Operational Amplifiers

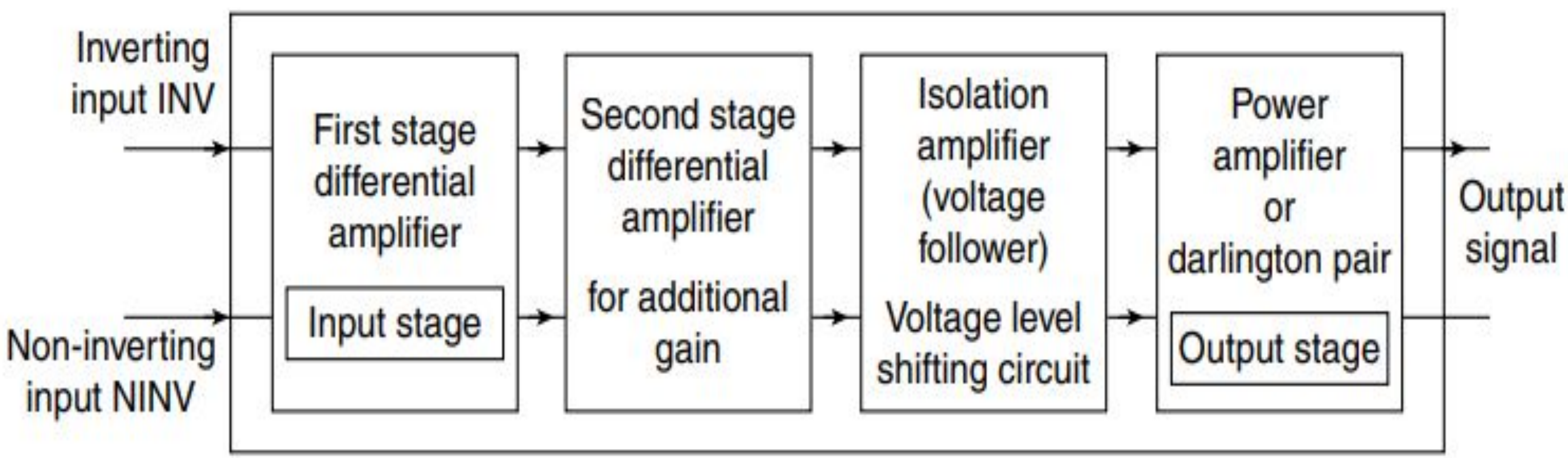
- Operational Amplifiers: Ideal v/s practical Op-amp
- Performance Parameters
- Op-Amp Applications
  - Peak detector circuit ,
  - Comparator,
  - Inverting and
  - Non-Inverting Amplifiers

- **Operational Amplifier, or op-amp,** is a very *high gain differential amplifier* with *high input impedance and low output impedance*.
- ***Uses:***
  - provide voltage amplitude changes (amplitude and polarity),
  - oscillators,
  - filter circuits, and
  - many types of instrumentation circuits
- It contains a *number of differential amplifier stages cascaded together to achieve a very high voltage gain*

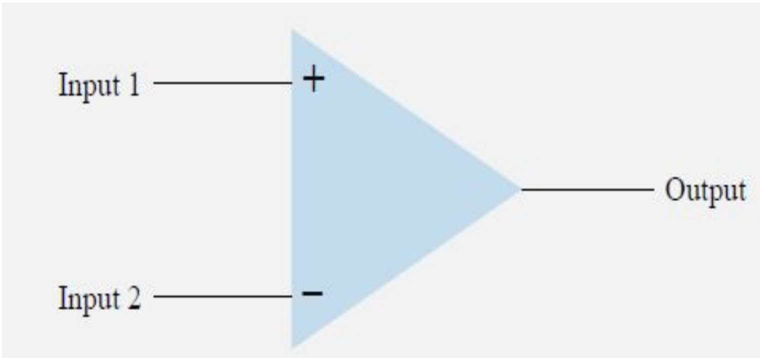
Block diagram of an Operational Amplifier

