

Lecture Notes

Module:3

Operational amplifier and its applications:

Topics Covered:

Operational Amplifiers: Introduction, The Operational Amplifier, Block Diagram Representation of Typical Op Amp, Schematic Symbol, Op-Amp Parameters: Gain, Input Resistance, Output Resistance, CMRR, Slew Rate, Bandwidth, Input Offset Voltage, Input Bias Current and Input Offset Current, The Ideal Op-Amp, Equivalent Circuit of Op-Amp, Open Loop Op-Amp Configurations, Differential Amplifier, Inverting & Non Inverting Amplifier Op-Amp Applications: Inverting Configuration, Non-Inverting Configuration, Differential Configuration, Voltage Follower, Integrator, Differentiator.

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INTRODUCTION:

An operational amplifier is a direct-coupled high-gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output stage. An operational amplifier is available as a single integrated circuit package. The operational amplifier is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for computing such mathematical functions as addition, subtraction, multiplication, and integration. Thus the name operational amplifier stems from its original use for these mathematical operations and is abbreviated to op-amp. With the addition of suitable external feedback components, the modern day op-amp can be used for a variety of applications, such as ac and dc signal amplification, active filters, oscillators, comparators, regulators, and others.



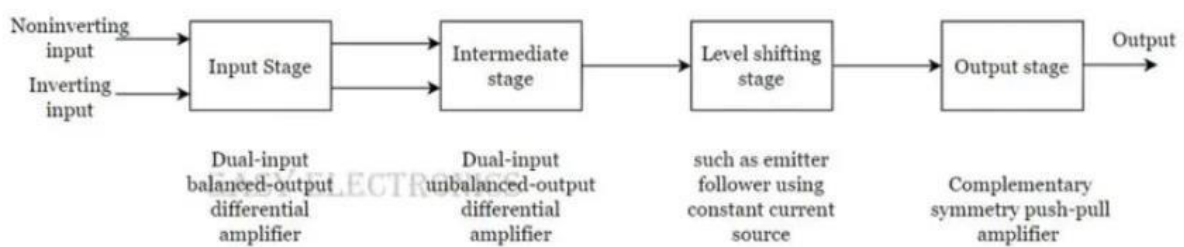
Operational Amplifier (Op-amp)

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**”.

Block Diagram of Op-Amp

Since an op-amp is a multistage amplifier, it can be represented by a block diagram as shown in the figure below.



Block Diagram of an Op-amp

Input stage:

- It consists of a dual input, balanced output differential amplifier.
- Its function is to amplify the difference between the two input signals.
- It provides high differential gain, high input impedance and low output impedance.
- It consists of another differential amplifier with dual input, and unbalanced (single ended) output.

Intermediate stage:

- The overall gain requirement of an Op-Amp is very high.
- Since the input stage alone cannot provide such a high gain.
- Intermediate stage is used to provide the required additional voltage gain.

Buffer and Level shifting stage:

- As the Op-Amp amplifies D.C signals also, the small D.C. quiescent voltage level of previous stages may get amplified and get applied as the input to the next stage causing distortion the final output.
- Hence the level shifting stage is used to bring down the D.C. level to ground potential, when no signal is applied at the input terminals. Buffer is usually an emitter follower used for impedance matching.

Output stage:

It consists of a push-pull complementary amplifier which provides large A.C. output voltage swing and high current sourcing and sinking along with low output impedance.

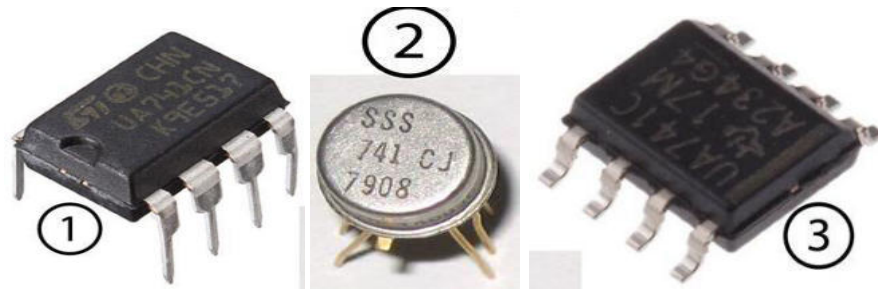
Operational Amplifier: IC 741

The 741 Op-Amp IC is a monolithic integrated circuit, comprising of a general purpose

Operational Amplifier. It was first manufactured by Fairchild semiconductors in the year 1963. The number 741 indicates that this operational amplifier IC has 7 functional pins, 4 pins capable of taking input and 1 output pin. This IC 741 Op-Amp is most commonly used in various electrical and electronic circuits. The main intention of this 741 op-amp is to strengthen AC & DC signals and for mathematical operations.

