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

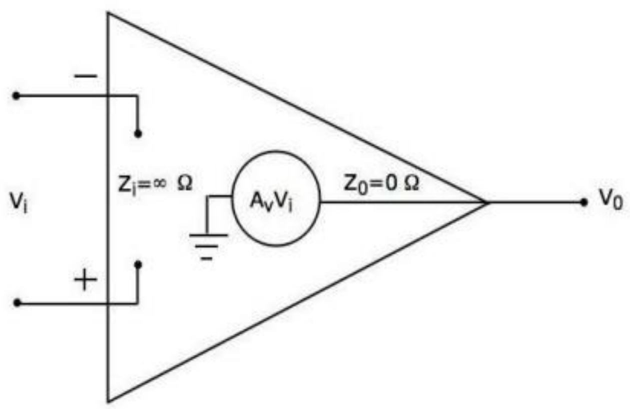
An op-amp is represented with a triangle symbol having two inputs and one output.

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:

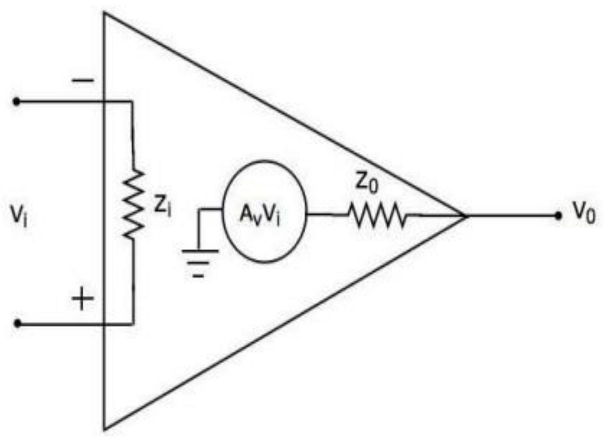


An **ideal op-amp** exhibits the following characteristics:

- 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:

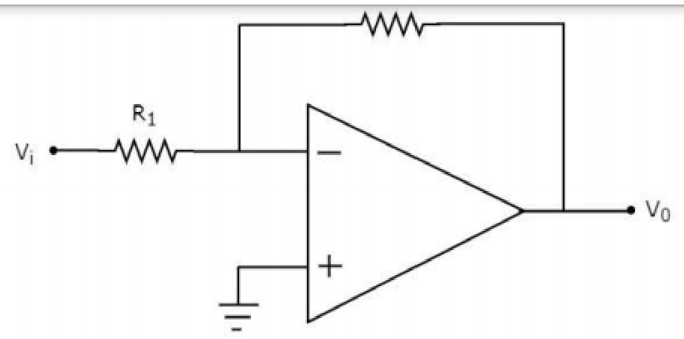
- Inverting Amplifier
- Non-inverting Amplifier
- Voltage follower

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.

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

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

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

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

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

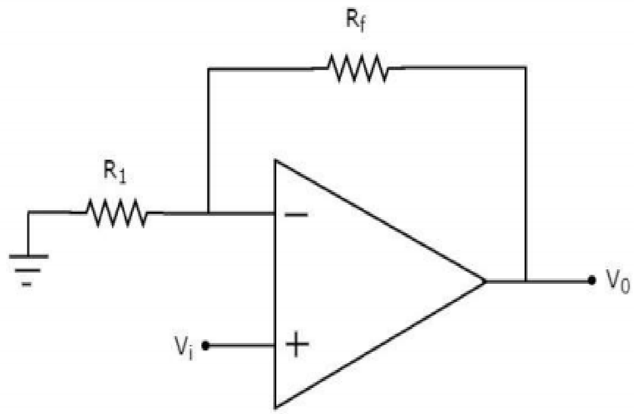
The ratio of the output voltage V_0 and the input voltage V_i is the voltage-gain or gain of the amplifier. Therefore, the **gain of inverting amplifier** is equal to $-\frac{R_f}{R_1}$.

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.

$$=> V_1 = V_i$$

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

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

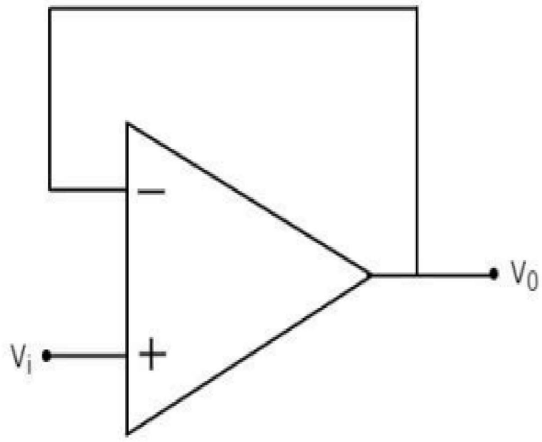
$$=> \frac{V_0}{V_i} = 1 + \frac{R_f}{R_1}$$

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.

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.

