Linear Integrated Circuits

Operational Amplifier:

- Operational amplifier is abbreviated as op-amp.
- It is a special type of direct coupled high gain amplifier with a very large input impedance and a very low output impedance.
- Because of its unique features, it is more widely used in linear functions and hence it is named as basic linear integrated circuit.
- A negative voltage-shunt feedback is normally employed to the amplifier to control the overall characteristics of the op-amp.

Op-Amp Block Diagram:

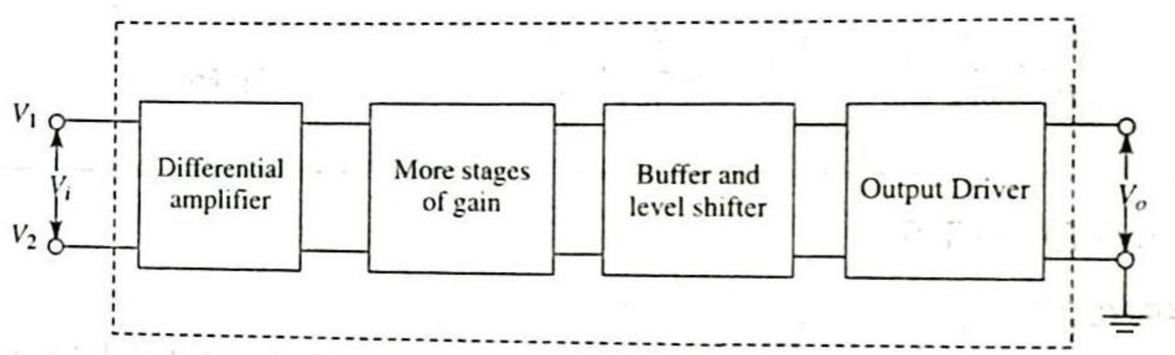


Fig: Block diagram of an Op-Amp

The basic block diagram for op-amp is shown in the above figure. It consists of 4 blocks.

- The first stage is the difference or differential amplifier, which is used to provide a high gain and high input impedance.
- The differential amplifier amplifies the difference signal

$$V_d = V_i = V_2 - V_1$$

- This stage mainly determines the input characteristics of an op-amp.
- After this, more number of cascaded differential amplifier stages to increase the overall gain and input impedance of the amplifier.

- All the operational amplifiers are designed with a single ended output.
- The third stage acts as a buffer as well as dc level shifter..
- The buffer is usually a class-B pushpull emitter follower which provides very high input impedance to prevent the loading effect of the high gain differential stage.
- The level transistor or level shifter adjusts the dc voltages of the direct coupled high gain stages to ensure zero output voltage for zero inputs.
- The output driver circuit is designed to provide symmetrical output swing with respect to ground.

(The amplifier is normally provided with equal positive and negative supply voltages) .

Schematic symbol and equivalent circuit:

The schematic symbol of op-amp is shown below.

It has totally 5 terminals.

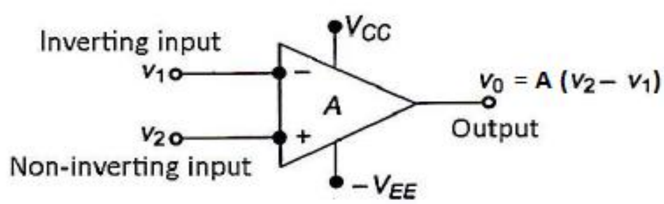


Figure: Schematic diagram for op-amp

The schematic consists of 5 terminals and are

1. Inverting terminal
2. Non inverting terminal
3. Positive power supply ($+V_{CC}$)
4. Negative power supply ($-V_{EE}$)
5. Output terminal

The inputs can be applied through inverting and non inverting terminals. Through we have two power supplies (positive & negative), both the values are same, which are using for the output voltage swing. Output is received from the output terminal.

Characteristics of an ideal op-amp:

1. Infinite voltage gain ($\boldsymbol{A} = \infty$): The voltage gain, also known as differential open loop gain is infinite in an ideal op-amp.

2. Infinite input impedance ($\boldsymbol{Zin} = \infty$): The input impedance is infinite in an ideal op-amp. This means that no current can flow into an ideal op-amp.

3. Zero output impedance ($\boldsymbol{Zout} = \mathbf{0}$): The output impedance is zero in an ideal op-amp. This means that the output voltage remains the same, irrespective of the value of the load connected.

4. Zero offset voltage ($\boldsymbol{VOS} = \mathbf{0}$): The presence of the small output voltage even when $V1 = V2 = 0$ is called offset voltage. In an ideal op-amp, offset voltage is zero. This means the output is zero if the input is zero.

5. Infinite bandwidth ($\boldsymbol{BW} = \infty$): The range of frequencies over which the amplifier performance is satisfactory is called its bandwidth. The bandwidth of an ideal op-amp is infinite.