IC 741 Op-Amp can provide high voltage gain and can be operated over a wide range of voltages, which makes it the best choice for use in integrators, summing amplifiers and general feedback applications. It also features short circuit protection and internal frequency compensation circuits built in it. This Op-amp IC comes in the following form factors:

- 8 Pin DIP Package
- TO5-8 Metal can package
- 8 Pin SOIC

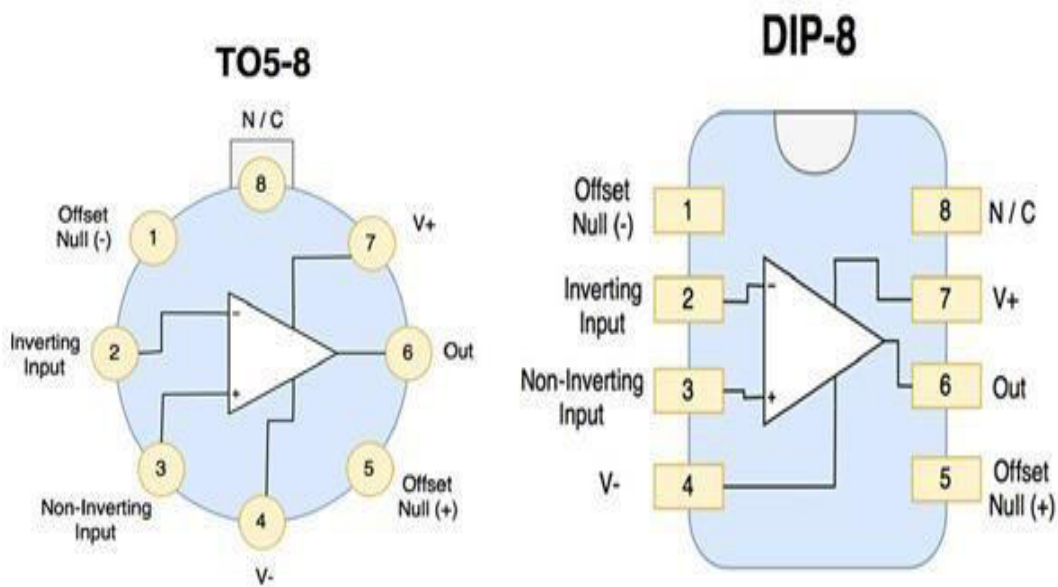


Pin-out of IC 741 Op Amp and their Functions

The below figure illustrates the pin configurations and internal block diagram of IC 741 in 8 pin DIP and TO5-8 metal can package.

Functions of different pins of 741 IC:

- **Pin4 & Pin7 (Power Supply):** Pin7 is the positive voltage supply terminal and Pin4 is the negative voltage supply terminal. The 741 IC draws in power for its operation from these pins. The voltage between these two pins can be anywhere between 5V and 18V.



- **Pin6 (Output):** This is the output pin of IC 741. The voltage at this pin depends on the signals at the input pins and the feedback mechanism used. If the output is said to be high, it means that voltage at the output is equal to positive supply voltage. Similarly, if the output is said to be low, it means that voltage at the output is equal to negative supply voltage.
- **Pin2 & Pin3 (Input):** These are input pins for the IC. Pin2 is the inverting input and Pin3 is the non-inverting input. If the voltage at Pin2 is greater than the voltage at Pin3, i.e., the voltage at inverting input is higher, the output signal stays low. Similarly, if the

voltage at Pin3 is greater than the voltage at Pin2, i.e., the voltage at non-inverting input is high, the output goes high.

