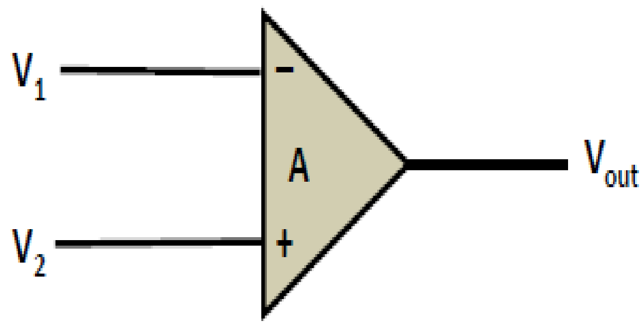
Module 4

Operational Amplifiers: Fundamental differential amplifier- Modes of operation.

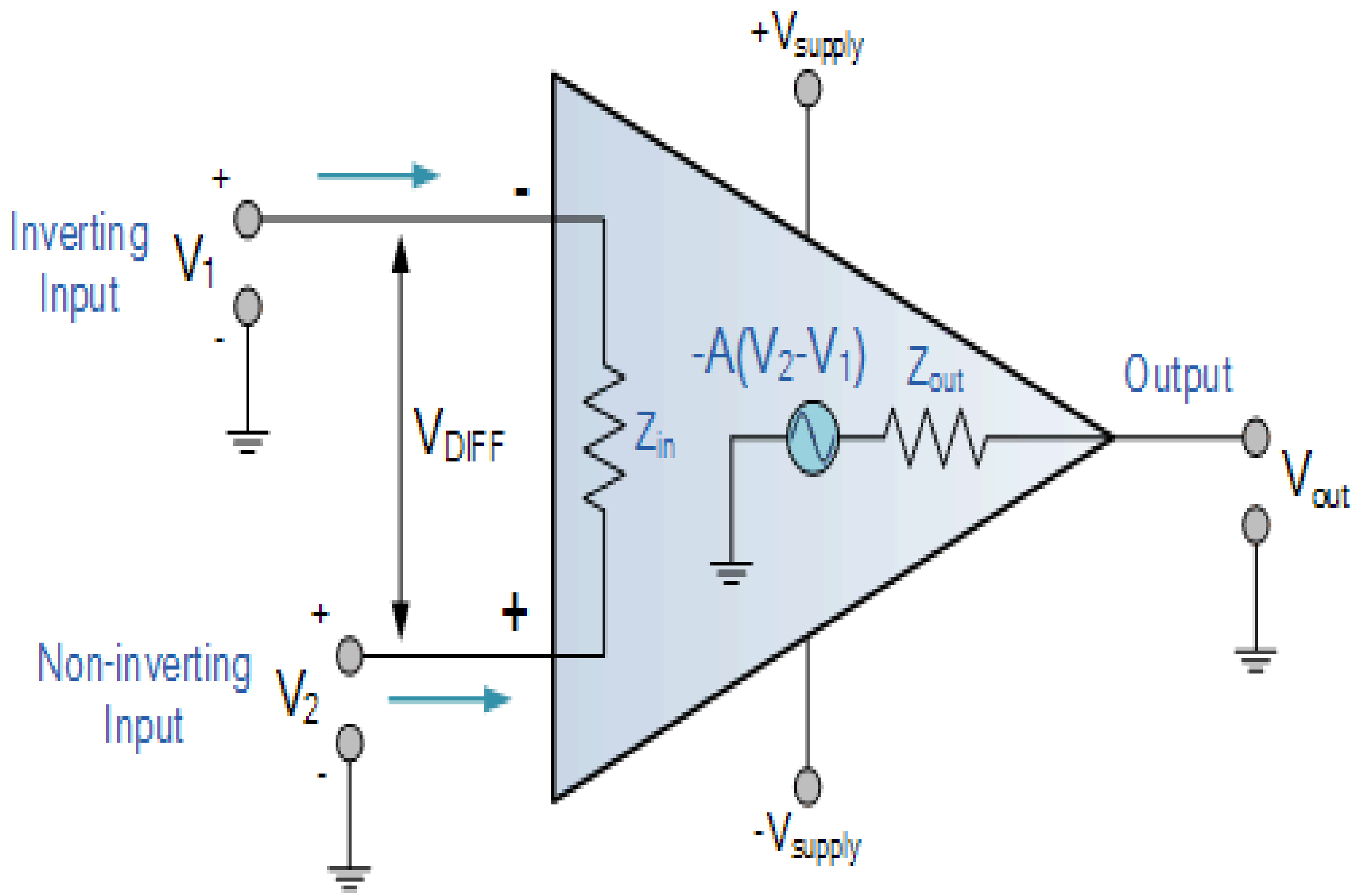
Properties of ideal and practical Op-amp - Gain, CMRR and Slew rate. Parameters of a typical Op-amp IC 741.

Open loop and Closed loop Configurations-Concept of virtual short. Negative feedback in Op-amps. Inverting and non- inverting amplifier circuits. Summing and difference amplifiers, Instrumentation amplifier.

OPERATIONAL AMPLIFIERS



Equivalent Circuit of an Ideal Operational Amplifier



Operational amplifiers are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation.

An **Operational Amplifier**, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals. These feedback components determine the resulting function or "operation" of the amplifier and by virtue of the different feedback configurations whether resistive, capacitive or both, the amplifier can perform a variety of different operations, giving rise to its name of "Operational Amplifier".

An *Operational Amplifier* is basically a three-terminal device which consists of two high impedance inputs. One of the inputs is called the **Inverting Input**, marked with a negative or "minus" sign, (–). The other input is called the **Non-inverting Input**, marked with a positive or "plus" sign (+).

A third terminal represents the operational amplifiers output port which can both sink and source either a voltage or a current. In a linear operational amplifier, the output signal is the amplification factor, known as the amplifiers gain (A) multiplied by the value of the input signal and depending on the nature of these input and output signals, there can be four different classifications of operational amplifier gain.

Voltage – Voltage "in" and Voltage "out"

Current – Current "in" and Current "out"

Transconductance – Voltage "in" and Current "out"

Transresistance – Current "in" and Voltage "out"

Op-amp Parameter and Idealised Characteristic

Open Loop Gain, (Avo)

Infinite – The main function of an operational amplifier is to amplify the input signal and the more open loop gain it has the better. Open-loop gain is the gain of the op-amp without positive or negative feedback and for such an amplifier the gain will be infinite but typical real values range from about 20,000 to 200,000.

Input impedance, (Z_{IN})

Infinite – Input impedance is the ratio of input voltage to input current and is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry ($I_{IN} = 0$). Real op-amps have input leakage currents from a few pico-amps to a few milli-amps.

Output impedance, (Z_{OUT})

Zero – The output impedance of the ideal operational amplifier is assumed to be zero acting as a perfect internal voltage source with no internal resistance so that it can supply as much current as necessary to the load. This internal resistance is effectively in series with the load thereby reducing the output voltage available to the load. Real op-amps have output impedances in the 100-20kΩ range.

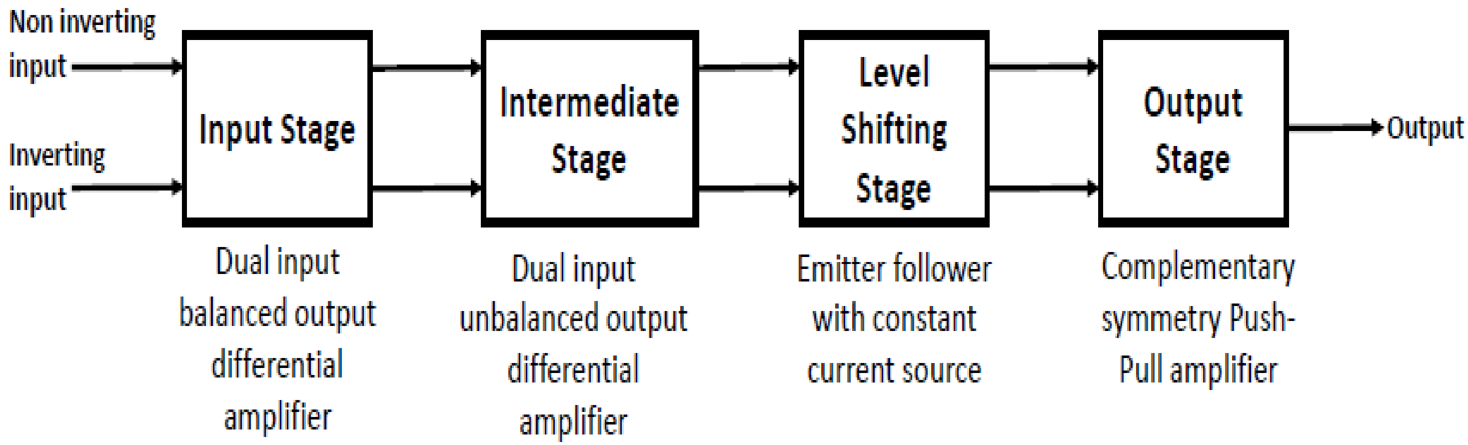
Bandwidth, (BW)

Infinite – An ideal operational amplifier has an infinite frequency response and can amplify any frequency signal from DC to the highest AC frequencies so it is therefore assumed to have an infinite bandwidth. With real op-amps, the bandwidth is limited by the Gain-Bandwidth product (GB), which is equal to the frequency where the amplifiers gain becomes unity.

Offset Voltage, (V_{IO})

> **Zero** – The amplifiers output will be zero when the voltage difference between the inverting and the non-inverting inputs is zero, the same or when both inputs are grounded. Real op-amps have some amount of output offset voltage.

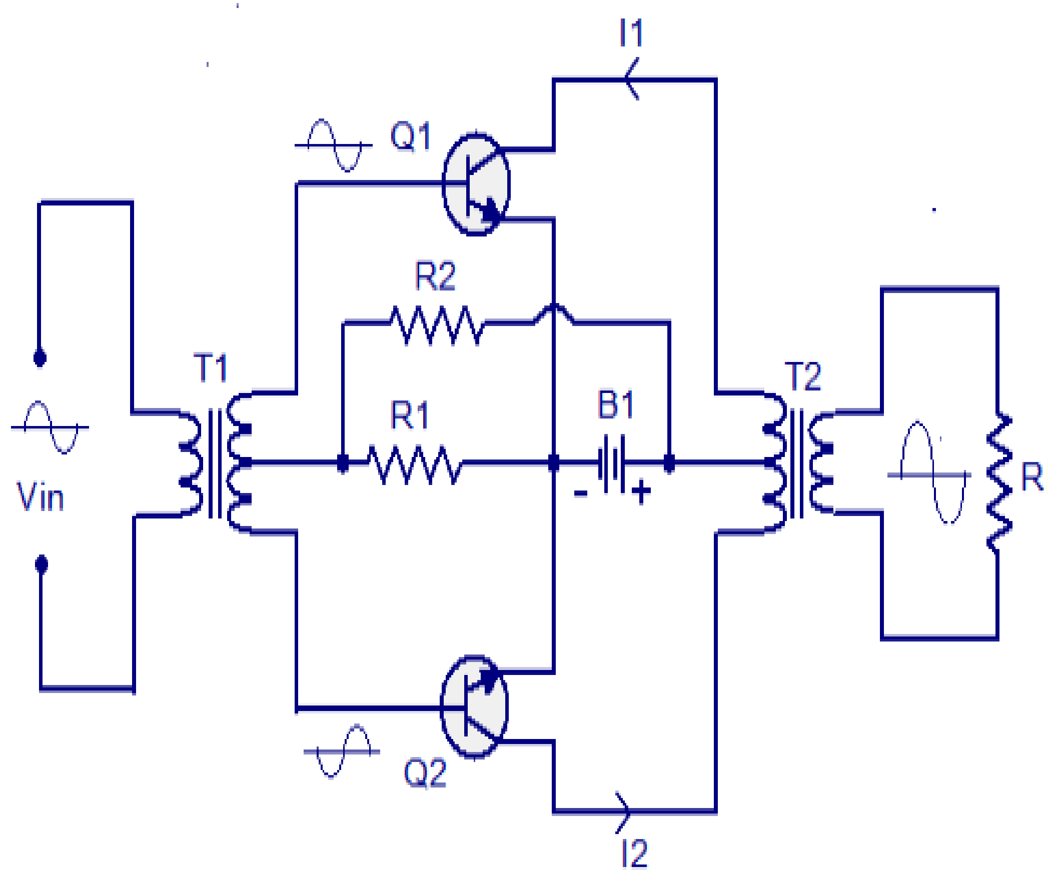
Block Diagram of an OP-AMP



- The input stage, is a dual input balanced output differential amplifier. This stage provide most of the voltage gain of the amplifier and also establishes the input resistance of the op-amp.
- Intermediate stage, is a dual input unbalanced output differential amplifier. This stage increase the overall gain of the amplifier.
- The level shifting stage is used to shift the dc level at the output of intermediate stage downward to zero volt.
- The last stage is a complementary symmetry Push-Pull amplifier. This stage increase the output voltage swing and the current supplying capability of op-amp. Also provide low output resistance.

