Lecture Notes

Unit:2

Operational amplifier and its applications:

Topics Covered:

Introduction to operational amplifiers, Op-amp input modes and parameters, Op-amp in open loop configuration, op-amp with negative feedback, study of practical op-amp IC 741, inverting and non-inverting amplifier applications: summing and difference amplifier, unity gain buffer, comparator, integrator and differentiator.

Designed by: Vipra Bohara

Assistant Professor

JECRC, Sitapura, Jaipur.

Operational Amplifier (Op-amp)

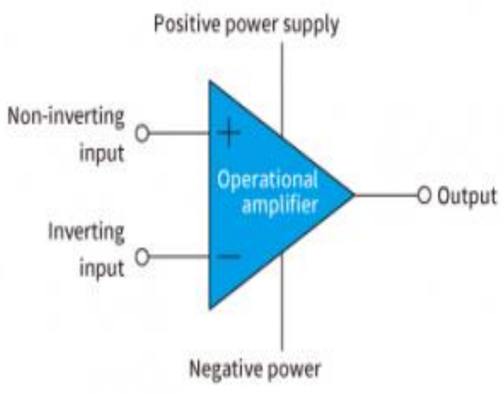
Operational amplifiers are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation.

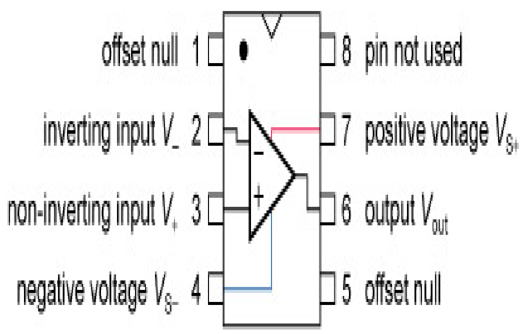
An **Operational Amplifier**, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals. These feedback components determine the resulting function or "operation" of the 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**".

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:

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

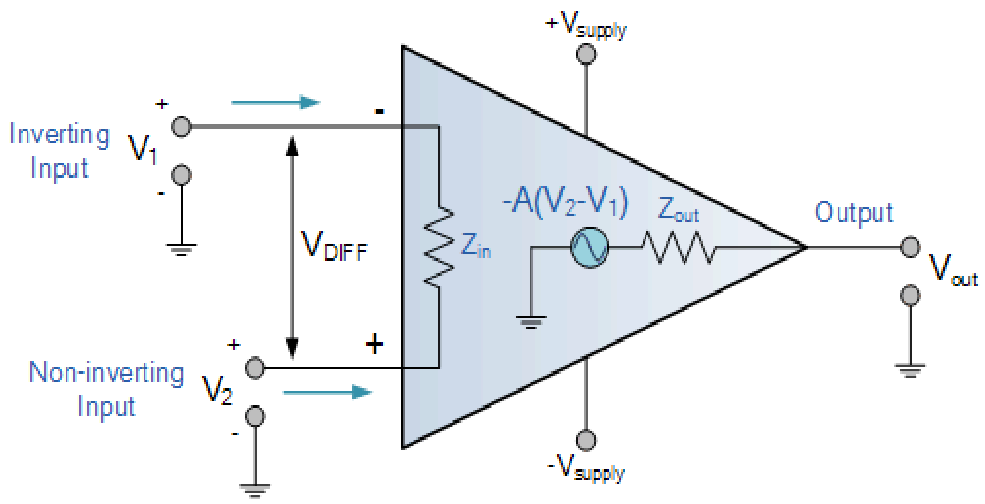
Where A_{OL} is the open-loop gain of the amplifier.

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.

There are **four** ways to **classify operational amplifiers**:

- **Voltage amplifiers** take voltage in and produce a voltage at the output.
- **Current amplifiers** receive a current input and produce a current output.
- **Transconductance amplifiers** convert a voltage input to a current output.
- **Transresistance amplifiers** convert a current input and produces a voltage output.

Equivalent Circuit of an Ideal Operational Amplifier



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

Open Loop Gain, (Avo):

Open-loop gain of an op-amp is defined as the gain of the op-amp when there is no feedback from the output to either of its inputs. For an ideal op-amp, the gain will be infinite theoretically, but practical value range from 20,000 to 200,000.

Input impedance, (Z_{IN})

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})

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)

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.

Common-Mode Input Voltage Range

All op-amps have limitations on the range of voltages over which they will operate. The common-mode input voltage range is the range of input voltages which, when applied to both inputs, will not cause clipping or other output distortion. Many op-amps have common-mode input voltage ranges of ±10 V with dc supply voltages of ±15 V.

Offset Voltage, (VIO)

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.

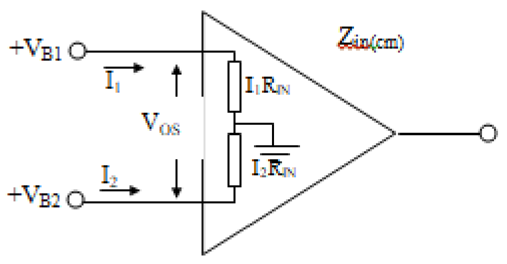
Input Offset Current

Ideally, the two input bias currents are equal, and thus their difference is zero. In a practical op-amp, however, the bias currents are not exactly equal.

The input offset current, Ios is the difference of the input bias currents, expressed as an absolute value.

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

Actual magnitudes of offset current are usually at least an order of magnitude (ten times) less than the bias current. In many applications, the offset current can be neglected. However, high-gain, high-input impedance amplifiers should have as little Ios as possible because the difference in currents through large input resistances develops a substantial offset voltage, as shown in figure.



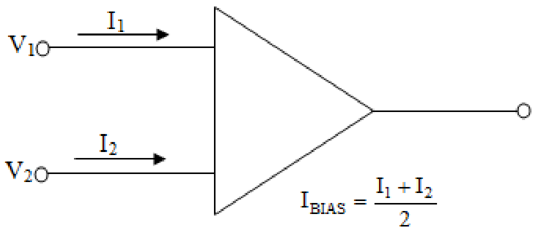
Input Bias Current

You have seen that the input terminals of a bipolar differential amplifier are the transistor bases and, therefore, the input currents are the base currents.