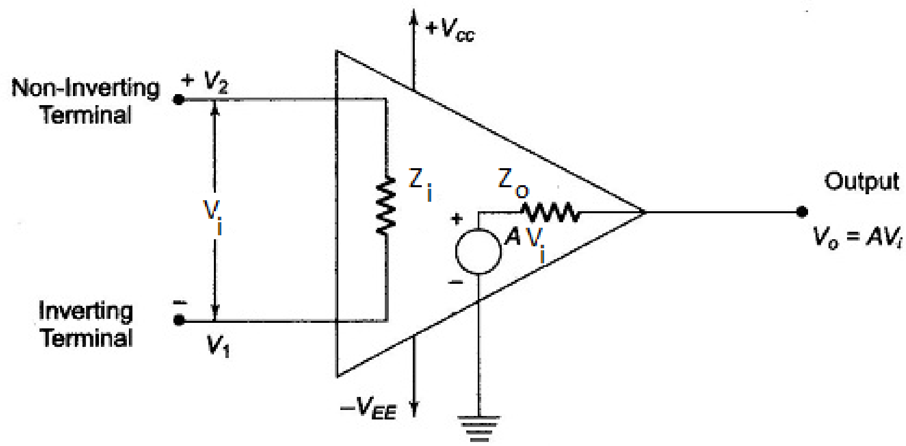
6. Infinite CMRR ($\boldsymbol{CMRR} = \infty$): The ratio of differential gain to common mode gain is called common mode rejection ratio (CMRR). In an ideal op-amp, CMRR is infinite. This means that the common mode gain is zero in an ideal op-amp.

7. Infinite slew rate ($\boldsymbol{S} = \infty$): Slew rate is the maximum rate of change of output voltage with time. In an ideal op-amp, slew rate is infinite. This means that the changes in the output voltage occur simultaneously with the changes in the input voltage.

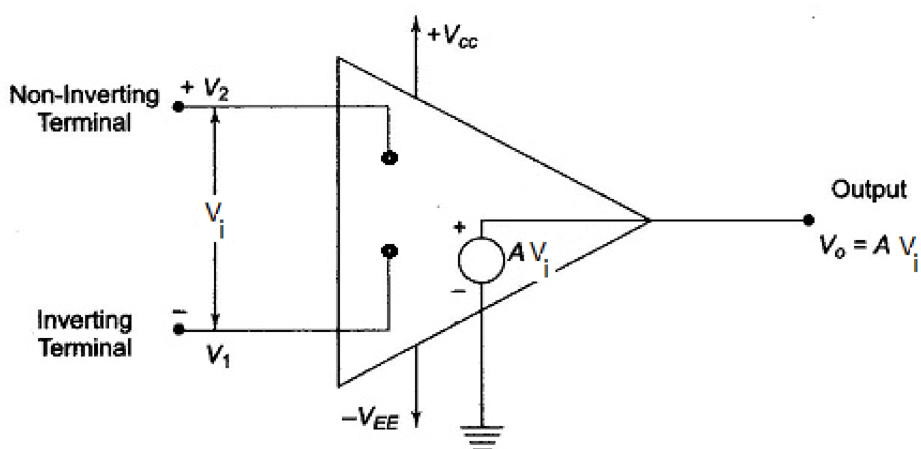
8. No effect of temperature: The characteristics of an ideal op-amp do not change with the changes in temperature.

9. Zero PSRR ($\boldsymbol{PSRR} = \mathbf{0}$): Power supply rejection ratio (PSRR) is defined as the ratio of the change in input offset voltage due to the change in supply voltage producing it, keeping other power supply voltage constant. In an ideal op-amp, PSRR is zero.

Equivalent Circuit of Op-Amp:



Equivalent Circuit of practical Op-Amp



Equivalent circuit of Ideal Op-Amp

The equivalent circuits of op-amp under practical and ideal scenarios are shown in the figures.

An ideal op-amp has zero output resistance & infinite input resistance and it is shown in the figure with short circuit (zero) & open circuit (infinity).

Basic Operating modes of Op-Amp:

Op-Amp is operated in two modes

1. Open loop configuration
2. Closed loop configuration

Open loop configuration:

- In this configuration, there is no connection from output to input.
- In open loop configuration, op-amp functions like a high gain amplifier.

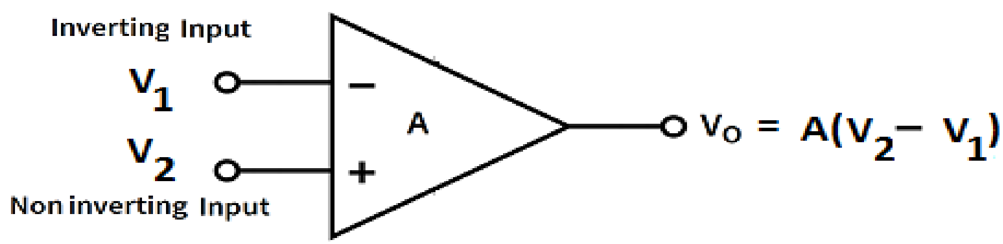


Figure: Open loop configuration of op-amp

There are three types of open loop configurations and are

a. Differential amplifier
b. Non – inverting amplifier
c. Inverting amplifier

(a) Differential amplifier:

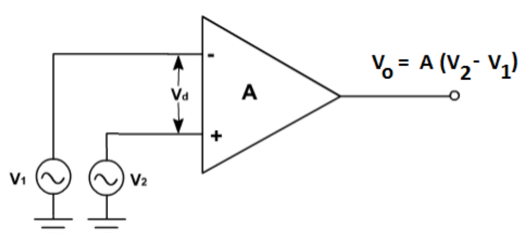
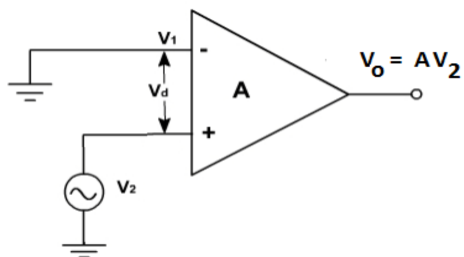


Figure: The circuit diagram of differential amplifier

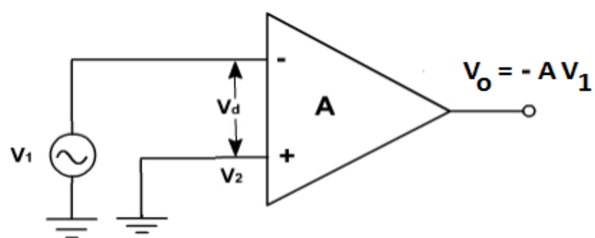
In the differential amplifier, the input signals are applied to both inverting and non inverting terminals. In this the output voltage depends on the difference voltage.