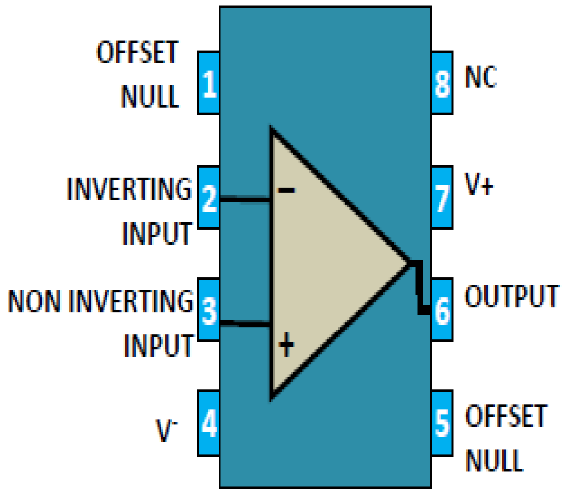
Push-Pull Amplifier

- In power amplifier using only one transistor is called single ended power amplifier
- Push-pull amplifier is a power amplifier
- It is employed when high output at high efficiency is required.

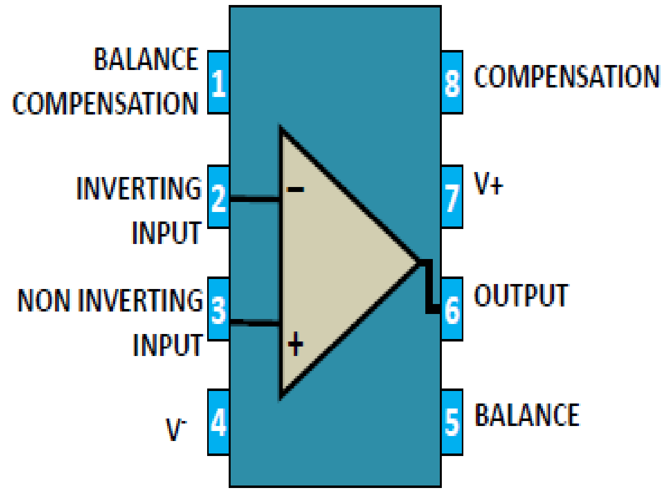


Push Pull amplifier circuit

OP-AMP ICS



LM741 Pin Configuration



LM301 Pin Configuration

Operational Amplifier Modes of Operation

The operational amplifier or OP-AMP is a direct coupled, high gain amplifier used to perform a wide variety of mathematical operation used to perform like summation, subtraction, multiplication, differentiation and integration etc. In analog computers it is often referred to as the basic linear (or analog) integrated circuit (IC). The operational amplifier works in different modes depending on the nature of its job. These modes are explained below.

1. Single-ended Operation

when a differential amplifier is operated in this mode, one input is ground and the signal voltage is applied only to the other input. In Figure (a) input signal is applied to terminal 1 and terminal 2 is ground.

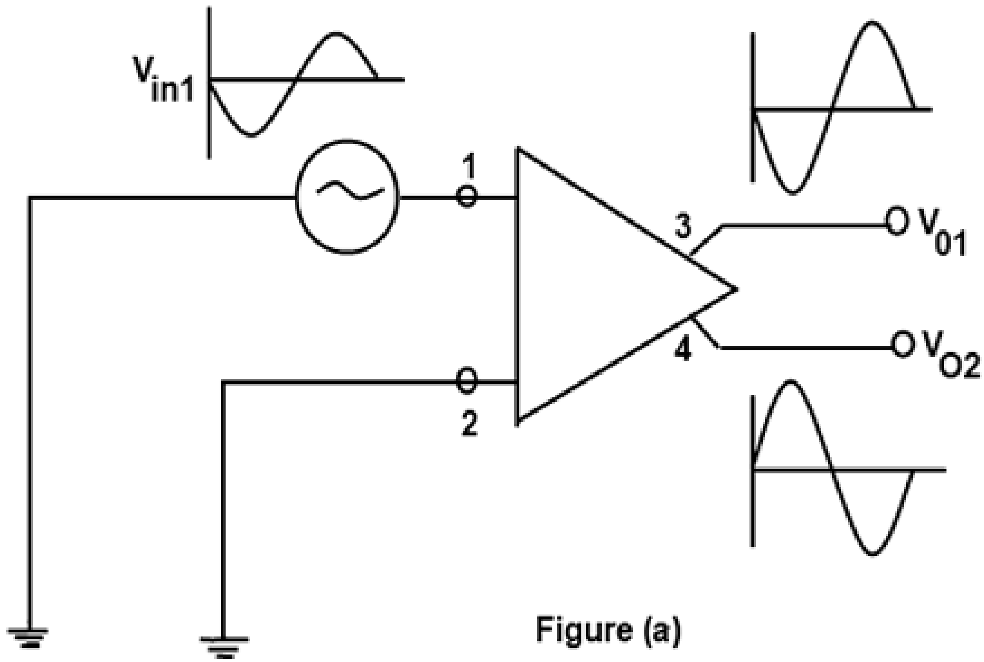


Figure (a)

Figure shows that an amplified and inverted output signal is obtained at V01 but an equally amplified and in phase signal appears at V02 which is terminal 4.

When input signal Vin2 is applied to input terminal 2, an amplified and inverted signal appears at output terminal 4 whereas equally amplified but in phase signal appears at terminal 3 this is shown in Figure (b).

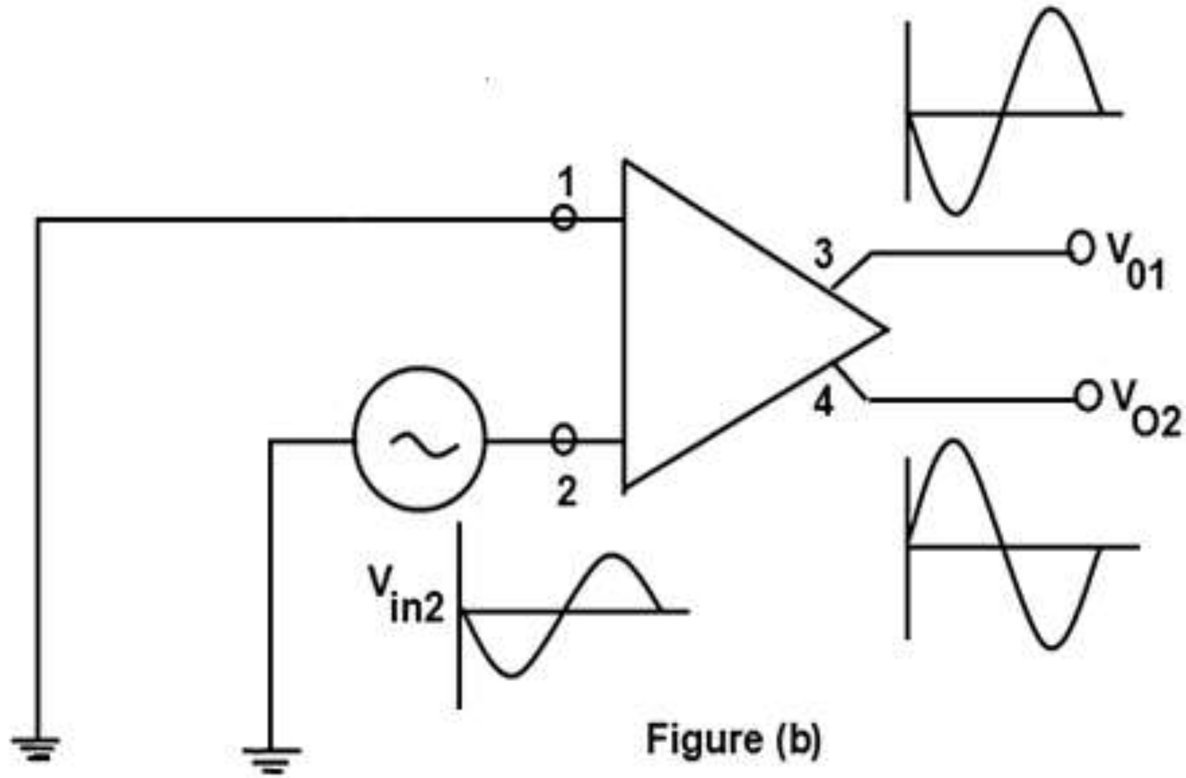


Figure (b)

Differential Operation

In this mode two opposite polarity (out of phase) signals are applied to the inputs as shown in Figure (c).

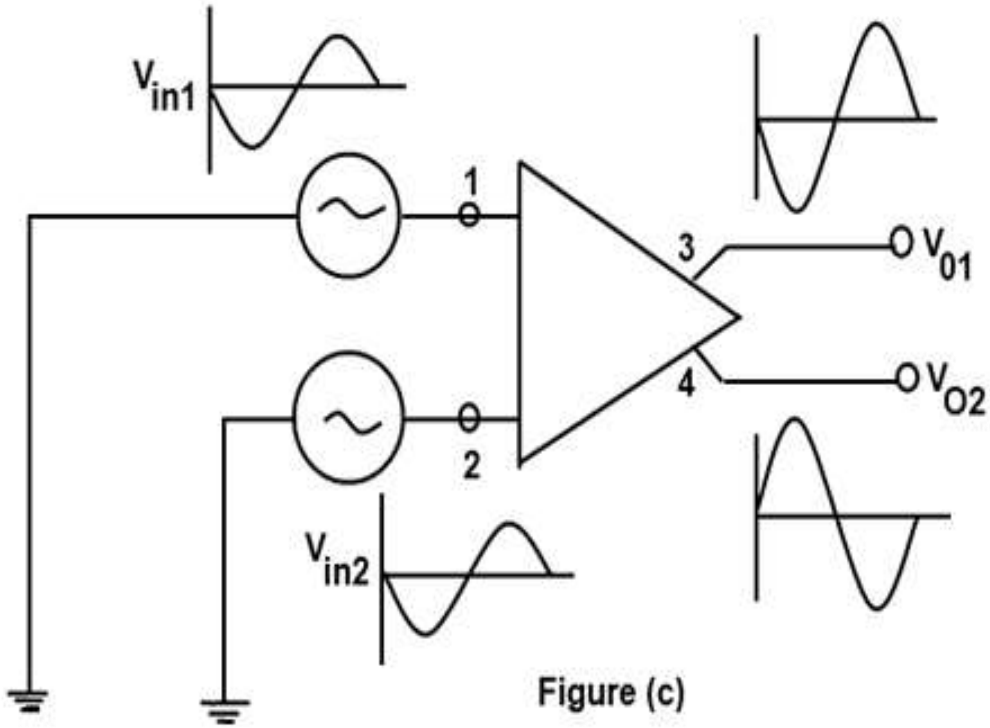


Figure (c)

This type of operation is also referred to as double ended operation.