The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage. By definition, the input bias current is the average of both input currents and is calculated as follows:

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

The concept of input bias current is illustrated in Figure



Common-Mode Rejection Ratio

The common-mode rejection ratio (CMRR), as discussed in conjunction with the diff-amp, is a measure of an op-amp's ability to reject common-mode signals. An infinite value of CMRR means that the output is zero when the same signal is applied to both inputs (common-mode),

An infinite CMRR is never achieved in practice, but a good op-amp does have a very high value of CMRR. Common-mode signals are undesired interference voltages such as 50 Hz power-supply ripple and noise voltages due to pick-up of radiated energy. A high CMRR enables the op-amp to virtually eliminate these interference signals from the output.

The accepted definition of CMRR for an op-amp is the open-loop voltage gain (Aol) divided by the common-mode gain.

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

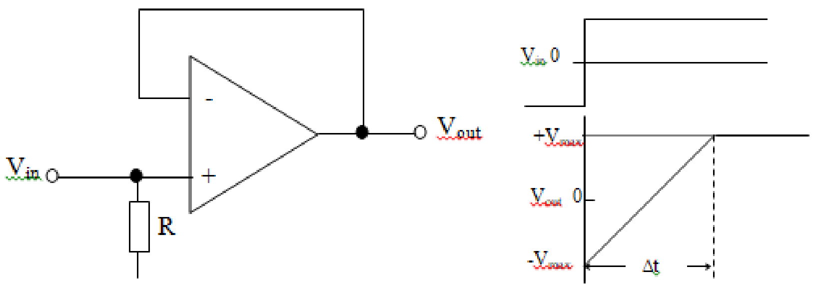
It is commonly expressed in decibels as follows:

$$CMRR = 20 \log\left(\frac{A_{ol}}{A_{cm}}\right)$$

Slew Rate

The maximum rate of change of the output voltage in response to a step input voltage is the slew rate of an op-amp. The slew rate is dependent upon the high-frequency response of the amplifier stages within the op- amp.

Slew rate is measured with an op-amp connected as shown in Figure. This particular op-amp connection is a unity-gain, non-inverting configuration, which will be discussed later. It gives a worst-case (slowest) slew rate. Recall that the high-frequency components of a voltage step are contained in the rising edge and that the upper critical frequency of an amplifier limits its response to step input. The lower the upper critical frequency is, the more slope there is on the output for a step input.



(a) Test circuit (b) Step input voltage and the resulting output voltage

A pulse is applied to the input as shown, and the ideal output voltage is measured as indicated in figure (b). The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit, as shown. As you can see, a certain time interval, At, is required for the output voltage to go from its lower limit -Vmax to its upper limit +Vmax, once the input step is applied. The slew rate is expressed as

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

where ΔVout= +Vmax- (-Vmax) The unit of slew rate is volts per microsecond (V/µs).

Now the ideal and practical value of operational amplifier

Property	Ideal	Practical(Typical)
Open-loop gain	Infinite	Very high (>10000)
Open-loop bandwidth	Infinite	Dominant pole(≅10 Hz)
CMRR	Infinite	High (> 60 dB)
Input Resistance	Infinite	High (>1 MΩ)
Output Resistance	Zero	Low(< 100 Ω)
Input Bias Currents	Zero	Low (< 50 nA)
Offset Voltages	Zero	Low (< 10 mV)
Offset Currents	Zero	Low (< 50 nA)
Slew Rate	Infinite	A few V/µs
Drift	Zero	Low

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

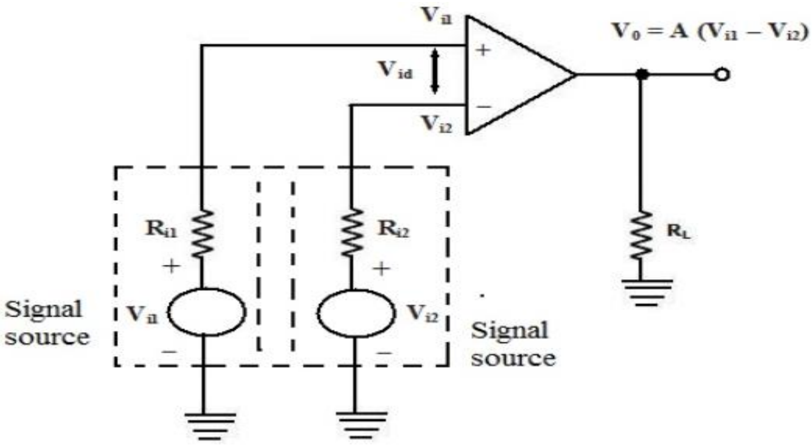
In this configuration, the inputs are applied to both the inverting and the non-inverting input terminals of the op-amp and it amplifies the difference between the two input voltages. figure shows the open-loop differential amplifier configuration.

The input voltages are represented by Vi_1 and Vi_2. The source resistance Ri_1 and Ri_2 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

$$V_0 = A(Vi_1 - Vi_2)$$

Where A is the large signal voltage gain.

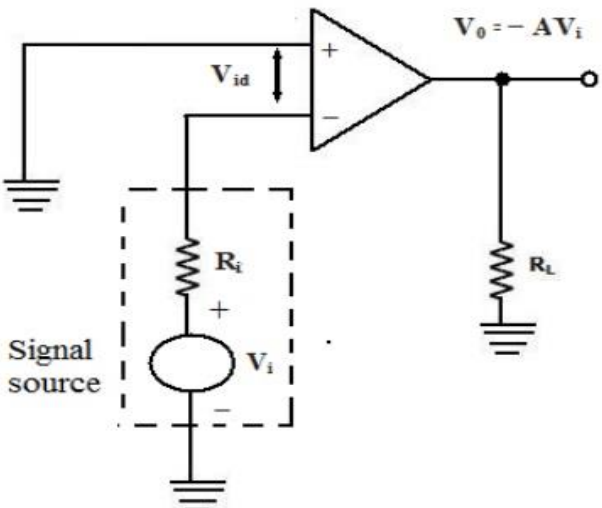
Thus the output voltage is equal to the voltage gain A times the difference between the two input voltages. This is the reason why this configuration is called a **differential amplifier**. In open – loop configurations, the large signal voltage gain A is also called open-loop gain A.