2.1 Sign Changer (Phase Inverter)

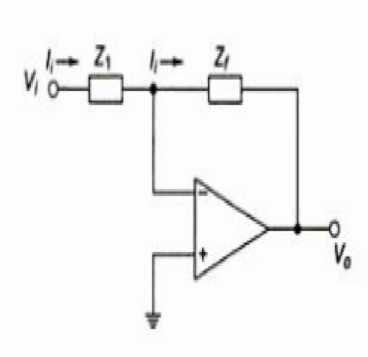


Fig 2.1 Basic inverting configuration

The basic inverting amplifier configuration using an op-amp with input impedance Z1 and feedback impedance Z_f. If the impedance Z1 and Z f are equal in magnitude and phase, then the closed loop voltage gain is -1, and the input signal will undergo a 180° phase shift at the output. Hence, such circuit is also called phase inverter. If two such amplifiers are connected in cascade, then the output from the second stage is the same as the input signal without any change of sign. Hence, the outputs from the two stages are equal in magnitude but opposite in phase and such a system is an excellent paraphase amplifier.

2.2 Scale Changer:

Referring the above diagram, if the ratio $Z_f / Z_1 = k$, a real constant, then the closed loop gain is –k, and the input voltage is multiplied by a factor –k and the scaled output is available at the output. Usually, in such applications, Z_f and Z_1 are selected as precision resistors for obtaining precise and scaled value of input voltage.

2.3 Phase Shift Circuits

The phase shift circuits produce phase shifts that depend on the frequency and maintain a constant gain. These circuits are also called constant-delay filters or all-pass filters. That constant delay refers to the fact the time difference between input and output remains constant when frequency is changed over a range of operating frequencies.

This is called all-pass because normally a constant gain is maintained for all the frequencies within the operating range. The two types of circuits, for lagging phase angles and leading phase angles.

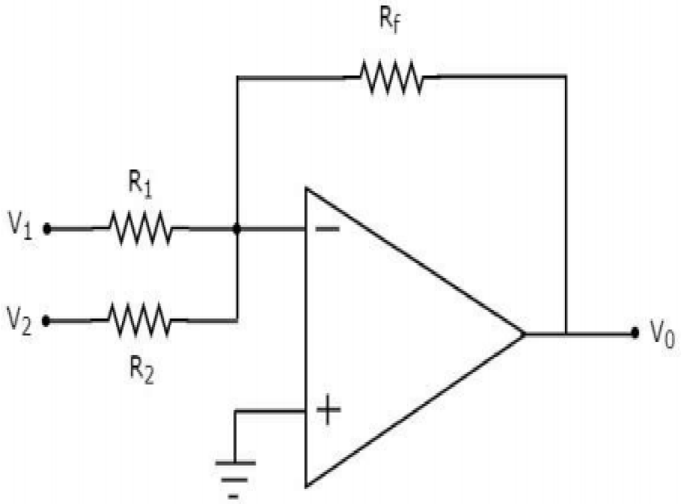
The electronic circuits, which perform arithmetic operations are called as **arithmetic circuits**. Using op-amps, you can build basic arithmetic circuits such as an **adder** and a **subtractor**. In this chapter, you will learn about each of them in detail.

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:



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

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

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

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

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

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

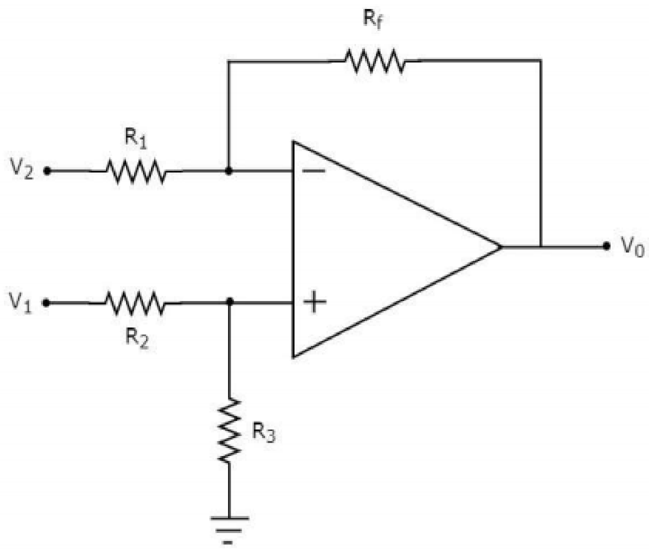
$$=> V_0 = -(V_1 + V_2)$$

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.



Now, let us find the expression for output voltage V_0 of the above circuit using **superposition theorem** using the following steps:

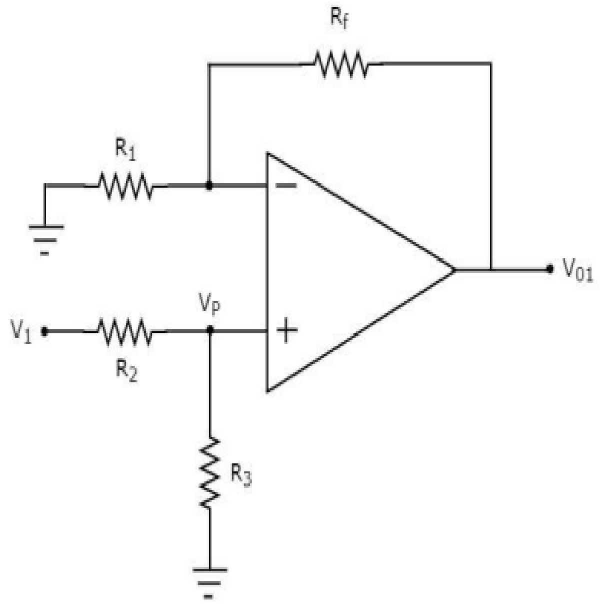
Step1

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:

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:



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

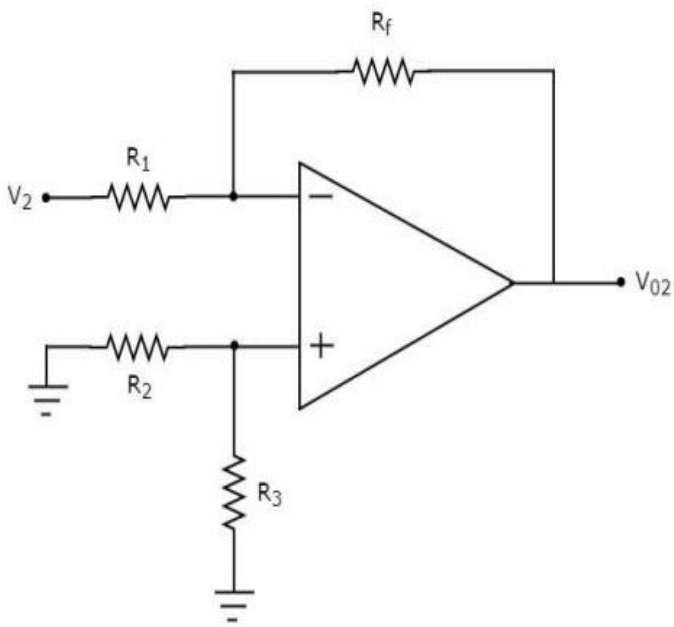
$$V_{01} = V_P\left(1 + \frac{R_f}{R_1}\right)$$

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.

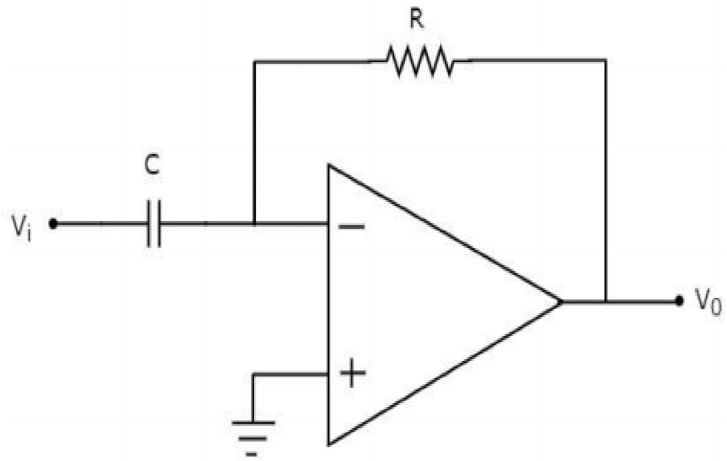
The electronic circuits which perform the mathematical operations such as differentiation and integration are called as differentiator and integrator, respectively.

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:

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

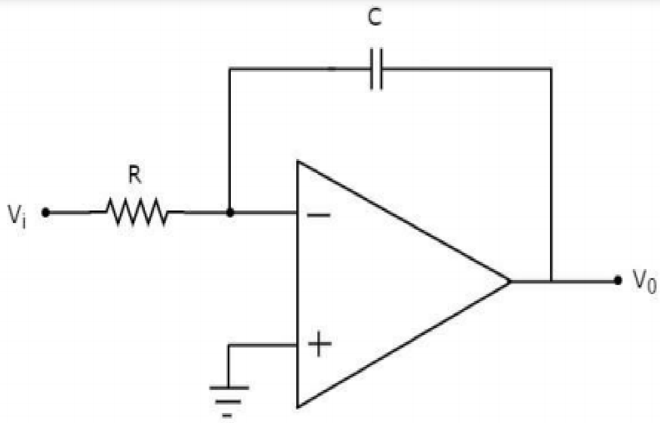
Thus, the op-amp based differentiator circuit shown above will produce an output, which is the differential of input voltage V_i, when the magnitudes of impedances of resistor and capacitor are reciprocal to each other.

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.

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.