Input signal at each input terminal causes signal to appear at both output terminals. The resultant output signals have a peak value twice the value for single ended operation.

3. Common Mode Operation

If two in-phase and equal signals are applied at the two input terminals, the resultant output signal at each output terminal would be zero this is shown in Figure (d). in other words the output between collectors would be zero.

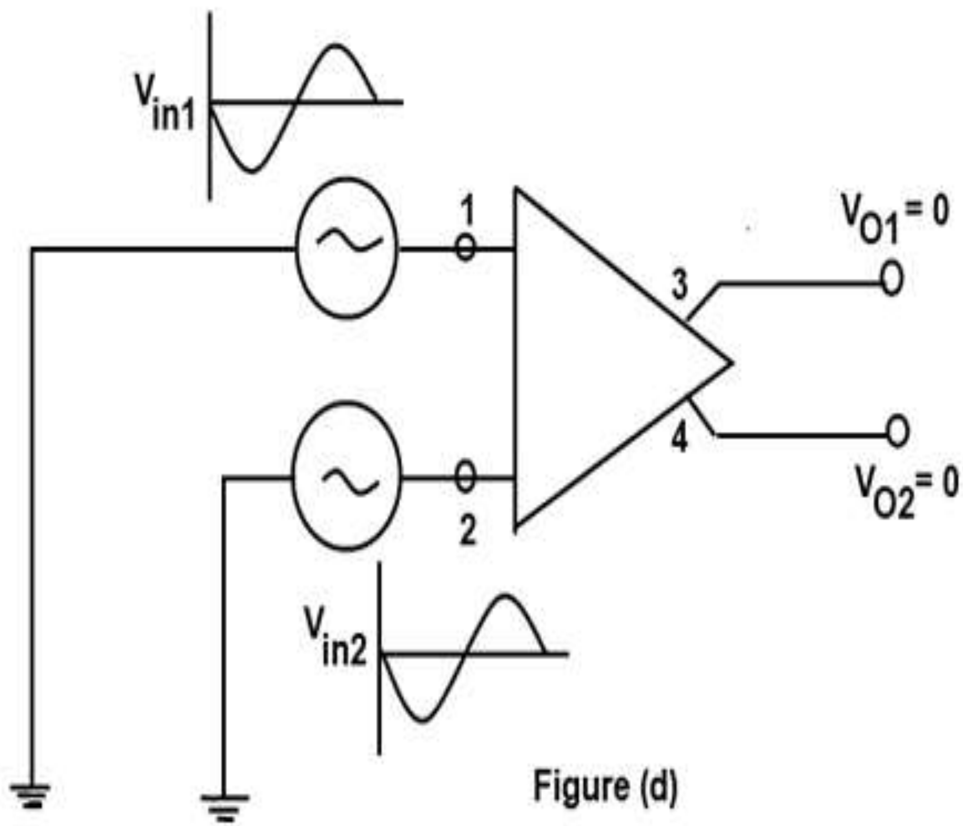


Figure (d)

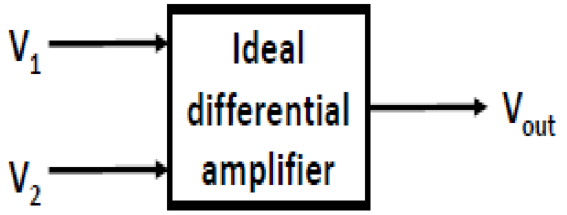
4. Inverting and non-inverting Inputs

When positive Vin1 acts alone, it produce a differential output voltage with terminal 4 positive with respect to terminal 3 that is why the input terminal 1 is called non-inverting input terminal. When positive Vin2 acts alone, the output voltage is inverted and terminal 3 becomes positive with respect to terminal 4. That is why input terminal 2 is called inverting terminal. It can be see in Figure (a) and (b).

Differential Amplifier

- A differential amplifier amplifies the difference between two input voltage signal. Therefore it is also called a difference amplifier.
- Consider an ideal differential amplifier shown in figure. Here, V_1 and V_2 are the two input signals while V_{out} is the single ended output. Is signal is measured with respect to the ground.
- In an ideal differential amplifier output voltage V_{out} is proportional to the difference between the two input signals this means that we can write

$$V_{out} \propto (V_1 - V_2)$$



Differential Gain (Ad)

- Using above equation we can write

$$V_{out} \propto A_d(V_1 - V_2)$$

Where A_d is the constant of proportionality. The A_d is the gain with which differential amplifier amplifies the difference between two input signals. Hence it is called **differential gain** of the differential amplifier.

Differential Amplifier

- **Common mode gain**
- If we apply two input voltages which are equal in all the respect to the differential amplifier that is $V_1=V_2$ then the output voltage $V_{out}=A_d(V_1-V_2)$ must be zero.
- However, the output voltage of the practical differential amplifier not only depend on the difference voltage but also depends on the average level of the two inputs. Such an average level of the two input signal is called common mode signal denoted as V_{cm}.

$$V_{cm} = \frac{V_1 + V_2}{2}$$

- The gain with which it amplifies the common mode signal to produce output is called common mode gain of the differential amplifier denoted as A_{cm}

Differential Amplifier

Common mode rejection ratio (CMRR)

- When the same voltage is applied to both input, the differential amplifier is said to be operated in a common mode configuration.
- Many disturbance signal, noise signals appears as a common input to both the input terminal of the differential amplifier. Such a common signal should be rejected by the differential amplifier.
- The ability of a differential amplifier to reject common mode signal is expressed by a ratio called **common mode rejection ratio** denoted as **CMRR.**

$$CMRR = \frac{A_d}{A_{cm}}$$

- Ideally common mode voltage gain is zero, hence the ideal value of CMRR is infinite.

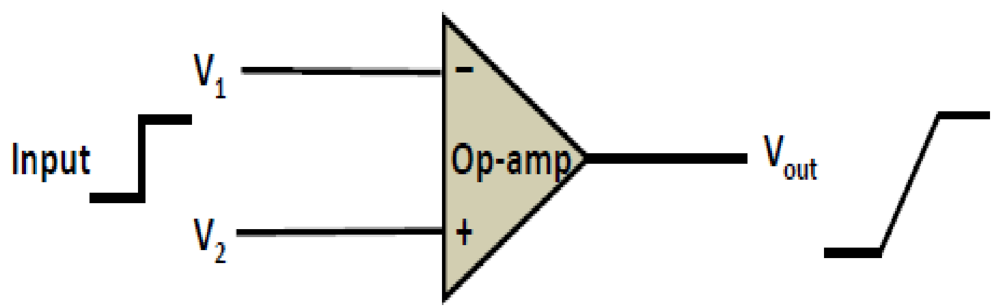
Differential Amplifier

Slew rate

- It is defined as the maximum rate at which the output voltage can change.

$$SR = \left.\frac{dV_{out}}{dt}\right|_{max}$$

- Usually measured in ${}^{V}/_{\mu s}$
- The instantaneous change in input does not appear instantaneously at the output but slews so many volts in a given period of time.



Differential Amplifier

Drift

- Offset current and offset voltage change with temperature.
- We may have carefully nulled a circuit shortly after switching on power supply at an ambient temperature of 25 ^{o}C.
- Later on, we may find that temperature has risen to 40 ^{o}C and the circuit is no longer nulled. This is called **drift.**

Properties of Ideal OP-AMP

1. Infinite voltage gain.
2. Infinite input impedance.
3. Zero output impedance.
4. Zero offset voltage.
   - The presence of small output voltage though $V_1=V_2=0$.
5. Infinite bandwidth.
6. Infinite CMRR.
7. Infinite slew rate.

Properties of Practical OP-AMP

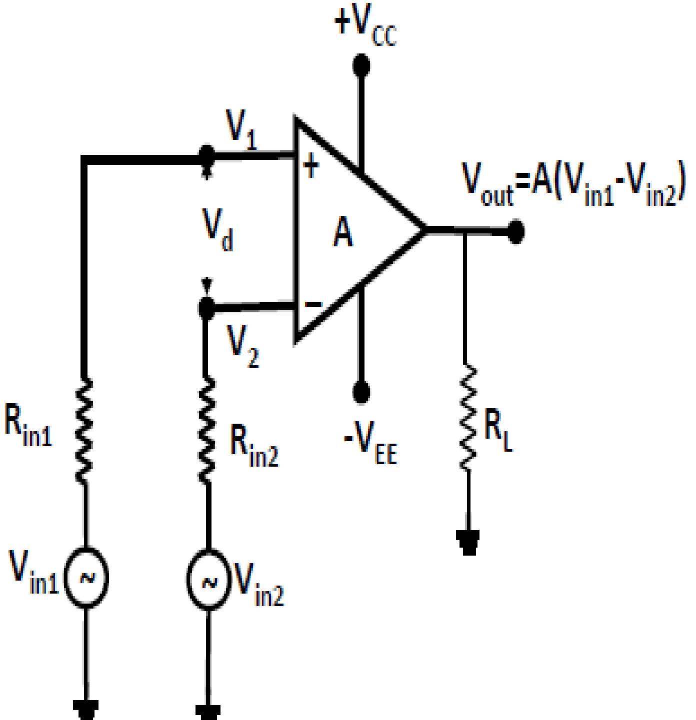
1. Open loop gain is several thousands.
2. Input impedance is greater than $1M\Omega$.
3. Output impedance is few hundreds of ohms.
4. Bandwidth if a practical op-amp in open loop configuration is very small.
5. Input offset voltage is of the order of Milli volts.
6. Input bias current is of the order of Micro ampere.
7. Input offset current is of the order of Nano ampere.

