OPAMP

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 −

$$A_v = \frac{v_0}{v_1 - v_2}$$

Av=v0v1−v2

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 Ad and the common mode gain, A_c Ac.

Mathematically, CMRR can be represented as −

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

CMRR=AdAc

Note that the common mode gain, A_c Ac 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 −

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

SR=MaximumofdV0dt

Where, V_0 V0 is the output voltage. In general, slew rate is measured in either $V/\mu Sec$ V/μSec or $V/m Sec$ V/mSec.

Types of Operational Amplifiers

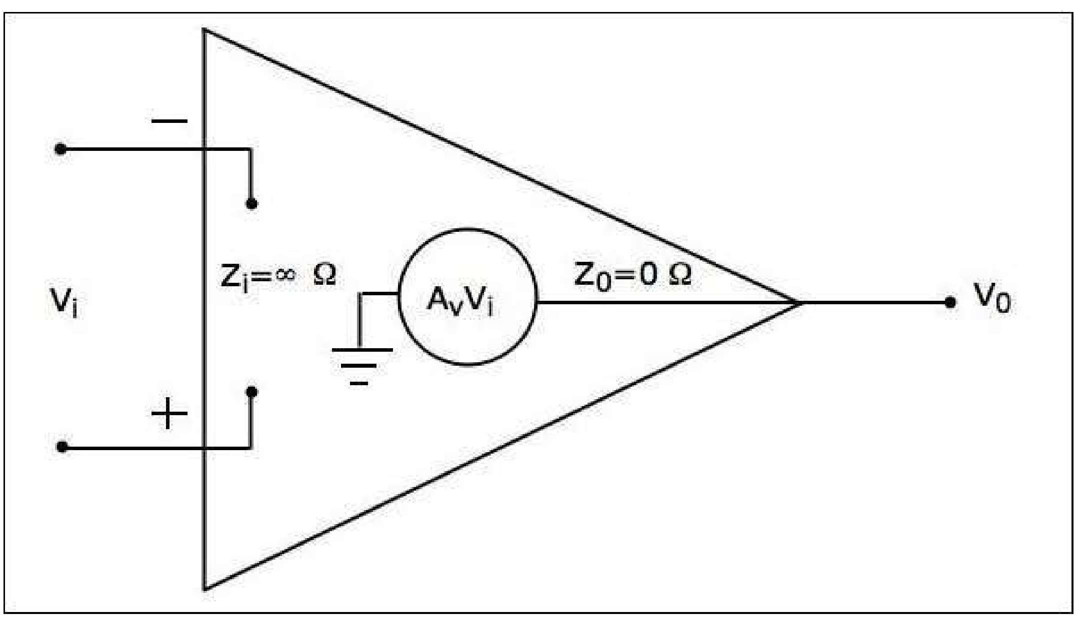
An op-amp is represented with a triangle symbol having two inputs and one output.

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 $Z_i = \infty\Omega$ Zi=∞Ω

Output impedance $Z_0 = 0\Omega$ Z0=0Ω

Open loop voltage gaine $A_v = \infty$ Av=∞

If (the differential) input voltage $V_i = 0V$ Vi=0V, then the output voltage will be $V_0 = 0V$ V0=0V

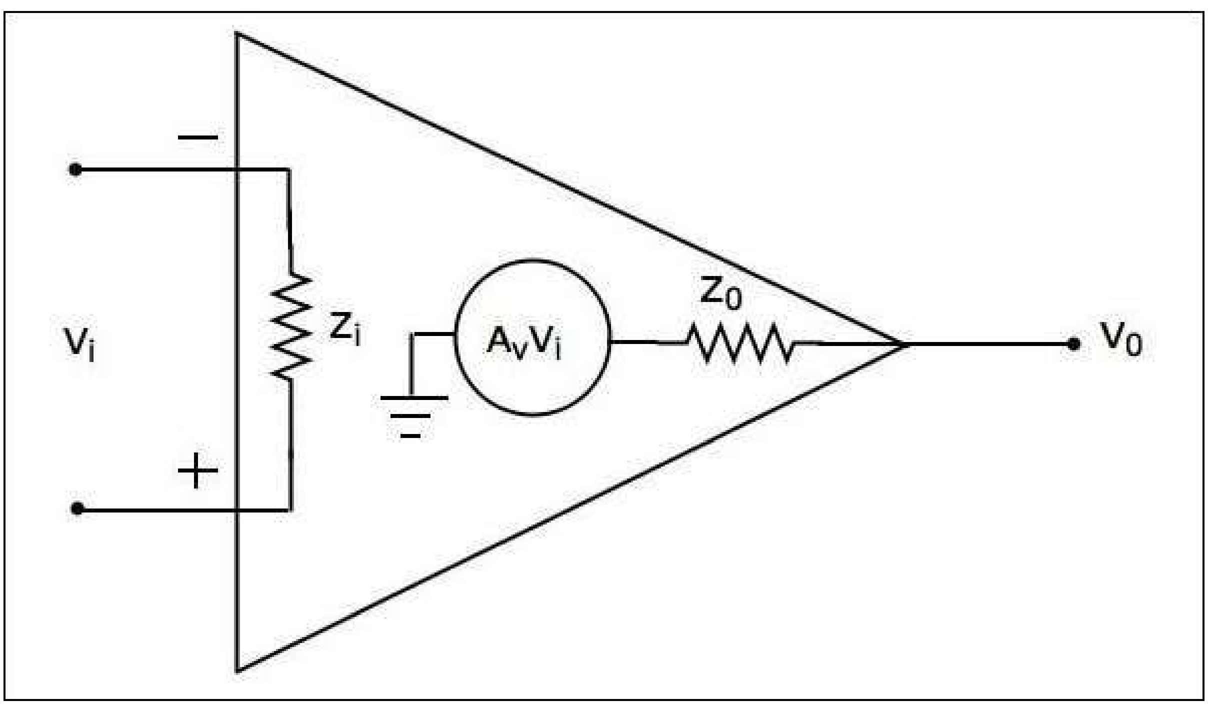
Bandwidth is **infinity**. It means, an ideal op-amp will amplify the signals of any frequency without any attenuation.