(b) Non – inverting amplifier:



In non-inverting amplifier, input signal is applied to non inverting terminal and inverting terminal is gets grounded. The output voltage depends upon the signal applied to non inverting terminal.

(c) Inverting amplifier:



In inverting amplifier, input signal is applied to inverting terminal and non-inverting terminal is gets grounded. The output voltage depends upon the signal applied to inverting terminal.

Closed loop configuration or feedback in op-amp:

In this configuration there is a feedback from output to input. Negative feedback is employed to operate as an amplifier. Op amp can also be used as an oscillator by using positive feedback.

There are two assumptions to be considered to use in the negative feedback.

1. The current drawn by either of the input terminals (inverting & non inverting) is negligible.

2. The differential input voltage V_d between non inverting and inverting input terminals is essentially zero.

1. Inverting Amplifier:

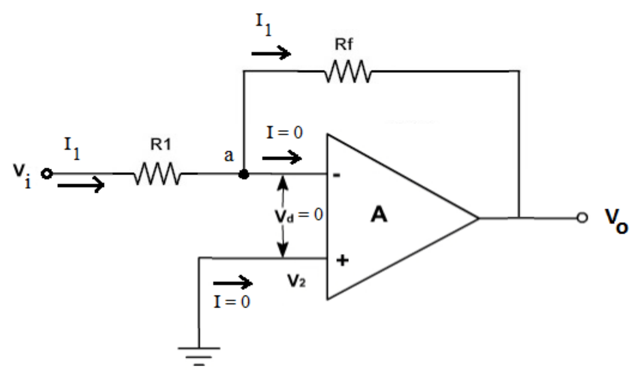


Figure: Inverting amplifier with feedback

$$I_1 = \frac{V_i - V_a}{R_1} \quad \text{— (1)}$$

$$I_1 = \frac{V_a - V_o}{R_f} \quad \text{— (2)}$$

From equation 1 and 2,

$$\frac{V_i - V_a}{R_1} = \frac{V_a - V_o}{R_f}$$

V_a is the voltage at node ‘a’, since the node ‘a’ is at virtual ground, V_a=0

$$\frac{V_i}{R_1} = \frac{-V_o}{R_f}$$

$$\therefore \boxed{A_v = \frac{V_o}{V_i} = -\frac{R_f}{R_1}}$$

2. Non -inverting Amplifier:

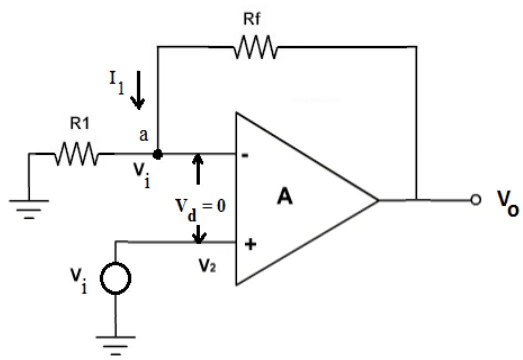


Figure: Non inverting amplifier with feedback

$$I_1 = \frac{V_o - V_a}{R_f} \quad \text{— (1)}$$

$$I_1 = \frac{V_a - 0}{R_1} \quad \text{— (2)}$$

$$\frac{V_o - V_a}{R_f} = \frac{V_a}{R_1}$$

Since $V_a = V_i$

$$\frac{V_o - V_i}{R_f} = \frac{V_i}{R_1}$$

$$R_1 [V_o - V_i] = V_i R_f$$

$$R_1 V_o - V_i R_1 = V_i R_f$$

$$R_1 V_o = V_i R_f + V_i R_1$$

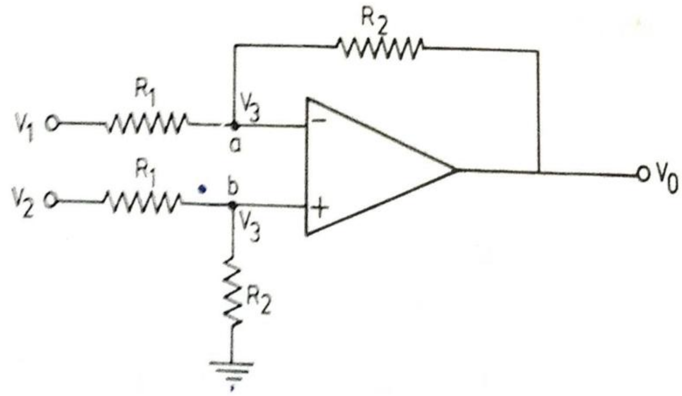
$$R_1 V_o = V_i [R_f + R_1]$$

$$\frac{V_o}{V_i} = \frac{R_f + R_1}{R_1}$$

$$\therefore A_V = \frac{V_o}{V_i} = 1 + \frac{R_f}{R_1}$$

3. Differential Amplifier:

- A circuit that amplifies the difference between two signals is called a differential amplifier.
- This type of amplifier is useful in instrumentation circuits.
- A differential amplifier circuit is shown below.