Open Loop Configurations of OP-AMP

- Open loop means there is no connection between input and output terminals either direct or via another network. It means there is no feedback
- The three open loop configurations are
  - Differential amplifier
  - Inverting amplifier
  - Non-inverting amplifier

Differential amplifier

- The circuit open loop op amp differential amplifier is shown in figure.
- In this circuit, inputs are applied to both the inverting and non-inverting terminals.
- Since, in this configuration, the difference between 2 input signal is amplified, the configuration is called the **differential amplifier**
- Input signal maybe either DC or AC
- $V_{out} = A(V_1 - V_2) = A(V_{in1} - V_{in2})$



Circuit Diagram

Inverting Amplifier

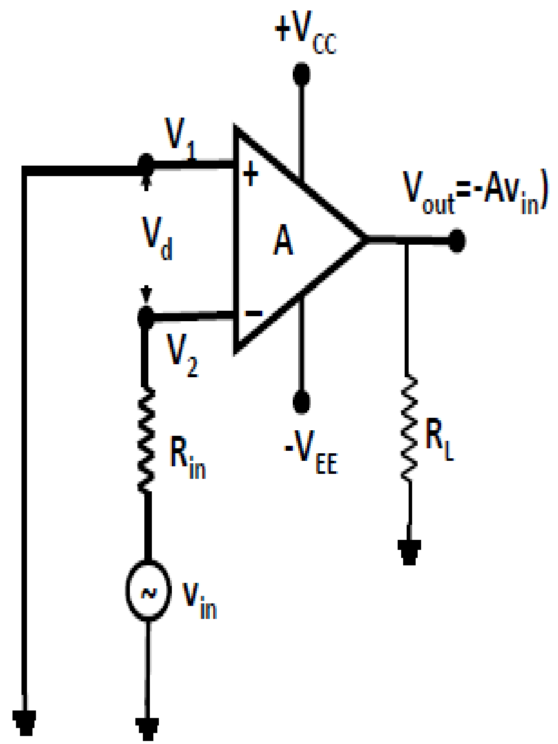
- In inverting amplifier the input signal is applied to the inverting terminal and non inverting terminal is grounded, as shown in figure.

$$V_{out} = A(V_1 - V_2)$$

$$\text{Here } V_1 = 0, and\ V_2 = v_{in}$$

$$V_{out} = A(0 - v_{in}) = -Av_{in}$$

- Negative sign indicate that's the output and input is out of phase.



Circuit Diagram

Non-Inverting Amplifier

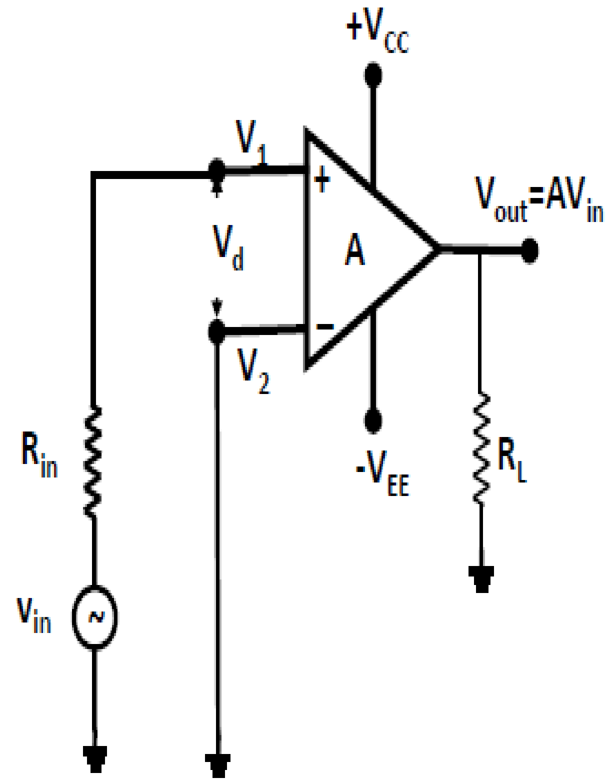
- In non-inverting amplifier the input signal is applied to the non-inverting terminal and inverting terminal is grounded, as shown in figure.

$$V_{out} = A(V_1 - V_2)$$

$$\text{Here } V_1 = v_{in}, and\ V_2 = 0$$

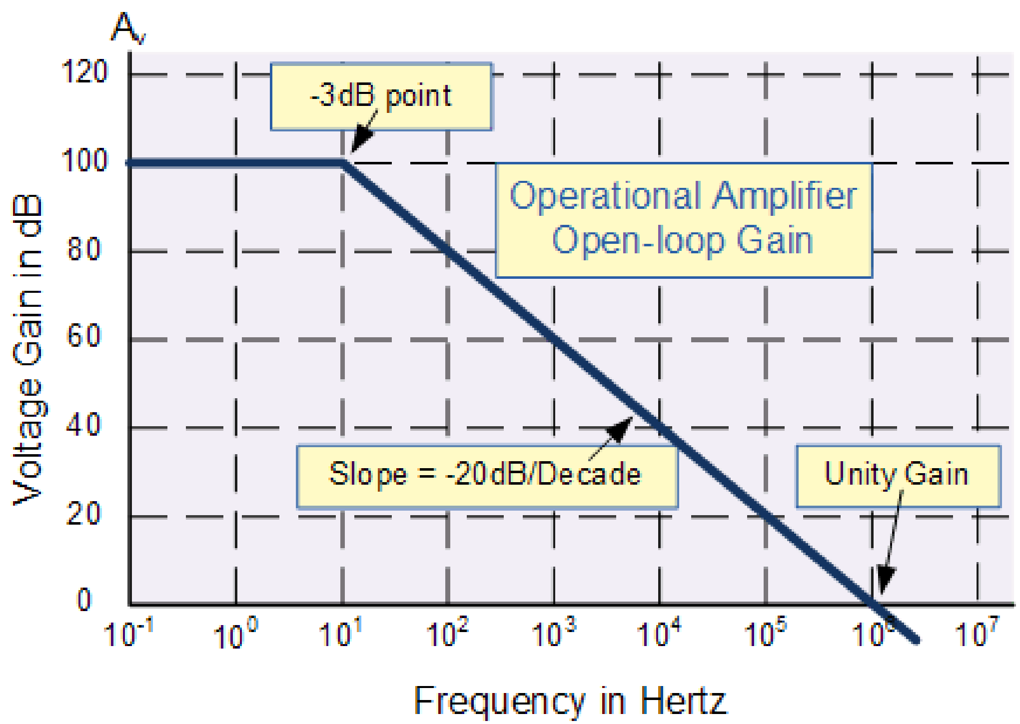
$$V_{out} = A(v_{in} - 0) = Av_{in}$$

- Input and output voltage is of same polarity.



Circuit Diagram

Open-loop Frequency Response Curve



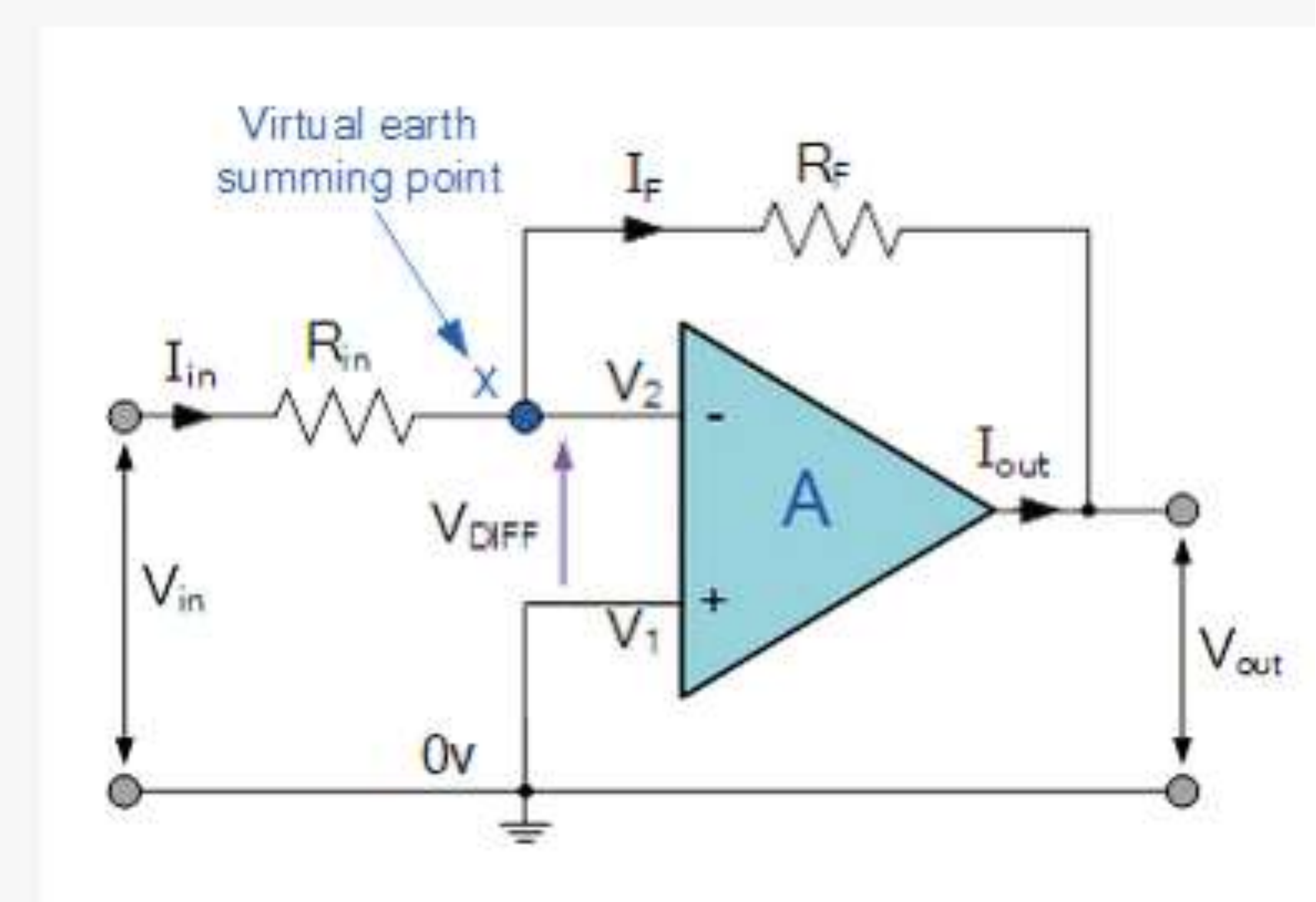
From this frequency response curve we can see that the product of the gain against frequency is constant at any point along the curve. Also that the unity gain (0dB) frequency also determines the gain of the amplifier at any point along the curve. This constant is generally known as the **Gain Bandwidth Product** or **GBP**. Therefore:

$$GBP = \text{Gain} \times \text{Bandwidth} = A \times BW$$

Closed Loop Configurations of OP-AMP

- An op-amp that uses feedback is called a closed loop amplifier.
- Feedback may be positive or negative.
- The most widely used configurations are
  - Closed loop non inverting amplifier
  - Closed loop inverting amplifier

Effect of Negative Feedback



Negative Feedback is the process of "feeding back" a fraction of the output signal back to the input, but to make the feedback negative, we must feed it back to the negative or "inverting input" terminal of the op-amp using an external **Feedback Resistor** called R*ƒ*. This feedback connection between the output and the inverting input terminal forces the differential input voltage towards zero.

This effect produces a closed loop circuit to the amplifier resulting in the gain of the amplifier now being called its **Closed-loop Gain**. Then a closed-loop inverting amplifier uses negative feedback to accurately control the overall gain of the amplifier, but at a cost in the reduction of the amplifiers gain.

This negative feedback results in the inverting input terminal having a different signal on it than the actual input voltage as it will be the sum of the input voltage plus the negative feedback voltage giving it the label or term of a *Summing Point*. We must therefore separate the real input signal from the inverting input by using an **Input Resistor**, Rin.