Open - loop Differential Amplifier

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.



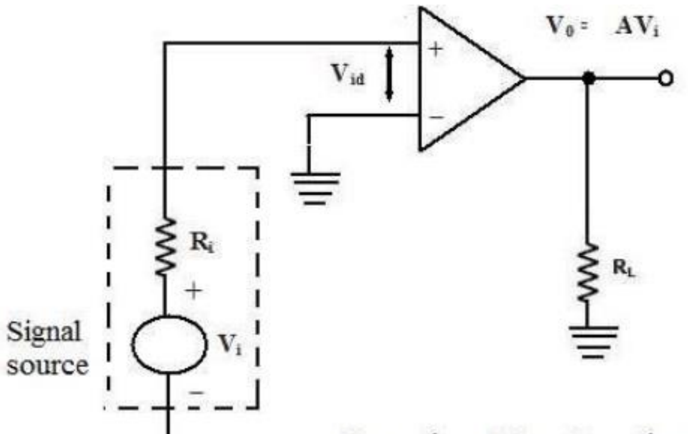
Open - loop Inverting Amplifier

The output voltage is 180^0 out of phase with respect to the input and hence, the output voltage V_0 is given by,

$$V_0 = -AVi$$

Thus, in an inverting amplifier, the input signal is amplified by the open-loop gain A and in phase shifted by 180^0.

Non-inverting Amplifier



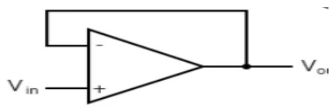
Open - loop Non - Inverting Amplifier

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

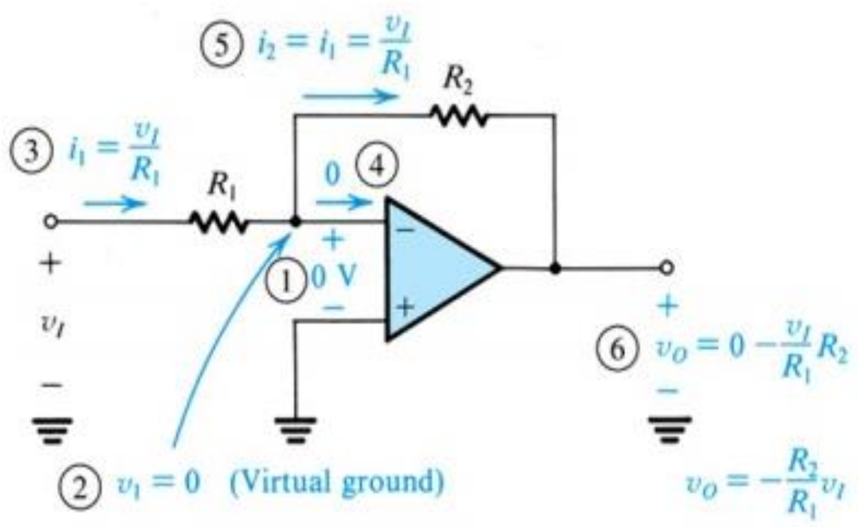
The input signal is amplified by the open – loop gain A and the output is in-phase with input signal.

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 with 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 Rf. This feedback connection between the output and the inverting input terminal forces the differential input voltage towards zero.



If we connect the output of an op-amp to its inverting input and apply a voltage signal to the non-inverting input, we find that the output voltage of the op-amp closely follows that input voltage.

As Vin increases, Vout will increase in accordance with the differential gain. However, as Vout increases, that output voltage is fed back to the inverting input, thereby acting to decrease the voltage differential between inputs, which acts to bring the output down. What will happen for any given voltage input is that the op-amp will output a voltage very nearly equal to Vin, but just low enough so that there's enough voltage difference left between Vin and the (-) input to be amplified to generate the output voltage.

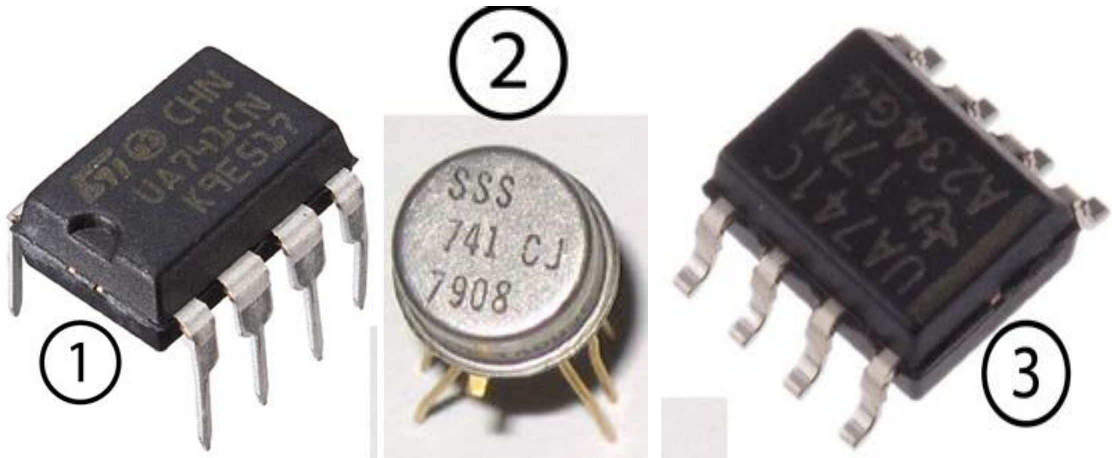
The circuit will quickly reach a point of stability, where the output voltage is just the right amount to maintain the right amount of differential. Taking the op-amp's output voltage and coupling it to the inverting input is a technique known as negative feedback, and it is the key to having a self-stabilizing system. This stability gives the op-amp the capacity to work in its linear (active) mode.

