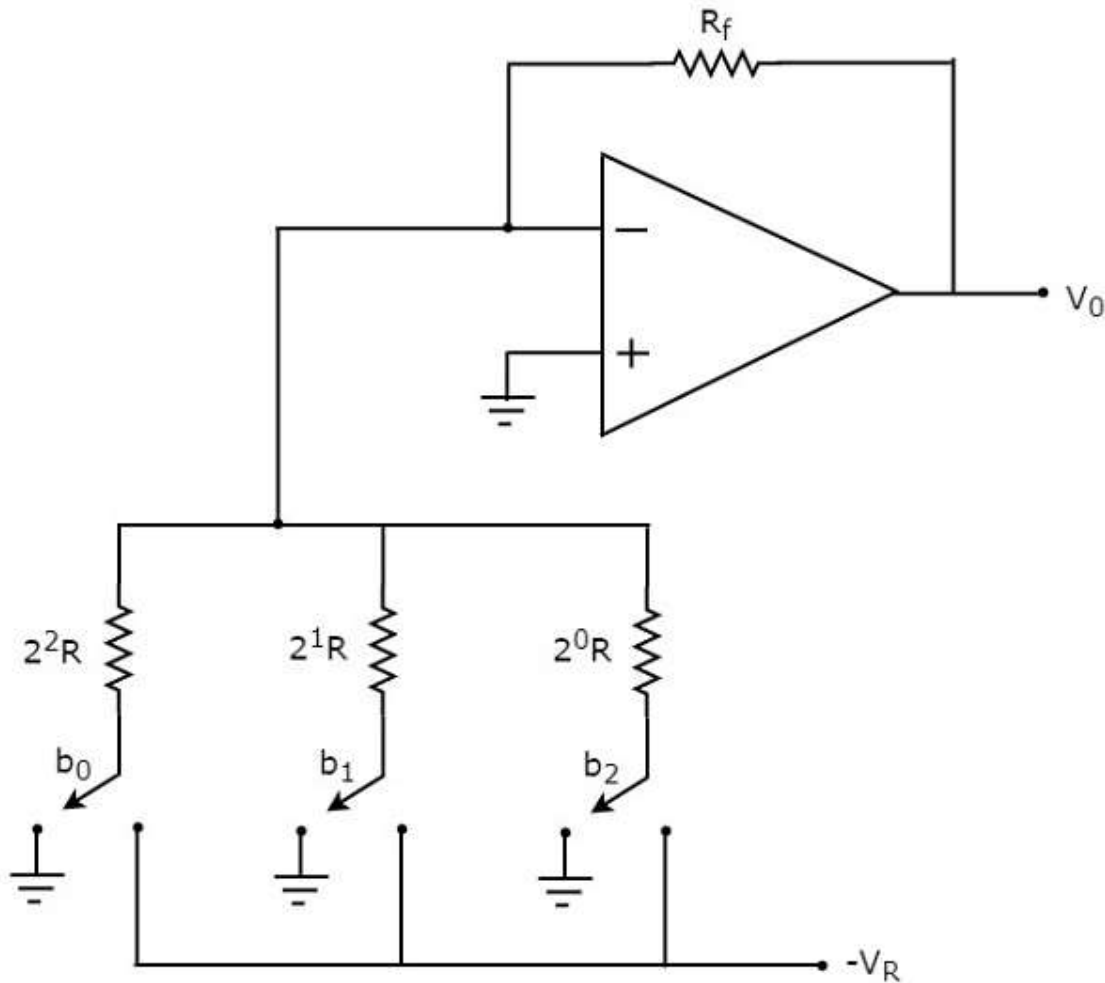
Recall that the bits of a binary number can have only one of the two values. i.e., either 0 or 1. Let the **3-bit binary input** is $b_2 b_1 b_0$. Here, the bits b_2 and b_0 denote the **Most Significant Bit (MSB)** and **Least Significant Bit (LSB)** respectively.

The **digital switches** shown in the above figure will be connected to ground, when the corresponding input bits are equal to '0'. Similarly, the digital switches shown in the above figure will be connected to the negative reference voltage, $-V_R$ when the corresponding input bits are equal to '1'.

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

According to the **virtual short concept**, the voltage at the inverting input terminal of op-amp is same as that of the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal's node will be zero volts.

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

$$\frac{0 + V_R b_2}{2^0 R} + \frac{0 + V_R b_1}{2^1 R} + \frac{0 + V_R b_0}{2^2 R} + \frac{0 - V_0}{R_f} = 0$$

$$=> \frac{V_0}{R_f} = \frac{V_R b_2}{2^0 R} + \frac{V_R b_1}{2^1 R} + \frac{V_R b_0}{2^2 R}$$

$$=> V_0 = \frac{V_R R_f}{R}\left\{\frac{b_2}{2^0} + \frac{b_1}{2^1} + \frac{b_0}{2^2}\right\}$$

Substituting, $R = 2R_f$ in above equation.

$$=> V_0 = \frac{V_R R_f}{2R_f}\left\{\frac{b_2}{2^0} + \frac{b_1}{2^1} + \frac{b_0}{2^2}\right\}$$

$$=> V_0 = \frac{V_R}{2}\left\{\frac{b_2}{2^0} + \frac{b_1}{2^1} + \frac{b_0}{2^2}\right\}$$

The above equation represents the **output voltage equation** of a 3-bit binary weighted resistor DAC. Since the number of bits are three in the binary (digital) input, we will get seven possible values of output voltage by varying the binary input from 000 to 111 for a fixed reference voltage, V_R.

We can write the **generalized output voltage equation** of an N-bit binary weighted resistor DAC as shown below based on the output voltage equation of a 3-bit binary weighted resistor DAC.

$$=> V_0 = \frac{V_R}{2}\left\{\frac{b_{N-1}}{2^0} + \frac{b_{N-2}}{2^1} + \cdots + \frac{b_0}{2^{N-1}}\right\}$$

The **disadvantages** of a binary weighted resistor DAC are as follows:

- The difference between the resistance values corresponding to LSB & MSB will increase as the number of bits present in the digital input increases.