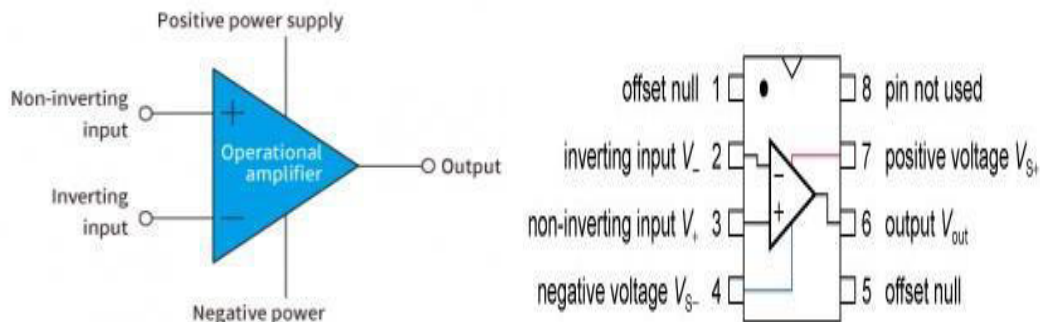
- **Pin1 & Pin5 (Offset Null):** Because of high gain provided by 741 Op-Amp, even slight differences in voltages at the inverting and non-inverting inputs, caused due to irregularities in manufacturing process or external disturbances, can influence the output. To nullify this effect, an offset voltage can be applied at pin1 and pin5, and is usually done using a potentiometer.
- **Pin8 (N/C):** This pin is not connected to any circuit inside 741 IC. It's just a dummy lead used to fill the void space in standard 8 pin packages.

Operational Amplifier Schematic Symbol

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.



Op-Amp Operation

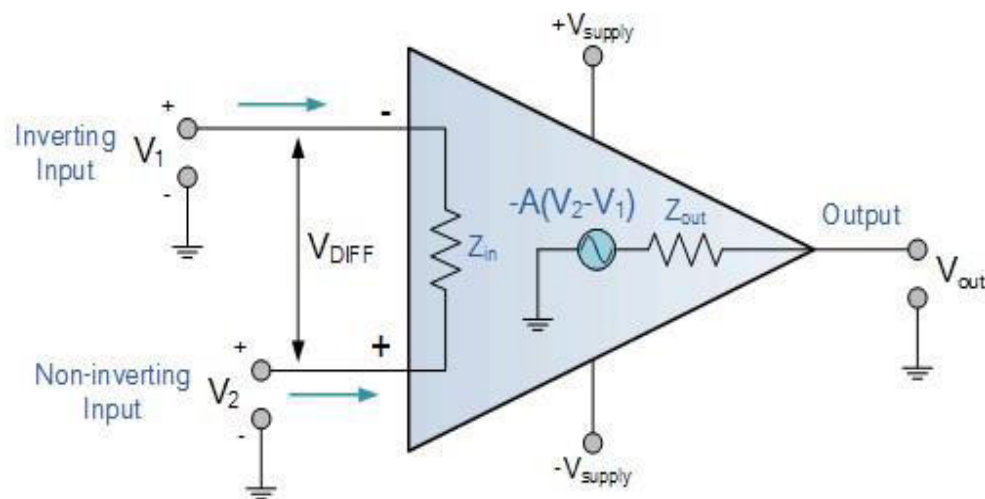
Ideally, an op-amp amplifies only the difference in voltage between the two, also called differential input voltage. The output voltage of the op-amp V_{out} is given by the equation:

$$V_{out} = A_{OL} (V_+ - V_-)$$

Where A_{OL} is the open-loop gain of the amplifier.

In a linear operational amplifier, the output signal is the amplification factor, known as the amplifier's gain (A) multiplied by the value of the input signal.

Equivalent Circuit of an Ideal Operational Amplifier



The equivalent circuit of an ideal op-amp is shown above. The input voltage V_{DIFF} is the difference voltage ($V_1 - V_2$). Z_{in} is the input impedance and Z_{out} is the output impedance.

The **gain parameter** A is called the open loop gain. If an op-amp does not have any feedback from the output to either of the inputs, it is said to be operating in **open-loop configuration**.

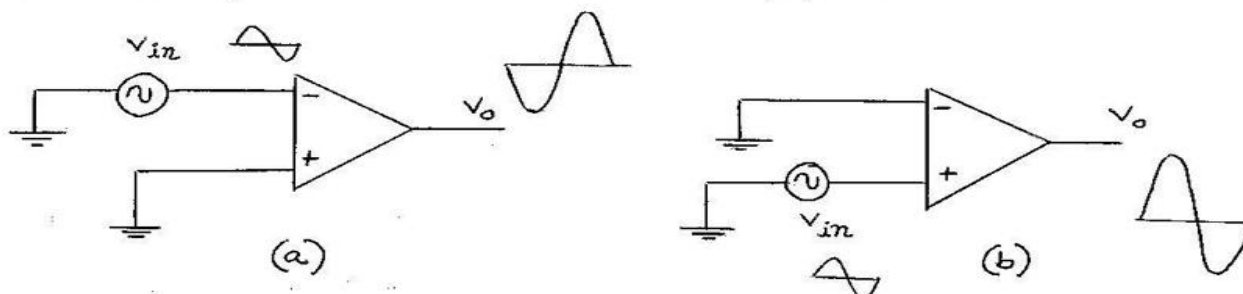
An **ideal op-amp** exhibits infinite open loop gain, infinite input impedance, zero output impedance, infinite voltage swing, infinite bandwidth, infinite slew rate and zero input offset voltage.