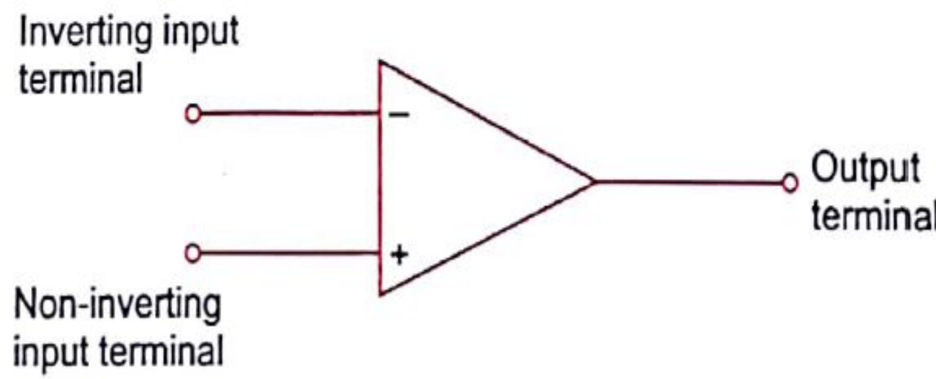
Basic building blocks inside an op amp IC are as follows:

- First-stage differential amplifier.
- Second-stage differential amplifier.
- Voltage-level shifter.
- Power output stage.



Circuit Symbol





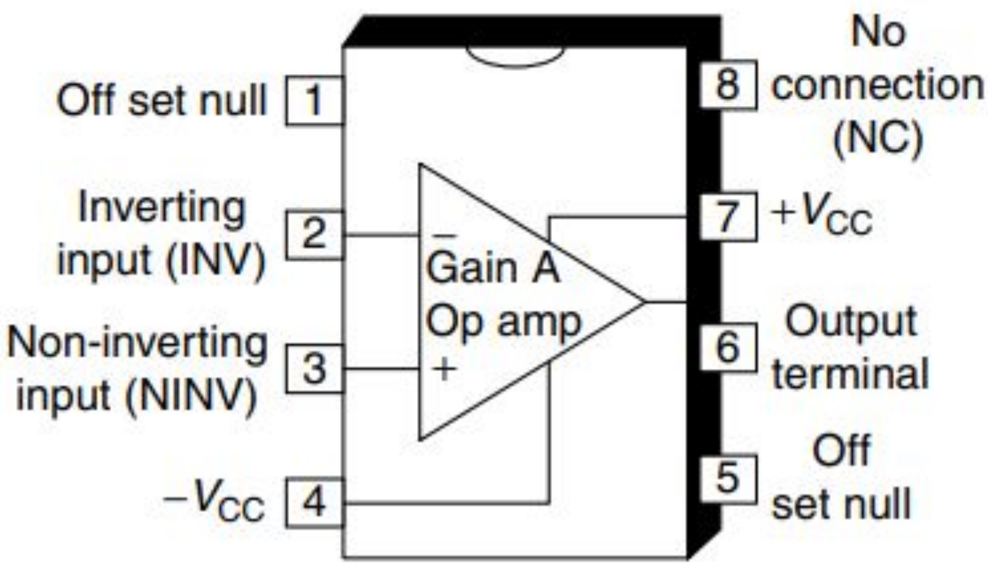
An *Operational Amplifier* is basically a three-terminal device which consists of two high impedance inputs.
One of the inputs is called the **Inverting Input**, marked with a negative or "minus" sign, (–).
The other input is called the **Non-inverting Input**, marked with a positive or "plus" sign (+).

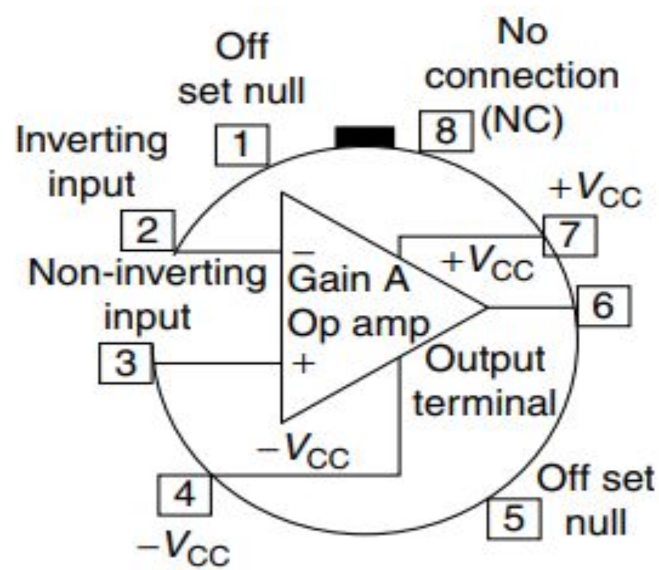
PIN configuration of Operational Amplifier

Packages

There are three popular packages available:

1. The metal can (TO) package
2. The dual-in-line package (DIP)
3. The flat package or flat pack





Pin-1: Offset null terminal.