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 Zi in the order of **Mega ohms**.

Output impedance, Z_0 Z0 in the order of **few ohms.**.

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

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

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

Output impedance, Z_0 Z0 should be as low as possible.

Open loop voltage gain, A_v Av 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.

Op-Amp-Applications

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 −

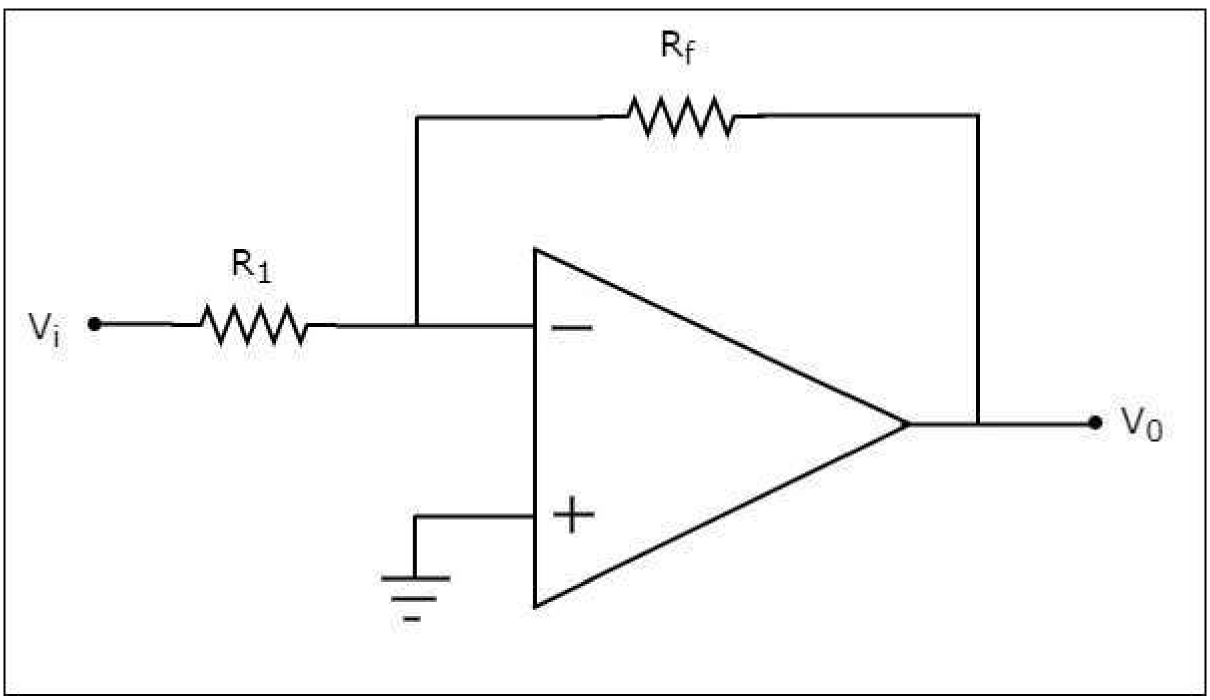
- Inverting Amplifier
- Non-inverting Amplifier
- Voltage follower

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 R1, 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 −