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

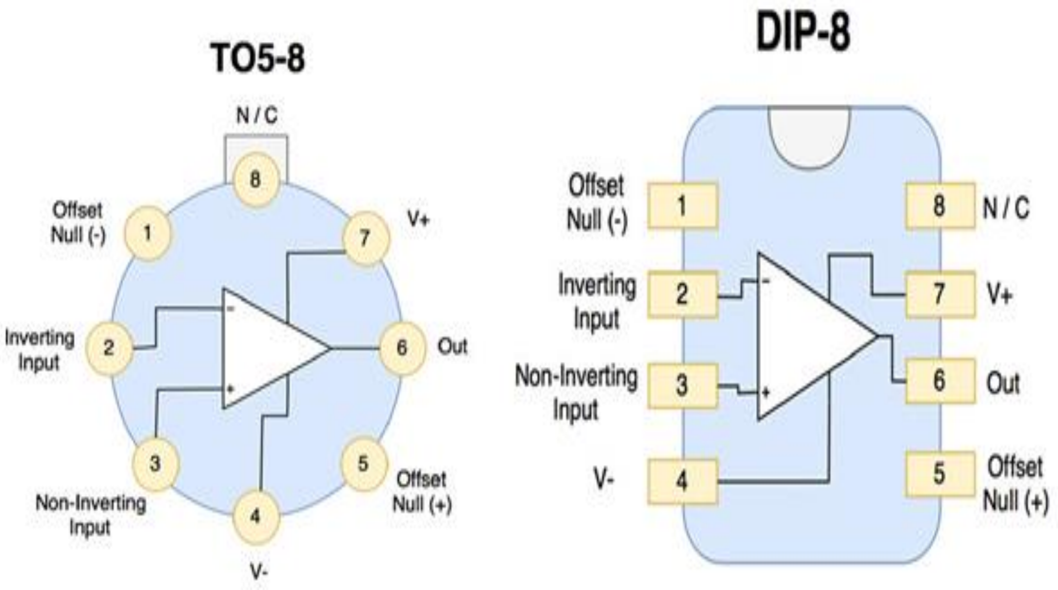


Pin-out of IC 741 Op Amp and their Functions

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.

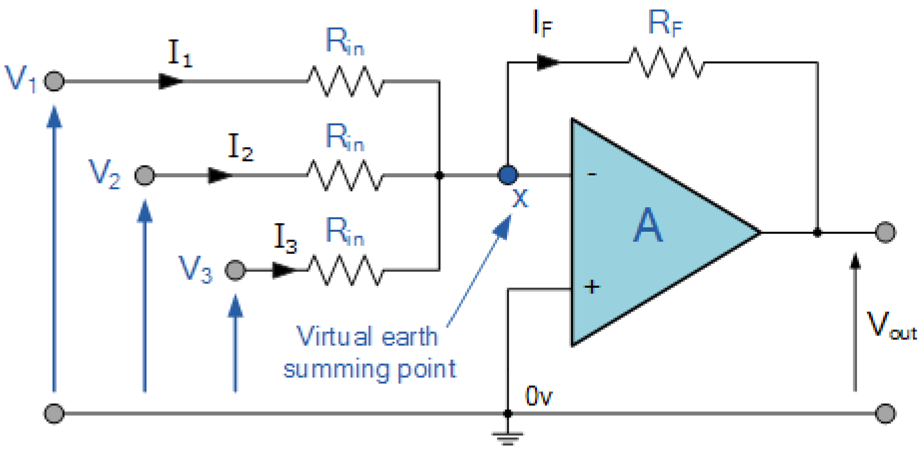
Specifications

The following are the basic specifications of IC 741:

- **Power Supply:** Requires a Minimum voltage of 5V and can withstand up to 18V
- **Input Impedance:** About 2 MΩ
- **Output impedance:** About 75 Ω
- **Voltage Gain:** 200,000 for low frequencies (200 V / mV)
- **Maximum Output Current:** 20 mA
- **Recommended Output Load:** Greater than 2 KΩ
- **Input Offset:** Ranges between 2 mV and 6 mV
- **Slew Rate:** 0.5V/µS (It is the rate at which an Op-Amp can detect voltage changes)

Summing Amplifier

Op-amp can be used to sum the input voltage of two or more sources into a single output voltage. The **Summing Amplifier** is another type of operational amplifier circuit configuration that is used to combine the voltages present on two or more inputs into a single output voltage. If we add more input resistors to the input, each equal in value to the original input resistor, (Rin) we end up with another operational amplifier circuit called a **Summing Amplifier**, "summing inverter" or even a "voltage adder" circuit as shown below.



In this simple summing amplifier circuit, the output voltage, (Vout) now becomes proportional to the sum of the input voltages, V1, V2, V3, etc. Then we can modify the original equation for the inverting amplifier to take account of these new inputs thus:

$$I_F = I_1 + I_2 + I_3 = -\left[\frac{V1}{Rin} + \frac{V2}{Rin} + \frac{V3}{Rin}\right]$$

$$\text{Inverting Equation: } Vout = -\frac{Rf}{Rin} \times Vin$$

$$\text{then, } -Vout = \left[\frac{R_F}{Rin}V1 + \frac{R_F}{Rin}V2 + \frac{R_F}{Rin}V3\right]$$

However, if all the input impedances, (R_{IN}) are equal in value, we can simplify the above equation to give an output voltage of:

$$-Vout = \frac{R_F}{R_{IN}}\left(V1 + V2 + V3....etc\right)$$

A Scaling Summing Amplifier can be made if the individual input resistors are **“NOT”** equal. Then the equation would have to be modified to:

$$-V_{OUT} = V_1\left(\frac{R_f}{R_1}\right) + V_2\left(\frac{R_f}{R_2}\right) + V_3\left(\frac{R_f}{R_3}\right)....etc$$