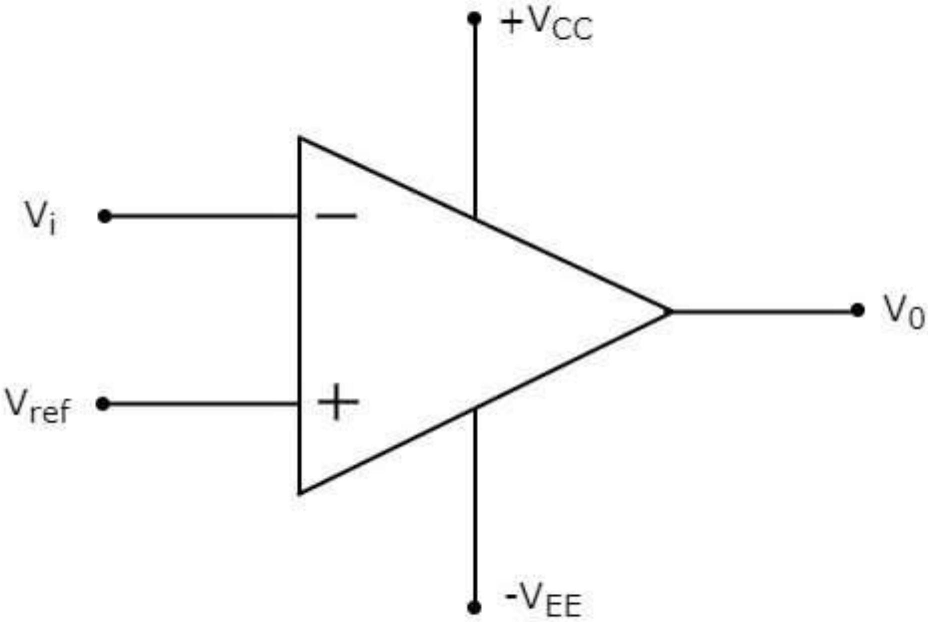
Inverting Comparator

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, $+VSat$ and $-VSat$ at the output based on the values of its input voltage Vi and the reference voltage $Vref$.

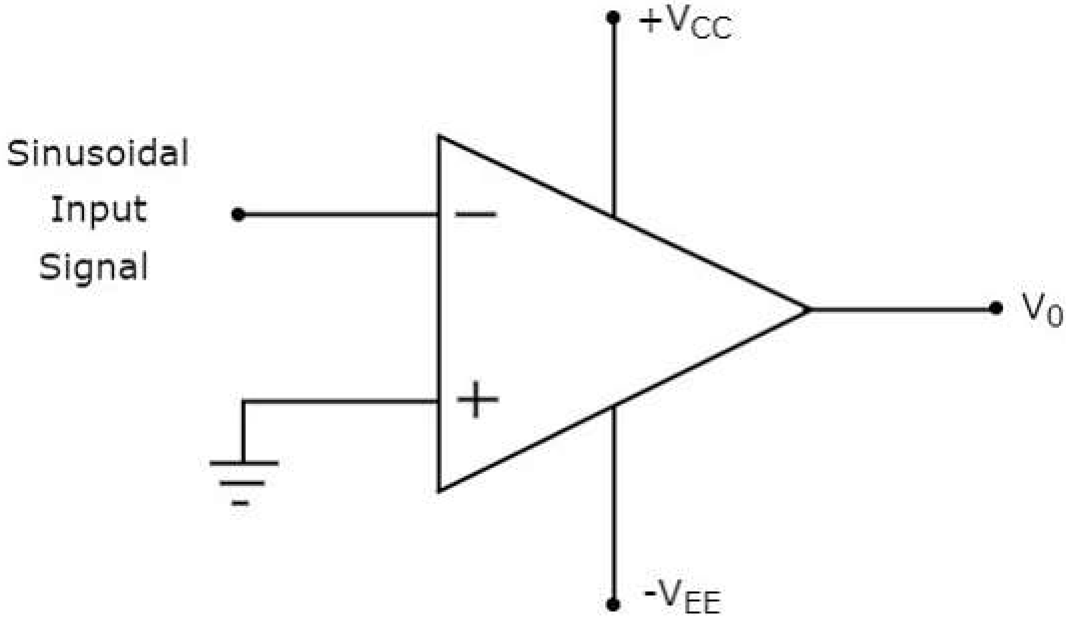
 The output value of an inverting comparator will be $-\boldsymbol{VSat}$, for which the input voltage Vi is greater than the reference voltage $Vref$.