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

0−ViR1+0−V0Rf=0

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

=>−ViR1=V0Rf

$$=> V_0 = (\frac{-R_f}{R_1}) V_t$$

=>V0=(−RfR1)Vt

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

=>V0Vi=−RfR1

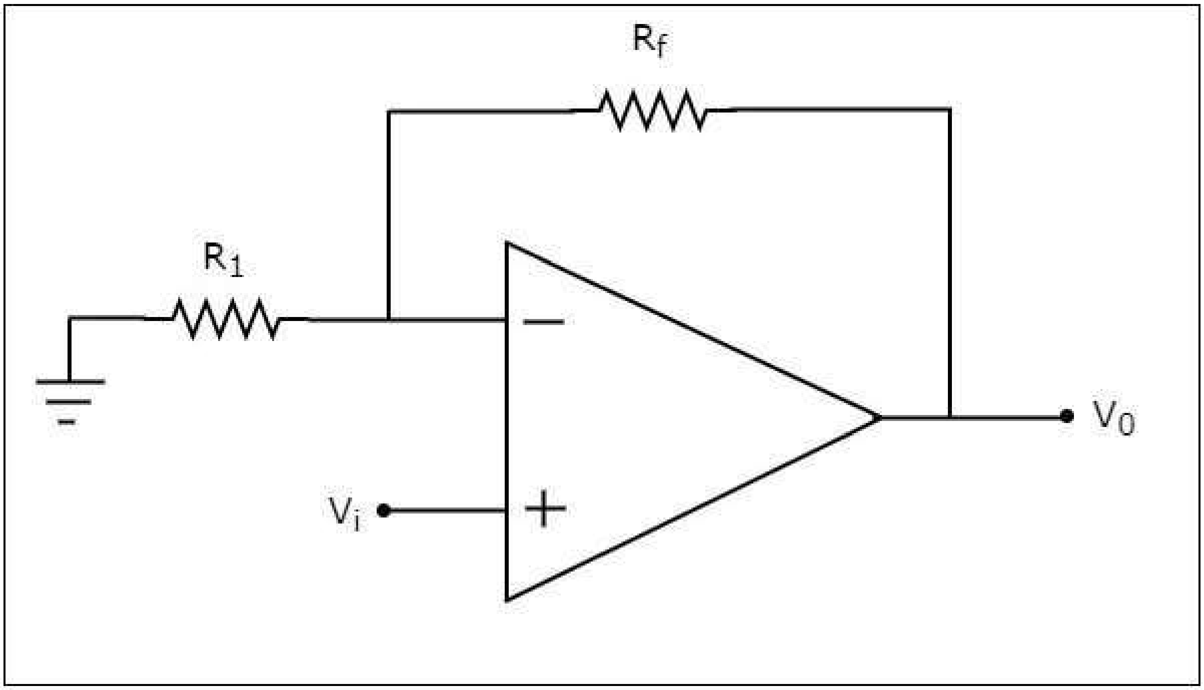
The ratio of the output voltage V_0 V0 and the input voltage V_i Vi is the voltage-gain or gain of the amplifier. Therefore, the **gain of inverting amplifier** is equal to $-\frac{R_f}{R_1}$ −RfR1.

Note that the gain of the inverting amplifier is having a **negative sign**. It indicates that there exists a 180^0phase 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 Vi 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 Vi.

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

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

=>V1=V0(R1R1+Rf)

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.

$$=> V_1 = V_i$$

=>V1=Vi

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

=>V0(R1R1+Rf)=Vi

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

=>V0Vi=R1+RfR1

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

=>V0Vi=1+RfR1

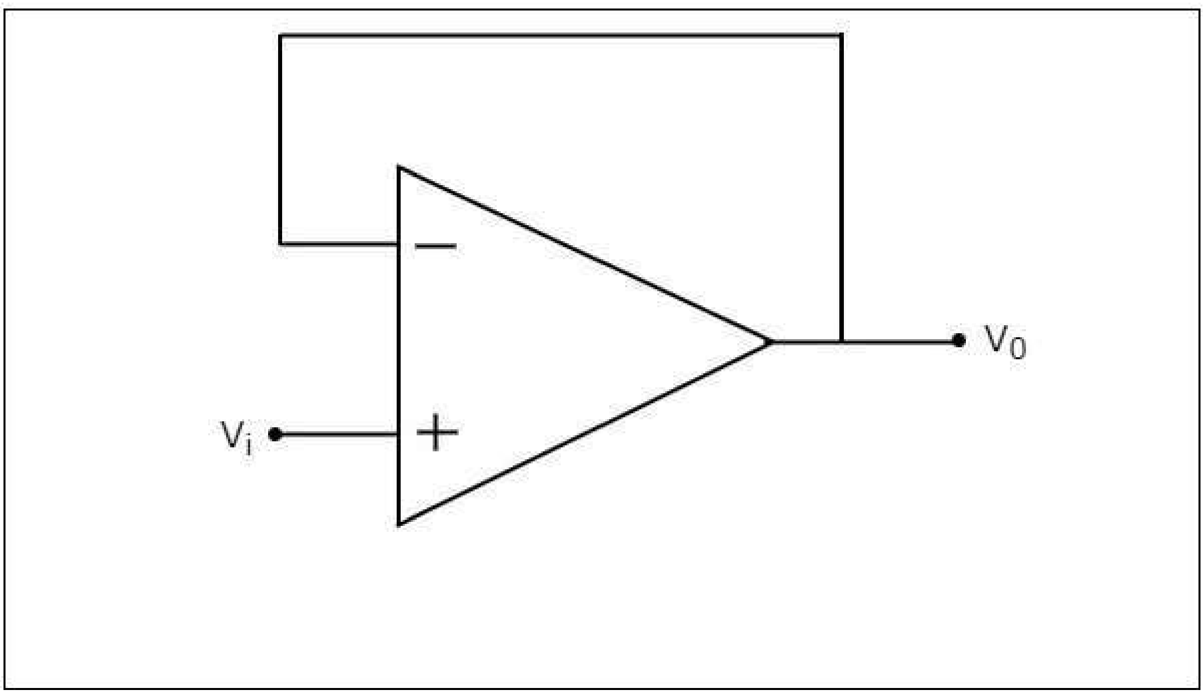
Now, the ratio of output voltage V_0 V0 and input voltage V_i Vi or the voltage-gain or **gain of the non-inverting amplifier** is equal to $1 + \frac{R_f}{R_1}$ 1+RfR1.