Op-amp Input Signal Modes :-

For op-amps we have two input signal modes. They are the differential mode and common mode.

In the differential mode either one signal is applied to an input with the other input grounded or two opposite polarity signals are applied to the inputs.

In the single ended differential mode, one input is grounded and a signal voltage is applied to the other input as shown in the figure below:

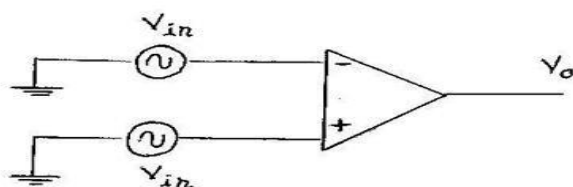


In the case when the signal voltage is applied to the inverting input as in figure (a), an inverted amplified signal voltage appears at the output. In case, when the signal voltage is applied to the non inverting input as in figure (b), a non inverted amplified signal voltage appears at the output.

Op-amp Parameters :-

1. Common Mode Rejection Ratio :

In common mode, the two signal voltages of same phase, frequency and magnitude are applied to the two inputs as shown in the figure below.



When equal input signals are applied to both inputs, they tend to cancel resulting in a zero output voltage. This action is called common mode rejection.

Unwanted signals or noise appearing with same polarity on both lines of input are common mode signals and are cancelled by the op-amp and do not appear on the output. The measure of the op-amp's ability to reject common mode signals is expressed in terms of Common Mode Rejection Ratio (CMRR). The CMRR is defined as follows:

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

where A_{ol} is the open loop differential gain and the A_{cm} is the common mode gain.

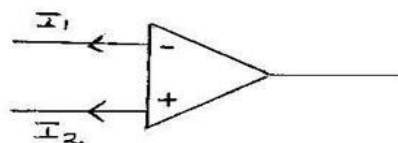
Practical op-amps exhibit a very small common mode voltage gain and a very high differential mode voltage gain. The higher the differential gain with respect to the common mode gain the better the performance of the op-amp in terms of common mode rejection. In other words, higher the value of CMRR the lower will be the value of common mode gain.

2. Maximum Output Voltage Swing $V_{o(p-p)}$:- This parameter indicates the maximum limit of the peak output voltage. The ideal limit is $\pm V_{cc}$, where $+V_{cc}$ and $-V_{cc}$ are the DC supply voltage of the op-amp. For practical opamps the limit approaches the ideal value i.e. if $\pm V_{cc} = \pm 12V$, then $V_{o(p-p)} \approx \pm 10V$.

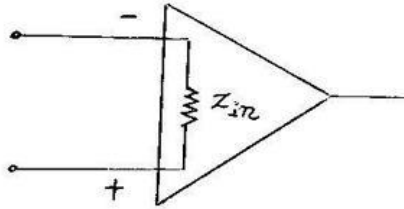
3. Input Offset Voltage :- The op-amp produces a small output voltage for zero input voltage. The input offset voltage V_{os} is the differential DC voltage between the input required to force the output to zero volts. Typical values of input offset voltage are in the range of 2mV or less.

4. Input Bias Current :- The differential amplifier at the input stage of the op-amp has two inputs. The two input terminals are nothing but the base terminals of the two transistors. Thus the input currents are the base currents. The input bias current is the DC current supplied by the inputs of the amplifier to properly operate the input stage. The input bias current is defined as the average of the two base currents.

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$



5. Input Impedance:- The input impedance in the differential mode is the total resistance between the inverting and the non inverting inputs as shown below:

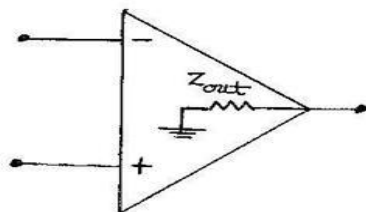


The input impedance in differential mode is obtained by the ratio of change in the differential input voltage and change in the bias current.