A differential amplifier

The node equation at 'a' is

$$\frac{V_3 - V_1}{R_1} + \frac{V_3 - V_0}{R_2} = 0 \quad \text{——} \; (1)$$

The node equation at 'b' is

$$\frac{V_3 - V_2}{R_1} + \frac{V_3}{R_2} = 0 \quad \text{——} \; (2)$$

Equation 2 – equation 1, we get

$$\left[\frac{V_3 - V_1}{R_1} + \frac{V_3 - V_0}{R_2}\right] - \left[\frac{V_3 - V_2}{R_1} + \frac{V_3}{R_2}\right] = 0$$

$$\cancel{\frac{V_3}{R_1}} - \frac{V_1}{R_1} + \cancel{\frac{V_3}{R_2}} - \frac{V_0}{R_2} - \cancel{\frac{V_3}{R_1}} + \frac{V_2}{R_1} - \cancel{\frac{V_3}{R_2}} = 0$$

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

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

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

Difference mode and common mode gains:

- From the equation $V_0 = \frac{R_2}{R_1}\left[V_2 - V_1\right]$ if $V_1 = V_2 = 0$, then the signal is common to both the inputs gets cancelled and produces no output voltage.
- This is true for ideal op-amp, but for practical op-amp exhibits small response to the common mode component of the input voltages too.
- The output voltage not only depends upon the difference signal V_d, but is also affected by the average voltage of the input signals, called the common mode signal V_c defined as

$$V_c = \frac{V_1 + V_2}{2}$$

  - For differential amplifier, though the circuit is symmetric, but because of the mismatch, the gain at the output with respect to the positive terminal is slightly different in magnitude to that of the negative terminal.
  - So, even with the same voltage applied to both the inputs, the output is not zero.
  - Therefore, the output is expressed as

$$V_o = A_1 V_1 + A_2 V_2$$

Where, A_1 and A_2 are the voltage amplification from input 1 and 2 to the output.

Since, $V_c = \frac{V_1 + V_2}{2}$ and $V_d = V_2 - V_1$

from $V_c = \frac{V_1 + V_2}{2}$ and $V_d = V_2 - V_1$

$$2V_c = V_1 + V_2 \qquad\qquad 2V_c = V_1 + V_2$$

$$V_1 = V_2 - V_d \qquad\qquad V_2 = V_1 + V_d$$

$$2V_c = V_2 - V_d + V_2 \qquad\qquad 2V_c = V_1 + V_1 + V_d$$

$$= 2V_2 - V_d \qquad\qquad = 2V_1 + V_d$$

$$V_2 = \frac{2V_c + V_d}{2} = V_c + \frac{1}{2}V_d \qquad V_1 = \frac{2V_c - V_d}{2} = V_c - \frac{1}{2}V_d$$

Substituting V_1 and V_2 in V_o, we get

$$V_o = A_1V_1 + A_2V_2$$

$$\begin{aligned}
V_o &= A_1V_1 + A_2V_2 \\
&= A_1[V_c - \frac{1}{2}V_d] + A_2[V_c + \frac{1}{2}V_d] \\
&= A_1V_c - A_1\frac{1}{2}V_d + A_2V_c + A_2\frac{1}{2}V_d \\
&= V_c(A_1 + A_2) + V_d[\frac{1}{2}(A_2 - A_1)] \\
V_o &= V_cA_c + V_dA_d
\end{aligned}$$

Where $A_c = A_1 + A_2$ and $A_d = \frac{1}{2}(A_2 - A_1)$

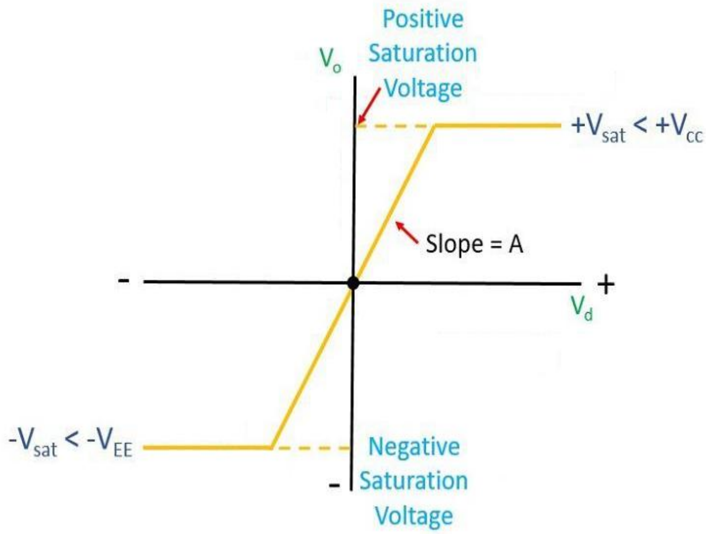
The voltage gain for difference signal is A_d and for common mode signal is A_c.