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 Rf as zero ohms and (or) the value of resistor, 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 Vi 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 Vi. Here, the output is directly connected to the inverting input terminal of opamp. Hence, the voltage at the inverting input terminal of op-amp is equal to V_0 V0.

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.

$$=> V_0 = V_i$$

=>V0=Vi

So, the output voltage V_0 V0 of a voltage follower is equal to its input voltage V_i Vi.

Thus, the **gain of a voltage follower** is equal to one since, both output voltage V_0 V0 and input voltage V_i Vi of voltage follower are same.

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.

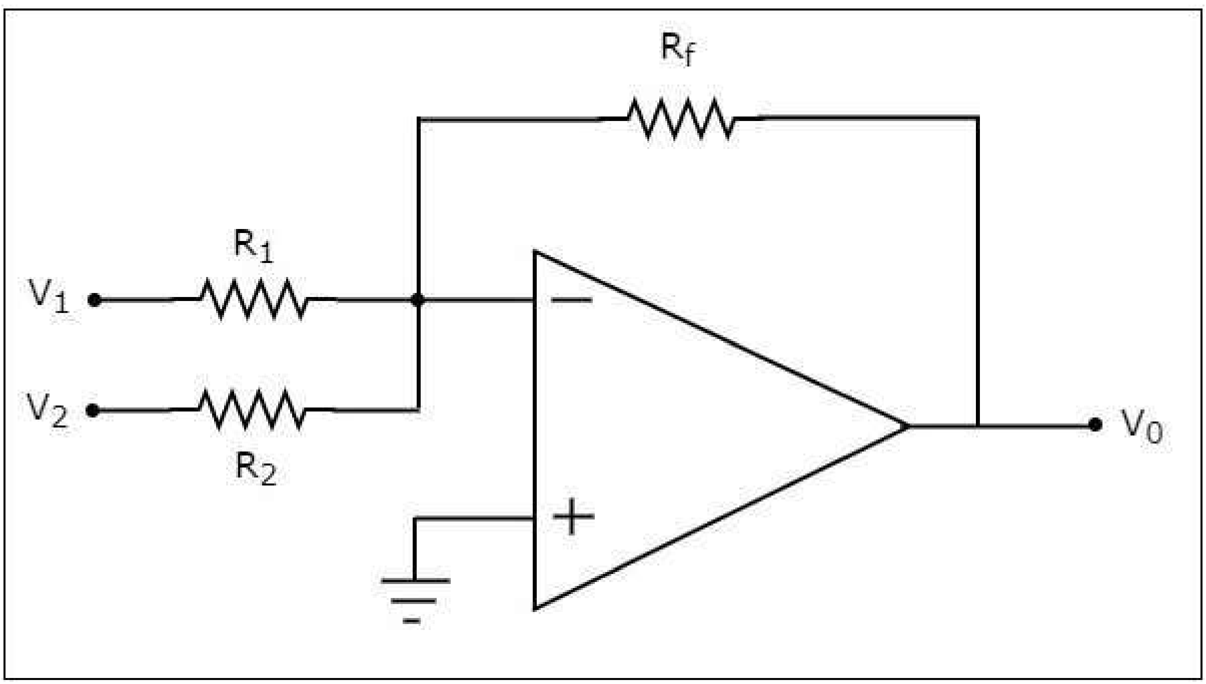
The electronic circuits, which perform arithmetic operations are called as **arithmetic circuits**. Using op-amps, you can build basic arithmetic circuits such as an **adder** and a **subtractor**. In this chapter, you will learn about each of them in detail.