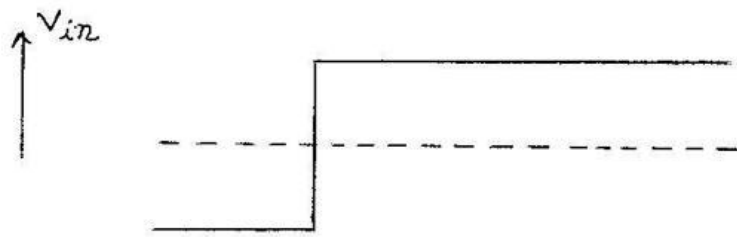
6. Input offset current:- The input offset current is the difference of the input bias currents expressed as an absolute value.

$$I_{os} = |I_1 - I_2|$$

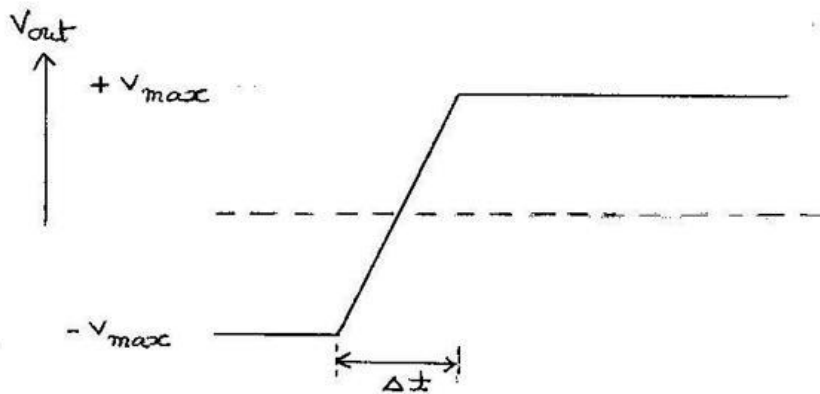
7. Output Impedance:- The output impedance is the resistance viewed from the output terminal of the op-amp as shown below:



8. Slew Rate:- The maximum rate of change of the output voltage in response to a step input voltage is called the slew rate of the op-amp.



Step input
voltage



output
voltage

A certain time interval Δt , is required for the output voltage to go from $-V_{max}$ to $+V_{max}$ when step input is applied.

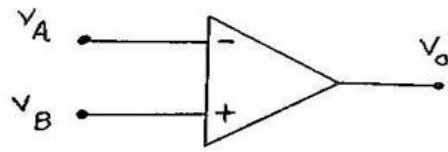
$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

Characteristics of an ideal op-amp

An ideal op-amp exhibits the following characteristics

1. Infinite voltage gain
2. Infinite input impedance
3. Zero output impedance
4. Zero input offset voltage
5. Zero input offset current
6. Infinite CMRR
7. Infinite Slew rate
8. Infinite Bandwidth.

Concept of virtual ground



Let V_A and V_B be the voltage at the input terminals. We know that

$$V_O = A_V (V_A - V_B)$$

The A_V is the differential voltage gain and its ideal value is infinity

$$A_V = \infty = \frac{V_O}{V_A - V_B}$$

$$\Rightarrow V_A - V_B = 0$$

This concept is called as virtual ground.

Open loop Op-amp Configuration

The term open-loop indicates that no feedback in any form is fed to the input from the output. When connected in open – loop, the op-amp functions as a very high gain amplifier. There are three open – loop configurations of op-amp namely

- Differential amplifier
- Inverting amplifier
- Non-inverting amplifier

The above classification is made based on the number of inputs used and the terminal to which the input is applied. The op-amp amplifies both ac and dc input signals. Thus, the input signals can be either ac or dc voltage.