Common Mode Rejection Ratio:

- The relative sensitivity of an op-amp to a difference signal as compared to a common mode signal is called Common Mode Rejection Ratio (CMRR).

$$CMRR = \left|\frac{A_d}{A_c}\right|$$

Op-Amp Transfer Characteristics:

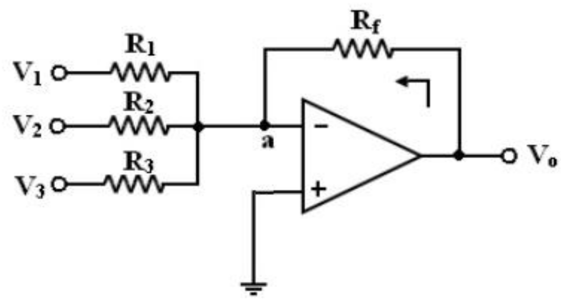


1. The output voltage of op-Amp is given by $V_o = A(V_2 - V_1)$
2. The graphic representation of this eqn. is shown in above figure, where the output voltage is plotted against input difference voltage V_d by keeping gain A constant.
3. This curve is called voltage transfer curve (VTC) of the op-Amp.
4. Note that, the output voltage can't exceed the +ve and -ve saturation levels. These saturation voltages are determined by the O/P voltage swing
5. This means that, the output voltage is directly proportional to the input difference voltage only until it reaches the saturation voltages and that thereafter the output remains constant as shown in figure.
6. The VTC has 2-regions (1) active region (2) saturation region.
7. The sloped curve is active region. In active region, the V_o is $< V_{sat}$ and is given by $V_o = A \cdot V_d$
8. For $V_o > V_{sat}$, we take the V_{sat} as the final value and the curve is a straight line - This is called saturation region.

Op-Amp Applications:

1. Scale changer inverter
2. Summing Amplifier
3. Inverting summing amplifier
4. Non inverting summing amplifier
5. Subtractor
6. Adder-Subtractor

1. Inverting Summing Amplifier:



Apply KCL at node 'a' is

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} + \frac{V_0 - V_a}{R_f} = 0$$

Since the voltage at node 'a' is zero.

$V_a = 0$

$$\therefore \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_0}{R_f} = 0$$

$$\frac{V_0}{R_f} = -\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

$$\therefore V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right]$$

Depending on R_f and R_1, R_2, R_3 values, this circuit can be used as scaling, summing or averaging

(a) Scaling or weighed:

If each input is amplified by a different factor or weighed differently at the output, then it is called scaling or scale changer. The condition can be accomplished if R_1, R_2, and R_3 are different.

$$V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right]$$

$$= -\left[k_1 V_1 + k_2 V_2 + k_3 V_3\right]$$

where k is a constant

(b) Summing or adder:

If $R_1 = R_2 = R_3 = R_f$ then

$$V_0 = -\left[V_1 + V_2 + V_3\right]$$

This is called phase inverter.

This means that the output is the negative sum of all the inputs.

(c) Averaging:

If $R_1 = R_2 = R_3 = R$, then

$$V_o = -\frac{R_f}{R}\{V_1 + V_2 + V_3\}$$

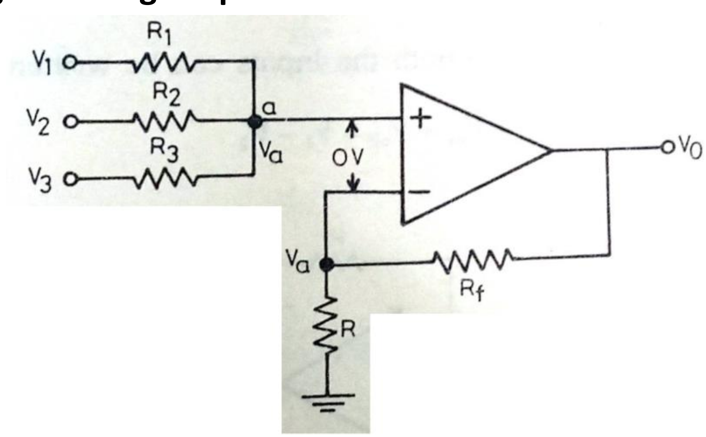
Now the output voltage = The negative sum of all inputs with gain R_f / R

If $R = 3R_f$, then

$$V_o = -\frac{1}{3}(V_1 + V_2 + V_3)$$

Thus the output is the average of the input signals. (inverted)

3. Non -inverting Summing Amplifier:



The node equation at node 'a' is given by

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} = 0$$

$$\frac{V_1}{R_1} - \frac{V_a}{R_1} + \frac{V_2}{R_2} - \frac{V_a}{R_2} + \frac{V_3}{R_3} - \frac{V_a}{R_3} = 0$$

$$V_a\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right] = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$\therefore \; V_a = \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

At the inverting terminal, at node 'a', the equation is given by

$$\frac{V_a - V_o}{R_f} + \frac{V_a - 0}{R} = 0$$

$$\frac{V_a}{R_f} - \frac{V_o}{R_f} + \frac{V_a}{R} = 0$$

$$\Rightarrow \frac{V_o}{R_f} = V_a\left[\frac{1}{R_f} + \frac{1}{R}\right]$$

$$\therefore \; V_o = V_a\left\{1 + \frac{R_f}{R}\right\}$$

Substituting V_a in the above equation, we get

$$V_o = \left[1 + \frac{R_f}{R}\right]\left[\frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}\right]$$

(a) Scaling:

If $R_1 = R_2 = R_3 = R$

$$V_o = \left\{1 + \frac{R_f}{R}\right\} \cdot \frac{1}{3}\left\{V_1 + V_2 + V_3\right\}$$

(b) Summing:

If $R_f = 2R$

$$\therefore V_0 = V_1 + V_2 + V_3$$

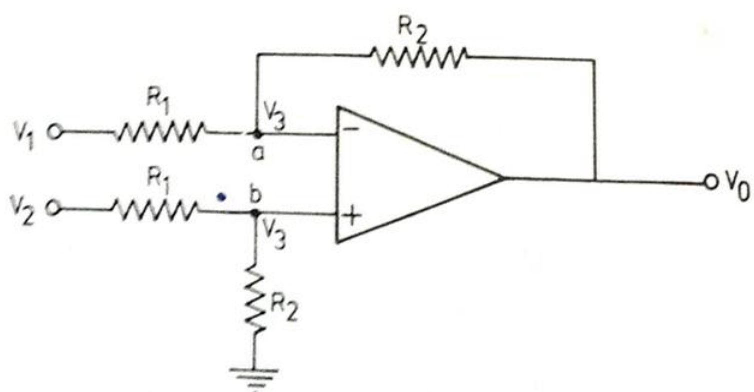
(c) Average:

If $R_f = 0$ (gain is unity)

$$V_0 = \frac{1}{3}(V_1 + V_2 + V_3)$$

Differential Amplifier:

A basic differential amplifier can be used as a Subtractor.