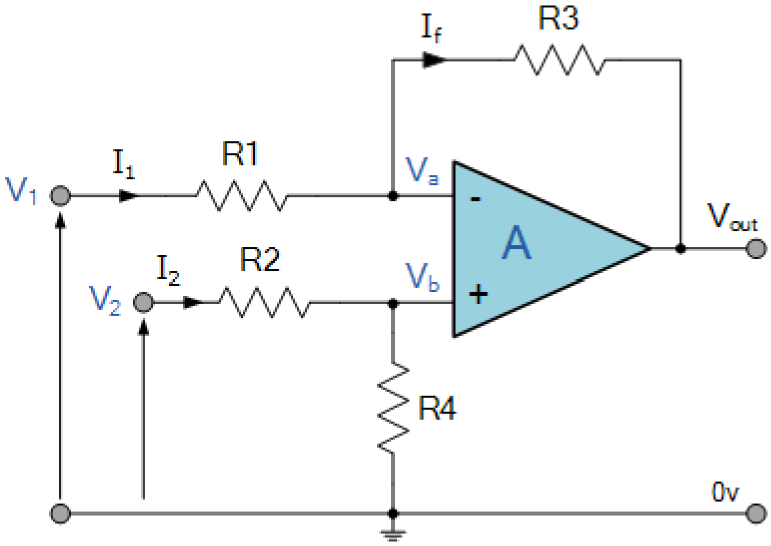
Differential Amplifier

The differential amplifier amplifies the voltage difference present on its inverting and non-inverting inputs. One of the operational amplifiers inputs is connect to the amplifier, using either the “inverting” or the “non-inverting” input terminal to amplify a single input signal with the other input being connected to ground.

But as a standard operational amplifier has two inputs, inverting and no-inverting, we can also connect signals to both of these inputs at the same time producing another common type of operational amplifier circuit called a **Differential Amplifier**.

All operational amplifiers are differential amplifiers because of their input configuration. When the first voltage signal is connected to the input terminal and another voltage signal is connected onto the opposite input terminal then the resultant output voltage are proportional to the difference between the two input voltage signals of V1 and V2.

Then differential amplifiers amplify the difference between two voltages making this type of operational amplifier circuit a **Subtractor** unlike a summing amplifier which adds or sums together the input voltages. This type of operational amplifier circuit is commonly known as a **Differential Amplifier** configuration and is shown below:



By connecting each input in turn to 0v ground we can use superposition to solve for the output voltage Vout. Then the transfer function for a **Differential Amplifier** circuit is given as:

$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_a - (V_{out})}{R_3}$$

$$\text{Summing point } V_a = V_b$$

$$\text{and } V_b = V_2\left(\frac{R_4}{R_2 + R_4}\right)$$

$$\text{If } V_2 = 0, \text{ then: } V_{out(a)} = -V_1\left(\frac{R_3}{R_1}\right)$$

$$\text{If } V_1 = 0, \text{ then: } V_{out(b)} = V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$$

$$V_{out} = -V_{out(a)} + V_{out(b)}$$

$$\therefore V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$$

When resistors, R1 = R2 and R3 = R4 the above transfer function for the differential amplifier can be simplified to the following expression:

Differential Amplifier Equation

$$V_{OUT} = \frac{R_3}{R_1}(V_2 - V_1)$$

If all the resistors are all of the same ohmic value, that is: R1 = R2 = R3 = R4 then the circuit will become a **Unity Gain Differential Amplifier** and the voltage gain of the amplifier will be exactly one or unity. Then the output expression would simply be

$$\mathbf{Vout = V_2 - V_1}$$

Note:

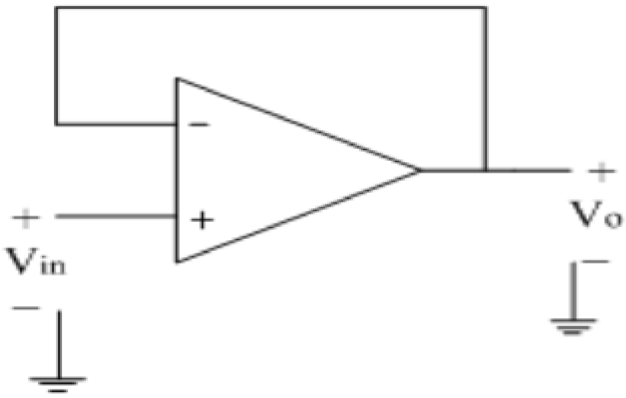
- If input V1 is higher than input V_2 the output voltage sum will be negative, and if V_2 is higher than V_1, the output voltage sum will be positive.
- Differential amplifier is used as a series negative feedback circuit by using an op-amp
- Usually, differential amplifier is used as a volume and automatic gain control circuit
- Some of the differential amplifiers can be used for AM (amplitude modulation).

Op-amp Unity Gain Buffer

A **unity gain buffer** (also called a unity-gain amplifier) is a op-amp circuit which has a voltage gain of 1.

This means that the op amp does not provide any amplification to the signal. The reason it is called a unity gain buffer (or amplifier) is because it provides a gain of 1, meaning there is no gain; the output voltage signal is the same as the input voltage.

Thus, for example, if 10V goes into the op amp as input, 10V comes out as output. A unity gain buffer acts as a true buffer, providing no amplification or attenuation to the signal.



The input is applied at the non-inverting terminal of op-amp. The output terminal and the inverting terminal are at the same potential. From the figure, due to virtual ground concept, the voltage at inverting terminal appears to be same as input voltage Vin. As mentioned above inverting terminal and the output terminal are at the same potential, we can have the output as,

$$V_o = V_{in}$$

Thus the output voltage Vo is equal to input voltage Vin. If Vin increases, Vo also increases. If Vin decreases, Vo also decreases. Thus output follows the input hence the circuit is also called as voltage follower. The gain of the circuit is 1; hence it is also called as unity gain amplifier.

What is the Purpose of a Unity Gain Buffer?

Since it outputs the same signal it inputs, what is its purpose in a circuit?