Open-loop Differential Amplifier

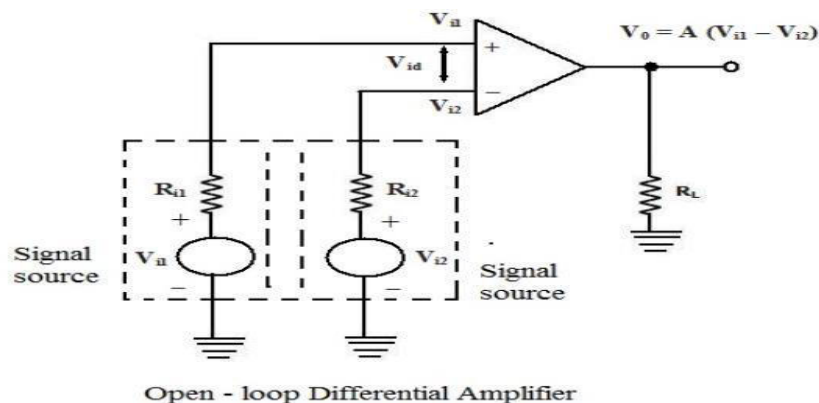
In this configuration, the inputs are applied to both the inverting and the non-inverting input terminals of the op-amp and it amplifies the difference between the two input voltages. Figure shows the open-loop differential amplifier configuration.

The input voltages are represented by V_{i1} and V_{i2} . The source resistance R_{i1} and R_{i2} are negligibly small in comparison with the very high input resistance offered by the op-amp, and thus the voltage drop across these source resistances is assumed to be zero. The output voltage V_0 is given by

$$V_0 = A(V_{i1} - V_{i2})$$

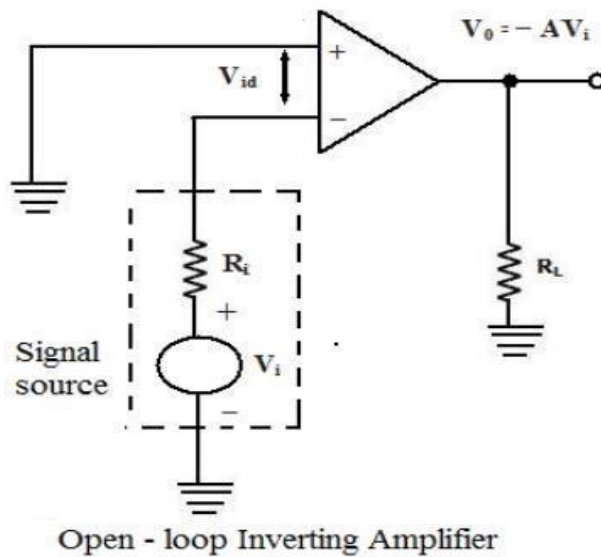
Where A is the large signal voltage gain.

Thus the output voltage is equal to the voltage gain A times the difference between the two input voltages. This is the reason why this configuration is called a **differential amplifier**. In open-loop configurations, the large signal voltage gain A is also called open-loop gain A .



Inverting amplifier:

In this configuration the input signal is applied to the inverting input terminal of the op-amp and the non-inverting input terminal is connected to the ground. Figure shows the circuit of an open-loop inverting amplifier.



The output voltage is 180° out of phase with respect to the input and hence, the output voltage V_0 is given by,

$$V_0 = -AV_i$$

Thus, in an inverting amplifier, the input signal is amplified by the open-loop gain A and in phase shifted by 180° .

Non-inverting Amplifier

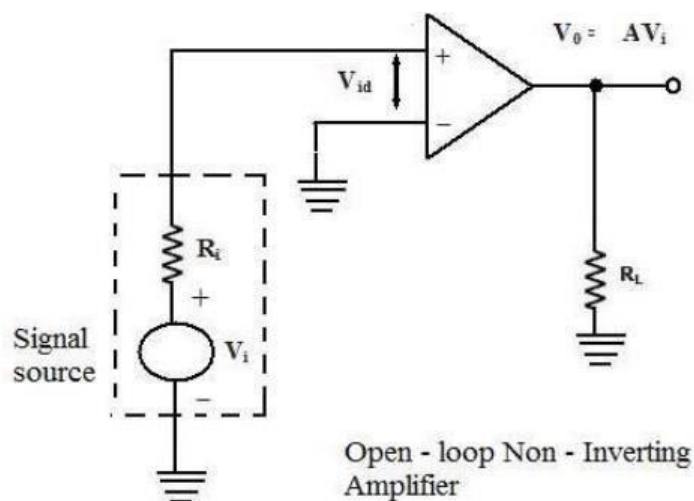


Figure shows the open – loop non- inverting amplifier. The input signal is applied to the noninverting input terminal of the op-amp and the inverting input terminal is connected to the ground.