A differential amplifier

The node equation at 'a' is

$$\frac{V_3 - V_1}{R_1} + \frac{V_3 - V_0}{R_2} = 0 \quad \text{—— (1)}$$

The node equation at 'b' is

$$\frac{V_3 - V_2}{R_1} + \frac{V_3}{R_2} = 0 \quad \text{——— (2)}$$

Equation 2 – equation 1, we get

$$\left[\frac{V_3 - V_1}{R_1} + \frac{V_3 - V_0}{R_2}\right] - \left[\frac{V_3 - V_2}{R_1} + \frac{V_3}{R_2}\right] = 0$$

$$\cancel{\frac{V_3}{R_1}} - \frac{V_1}{R_1} + \cancel{\frac{V_3}{R_2}} - \frac{V_0}{R_2} - \cancel{\frac{V_3}{R_1}} + \frac{V_2}{R_1} - \cancel{\frac{V_3}{R_2}} = 0$$

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

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

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

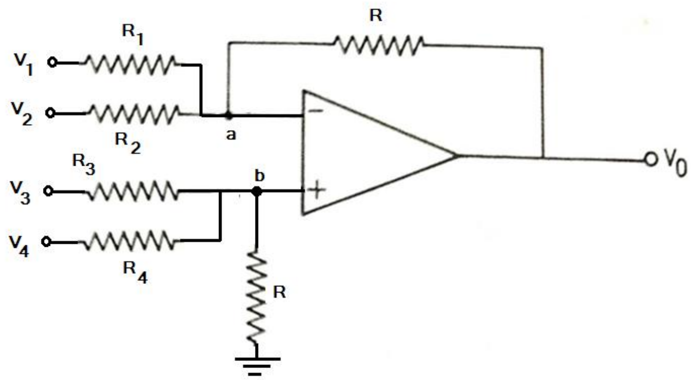
(a) Subtractor:

If $R_1 = R_2$ then

$V_0 = V_2 - V_1$

So, the differential amplifier is used a s Subtractor.

(b) Adder –Subtractor:



Apply KCL at node 'b',

$$\frac{V_b - V_3}{R_3} + \frac{V_b - V_4}{R_4} + \frac{V_b}{R} = 0$$

$$V_b \left\{ \frac{1}{R} + \frac{1}{R_3} + \frac{1}{R_4} \right] = \frac{V_3}{R_3} + \frac{V_4}{R_4}$$

$$\therefore V_b = \frac{\frac{V_3}{R_3} + \frac{V_4}{R_4}}{\frac{1}{R} + \frac{1}{R_3} + \frac{1}{R_4}}$$

Apply KCL at node 'a',

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

$$V_a \left\{ \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R} \right] = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_0}{R}$$

Since $V_a = V_b$

$$\left[\frac{\frac{V_3}{R_3}+\frac{V_4}{R_4}}{\frac{1}{R}+\frac{1}{R_3}+\frac{1}{R_4}}\right]\left[\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R}\right] = \frac{V_1}{R_1}+\frac{V_2}{R_2}+\frac{V_0}{R}$$

If $R_1 = R_2 = R_3 = R_4 = R$, then

$$\left[\frac{\frac{V_3+V_4}{\cancel{R}}}{\frac{3}{\cancel{R}}}\right]\left[\frac{\cancel{3}}{\cancel{R}}\right] = \frac{V_1+V_2+V_0}{\cancel{R}}$$

$$V_3+V_4 = V_1+V_2+V_0$$

$$\therefore \quad V_0 = V_3+V_4-V_1-V_2$$

µA 741 c Op-Amp Specifications:

µA $\Rightarrow$ manufacturer's code

It is manufactured by Fairchild

Another examples : (1) MC1741 : MC for Motorola

(2) LM 741 : LM for National semiconductor

Different versions of same operational are

741 : Military grade op-Amp (operating temp. range -55 to $125\,^\circ C$)

741 C : commertial grade op-Amp (" " 0 to $70\,^\circ C$)

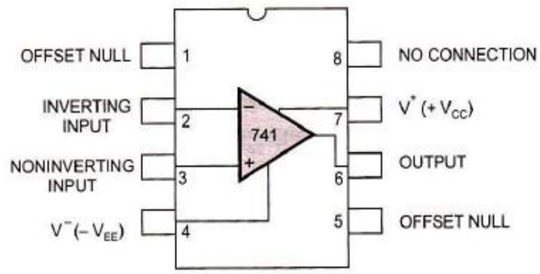
741 A : improved version of 741

741 E : " " 741 C

741 S : military grade op-Amp with high SR

741 SC : commertial grade op-Amp with high SR.

IC 741is the most popular IC version of op-amp. It is an 8-pin IC as shown in Figure.