An op amp circuit is a circuit with very high input impedance. This high input impedance is the reason unity gain buffers are used. This can be understood as:

- When in a circuit in which a power source feeds a low-impedance load, the load demands and draws a huge amount of current, because the load is low impedance. According to ohm's law, again, current, I=V/R. If a load has very low resistance, it draws huge amounts of current. This causes huge amounts of power to be drawn by the power source and, because of this, causes high disturbances and use of the power source powering the load.

- Whereas if we have a circuit has a very high input impedance, very little current is drawn from the circuit. Then according to ohm's law the current, I=V/R. Thus, the greater the resistance, the less current is drawn from a power source. Thus, the power of the circuit isn't affected when current is feeding a high impedance load.

This is the reason unity gain buffers are used. They draw very little current, not disturbing the original circuit, and give the same voltage signal as output. They act as isolation buffers, isolating a circuit so that the power of a circuit is disturbed very little.

It can completely isolates the input side of the circuit from the output side of the circuit. Op amps are often used as unity gain amplifiers to isolate stages of a circuit from one another.

Unity gain amplifiers come in two types:

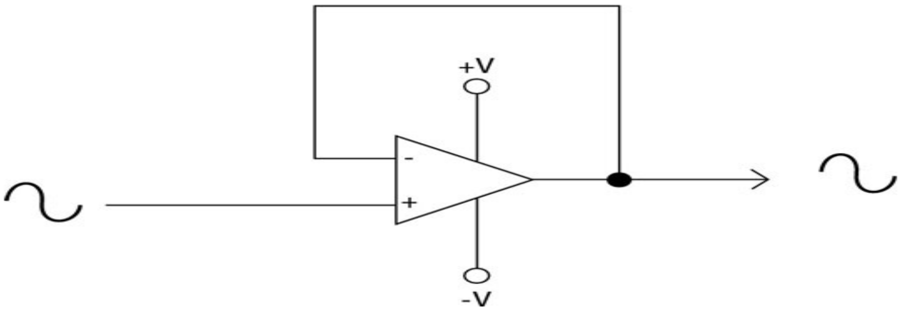
- Voltage Followers
- Voltage Inverters

Voltage Followers:

A follower is a circuit in which the output is exactly the same voltage as the input. A unity gain follower is simply a non-inverting amplifier with a gain of 1. The formula for calculating the value of a non-inverting amplifier is this:

$$A_{CL} = 1 + \frac{R2}{R1}$$

To create a unity gain follower, you just omit R2 and connect the output directly to the inverting input. Because R2 is zero, the value of R1 doesn’t matter, because zero divided by anything equals zero. So R1 is usually omitted as well, and the V_- input isn’t connected to ground.



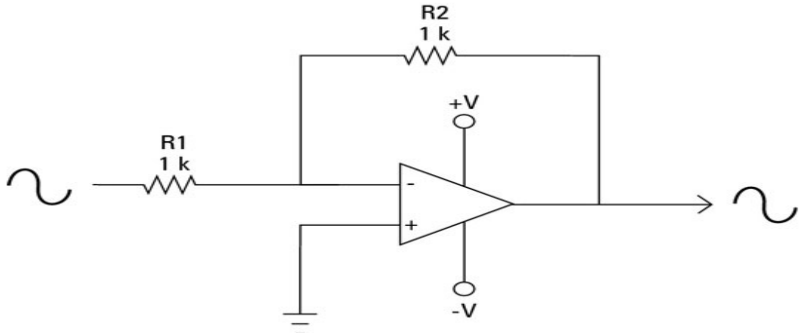
Voltage Inverters:

An inverter is a circuit in which the output is the same voltage level as the input but with the opposite polarity.

The formula for calculating gain for an inverting amplifier is this:

$$A_{CL} = -\frac{R2}{R1}$$

In this case, all you have to do is use identical values for R1 and R2 to make the amplifier gain equal to 1. Here is a unity gain inverter circuit using 1 k resistors.



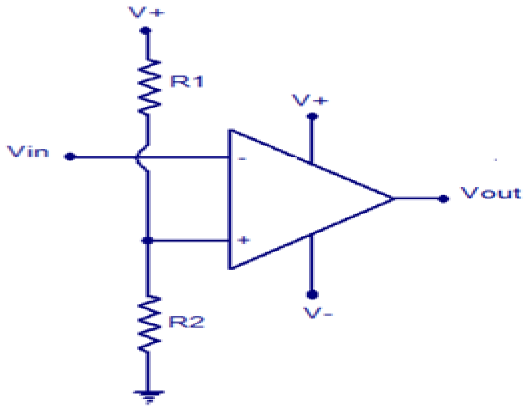
Op-amp Comparator

The **Op-amp comparator** compares one analogue voltage level with another analogue voltage level, or some preset reference voltage, V_{REF} and produces an output signal based on this voltage comparison. In other words, the op-amp voltage comparator compares the magnitudes of two voltage inputs and determines which is the largest of the two.

Theoretically, an op-amp in open-loop configuration (no feedback) can be used as a comparator. When the input voltage at the non-inverting terminal V_+ is greater than the voltage at the inverting input terminal V_-, the output of the op-amp saturates at its positive extreme. When the non-inverting input voltage drops below the inverting input voltage, the op-amp output switches to its negative saturation level.

Op-amp Inverting Comparator

In an inverting comparator, the input voltage V_{in} is applied to the inverting input terminal of the op-amp and the non-inverting input terminal is connected to reference voltage, through resistors R_1 and R_2. As long as the input voltage V_{in} is lesser than the reference voltage V_{ref}, the output of the op-amp remains positively saturated. When V_{in} goes above the reference voltage, the output of the op-amp switches to its negative saturation level and remains negatively saturated as long as V_{in} is less than V_{ref}. The circuit of a comparator using op-amp is shown in the figure below.