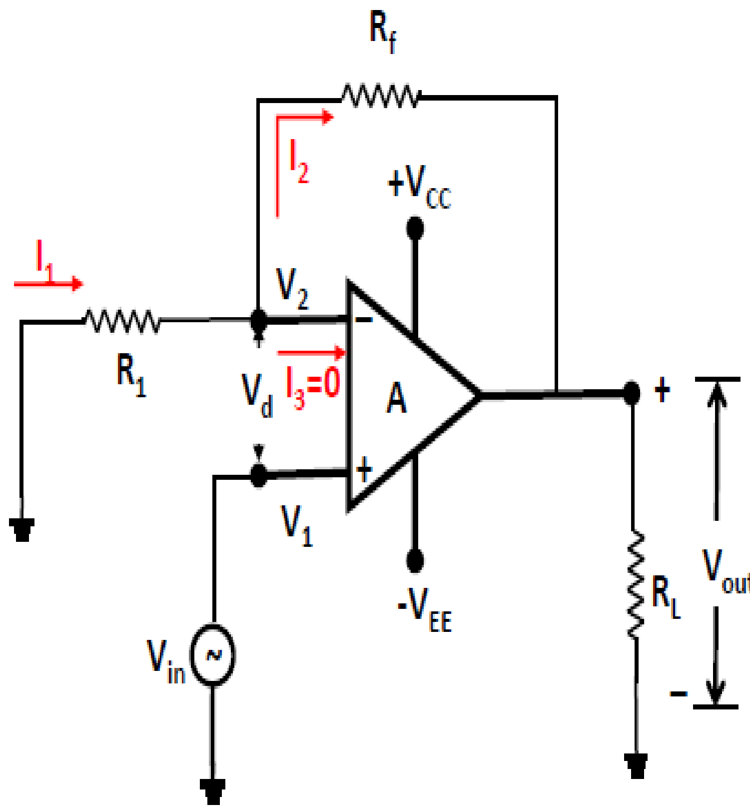
Non-Inverting Amplifier

The gain of the op-amp is marked as A.

The feedback circuits is composed of two resistors R_1 and R_f.

The circuit shown in figure is commonly known as non inverting amplifier with feedback are closed loop non inverting amplifier because it uses a feedback and input signal is applied to the non inverting input terminal of the op-amp.

in this circuit inverting input terminal is grounded through R_1 and output is applied to the inverting input terminal through feedback circuit composed of two resistors R_1 and R_f.



Circuit Diagram

Non-Inverting Amplifier

The closed loop gain of non inverting amplifier can be determined as follows

$$A_f = \frac{V_{out}}{V_{in}}$$

$$V_{out} = A(V_1 - V_2)$$

$$V_1 = V_{in} \; and \; V_2 = V_1 = V_{in}$$

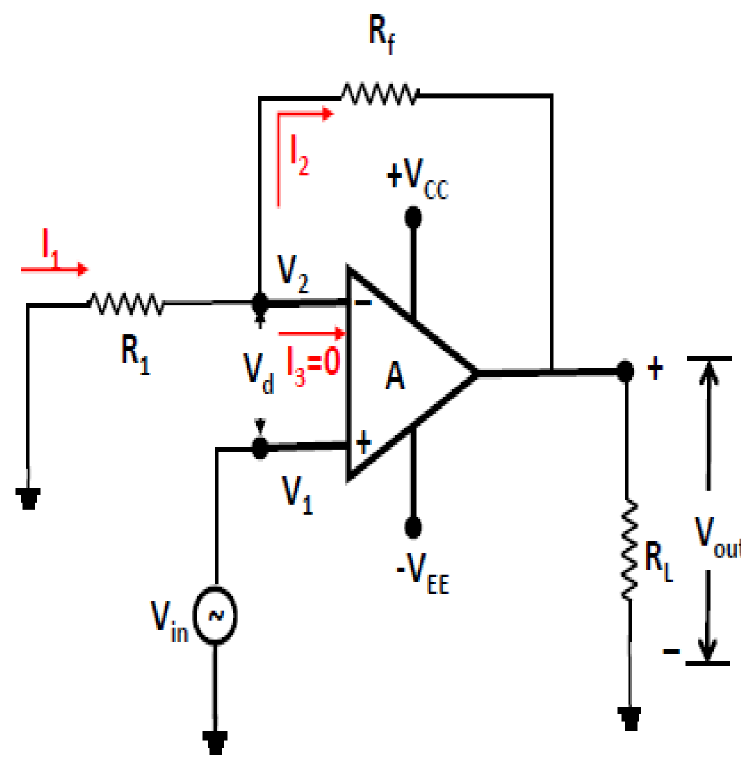
Applying ohms law to find current I_1 through resistor R_1,we have

$$I_1 = \frac{-V_2}{R_1} = \frac{-V_{in}}{R_1}$$

$$I_1 = I_2 + I_3$$

$$I_1 = I_2 \;\; since \;\; I_3 = 0$$

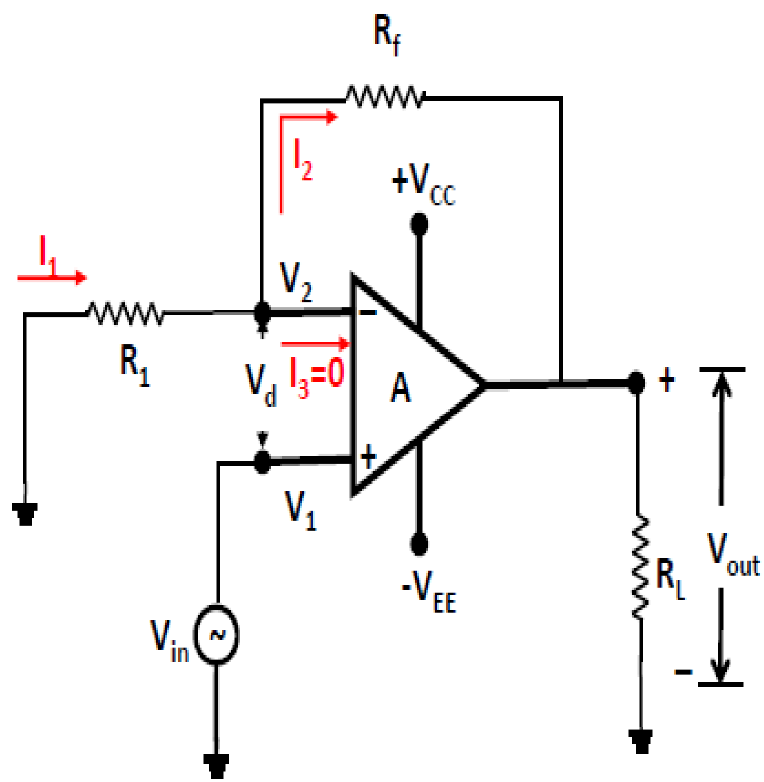
$$I_2 = \frac{-V_{in}}{R_1}$$



Circuit Diagram

Non-Inverting Amplifier

- $V_2 = I_2 R_f + V_{out}$
- But $V_2 = V_{in}$ and $I_2 = \frac{-V_{in}}{R_1}$
- $\therefore V_{in} = \frac{-V_{in} R_f}{R_1} + V_{out}$
- $V_{out} = V_{in} + \frac{V_{in} R_f}{R_1}$
- $V_{out} = V_{in}\left(1 + \frac{R_f}{R_1}\right)$
- $\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$
- $A_f = 1 + \frac{R_f}{R_1}$



Circuit Diagram

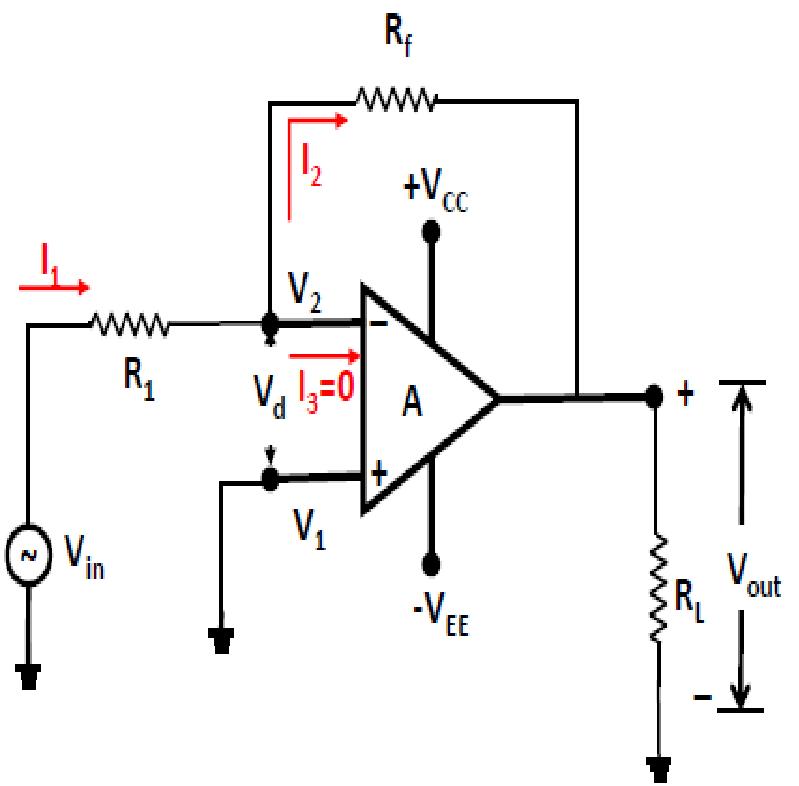
Inverting Amplifier

- Inverting amplifier is it closed the loop amplifier in which the input is applied at the inverting terminal.
- The output of inverting amplifier is out of phase by 180 degree with respect to input.

$$A = \frac{V_{out}}{V_d} = \frac{V_{out}}{V_1 - V_2}$$

$$V_1 - V_2 = \frac{V_{out}}{A} = \frac{V_{out}}{\infty} = 0$$

$$V_1 = V_2$$



Circuit Diagram

Inverting Amplifier

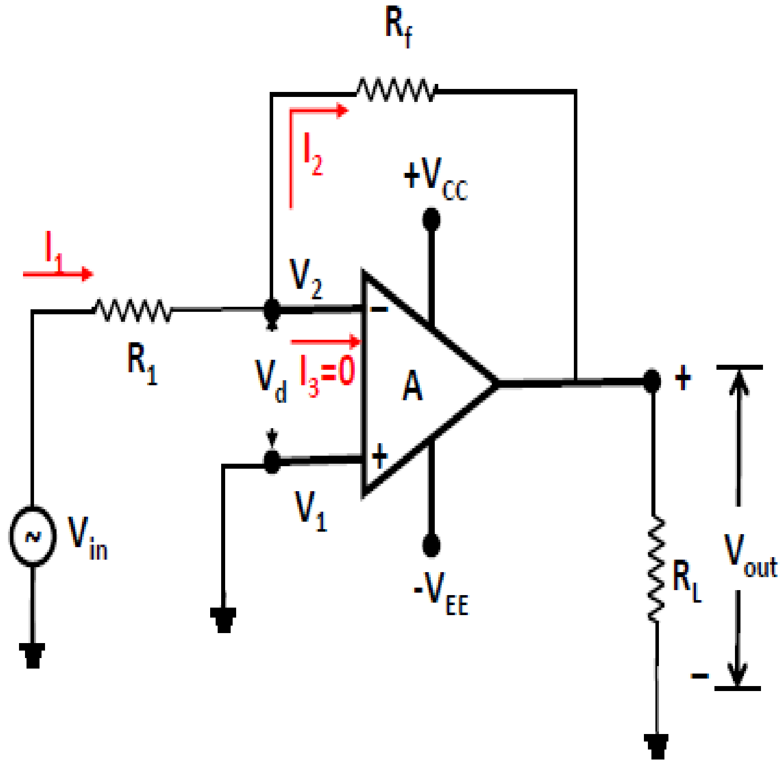
- The closed loop gain of inverting amplifier can be determined as follows.
- Applying ohms law to find current I_1 through resistor R_1, we have