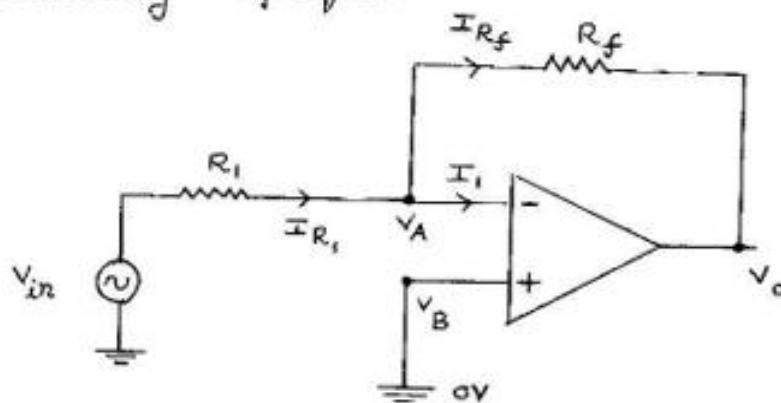
The input signal is amplified by the open – loop gain A and the output is in-phase with input signal.

In all the above open-loop configurations, only very small values of input voltages can be applied. Even for voltages levels slightly greater than zero, the output is driven into saturation, which is observed from the ideal transfer characteristics of op-amp shown in figure. Thus, when operated in the open-loop configuration, the output of the op-amp is either in negative or positive saturation, or switches between positive and negative saturation levels. This prevents the use of open – loop configuration of op-amps in linear applications.

Op-amp Applications

Op-amp as an inverting amplifier

An inverting amplifier is a circuit whose output is amplified and inverted with respect to the input. Figure below shows the circuit diagram of an inverting amplifier.



By the concept of virtual ground, we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have,

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_i = 0$

Hence $I_{R_i} = I_{R_f}$

$$\frac{V_{in} - V_A}{R_i} = \frac{V_A - V_o}{R_f}$$

Substituting $V_A = 0V$ we have

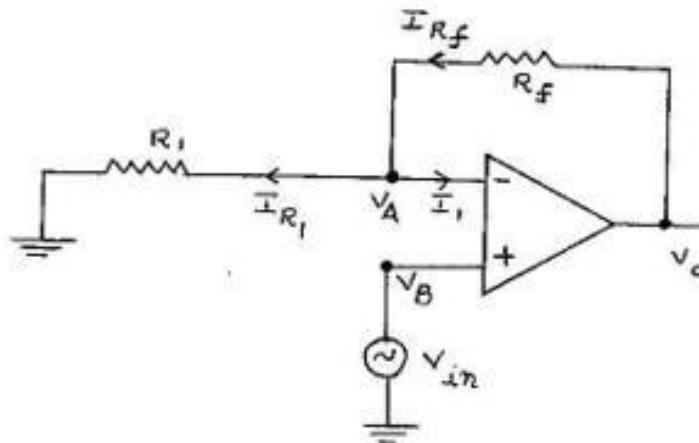
$$\frac{V_{in}}{R_i} = \frac{-V_o}{R_f}$$

$$\therefore \boxed{V_o = -\left(\frac{R_f}{R_i}\right) V_{in}}$$

The term (R_f/R_i) is called the gain of the inverting amplifier. The negative sign indicates that the output is inverted with respect to the input.

Op-amp as a non inverting amplifier :-

Figure below shows the circuit diagram of a non inverting amplifier.



By the concept of virtual ground we have

$$V_A - V_B = 0$$

Since V_B is maintained at a voltage V_{in} we have

$$V_A = V_B = V_{in}$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_i = 0$.

Hence

$$I_{R_f} = I_{R_i}$$

$$\frac{V_o - V_A}{R_f} = \frac{V_A - 0}{R_i}$$

$$\frac{V_o}{R_f} = \frac{V_A}{R_f} + \frac{V_A}{R_i} = V_A \left[\frac{1}{R_f} + \frac{1}{R_i} \right]$$

Substituting $V_A = V_{in}$ we have

$$\frac{V_o}{R_f} = V_{in} \left[\frac{1}{R_f} + \frac{1}{R_i} \right]$$

$$\therefore V_o = V_{in} \left(1 + \frac{R_f}{R_i} \right)$$

The term $\left(1 + \frac{R_f}{R_i} \right)$ is called gain of the non-inverting amplifier.