- It is difficult to design more accurate resistors as the number of bits present in the digital input increases.

R-2R Ladder DAC

The R-2R Ladder DAC overcomes the disadvantages of a binary weighted resistor DAC. As the name suggests, R-2R Ladder DAC produces an analog output, which is almost equal to the digital (binary) input by using a **R-2R ladder network** in the inverting adder circuit.

The **circuit diagram** of a 3-bit R-2R Ladder DAC is shown in the following figure:
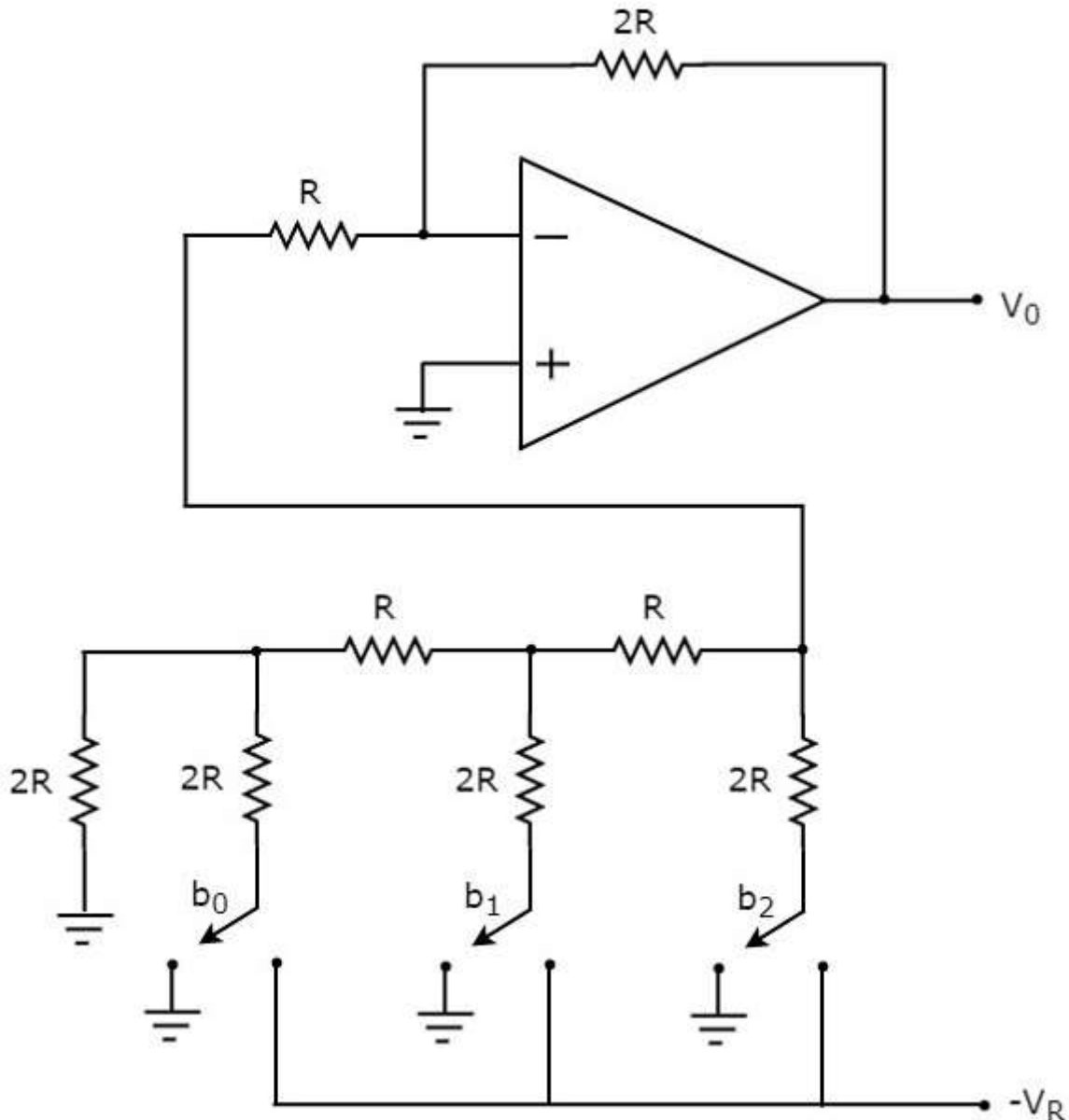
Recall that the bits of a binary number can have only one of the two values. i.e., either 0 or 1. Let the **3-bit binary input** is $b_2b_1b_0$. Here, the bits b_2 and b_0 denote the Most Significant Bit (MSB) and Least Significant Bit (LSB) respectively.

The **digital switches** shown in the above figure will be connected to ground, when the corresponding input bits are equal to '0'. Similarly, the digital switches shown in above figure will be connected to the negative reference voltage, $-V_R$ when the corresponding input bits are equal to '1'.

It is difficult to get the generalized output voltage equation of a R-2R Ladder DAC. But, we can find the analog output voltage values of R-2R Ladder DAC for individual binary input combinations easily.

The **advantages** of a R-2R Ladder DAC are as follows:

- R-2R Ladder DAC contains only two values of resistor: R and 2R. So, it is easy to select and design more accurate resistors.

- If more number of bits are present in the digital input, then we have to include required number of R-2R sections additionally.

Due to the above advantages, R-2R Ladder DAC is preferable over binary weighted resistor DAC.

In the previous chapter, we discussed the two types of DACs. This chapter discusses an example problem based on R-2R ladder DAC.