Pin-2: Inverting (INV) input terminal. All input signals connected to this terminal on op amp will appear at the output terminal with 180° phase shift.

Pin-3: Non-inverting (N-INV) input terminal. All input signals applied to this terminal on op amp appears as it is in waveform (shape) at the output terminal. Changes occur only in levels of amplitudes at the output voltage.

Pin-4: Supply voltage - VCC (negative supply voltage terminal).

Pin-5: Offset null terminal.

Pin-6: Output terminal; output signal.

1. Output signal will have 180° phase shift to input signals applied to inverting input terminal pin-2.

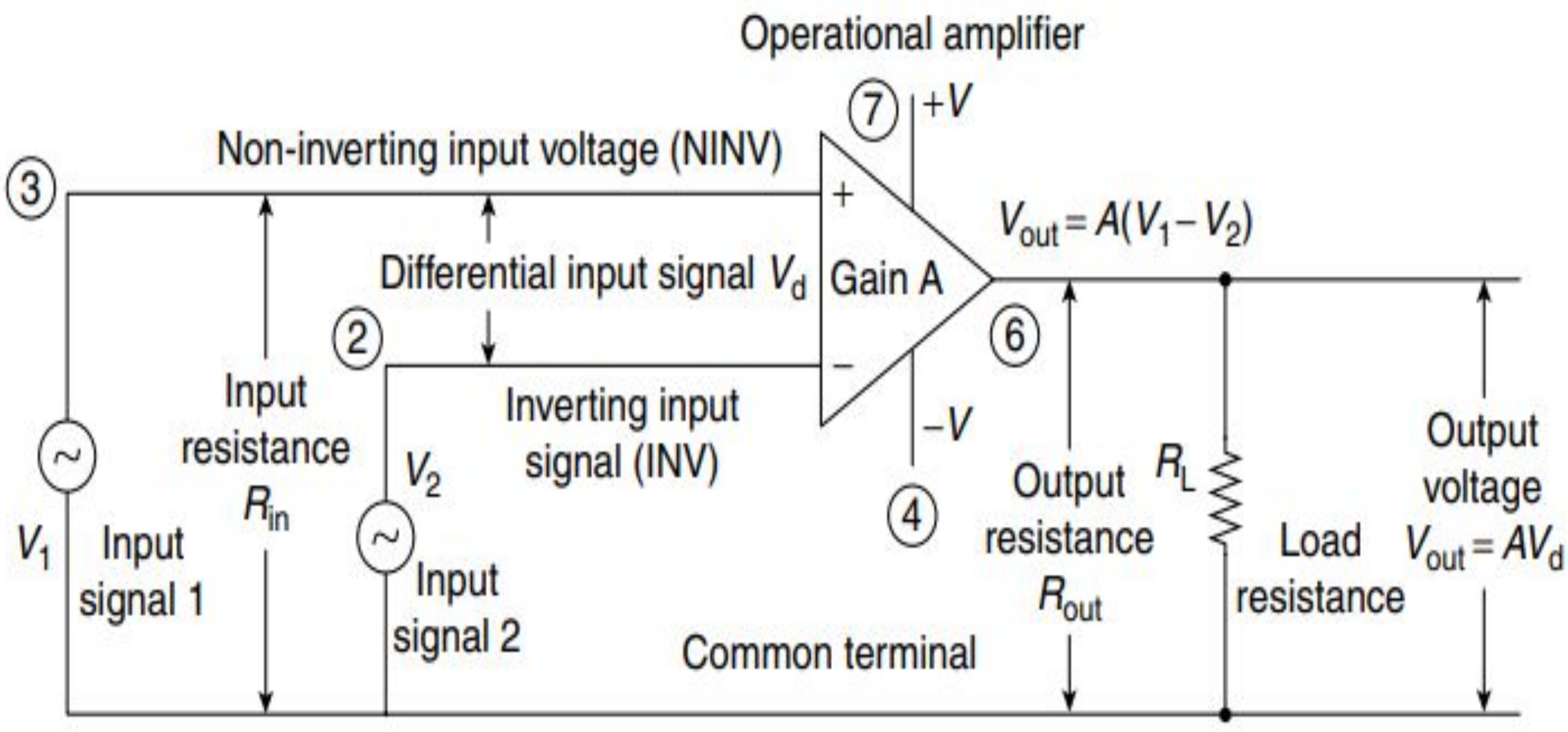
2. Output signal will be in-phase to input signals applied to non-inverting input terminal pin-3.