• 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

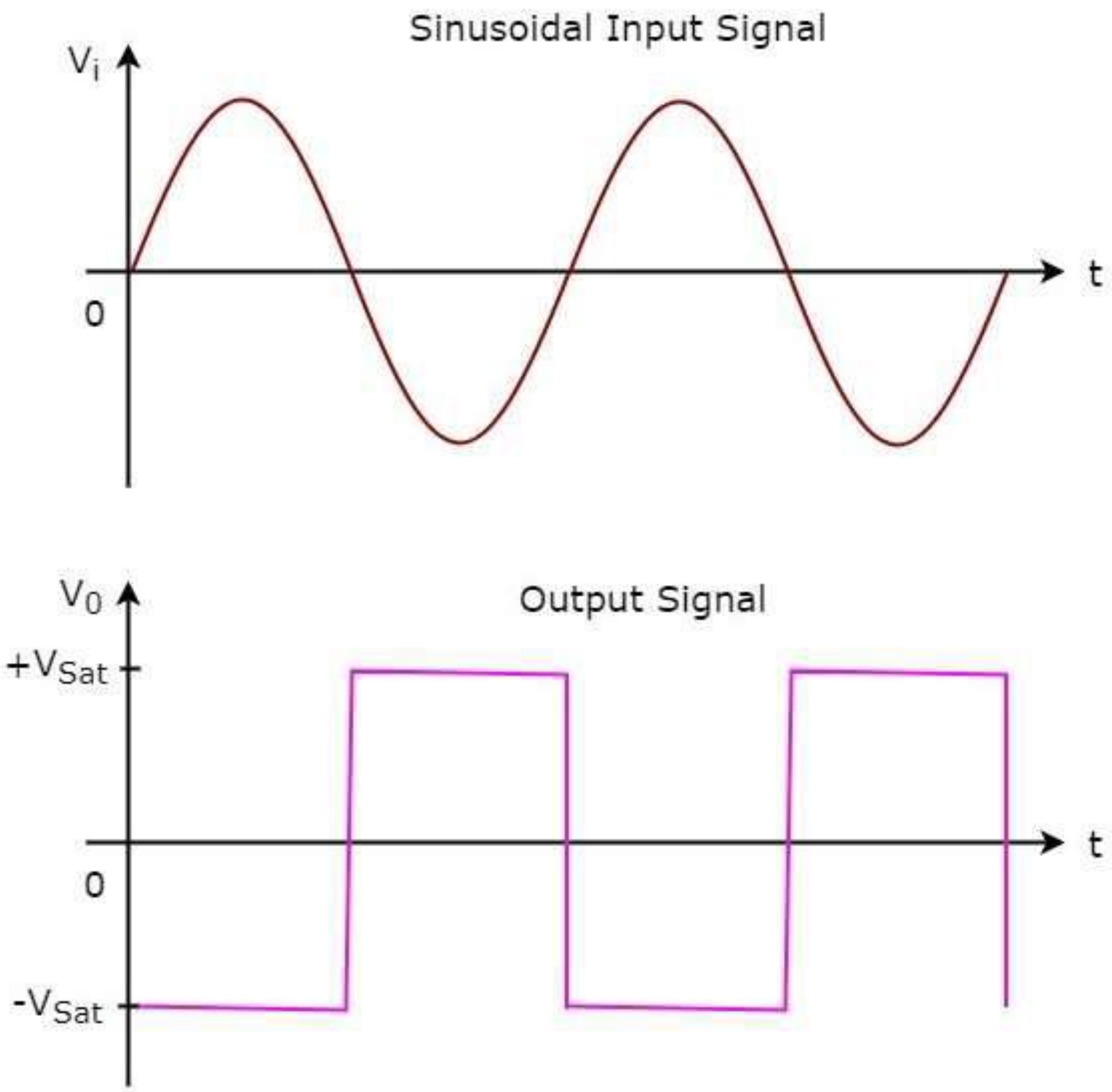


The **operation** of the inverting comparator shown above is discussed below:

• 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.

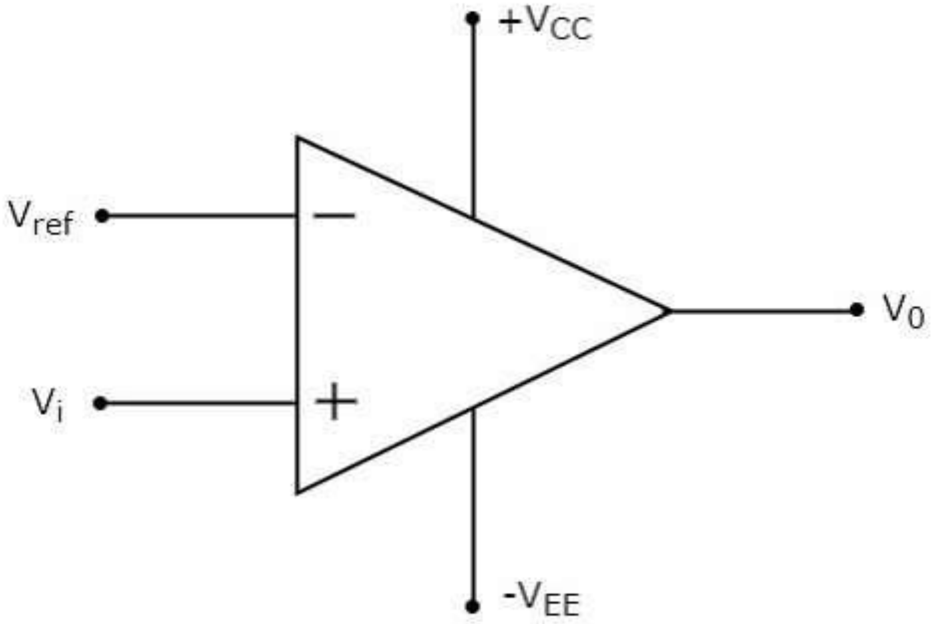
The following figure shows the **input and output waveforms** of an inverting comparator, when the reference voltage is zero volts.



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:

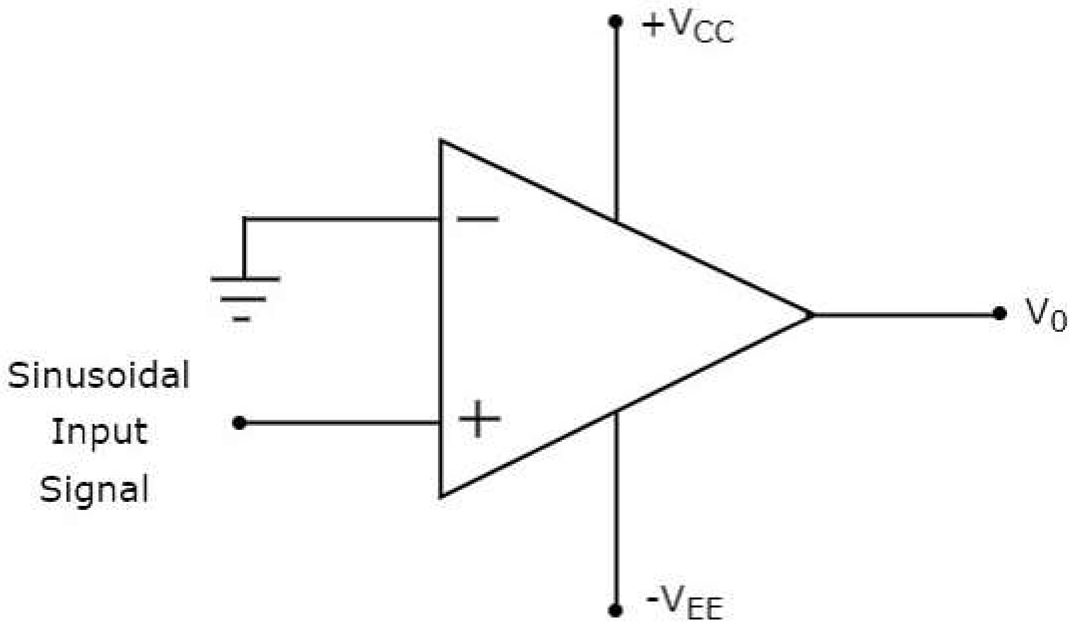


The **operation** of a non-inverting comparator is very simple. It produces one of the two values, $+V_{Sat}$ and $-V_{Sat}$ at the output based on the values of input voltage V_i and the reference voltage V_{ref}.

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

Example

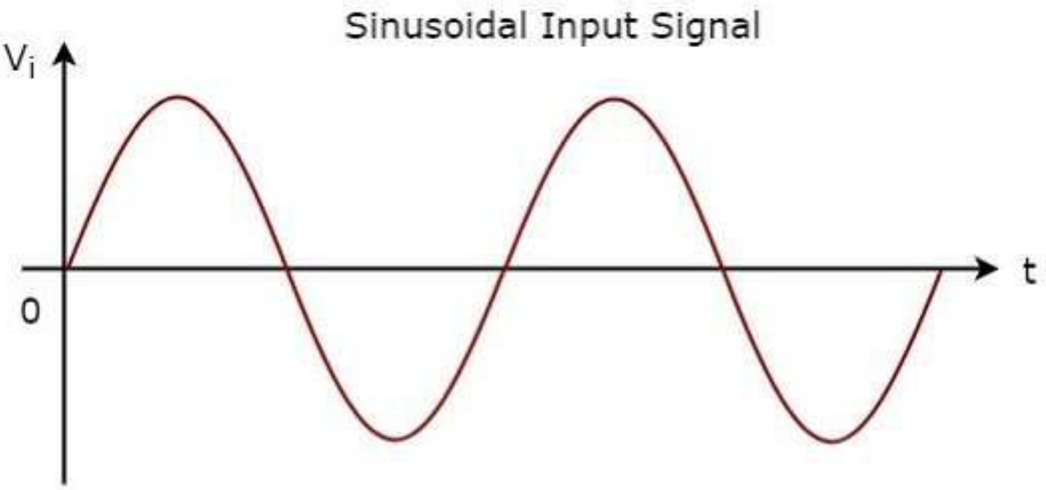
Let us draw the **output wave form** of a non-inverting comparator, when a sinusoidal input signal and reference voltage of zero volts are applied to the non-inverting and inverting terminals of the op-amp respectively.

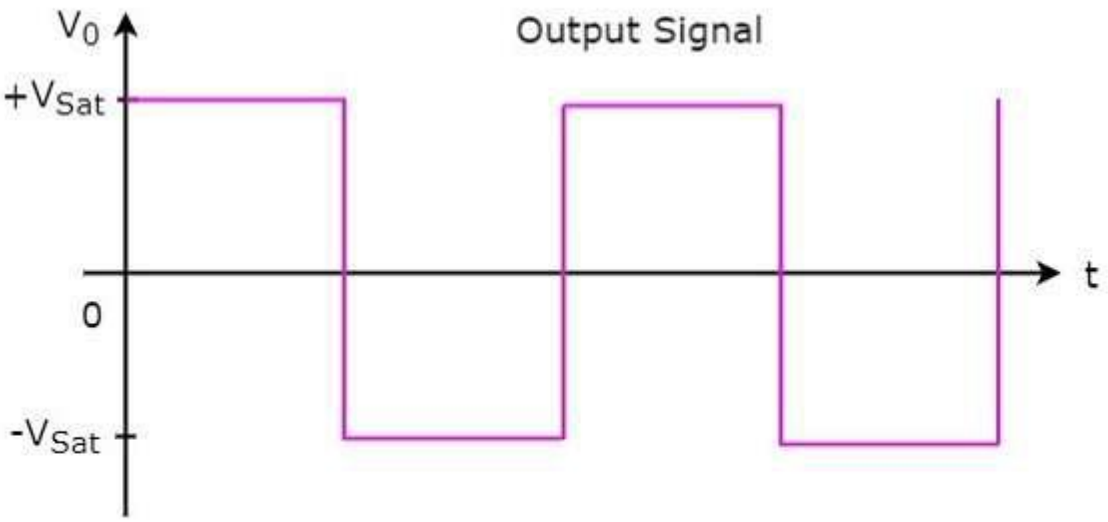


The **operation** of a non-inverting comparator is explained below:

- 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**.