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

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

0−V1R1+0−V2R2+0−V0Rf=0

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

=>V1R1−V2R2=V0Rf

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

=>V0=Rf(V1R1+V2R2)

If $R_f = R_1 = R_2 = R$ Rf=R1=R2=R, then the output voltage V_0 V0 will be −

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

V0=−R(V1R+V2R)

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

=>V0=−(V1+V2)

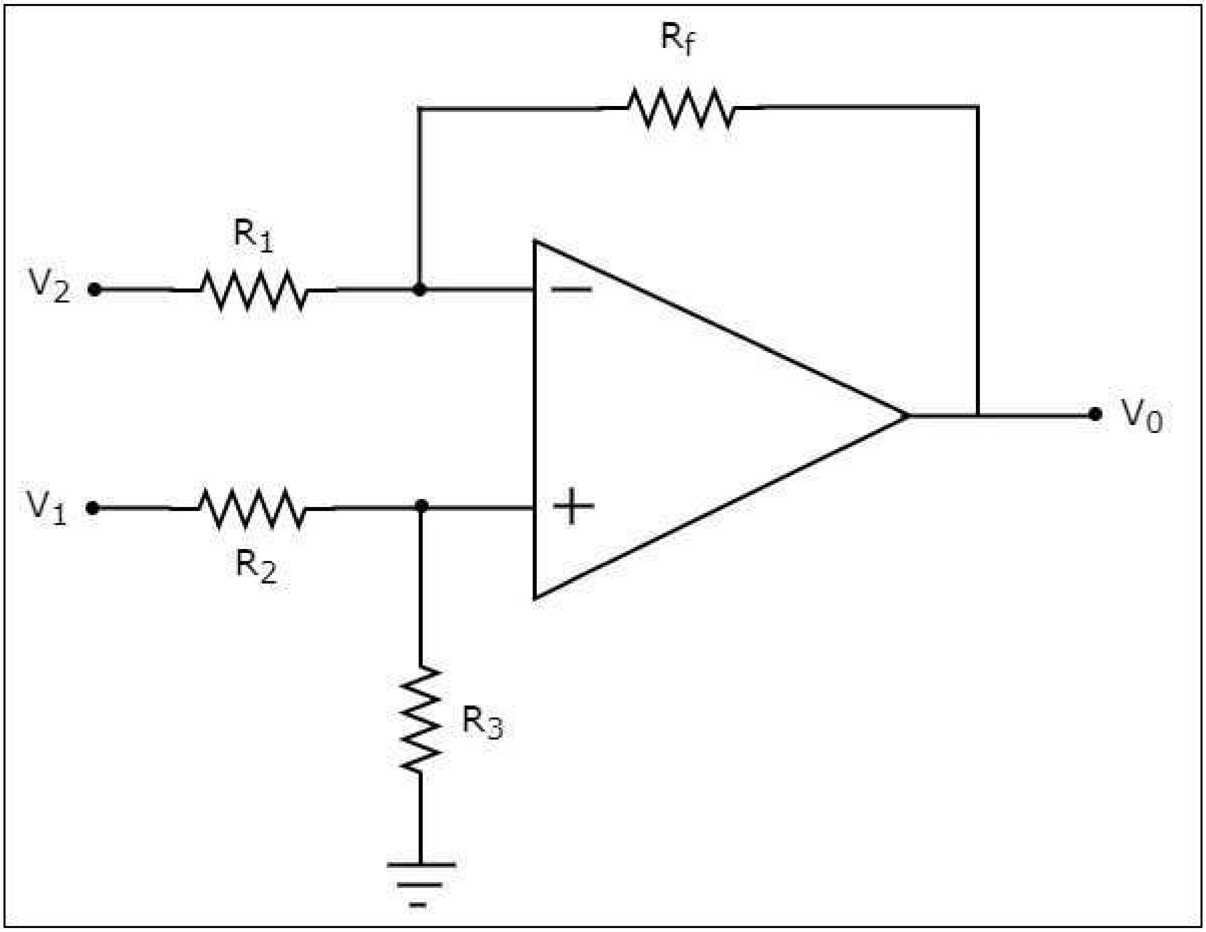
Therefore, the op-amp based adder circuit discussed above will produce the sum of the two input voltages v_1 v1 and v_1 v1, as the output, when all the resistors present in the circuit are of same value. Note that the output voltage V_0 V0 of an adder circuit is having a **negative sign**, which indicates 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 −