3. Output signal depends upon the voltage gain of operational amplifier.

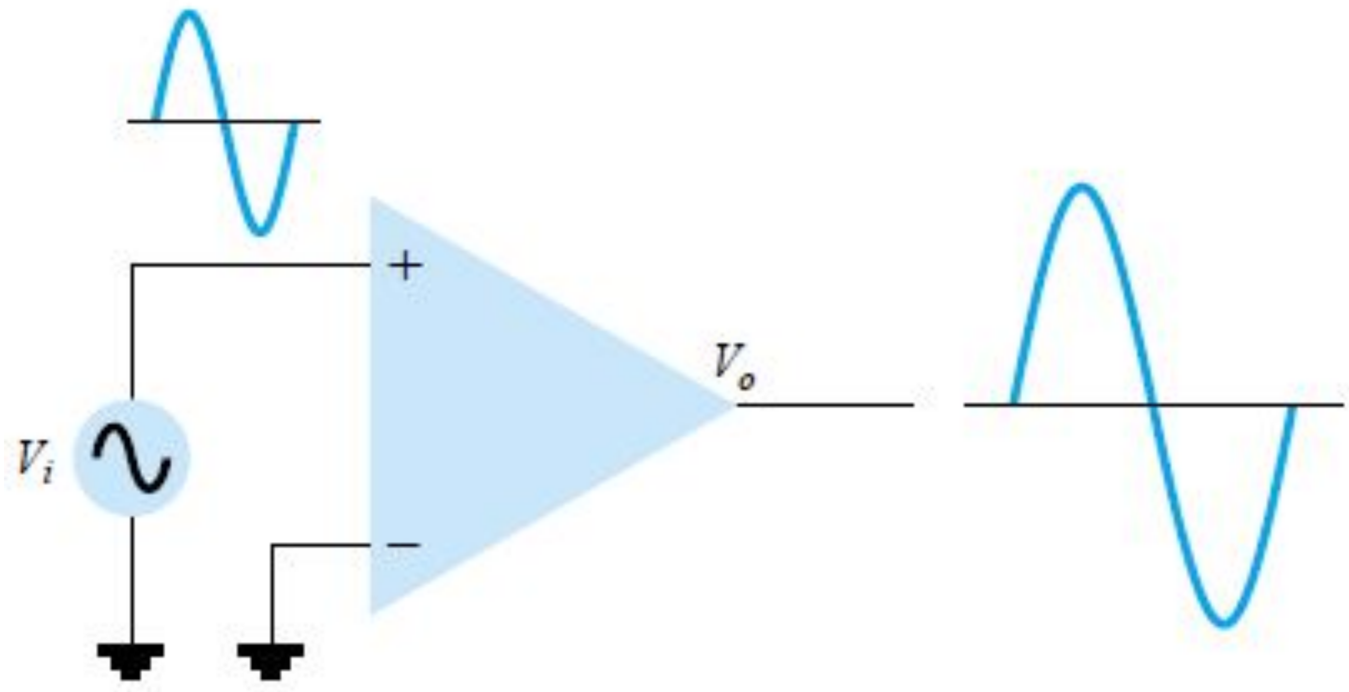
Pin-7: supply voltage +VCC terminal (positive supply voltage terminal).

Pin-8: no connection.