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:

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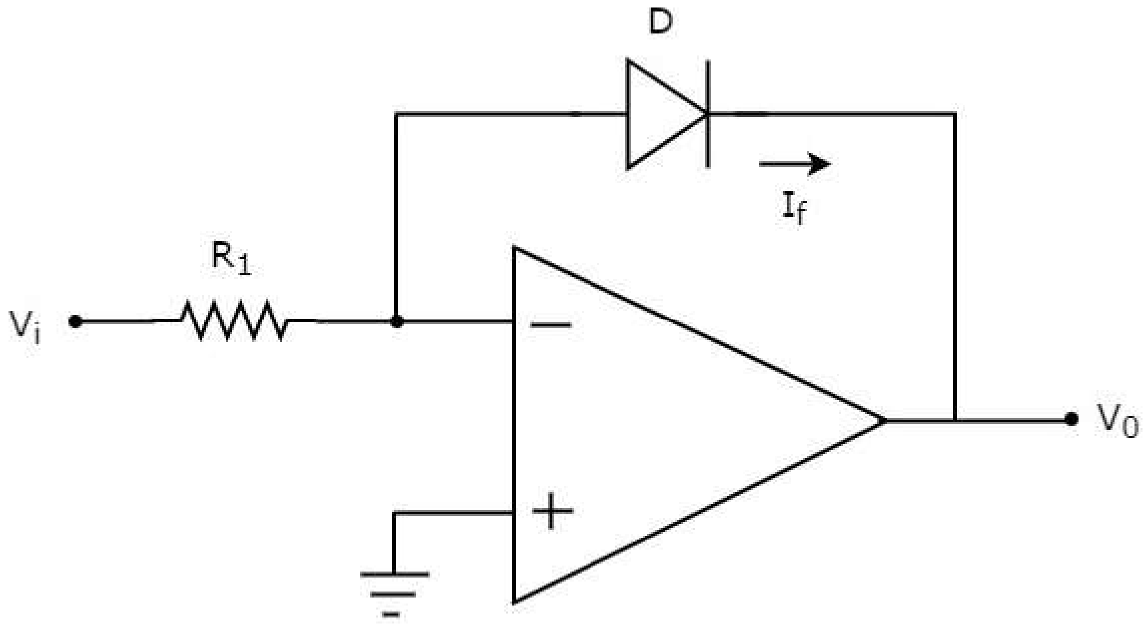


In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied at the non-inverting input terminal of the opamp. According to the **virtual short concept**, the voltage at the inverting input terminal of an op-amp will be equal to the voltage 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 $R_1 I_s$ = $1V$.

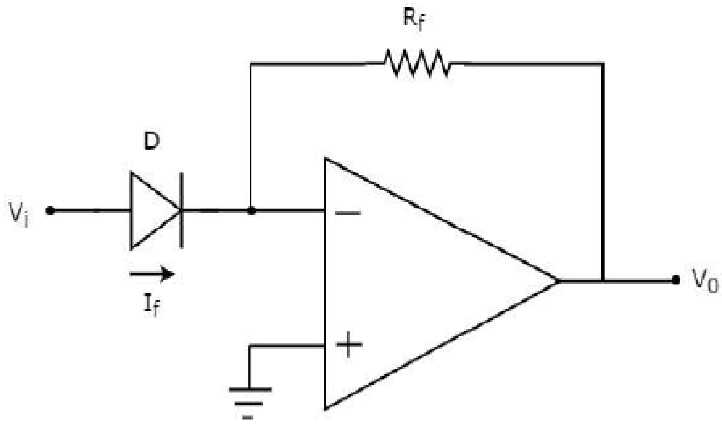
Observe that the output voltage V_0 has a **negative sign**, which indicates that there exists a 180^0 phase difference between the input and the output.

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:

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

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

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

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:

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

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

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

$$V_i - V_f = 0$$

$$=> V_f = V_i$$

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.