$$I_1 = \frac{V_{in} - V_2}{R_1} = \frac{V_{in} - 0}{R_1} = \frac{V_{in}}{R_1}$$

$$I_1 = I_2 + I_3$$

$$I_1 = I_2 \;\; since \;\; I_3 = 0$$

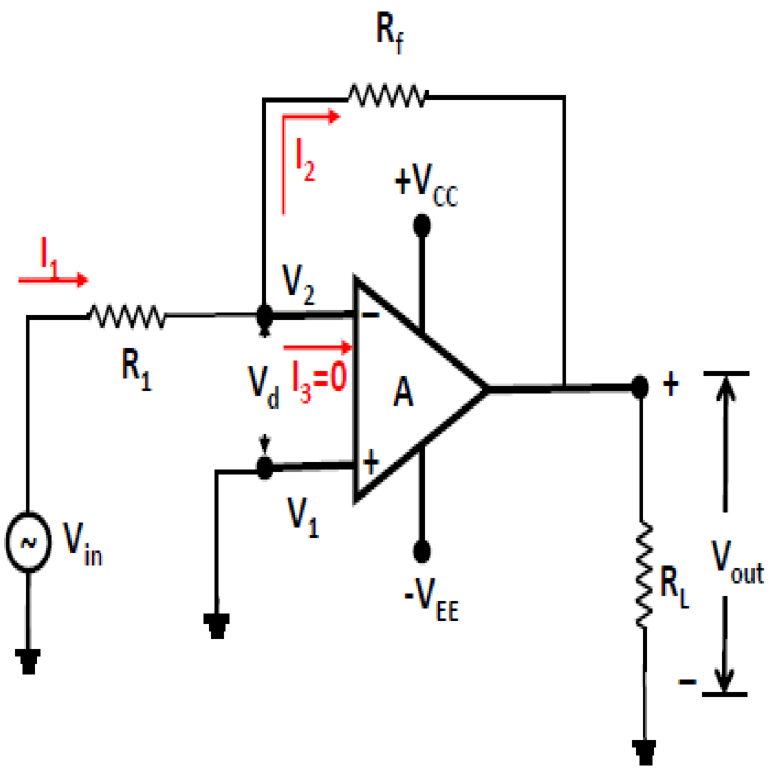
$$I_2 = \frac{V_{in}}{R_1}$$



Circuit Diagram

Inverting Amplifier

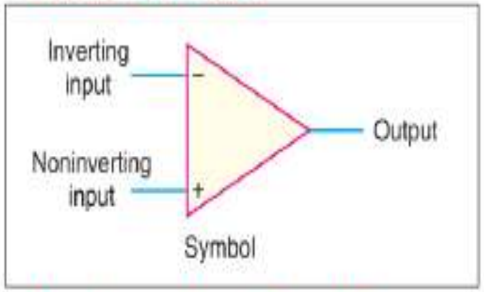
- $V_2 = I_2 R_f + V_{out}$
- But $V_2 = 0$ and $I_2 = \frac{V_{in}}{R_1}$
- $\therefore 0 = \frac{V_{in} R_f}{R_1} + V_{out}$
- $V_{out} = -\frac{V_{in} R_f}{R_1}$
- $\frac{V_{out}}{V_{in}} = \frac{-R_f}{R_1}$
- $A_f = \frac{-R_f}{R_1}$



Circuit Diagram

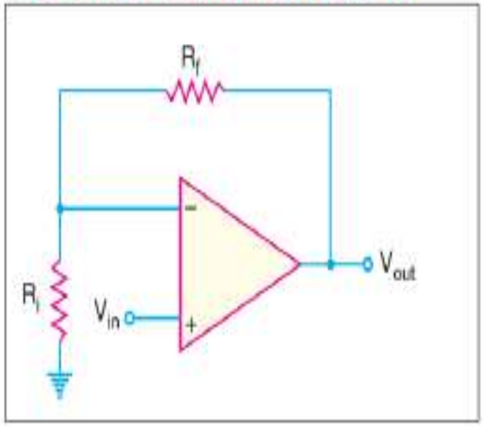
Summary of OPAMP Configurations

Basic OP-AMP



- Very high open-loop voltage g
- Very high input impedance
- Very low output impedance

Noninverting Amplifier



- Voltage gain:

$$A_{CL}(NI) = 1 + \frac{R_f}{R_i}$$

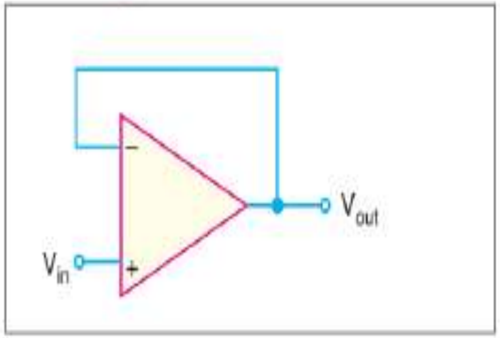
- Input impedance:

$$Z_{in(NI)} = (1 + A_{OL}m_v)\, Z_{in}$$

- Output impedance:

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{OL}m_v}$$

Voltage Follower



- Voltage gain:

$$A_{CL(VF)} = 1$$

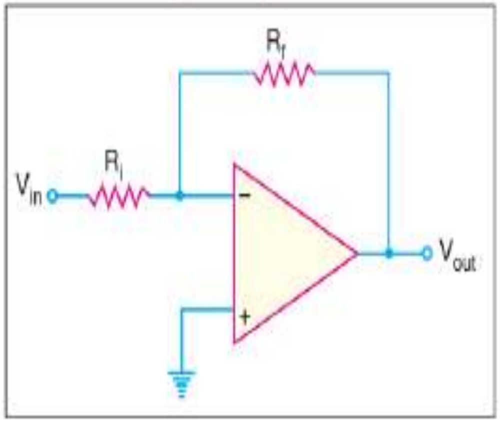
- Input impedance:

$$Z_{in(VF)} = (1 + A_{OL})\, Z_{in}$$

- Output impedance:

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{OL}}$$

Inverting Amplifier



- Voltage gain:

$$A_{CL} = -\frac{R_f}{R_i}$$

- Input impedance:

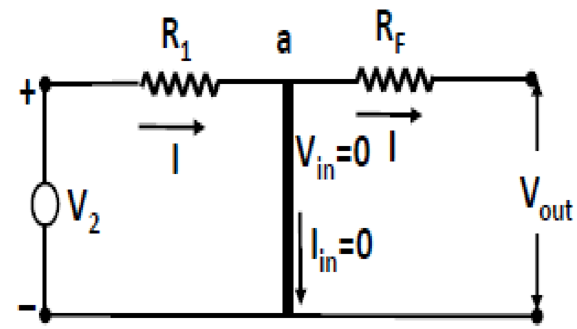
$$Z_{in(I)} \cong R_i$$

- Output impedance:

$$Z_{out(I)} \cong Z_{out}$$

Virtual Short And Its Relation To Negative Feedback

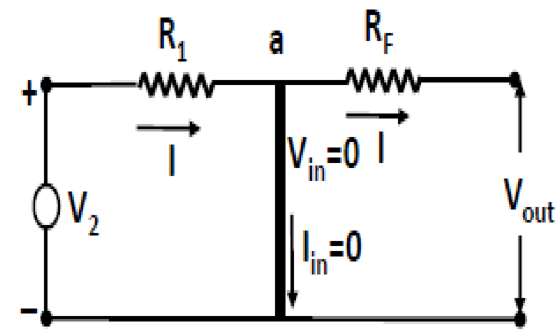
- The output voltage of op-amp is limited to the supply voltage V_{cc}, which is of the order of 10 or 15V, then input voltage $V_{in} = \frac{V_{out}}{A} = \frac{10}{10^5} = 100\mu V$
- The value of V_{in} compared to all other voltage, is very small and maybe considered to be zero volt.
- V_{in} is almost zero but not exactly zero because output voltage is V_{in} time the amplifier gain.
- The fact that V_{in}=0 volt leads to the concept that at the input to the amplifier there exist virtual short circuits or virtual ground.
- The concept of virtual short implies that although the input voltage is nearly zero there is no current through the amplifier input to ground.
- The concept of virtual ground is depicted in figure



Virtual ground in an op-amp

Virtual Short And Its Relation To Negative Feedback

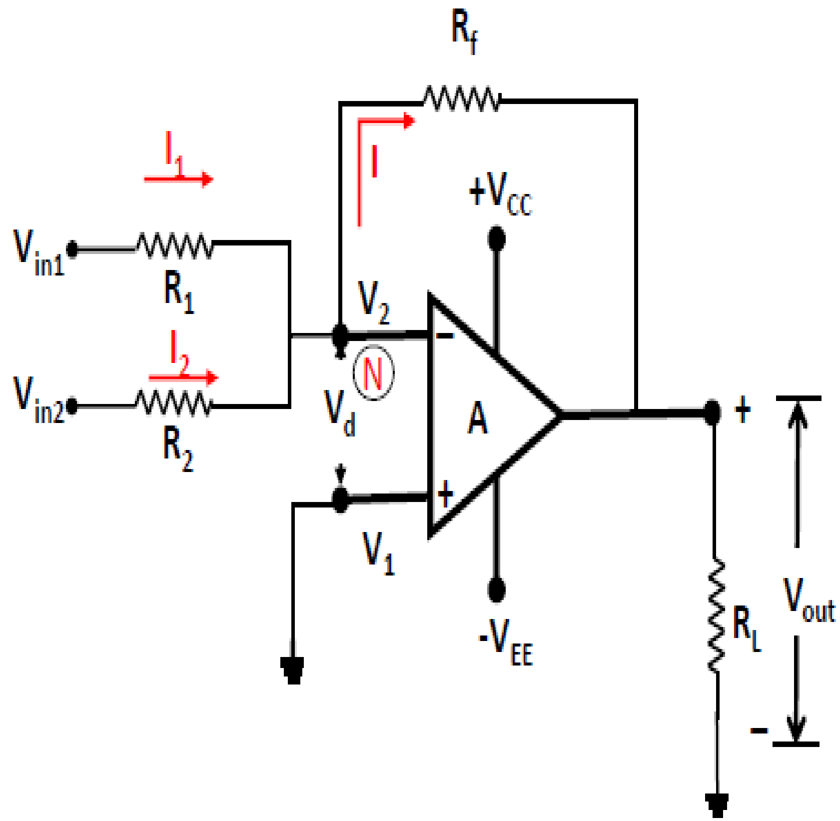
- The thick indicates that a short may be considered to exists with V_{in}=0 but this is a virtual short in that no current passes through the short to the ground
- Current through resistor R_1 and R_F is same $I = \frac{V_2}{R_1} = \frac{-V_{out}}{R_F}$
- Virtual shot is not a physical connection.
- When voltage V_2 is applied, point a attain some positive potential but simultaneously output voltage come into existence. Some fraction of this output voltage is feedback to point a in phase opposition to the voltage already existing there, due to input voltage signal V_2. This is due to negative feedback. The algebraic sum of these two voltages is almost zero giving $V_{in} \cong 0$



Virtual ground in an op-amp

Inverting Summing Amplifier

- Since the input impedance of an op-amp is extremely large, more than one input signal can be applied to the inverting amplifier. Such circuit gives addition of the applied signals at the output. Hence, it is called as summer or adder circuits