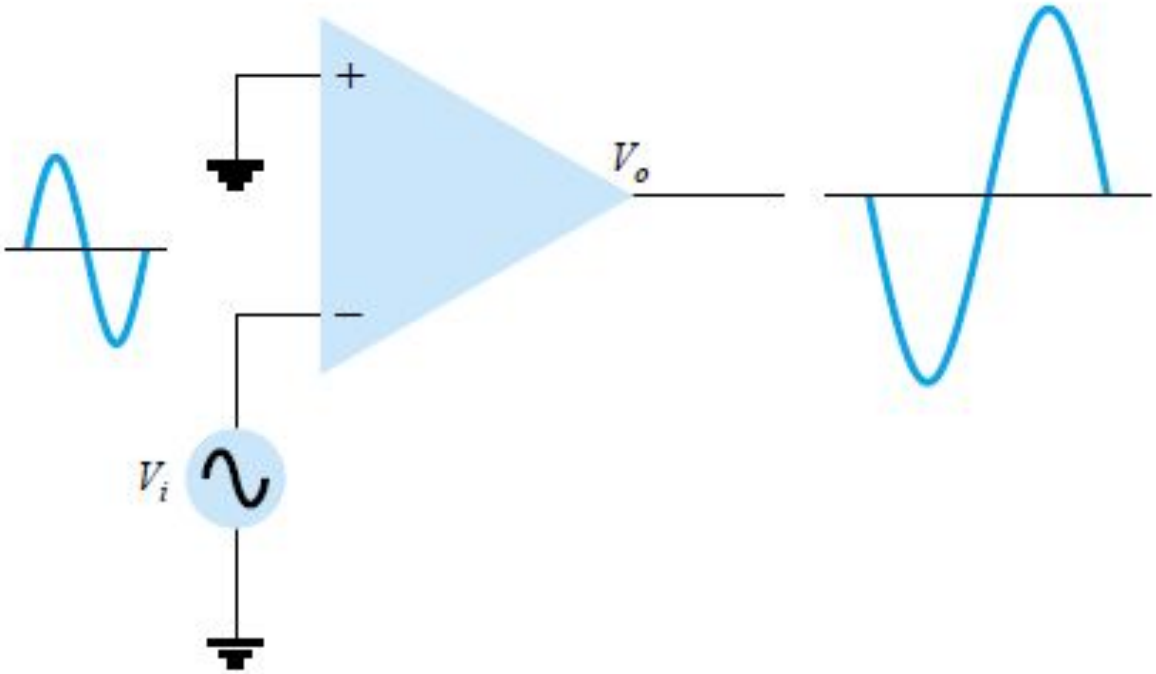
SCHEMATIC DIAGRAM OF OPERATIONAL AMPLIFIER



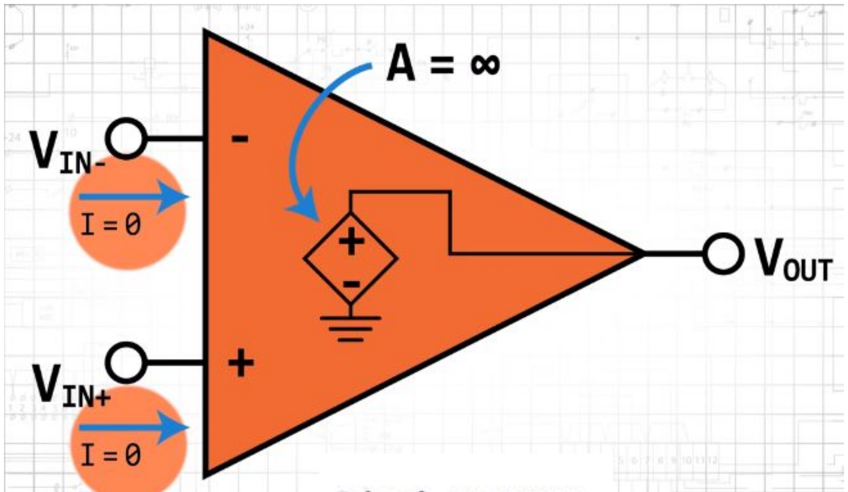
Non-inverting Input



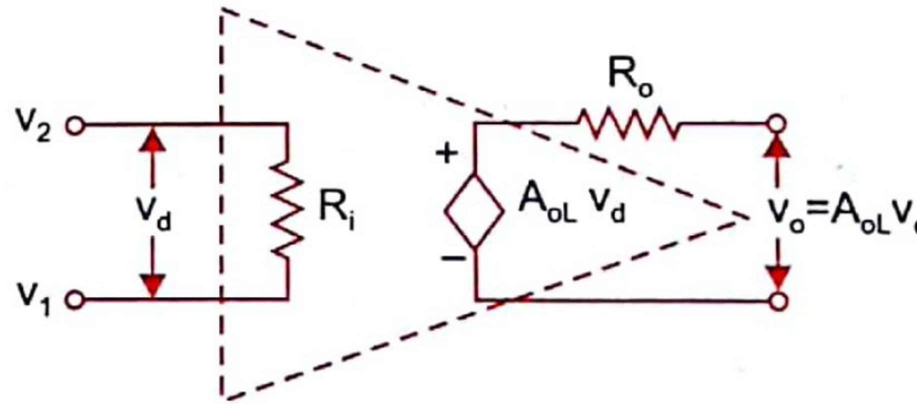
Inverting Input



THE IDEAL OPERATIONAL AMPLIFIER



Ideal op-amp,



Equivalent circuit of an op-amp

- The **<u>input resistance of an op amp must be very high</u>** where as the **<u>output resistance should be quite low</u>**.
- An op amp should also **<u>have very high open loop gain</u>**.
- In **<u>Ideal Cases,</u>** the input resistance and open loop gain of an op amp should be infinity whereas the output resistance would be zero.

Characteristic	Value
Open Loop Gain (A)	$\propto$
Input Resistance (Impedance)	$\propto$
Output Resistance (Impedance)	0
Bandwidth of Operation	$\propto$
Offset Voltage	0

$$V_o = A(V_1 - V_2)$$

It can be observed that

i)An ideal op-amp allows zero current to enter into its input terminals, i.e. $i_1 = i_2 = 0$.

Due to infinite input impedance, any signal with source impedance can drive the op-amp without getting inflicted with any loading effect.

(ii) The gain of the ideal op-amp is infinite.

Hence, the voltage between the inverting and non-inverting terminals is essentially zero for a finite output voltage.