Op-Amp Based Oscillators

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

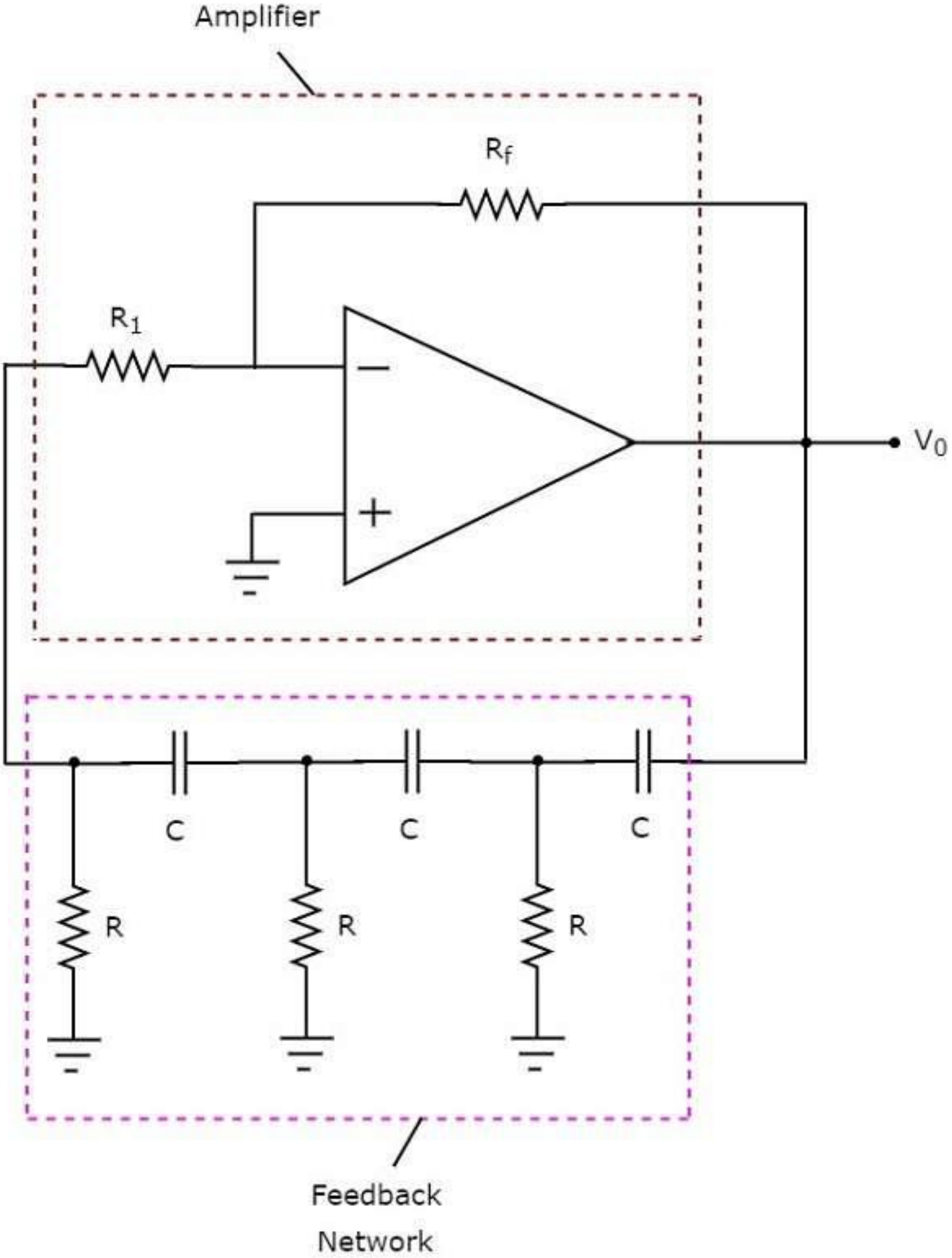
- RC phase shift oscillator
- Wien bridge oscillator

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 $\mathbf{360^0}$ 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,

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

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

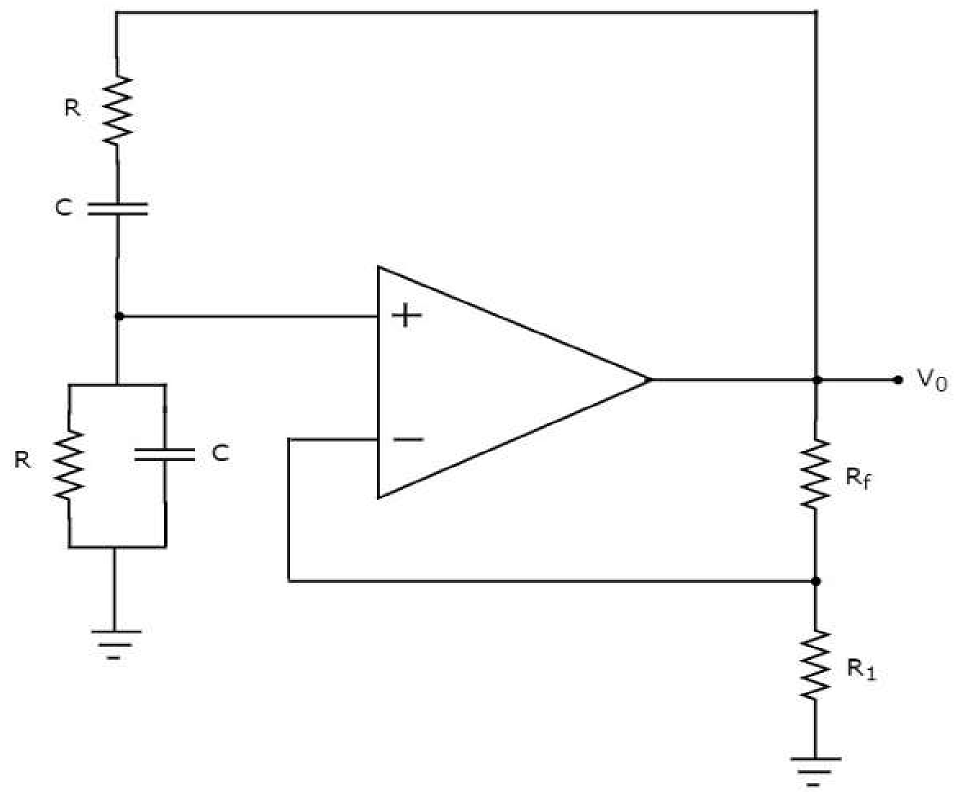
$$=> R_f \geq 29\, R_1$$

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 $\mathbf{0^0}$ 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.

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

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

$$=> R_f \geq 2R_1$$

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.