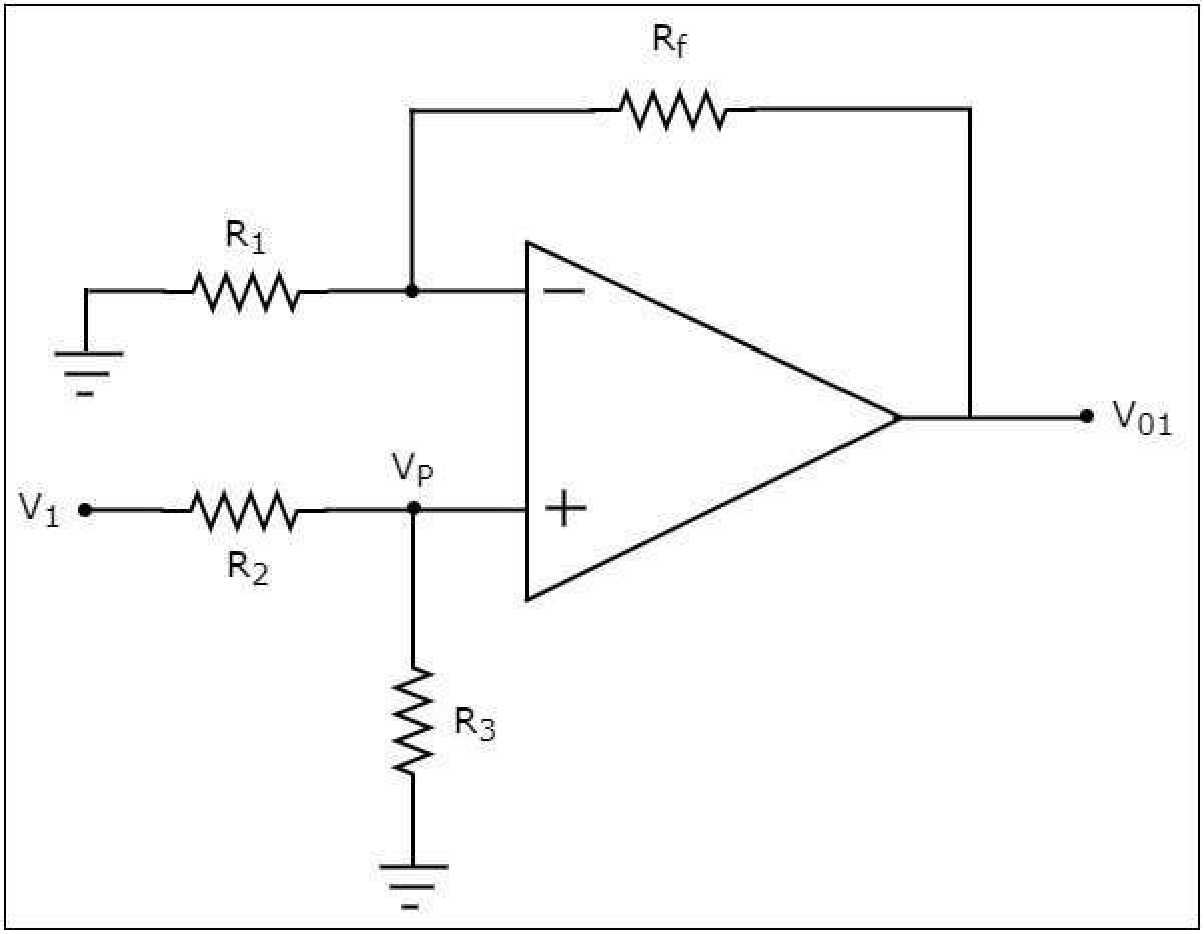


Now, let us find the expression for output voltage V_0 V0 of the above circuit using **superposition theorem**using the following steps −

Step 1

Firstly, let us calculate the output voltage V_{01} V01 by considering only V_1 V1.

For this, eliminate V_2 V2 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.

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

=>Vp=V1(R3R2+R3)

Now, the above circuit looks like a non-inverting amplifier having input voltage V_p Vp. Therefore, the output voltage V_{01} V01 of above circuit will be

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

V01=Vp(1+RfR1)