Example

Let us find the value of analog output voltage of R-2R Ladder DAC for a binary input, $b_2b_1b_0 = 100$.

Circuit Diagram and its Simplification

The **circuit diagram** of a 3-bit R-2R Ladder DAC when binary input, $b_2b_1b_0 = 100$ applied to it is shown in the following figure:
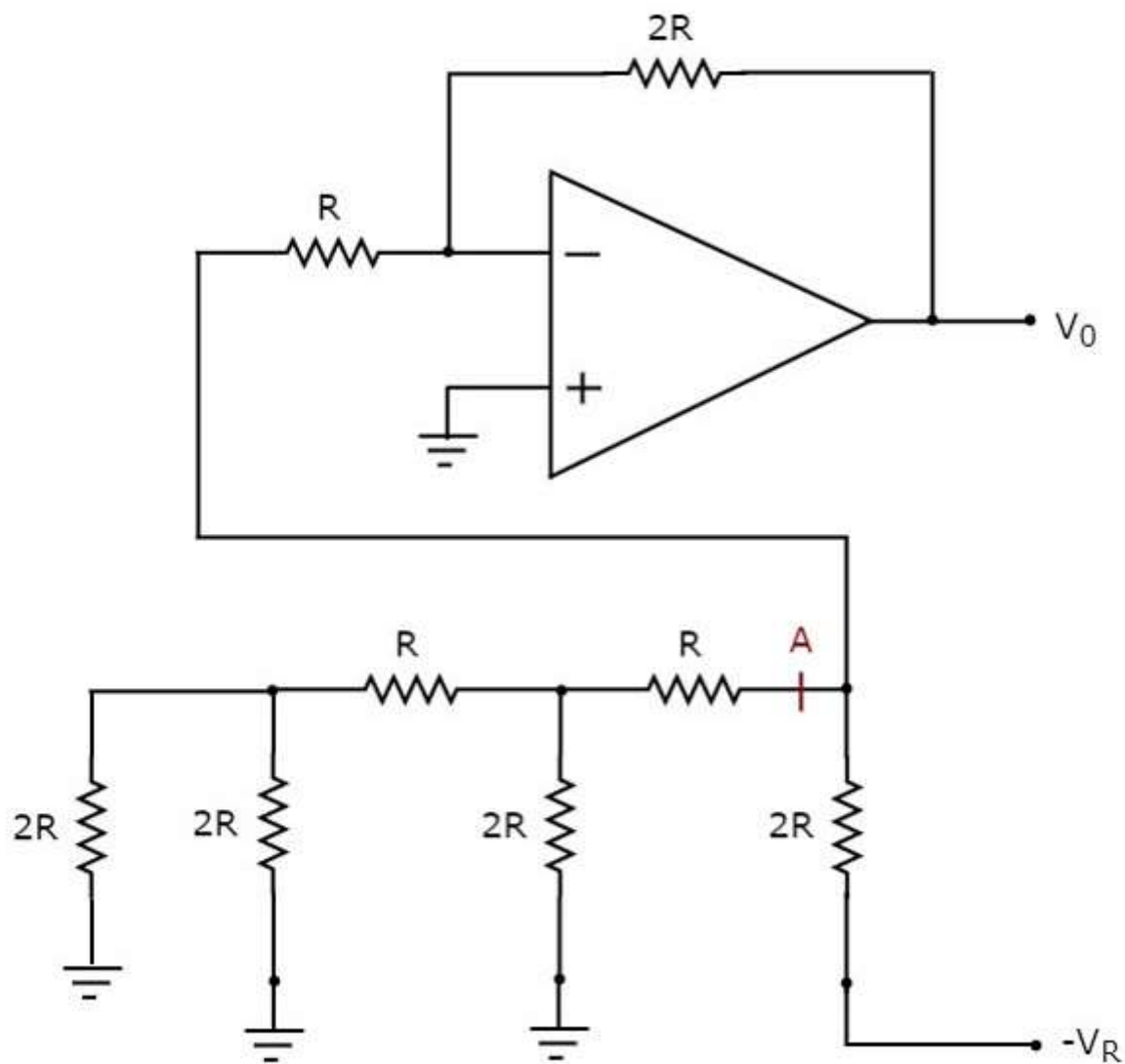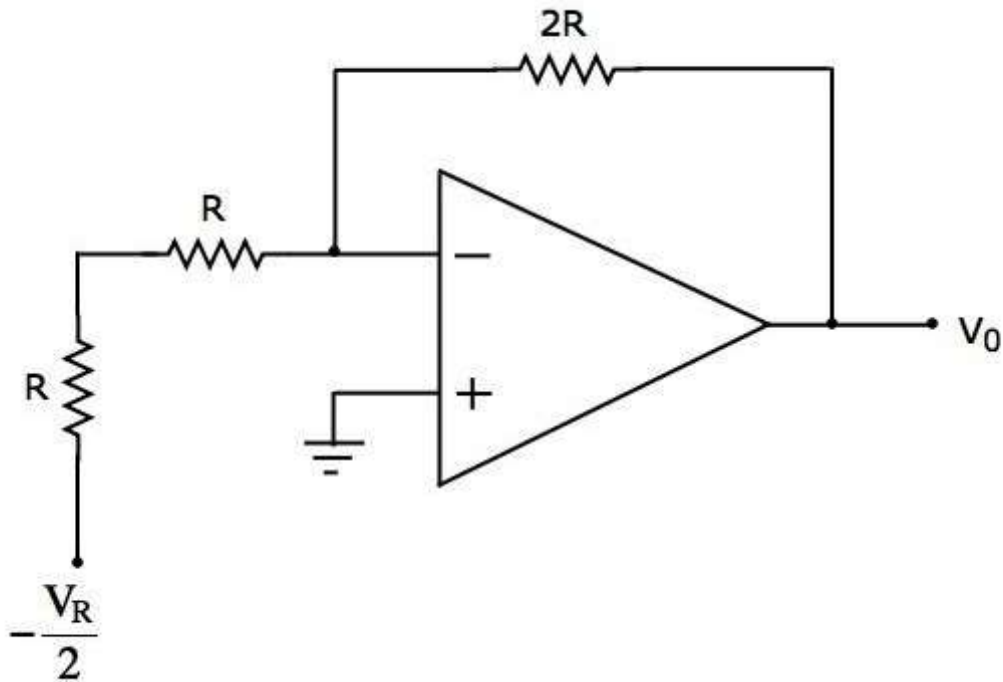
In the above circuit, there exists series and parallel combinations of resistors to the left of **point A** with respect to ground. So, we can replace that entire resistor network with a single resistor having resistance of $2R\ \Omega$.