Pin diagram of IC 741

- Pin 2 is the inverting input terminal and Pin 3 is the non-inverting input terminal
- Pin 6 is the output terminal
- Pin 4 is for $-V_{EE}$ ($V-$) supply and pin 7 is for +V_{CC} ($V+$) supply
- Pins 1 and 5 are offset null pins. These are used to nullify offset voltage
- Pin 8 is a dummy pin and no connection is made to this pin

Features of 741 :

1. No frequency compensation is required
2. Short circuit protection
3. Offset voltage null capacity
4. Lower power consumption
5. Large common mode voltage range
6. Large differential mode voltage range

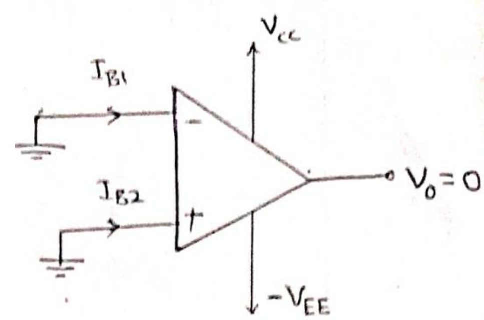
ELECTRICAL CHARACTERISTICS: (For $V_S = \pm 15V$ @ 25 °C)

1. Input bias current = 500 nA (max. value)
2. Input offset current = 200 nA (")
3. Input offset voltage = 60 mV (")
4. Input Resistance R_i = 2 MΩ
5. output Resistance R_o = 75 Ω
6. CMRR = 90 dB
7. PSRR = 150μ/V
8. slew Rate = 0.5 V/μs
9. output voltage swing: ± 14 V if $R_L \geq 10K\Omega$; ± 13V if $R_L \geq 2K\Omega$
10. Large signal voltage gain : 2×10^5

Op-Amp Parameters:

1. Input Bias Current:

The input bias current I_B is the average of the currents that flow into the inverting and non-inverting terminals of the op-amp with output zero volts.



$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

I_B = 500 nA (max) for 741C op-Amp.

2. Input offset current:

It is the difference of the currents in the non-inverting terminal (IB2) and in the inverting terminal (IB2) into the input terminals with output zero volts.

$$I_{io} = |I_{B2} - I_{B1}|$$

I_{io} = 200 nA (max) for 741C op-Amp.

3. Input offset voltage:

This is the input voltage required to make the zero output voltage when $V_1=V_2=0$.

$$V_{io} = |V_2 - V_1| \quad \text{when } V_o = 0$$

V_{io} = 60 mV (max) for 741C op-Amp.

4. Input Resistance:

Differential input resistance is the equivalent resistance that can be measured at either the non-inverting or inverting input terminal with other terminal connected to ground.

R_i = 2 MΩ for 741C

5. Output Resistance :

The output resistance is the resistance measured between the output terminal of the op-amp and ground.

R_o = 75 Ω for 741 C

6. Common Mode Rejection Ratio:

The CMRR is defined as the ratio of the differential mode open loop voltage gain to the common mode open loop gain.

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

where A_d = gain under differential mode of operation
A_c = gain under common mode of operation

(a) Differential mode gain = Large signal voltage gain

It is defined as the ratio of output voltage to the difference input voltage.

$$\rightarrow A_d = \frac{V_o}{V_d}$$

Since the amplitude of the output signal is much larger than the input signal, the voltage gain is commonly referred to as large signal voltage gain. For 741 C op-amp, A_d is $2x10^5$.

(b) Common Mode gain

It is defined as

$$A_c = \frac{V_{ocm}}{V_{cm}}$$

V_{ocm} → common mode o/p voltage

V_{cm} → input voltage applied to both terminals.

Generally A_c is very small.

(c) The CMRR serves as a figure of merit of an op-amp.

(d) A high CMRR is desirable. Which means that differential gain must be large and common mode gain is small. For 741C op-amp, the CMRR is 90 dB.

7. Power Supply Rejection Ratio:

The change in input offset voltage due to variation in the supply voltage (or power supply) is called the PSRR.

It is also called as Supply Voltage Rejection Ratio (SVRR).

$$PSRR = \frac{\Delta V_{io}}{\Delta V}$$

For better op-Amp, PSRR should be low.

$PSRR = 150\ \mu V / V$ for 741 C

8. Slew Rate:

It is defined as the maximum rate of change of output voltage per unit time and is expressed in volts/µsec.

$$SR = \left.\frac{dV_o}{dt}\right|_{max} \quad Volts/\mu sec$$

For 741 C, $SR = 0.5\ V/\mu Sec.$

9. Output Voltage Swing:

It is the maximum peak to peak output voltage which can be obtained without waveform clipping when the dc output is zero.

It indicates the values of +ve and –ve saturation levels of the op-amp.

For 741C, the output voltage swing is $+13V$ & $-13V$ $(R_L \geq 2K\Omega)$

10. Thermal Drift:

The change in the temperature causes corresponding changes in V_{io} and I_{io} and such changes are called thermal drifts.

$$\text{Thermal voltage drift} = \frac{\Delta V_{io}}{\Delta T} \simeq 15\,\mu V/^{\circ}C$$

$$\text{Thermal current drift} = \frac{\Delta I_{io}}{\Delta T} \simeq 200\,pA/^{\circ}C.$$

11. Transient Response:

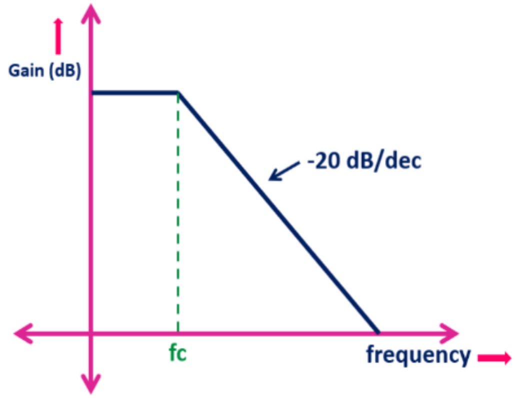
Transient response gives us the information about how an op-amp will work for an ac input. The two characteristics that are involved are **rise time** and **overshoot**. Rise time is the time taken by a signal to rise from 10% to 90% of its final value while overshoot is the occurrence of the signal exceeding its target.