Circuit Diagram

Inverting Summing Amplifier

- $V_1 = V_2 = 0$
- $I_1 = \frac{V_{in1} - V_2}{R_1} = \frac{V_{in1}}{R_1}$
- $I_2 = \frac{V_{in2} - V_2}{R_2} = \frac{V_{in2}}{R_2}$

Applying KCL at node N,

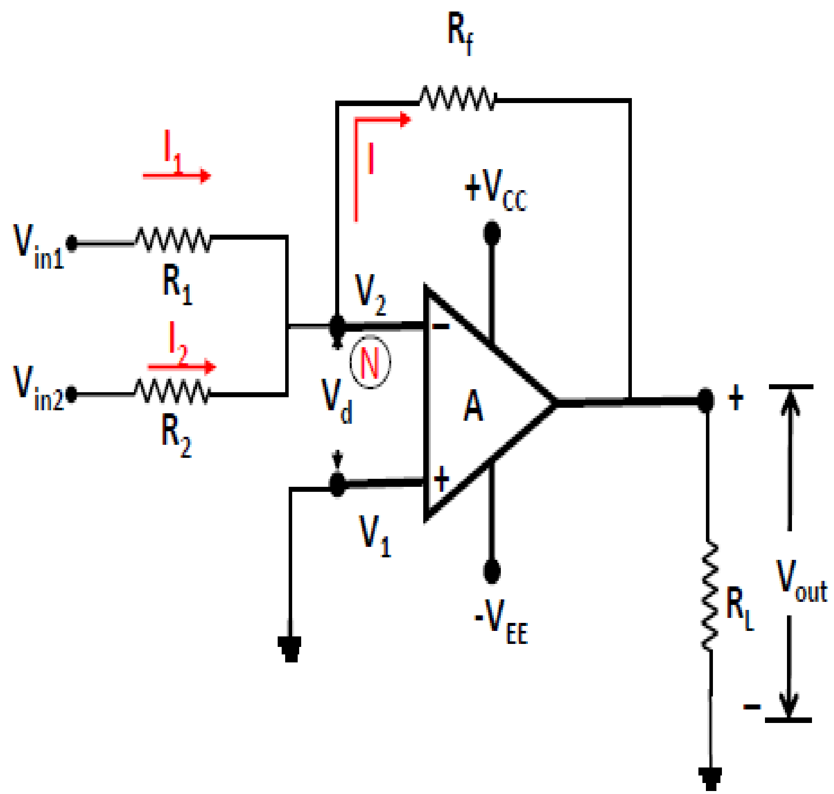
- $I = I_1 + I_2$

From output side,

- $I = \frac{V_2 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$
- $\frac{-V_{out}}{R_f} = \frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2}$
- $V_{out} = -\left[\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2}\right]$

If $R_1 = R_2 = R_f$

- $V_{out} = -(V_{in1} + V_{in2})$



Circuit Diagram

Non-Inverting Summing Amplifier

- Summer that give non-inverted sum of the input signals is known as non-inverting summing amplifier.
- $V_1 = V_2$

From the input side,

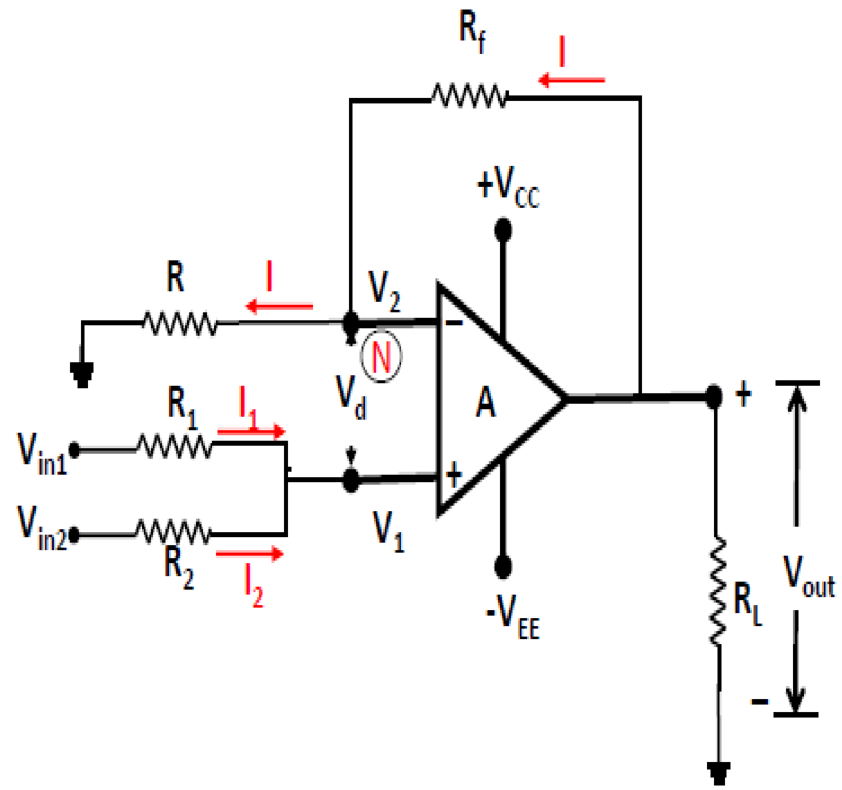
- $I_1 = \frac{V_{in1} - V_1}{R_1}$ *and* $I_1 = \frac{V_{in2} - V_1}{R_2}$

Since current through op-amp is zero

$$I_1 + I_2 = 0$$

$$\frac{V_{in1} - V_1}{R_1} + \frac{V_{in2} - V_1}{R_2} = 0$$

$$\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2} = V_1 \left[\frac{1}{R_1} + \frac{1}{R_2} \right]$$



Circuit Diagram

Non-Inverting Summing Amplifier

$$V_1 = \frac{(R_2 V_{in1} + R_1 V_{in2})}{(R_1 + R_2)}$$

At node N

$$I = \frac{V_2}{R} = \frac{V_1}{R}$$

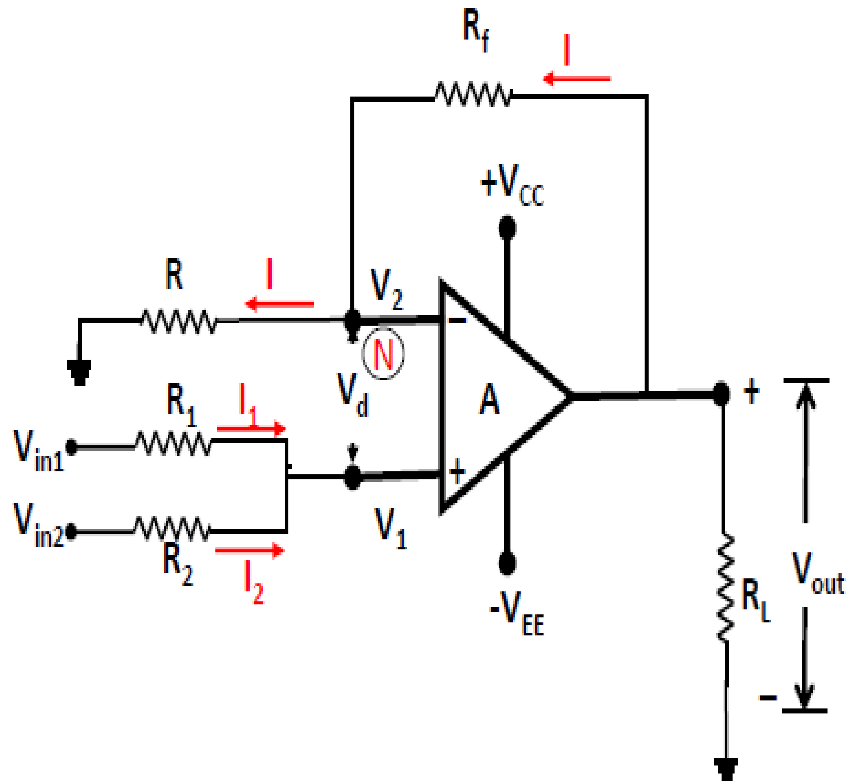
And

$$I = \frac{V_{out} - V_2}{R_f} = \frac{V_{out} - V_1}{R_f}$$

$$\frac{V_1}{R} = \frac{V_{out} - V_1}{R_f}$$

$$\frac{V_{out}}{R_f} = V_1\left[\frac{1}{R} + \frac{1}{R_f}\right] = V_1\left[\frac{R + R_f}{R.R_f}\right]$$

$$V_{out} = V_1\left[\frac{R + R_f}{R}\right]$$



Circuit Diagram

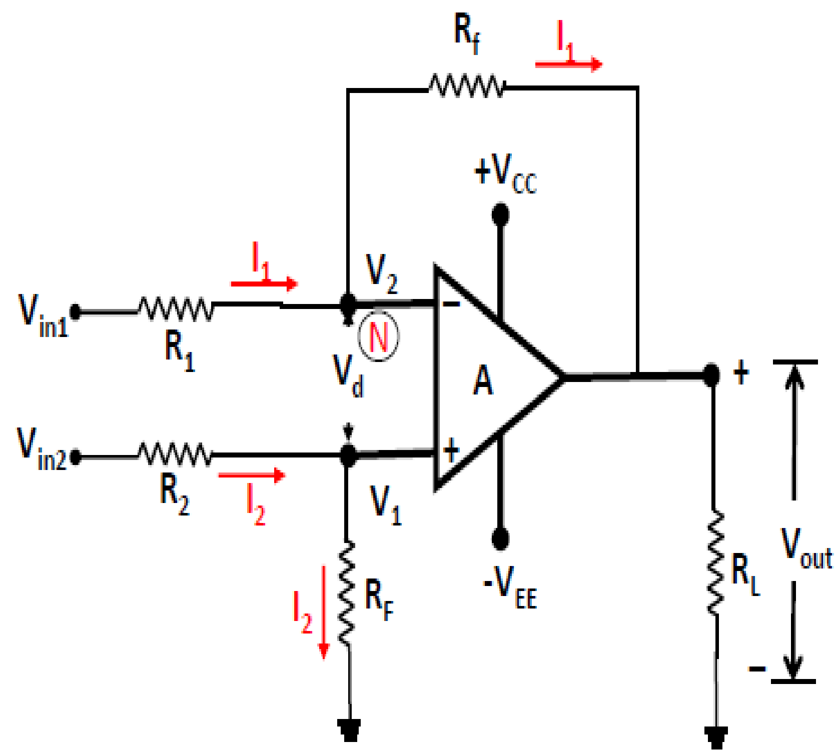
$$V_{out} = \frac{(R_2 V_{in1} + R_1 V_{in2})}{(R_1 + R_2)} \cdot \left[\frac{R + R_f}{R}\right]$$

If $R_1 = R_2 = R = R_f$

$$V_{out} = V_{in1} + V_{in2}$$

Difference Amplifier (Subtractor)

- Similar to summer circuits the subtraction of two input voltages is possible with the help of op-amp circuits, called as subtractor difference amplifier circuits.
- The circuit diagram has been shown in figure.
- To find the relation between the inputs and outputs, let us use superposition principle