The **simplified circuit diagram** is shown in the following figure:
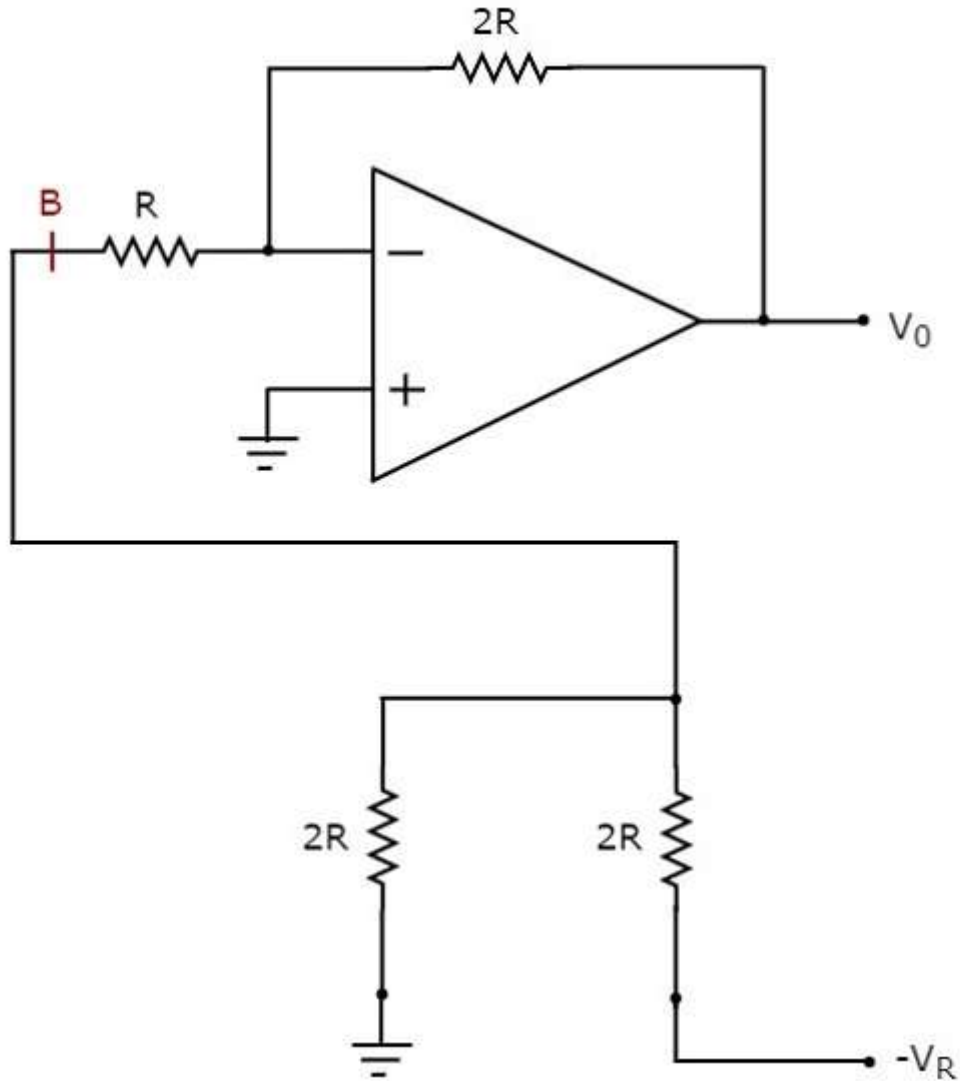
We can replace the part of the network that is connected to the left of point B with respect to ground by using a Thevenin's equivalent circuit. The **modified circuit diagram** is shown in the following figure:

In the above circuit, there exist a series combination of two resistors. Replace this combination with a single resistor. The final **circuit diagram** after simplification is shown in the following figure:
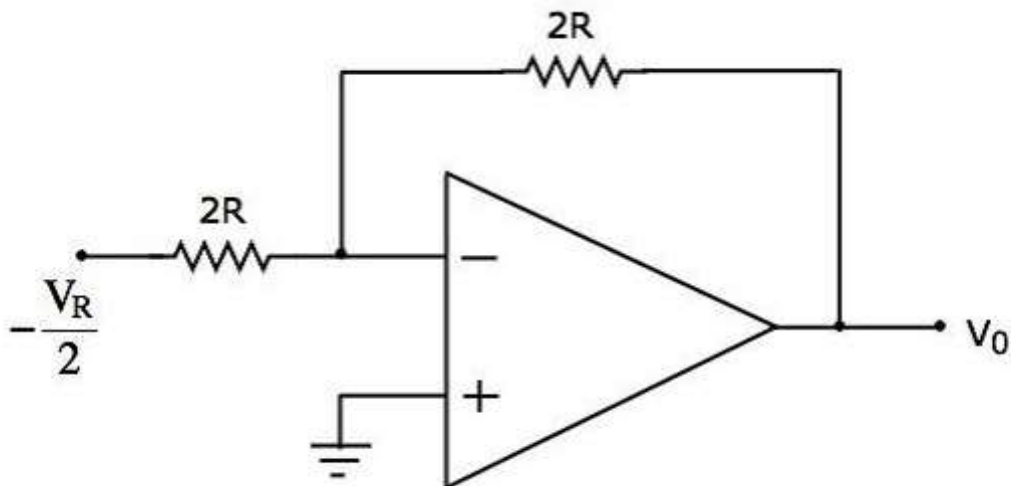
Now, the above circuit diagram looks like an **inverting amplifier**. It is having an input voltage of $-\frac{V_R}{2}$ volts, input resistance of $2R\ \Omega$ and feedback resistance of $2R\ \Omega$.