Gain Bandwidth Product:

The gain bandwidth product is an important parameter.

Frequency Response of the Op-Amp:

- For the ideal op-amp, the gain is infinite and it has infinite bandwidth. But the actual op-amp has finite bandwidth and finite gain.
- The gain versus frequency curve is shown in the figure.
- The Y-axis on the curve is the voltage gain of the op-amp in dB, while the X-axis is the frequency in the logarithmic scale.



Frequency Response of the operational amplifier

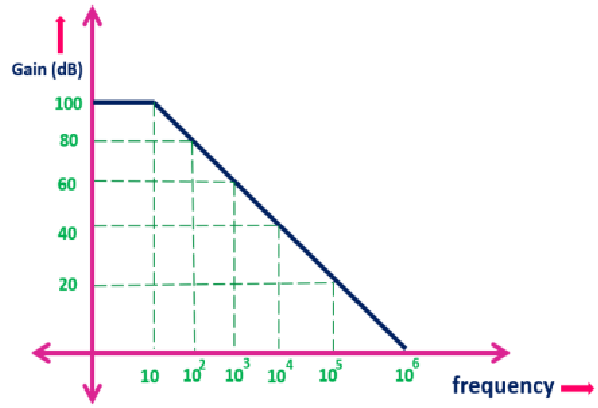
Cut-off Frequency of the op-amp:

- The frequency at which the gain of the op-amp reduces by 3dB from the maximum value is known as the **cut-off frequency of the op-amp**.
- As seen from the above frequency response curve of the op-amp, the cut-off frequency is very low. Typically for the op-amp, it used to be in the range of 10 to 100 Hz. And up to cut-off frequency, the op-amp provides very high gain.
- Although we typically say that, the gain of the op-amp is very high. But actually, the op-amp provides a very high gain up to cut-off frequency.
- The reason is, all the op-amps are internally compensated. That means all the op-amps have an internal compensation capacitor. And this internal compensation capacitor ensures that the op-amp has a stable response at the high frequencies.

Unity Gain Frequency :

The frequency where the gain of the op-amp is unity is called unity gain frequency.

As, shown in the following Figure, because of the internal compensation, it is easy to understand the behavior of the op-amp with frequency (particularly in the closed-loop configuration). And the product of gain and frequency remains constant till the unity gain frequency for the op-amp, which is known as the **gain-bandwidth product** of the op-amp.

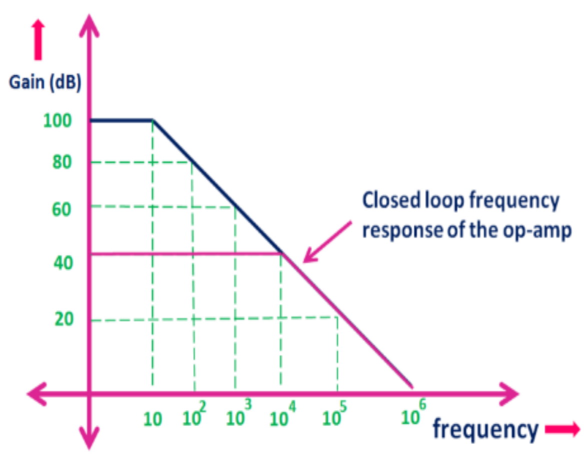


Gain-Bandwidth Product of Op-Amp

The Gain Bandwidth Product:

For example, from the above figure, at 1 kHz frequency, the gain of the op-amp is 60 dB = 10^3. Therefore, the gain-bandwidth product (GBP) is 1000Hz x 10^3 = 10^6

On the other end, at 1MHz, the gain of the op-amp is 1. Therefore, the GBP is 10^6.



The Frequency Response of the op-amp in the closed loop configuration

Using the gain-bandwidth product, it is easy to identify the cut-off frequency of the op-amp, in the closed-loop configuration. Let's say in the closed-loop configuration, the gain of the op-amp is 40 dB (100). In that case, the frequency response of the op-amp is shown in the figure.

The gain of the op-amp is flat up to a certain frequency. And then it starts reducing at 20 dB/dec. The frequency from where the gain starts reducing is known as the cut-off frequency in the closed-loop configuration. And it can be found using the Gain Bandwidth Product.

For example, the gain of the op-amp is 100. (40 dB) and the gain-bandwidth product is 10^6. Therefore, the cut-off frequency in the closed-loop configuration is 10^6 / 100 = 10 kHz.

As, seen from the above calculation, when the op-amp is used in the closed-loop configuration, then the cut-off frequency of the op-amp increases. Or in other words, using the op-amp in the closed-loop configuration, the gain up to which we get a constant gain (Flat gain response) can be increased. Also, here the product of closed-loop gain, and the cut-off frequency is equal to Gain Bandwidth Product (GBP).

$$\mathbf{GBP = A_{CL} \times f_{CL}}$$