Op-amp as an inverting adder (summer)

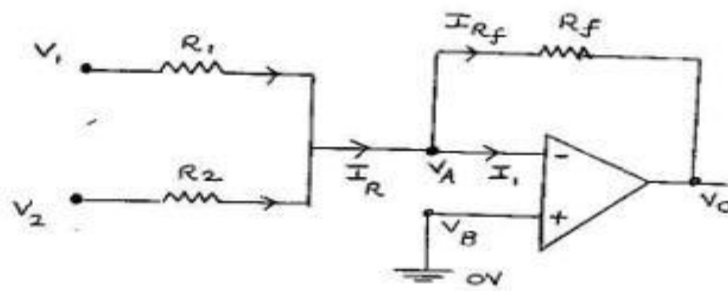


Figure above shows the circuit diagram of an inverting adder. By the concept of virtual ground we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have,

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_i = 0$

Hence

$$I_R = I_{Rf}$$

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

Substituting $V_A = 0$ we have

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

$$\therefore V_0 = - \left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 \right]$$

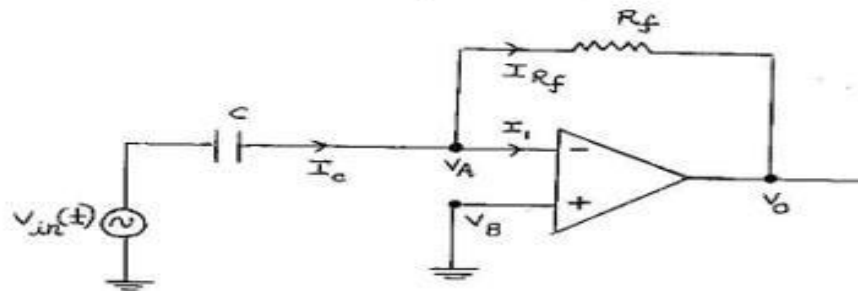
If $R_1 = R_2 = R_f$ is chosen, then we have,

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

Since the output of the circuit is equal to negative of sum of input voltages, the circuit is called as the inverting summer

op-amp as a differentiator

A differentiator is a circuit, in which the output voltage is proportional to the time derivative of the input voltage. Figure shows the circuit diagram of a differentiator using op-amp.



By the concept of virtual ground, we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$, thus we have

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_i = 0$

Hence
$$I_C = I_{R_f}$$

$$C \frac{d}{dt} \{V_{in}(t) - V_A\} = \frac{V_A - V_o}{R_f}$$

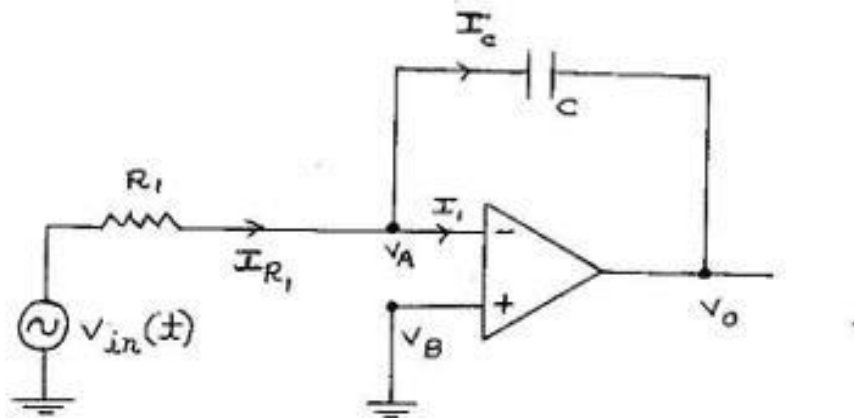
Substituting $V_A = 0$ we have,

$$C \frac{d}{dt} V_{in}(t) = -\frac{V_o}{R_f}$$

or
$$V_o = -R_f C \frac{d}{dt} V_{in}(t)$$

op-amp as an integrator :-

An integrator is a circuit, in which the output voltage is proportional to the integral of the input voltage. Figure below shows the circuit diagram of the integrator using op-amp



By the concept of Virtual ground, we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_i = 0$.

Hence
$$I_{R_1} = I_c$$

$$\frac{V_{in} - V_A}{R_1} = C \frac{d}{dt} (V_A - V_o)$$

Substituting $V_A = 0$, we have

$$\frac{V_{in}(t)}{R_1} = -C \frac{dV_o}{dt}$$

$$\text{or } \frac{dV_o}{dt} = -\frac{1}{R_1 C} V_{in}(t)$$

Integrating on both sides w.r.t. t

$$V_o = -\frac{1}{R_1 C} \int_0^t V_{in}(t) dt$$