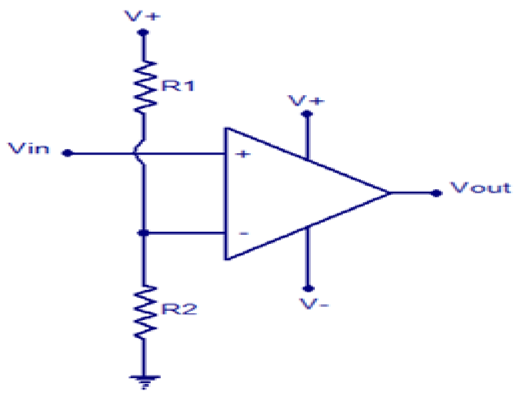
By choosing the values of resistors R_1 and R_2, the reference voltage V_{ref} can be adjusted and comparator can be used to compare input voltage with the corresponding reference voltage.

$$V_{out} = +V_{sat}; \text{ if } V_{in} < V_{ref}$$

$$= -V_{sat}; \text{ if } V_{in} > V_{ref}\backslash\backslash$$

Op-amp Non-Inverting Comparator

In the case of an op-amp non-inverting comparator, the input voltage V_{in} is applied to the non-inverting input terminal and the reference voltage, V_{ref}, is connected to the inverting input terminal. When the input voltage V_{in} is greater than the reference voltage V_{ref}, the op-amp output is positively saturated. In practice, the difference (V_{in}-V_{ref}) will be a positive value. Since there is no feedback to the op-amp input, the open-loop gain of the op-amp will be infinity.



Hence the output will swing to its maximum possible value, +**Vsat**. When the input voltage falls below the reference voltage, the output switches to its negative saturation voltage.

$$V_{out} = +V_{sat}\ ;\ \text{if } V_{in} > V_{ref}$$

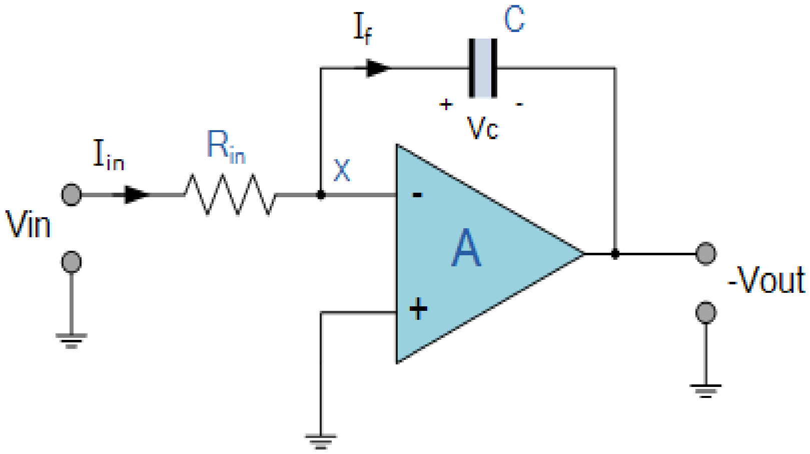
$$= -V_{sat}\ ;\ \text{if } V_{in} < V_{ref}$$

Op-amp Integrator

As its name implies, the **Op-amp Integrator** is an operational amplifier circuit that performs the mathematical operation of **Integration**, that is we can cause the output to respond to changes in the input voltage over time as the op-amp integrator produces an output voltage which is proportional to the integral of the input voltage.

Thus in other words an operational amplifier integrator circuit produces an output voltage which is proportional to the area (amplitude multiplied by time) contained under the waveform.

An ideal op-amp integrator uses a capacitor C_f, connected between the output and the op-amp inverting input terminal, as shown in the figure below. The output signal is determined by the length of time a voltage is present at its input as the current through the feedback loop **charges or discharges** the capacitor as the required negative feedback occurs through the capacitor.



The negative feedback to the inverting input terminal ensures that the node X is held at ground potential (virtual ground). If the input voltage is 0 V, there will be no current through the input resistor R_1, and the capacitor is uncharged.

Hence, the output voltage is **ideally zero**.

If a constant positive voltage (DC) is applied to the input of the integrating amplifier, the output voltage will fall negative at a linear rate, in an attempt to keep the inverting input terminal at ground potential.

Conversely, a constant negative voltage at the input results in a linearly rising (positive) voltage at the output. The rate of change of the output voltage is proportional to the value of the applied input voltage.

Output Voltage Calculation

From the circuit, it is seen that node Y is grounded through a compensating resistor R_1. Node X will also be at ground potential, due to the virtual ground.

$$V_X = V_Y = 0$$

Since the input current to an op-amp is ideally zero, the current flowing through the input resistor, due to Vin, also flows through the capacitor C_f.

- From the **input** side, the current I is given as,

$$I = (V_{IN} – V_X) / R_1 = V_{IN} / R_1$$

- From the **output** side, the current I is given as,

$$I = C_f [d(V_X – V_{OUT})/dt] = -C_f [d(V_{OUT})/dt]$$

Equating the above two equations of I, we get,

$$[V_{IN} / R_1] = – C_f [d(V_{OUT})/dt]$$

Integrating both the sides of the above equation,

$$\int_0^t \frac{Vin}{R1} . dt = - C_f \int_0^t d \frac{Vout}{dt} \; dt$$

$$\int_0^t \frac{Vin}{R1} . dt = -C_f . V_{out}$$

$$\text{Therefore, } V_{out} = - \frac{1}{R1.Cf} \int_0^t Vin . dt$$

In the above equation, the output is -{1/(R_1 * C_f)} times the integral of the input voltage, where the term (R_1 * C_f) is known as the time constant of the integrator.

The negative sign indicates that there is a phase shift of 180^o between input and output, because the input is provided to the inverting input terminal of the op-amp.

The main advantage of an active integrator is the large time constant, which results in the accurate integration of the input signal.