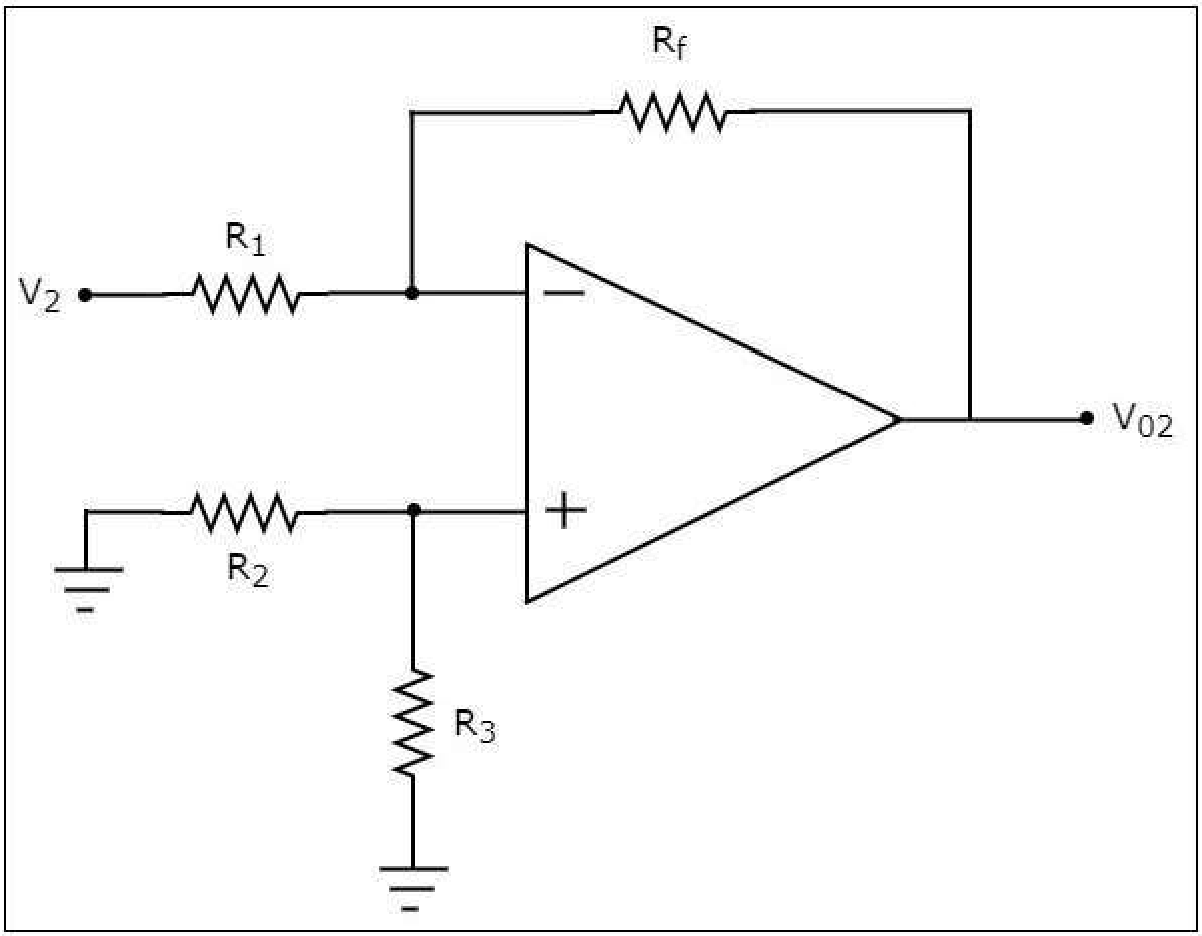
Substitute, the value of V_p Vp in above equation, we obtain the output voltage V_{01} V01 by considering only V_1 V1, as −

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

V01=V1(R3R2+R3)(1+RfR1)

Step 2

In this step, let us find the output voltage, V_{02} V02 by considering only V_2 V2. Similar to that in the above step, eliminate V_1 V1 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} V02 of above circuit will be −

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

V02=(−RfR1)V2

Step 3

In this step, we will obtain the output voltage V_0 V0 of the subtractor circuit by **adding the output voltages** obtained in Step1 and Step2. Mathematically, it can be written as

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

V0=V01+V02

Substituting the values of V_{01} V01 and V_{02} V02 in the above equation, we get −

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

V0=V1(R3R2+R3)(1+RfR1)+(−RfR1)V2

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

=>V0=V1(R3R2+R3)(1+RfR1)−(RfR1)V2

If $R_f = R_1 = R_2 = R_3 = R$ Rf=R1=R2=R3=R, then the output voltage V_0 V0 will be

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

V0=V1(RR+R)(1+RR)−(RR)V2

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

=>V0=V1(R2R)(2)−(1)V2

$$V_0 = V_1 - V_2$$

V0=V1−V2

Thus, the op-amp based subtractor circuit discussed above will produce an output, which is the difference of two input voltages V_1 V1 and V_2 V2, when all the resistors present in the circuit are of same value.