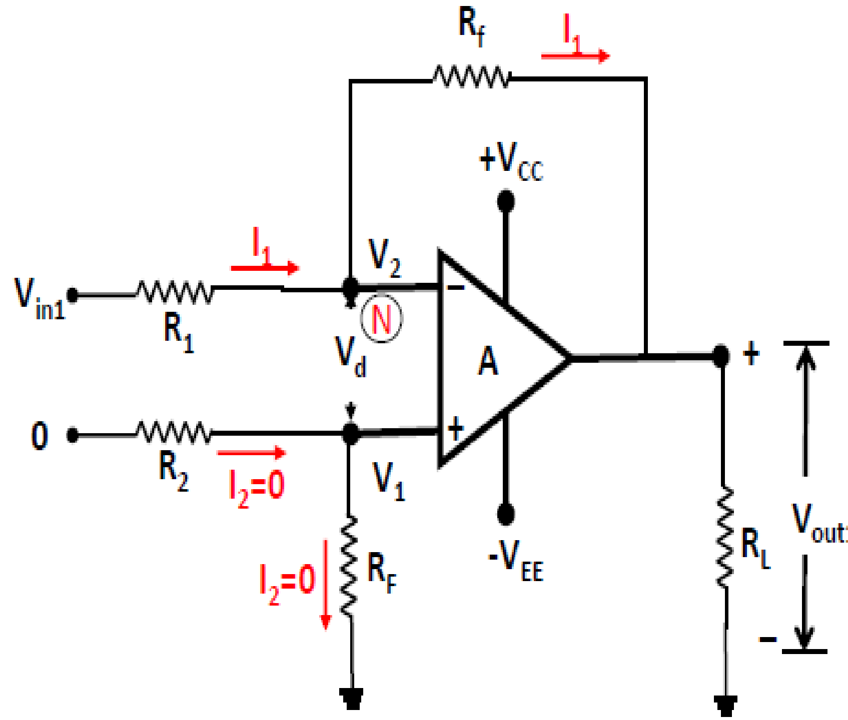


Circuit Diagram

Difference Amplifier (Subtractor)

- With V_{in2}=0, the circuit act as an inverting amplifier. Hence we can write

$$V_{out1} = -\frac{R_f}{R_1} V_{in1}$$



Circuit Diagram

Difference Amplifier (Subtractor)

With V_{in2}=0, the circuit act as an inverting amplifier. Hence we can write

$$V_{out1} = -\frac{R_f}{R_1} V_{in1}$$

With V_{in1}=0, the circuit reduces as shown in figure

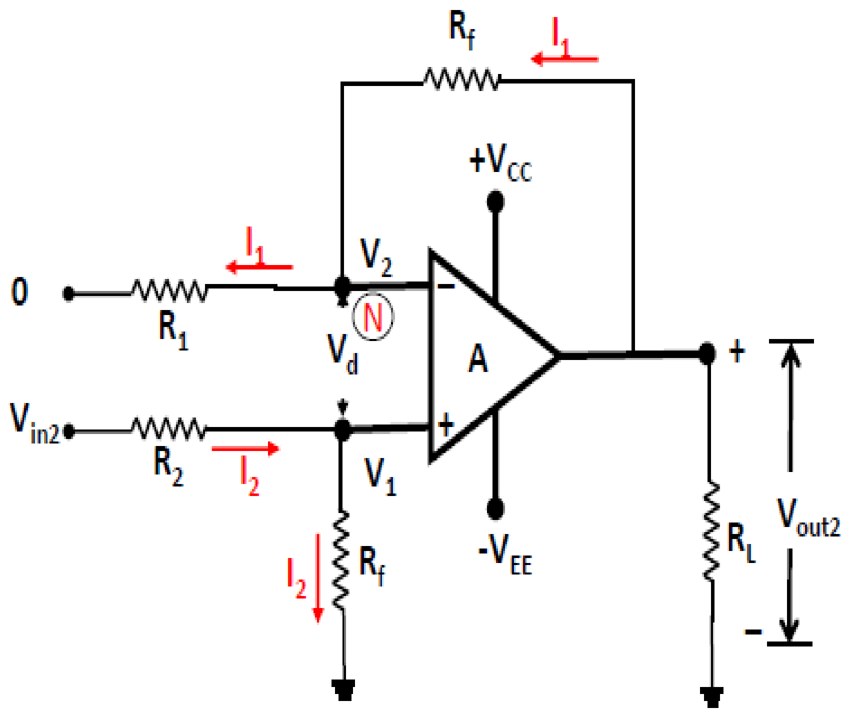
$$V_1 = \frac{V_{in2}}{R_2 + R_f} R_f$$

$$I_1 = \frac{V_2}{R_1} = \frac{V_1}{R_1}$$

$$I_1 = \frac{V_{out2} - V_2}{R_f} = \frac{V_{out2} - V_1}{R_f}$$

$$\frac{V_1}{R_1} = \frac{V_{out2} - V_1}{R_f}$$

$$V_{out2} = \left[\frac{R_1 + R_f}{R_1}\right] V_1 \Rightarrow V_{out2} = \left[\frac{R_1 + R_f}{R_1}\right]\left[\frac{R_f}{R_2 + R_f}\right] V_{in2}$$



Circuit Diagram

Difference Amplifier (Subtractor)

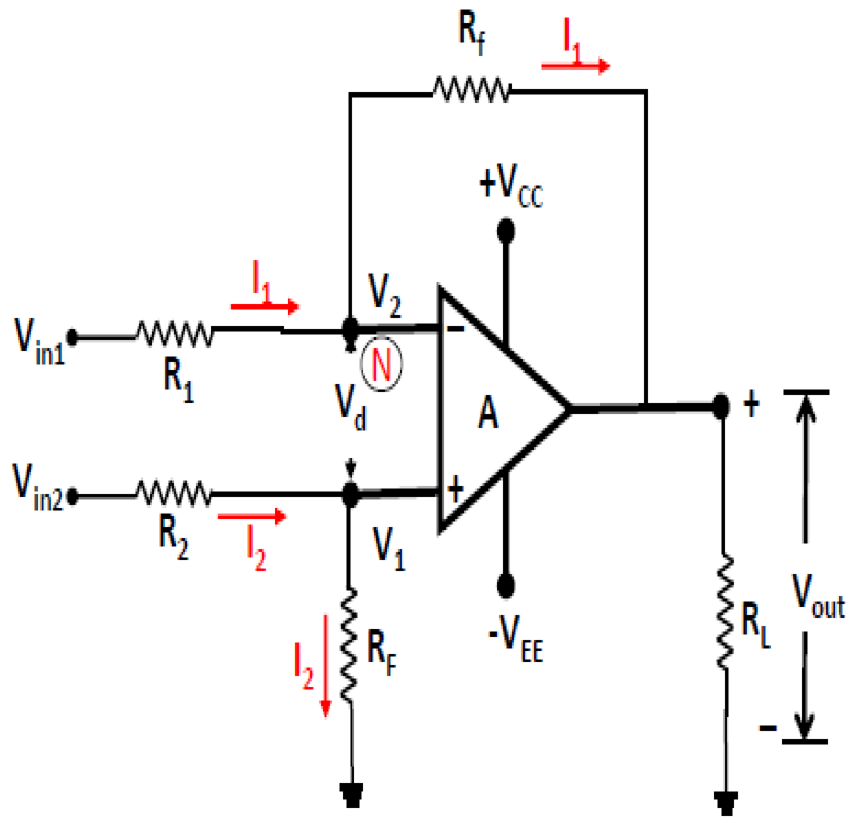
- Using superposition principle

$$V_{out} = V_{out1} + V_{out2}$$

$$V_{out} = -\frac{R_f}{R_1}V_{in1} + \left[\frac{R_1 + R_f}{R_1}\right]\left[\frac{R_f}{R_2 + R_f}\right]V_{in2}$$

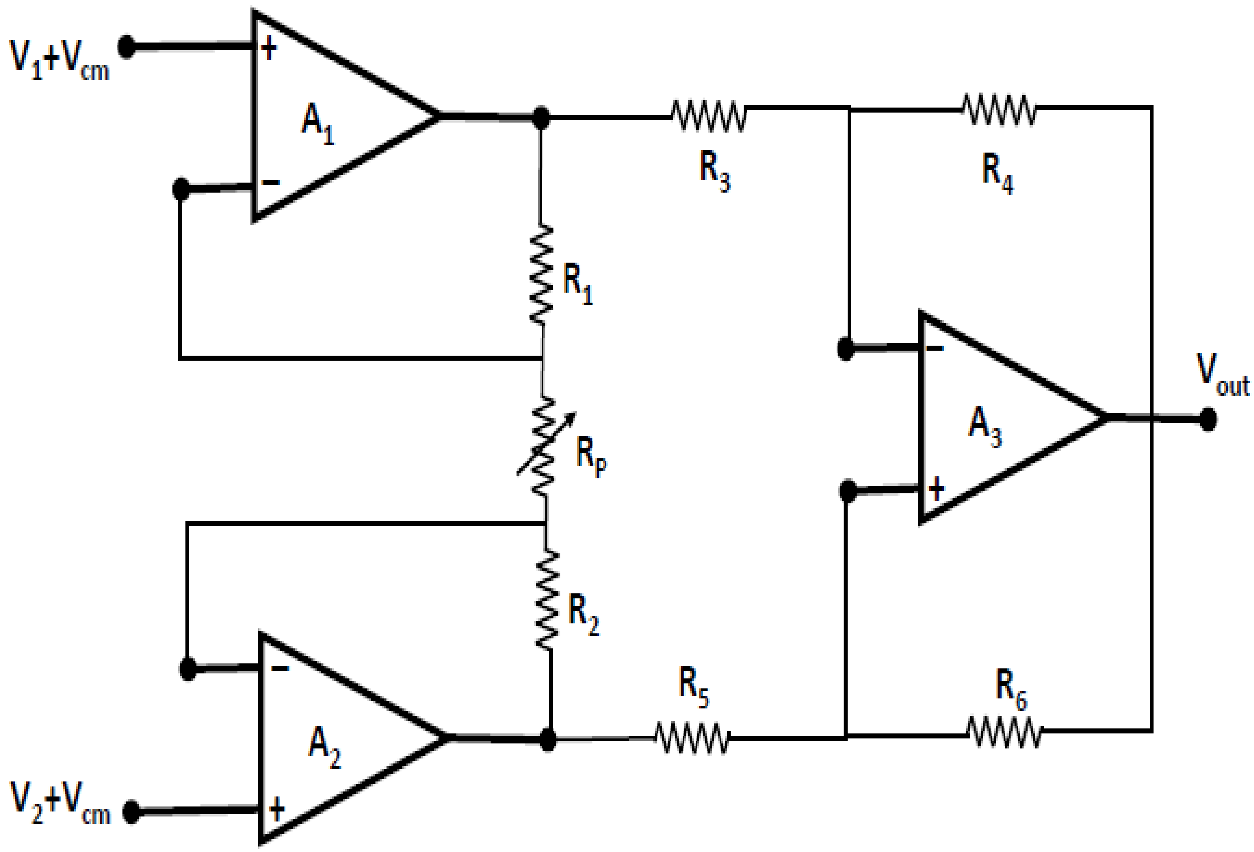
- If $R_1 = R_2 = R_f$

$$V_{out} = V_{in2} - V_{in1}$$



Circuit Diagram

Instrumentation Amplifier



Circuit Diagram

Instrumentation Amplifier

- An instrumentation amplifier is a differential amplifier optimised for high input impedance and high CMRR.
- An instrumentation amplifier is typically used in applications in which a small differential voltage and a large common mode voltage are the inputs.
- Requirements of a good instrumentation amplifier
  - Finite, accurate and stable gain
  - Easier gain adjustment
  - High input impedance
  - Low output impedance
  - High CMRR
  - Low power consumption
  - High slew rate