The **output voltage** of the circuit shown above will be:

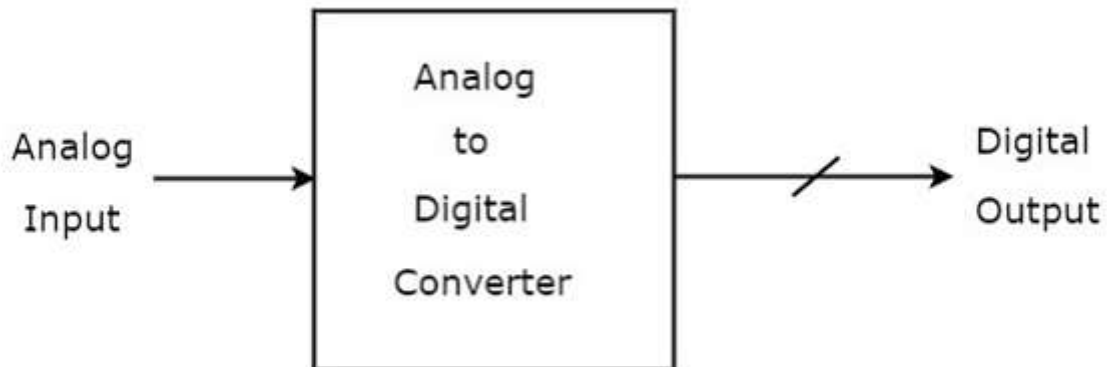$$V_0 = -\frac{2R}{2R}\left(-\frac{V_R}{2}\right)$$

$$V_0 = \frac{V_R}{2}$$

Therefore, the **output voltage** of 3-bit R-2R Ladder DAC is $\frac{V_R}{2}$ volts for a binary input, $b_2 b_1 b_0 = 100$.

An Analog to Digital Converter (**ADC**) converts an analog signal into a digital signal. The digital signal is represented with a binary code, which is a combination of bits 0 and 1.

The **block diagram** of an ADC is shown in the following figure:

Observe that in the figure shown above, an Analog to Digital Converter (**ADC**) consists of a single analog input and many binary outputs. In general, the number of binary outputs of ADC will be a power of two.

There are **two types** of ADCs: Direct type ADCs and Indirect type ADC. This chapter discusses about the Direct type ADCs in detail.

If the ADC performs the analog to digital conversion directly by utilizing the internally generated equivalent digital (binary) code for comparing with the analog input, then it is called as **Direct type ADC**.

The following are the **examples** of Direct type ADCs:

- Counter type ADC

- Successive Approximation ADC
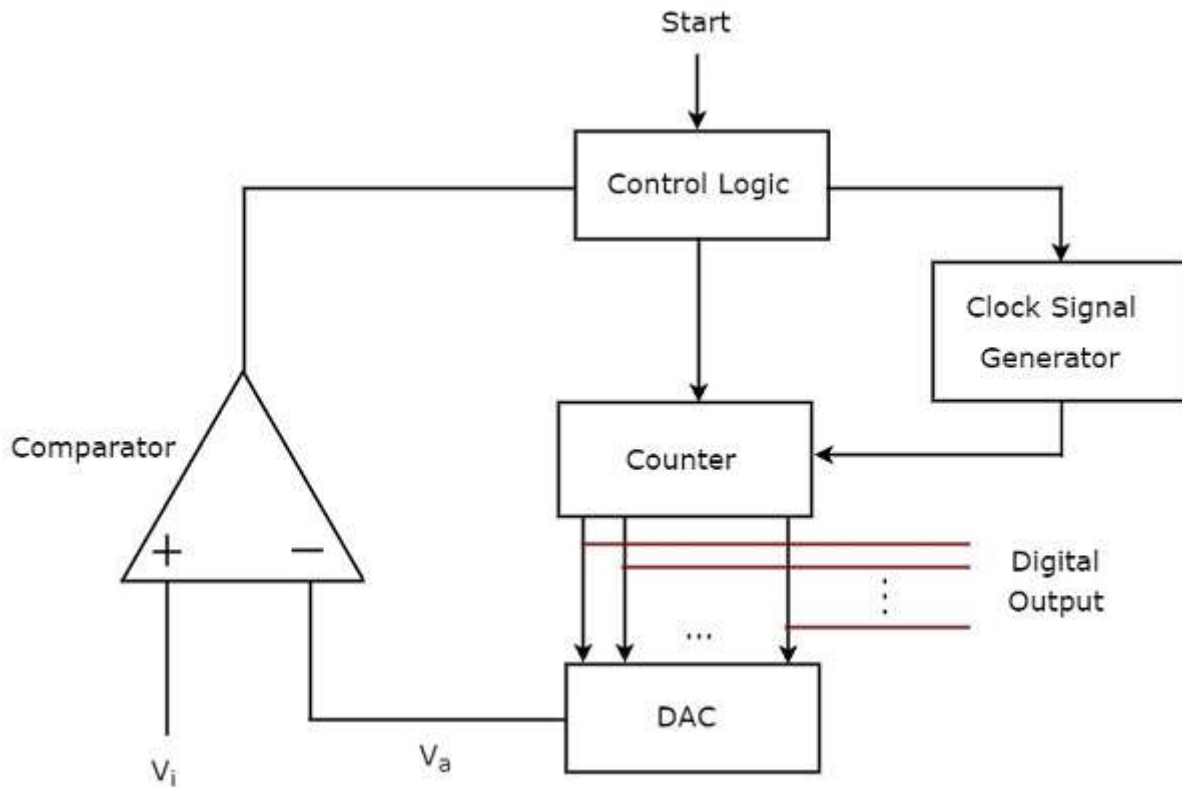
- Flash type ADC

This section discusses about these Direct type ADCs in detail.