Differentiator And Integrator

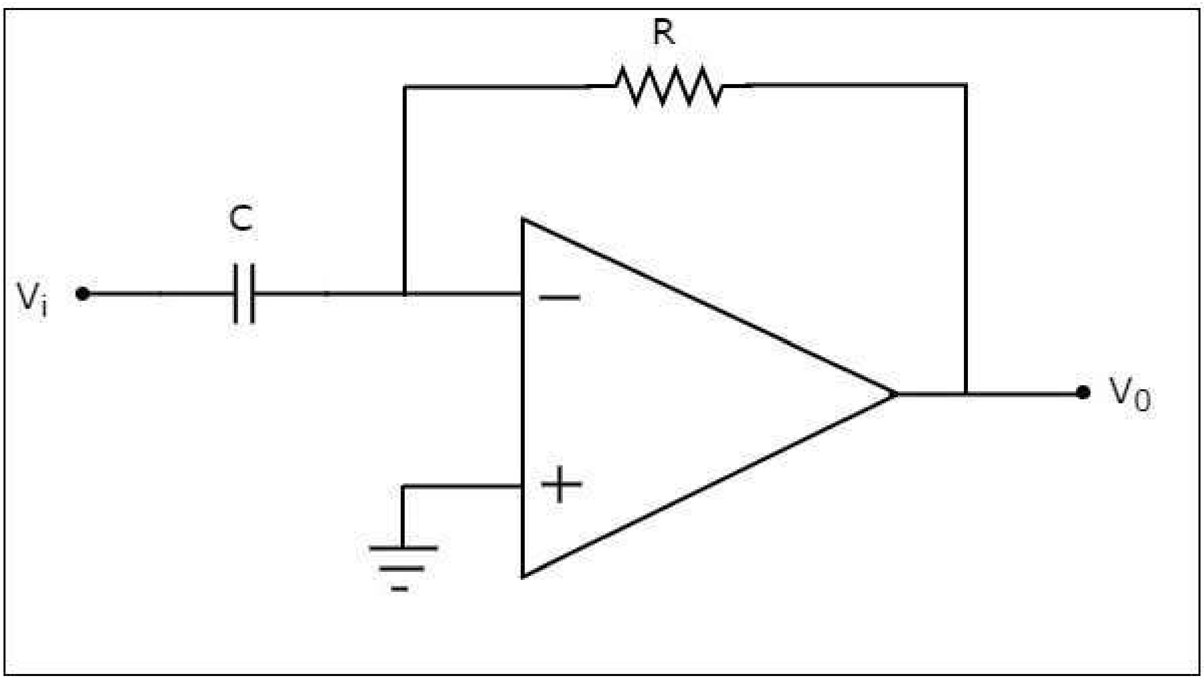
The electronic circuits which perform the mathematical operations such as differentiation and integration are called as differentiator and integrator, respectively.

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 opamp 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 −

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

Cd(0−Vi)dt+0−V0R=0

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

=>−CdVidt=V0R

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

=>V0=−RCdVidt

If $RC = 1 \sec$ RC=1sec, then the output voltage V_0 V0 will be −

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

V0=−dVidt

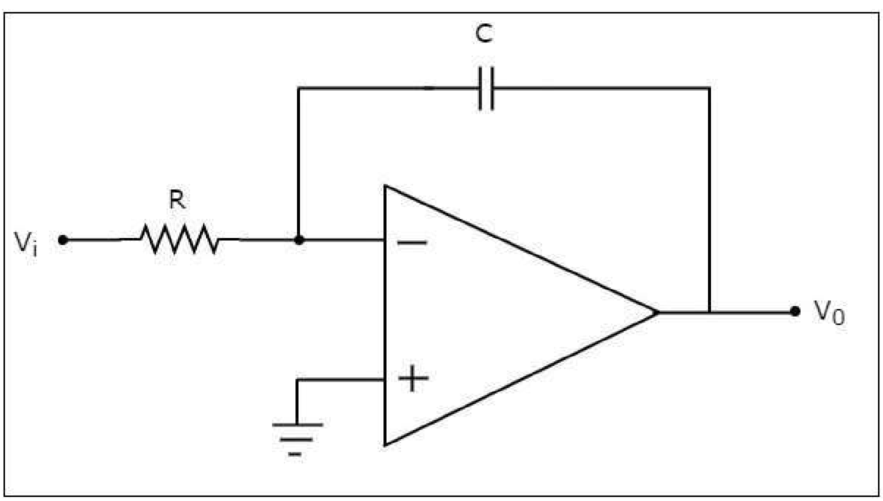
Thus, the op-amp based differentiator circuit shown above will produce an output, which is the differential of input voltage V_i Vi, when the magnitudes of impedances of resistor and capacitor are reciprocal to each other.

Note that the output voltage V_0 V0 is having a **negative sign**, which indicates that there exists a 180^0phase 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 −

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

0−ViR+Cd(0−V0)dt=0

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

=>−ViR=CdV0dt

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

=>dV0dt=−ViRC

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

=>dV0=(−ViRC)dt

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

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

∫dV0=∫(−ViRC)dt

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

=>V0=−1RC∫Vtdt

If $RC = 1\ \text{sec}$ RC=1sec, then the output voltage, V_0 V0 will be −

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

V0=−∫Vidt

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

Note − The output voltage, V_0 V0 is having a **negative sign**, which indicates that there exists 180^0 phase difference between the input and the output.