Differentiator Amplifier

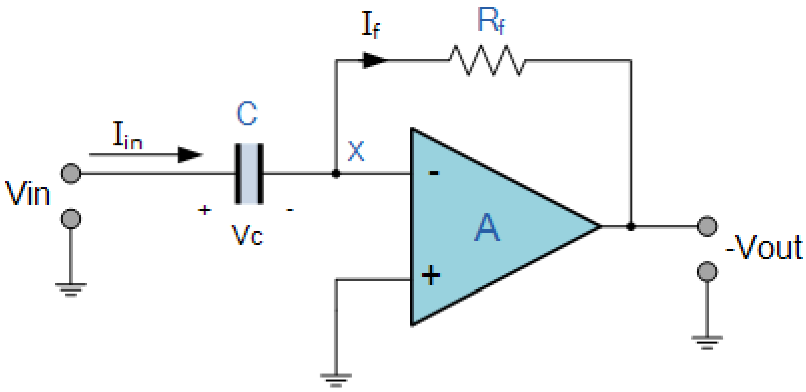
The basic operational amplifier differentiator circuit produces an output signal which is the first derivative of the input signal

This operational amplifier circuit performs the mathematical operation of **Differentiation**, that is it "**produces a voltage output which is directly proportional to the input voltage's rate-of-change with respect to time**".

In other words the faster or larger the change to the input voltage signal, the greater the input current, the greater will be the output voltage change in response, becoming more of a "spike" in shape.

As with the integrator circuit, we have a resistor and capacitor forming an RC Network across the operational amplifier and the reactance (Xc) of the capacitor plays a major role in the performance of a **Op-amp Differentiator**.

Op-amp Differentiator Circuit



The input signal to the differentiator is applied to the capacitor. The capacitor blocks any DC content so there is no current flow to the amplifier summing point, X resulting in zero output voltage. The capacitor only allows AC type input voltage changes to pass through and whose frequency is dependant on the rate of change of the input signal.

At low frequencies the reactance of the capacitor is "High" resulting in a low gain (R*f*/Xc) and low output voltage from the op-amp. At higher frequencies the reactance of the capacitor is much lower resulting in a higher gain and higher output voltage from the differentiator amplifier.

However, at high frequencies an op-amp differentiator circuit becomes unstable and will start to oscillate. This is due mainly to the first-order effect, which determines the frequency response of the op-amp circuit causing a second-order response which, at high frequencies gives an output voltage far higher than what would be expected. To avoid this the high frequency gain of the circuit needs to be reduced by adding an additional small value capacitor across the feedback resistor R*f*.

The current, i flowing through the capacitor will be given as:

$$I_{IN} = I_F \quad \text{and} \quad I_F = -\frac{V_{OUT}}{R_F}$$

The charge on the capacitor equals Capacitance times Voltage across the capacitor

$$Q = C \times V_{IN}$$

Thus the rate of change of this charge is:

$$\frac{dQ}{dt} = C\frac{dV_{IN}}{dt}$$

But dQ/dt is the capacitor current, *i*

$$I_{IN} = C\frac{dV_{IN}}{dt} = I_F$$

$$\therefore \; -\frac{V_{OUT}}{R_F} = C\frac{dV_{IN}}{dt}$$

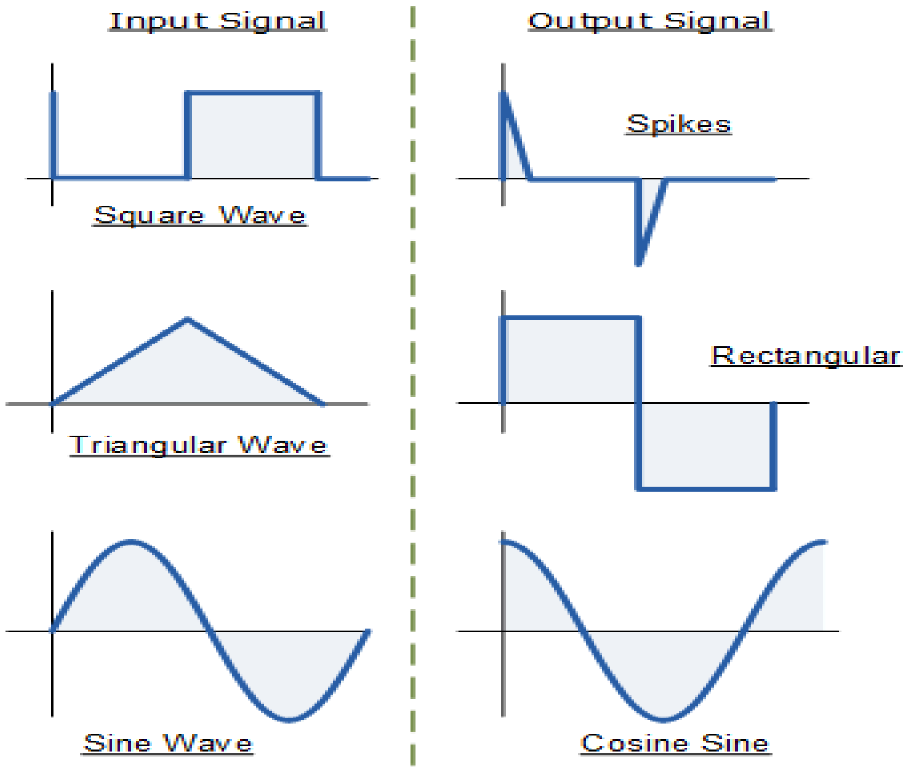
From which we have an ideal voltage output for the op-amp differentiator is given as:

$$V_{OUT} = -R_F C\frac{dV_{IN}}{dt}$$

Therefore, the output voltage Vout is a constant –R*f**C times the derivative of the input voltage Vin with respect to time. The minus sign (–) indicates a 180^o phase shift because the input signal is connected to the inverting input terminal of the operational amplifier.

Op-amp Differentiator Waveforms

If we apply a constantly changing signal such as a Square-wave, Triangular or Sine-wave type signal to the input of a differentiator amplifier circuit the resultant output signal will be changed and whose final shape is dependant upon the RC time constant of the Resistor/Capacitor combination.



Assignment

Q.1 Why OPAMP called operational Amplifier?

Q.2 What is perfect balance in OPAMP?

Designed by: Vipra Bohara

Assistant Professor

JECRC, Sitapura, Jaipur.