Counter type ADC

A **counter type ADC** produces a digital output, which is approximately equal to the analog input by using counter operation internally.

The **block diagram** of a counter type ADC is shown in the following figure:

The counter type ADC mainly consists of 5 blocks: Clock signal generator, Counter, DAC, Comparator and Control logic.

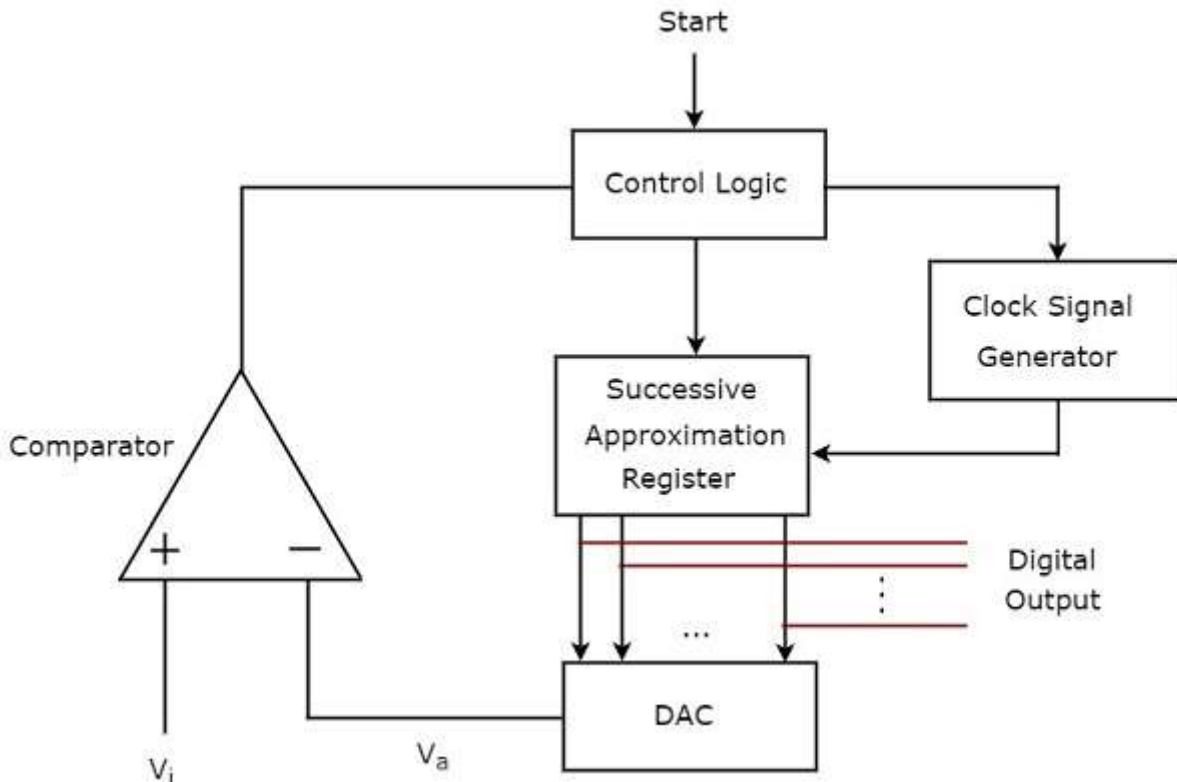The **working** of a counter type ADC is as follows:

- The **control logic** resets the counter and enables the clock signal generator in order to send the clock pulses to the counter, when it received the start commanding signal.

- The **counter** gets incremented by one for every clock pulse and its value will be in binary (digital) format. This output of the counter is applied as an input of DAC.

- **DAC** converts the received binary (digital) input, which is the output of counter, into an analog output. Comparator compares this analog value, V_a with the external analog input value V_i.

- The **output of comparator** will be '**1**' as long as V_i is greater than V_a. The operations mentioned in above two steps will be continued as long as the control logic receives '1' from the output of comparator.

- The **output of comparator** will be '**0**', when V_i is less than or equal to V_a. So, the control logic receives '0' from the output of comparator. Then, the control logic disables the clock signal generator so that it doesn't send any clock pulse to the counter.

- At this instant, the output of the counter will be displayed as the **digital output**. It is almost equivalent to the corresponding external analog input value V_i.

Successive Approximation ADC

A **successive approximation type ADC** produces a digital output, which is approximately equal to the analog input by using successive approximation technique internally.

The **block diagram** of a successive approximation ADC is shown in the following figure:

The successive approximation ADC mainly consists of 5 blocks: Clock signal generator, Successive Approximation Register (SAR), DAC, comparator and Control logic.

The **working** of a successive approximation ADC is as follows:

- The **control logic** resets all the bits of SAR and enables the clock signal generator in order to send the clock pulses to SAR, when it received the start commanding signal.

- The binary (digital) data present in **SAR** will be updated for every clock pulse based on the output of comparator. The output of SAR is applied as an input of DAC.

- **DAC** converts the received digital input, which is the output of SAR, into an analog output. The comparator compares this analog value V_a with the external analog input value V_i.

tutorialspoint
SIMPLY EASY LEARNING

- The **output of a comparator** will be '1' as long as V_i is greater than V_a. Similarly, the output of comparator will be '0', when V_i is less than or equal to V_a.

- The operations mentioned in above steps will be continued until the digital output is a valid one.

The digital output will be a valid one, when it is almost equivalent to the corresponding external analog input value V_i.

Flash type ADC

A **flash type ADC** produces an equivalent digital output for a corresponding analog input in no time. Hence, flash type ADC is the fastest ADC.

The **circuit diagram** of a 3-bit flash type ADC is shown in the following figure:
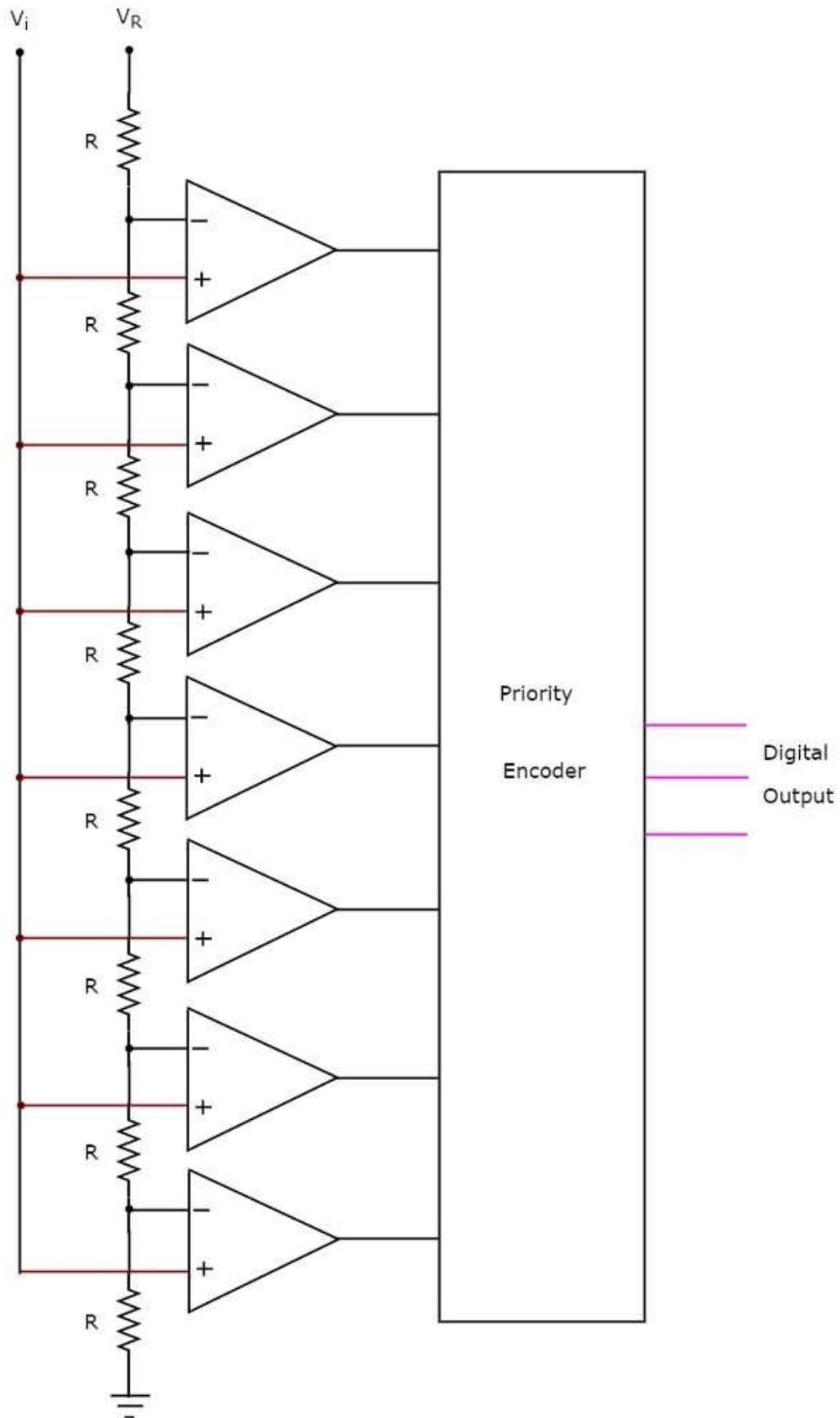
The 3-bit flash type ADC consists of a voltage divider network, 7 comparators and a priority encoder.

The **working** of a 3-bit flash type ADC is as follows:

- The **voltage divider network** contains 8 equal resistors. A reference voltage V_R is applied across that entire network with respect to the ground. The voltage drop across each resistor from bottom to top with respect to ground will be the integer multiples (from 1 to 8) of $\frac{V_R}{8}$.

- The external **input voltage** V_i is applied to the non-inverting terminal of all comparators. The voltage drop across each resistor from bottom to top with respect to ground is applied to the inverting terminal of comparators from bottom to top.

- At a time, all the comparators compare the external input voltage V_i with the voltage drops present at the respective other input terminal. That means, the comparison operations take place by each comparator **parallelly**.

- The **output of the comparator** will be '1' as long as V_i is greater than the voltage drop present at the respective other input terminal. Similarly, the output of comparator will be '0', when, V_i is less than or equal to the voltage drop present at the respective other input terminal.

- All the outputs of comparators are connected as the inputs of **priority encoder**. This priority encoder produces a binary code (digital output), which is corresponding to the high priority input that has '1'.

- Therefore, the output of priority encoder is nothing but the binary equivalent (**digital output**) of external analog input voltage, V_i.

The flash type ADC is used in the applications where the conversion speed of analog input into digital data should be very high.

In the previous chapter, we discussed about what an ADC is and the examples of a Direct type ADC. This chapter discusses about the Indirect type ADC.

If an ADC performs the analog to digital conversion by an indirect method, then it is called an **Indirect type ADC**. In general, first it converts the analog input into a linear function of time (or frequency) and then it will produce the digital (binary) output.
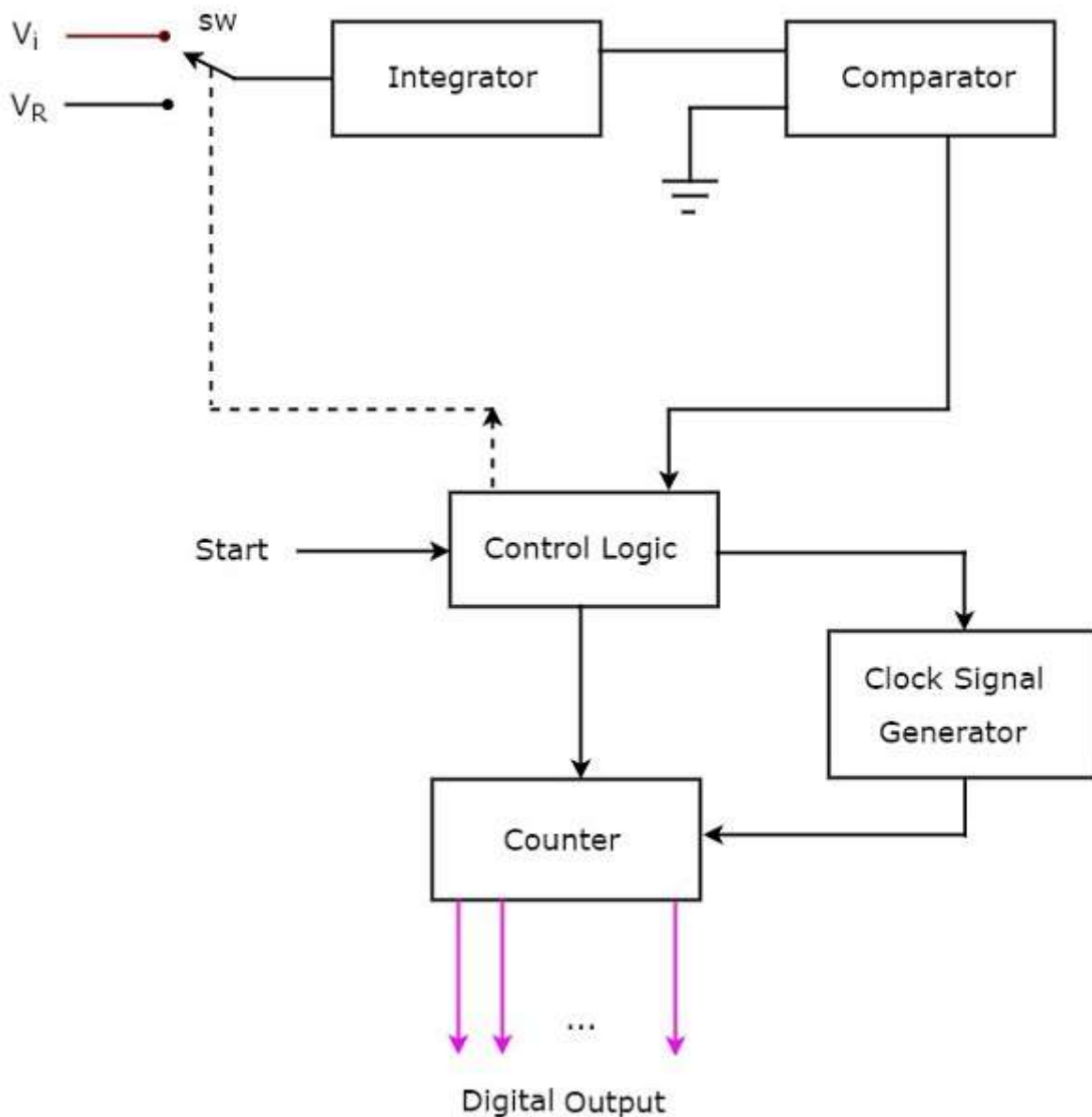
Dual slope ADC is the best **example** of an Indirect type ADC. This chapter discusses about it in detail.

Dual Slope ADC

As the name suggests, a **dual slope ADC** produces an equivalent digital output for a corresponding analog input by using two (dual) slope technique.

The **block diagram** of a dual slope ADC is shown in the following figure:

The dual slope ADC mainly consists of 5 blocks: Integrator, Comparator, Clock signal generator, Control logic and Counter.

The **working** of a dual slope ADC is as follows:

- The **control logic** resets the counter and enables the clock signal generator in order to send the clock pulses to the counter, when it is received the start commanding signal.

- Control logic pushes the switch **sw** to connect to the **external analog input voltage V_i**, when it is received the start commanding signal. This input voltage is applied to an integrator.

- The output of the **integrator** is connected to one of the two inputs of the comparator and the other input of comparator is connected to ground.

- **Comparator** compares the output of the integrator with zero volts (ground) and produces an output, which is applied to the control logic.

- The **counter** gets incremented by one for every clock pulse and its value will be in binary (digital) format. It produces an overflow signal to the control logic, when it is incremented after reaching the maximum count value. At this instant, all the bits of counter will be having zeros only.

- Now, the control logic pushes the switch **sw** to connect to the **negative reference voltage** $-V_{ref}$. This negative reference voltage is applied to an integrator. It removes the charge stored in the capacitor until it becomes zero.

- At this instant, both the inputs of a comparator are having zero volts. So, comparator sends a signal to the control logic. Now, the control logic disables the clock signal generator and retains (holds) the **counter value**. The counter value is proportional to the external analog input voltage.

- At this instant, the output of the counter will be displayed as the **digital output**. It is almost equivalent to the corresponding external analog input value V_i.

The dual slope ADC is used in the applications, where **accuracy** is more important while converting analog input into its equivalent digital (binary) data.