(iii) The output voltage V_o is independent of the output current drawn from the op-amp, since $R_o = 0$.

This means that the output can drive an infinite number of output devices of any impedance value.

Op-Amp Parameters

- Common-mode Rejection (CMRR)
- Common-mode input voltage
- Input offset voltage
- Input bias current
- Input impedance
- Input offset current
- Output impedance
- Slew rate

Op-Amp Parameters

- **Common-Mode Rejection Ratio (CMRR)**
  - The ability of amplifier to reject the common-mode signals (unwanted signals) while amplifying the differential signal (desired signal)
  - Ratio of open-loop gain, A_{ol} to common-mode gain, A_{cm}
  - The open-loop gain is a datasheet value

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

- The higher the CMRR, the better, in which the open-loop gain is high and common-mode gain is low.

- CMRR is usually expressed in dB & decreases with frequency

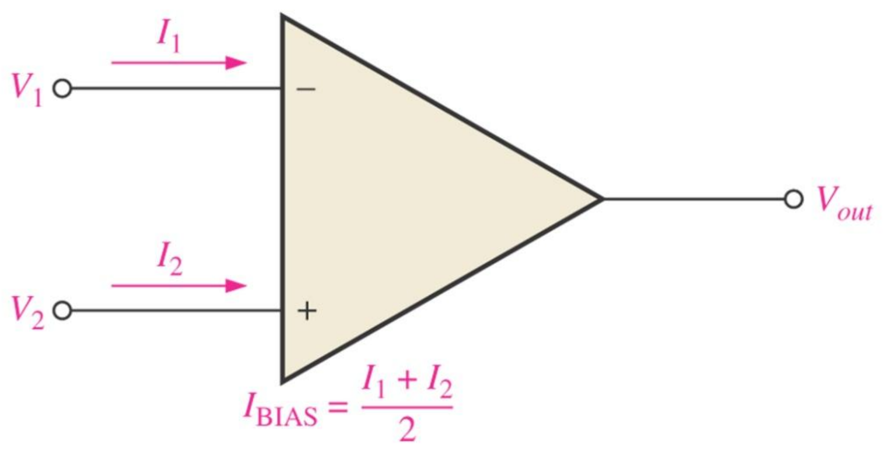
Op-Amp Parameters

- **Common-Mode Input Voltage**
  - The range of input voltages which, when applied to both inputs, will not cause clipping or other output distortion.

- **Input Offset Voltage**
  - Ideally, output of an op-amp is 0 Volt if the input is 0 Volt.
  - Realistically, a small dc voltage will appear at the output when no input voltage is applied.
  - Thus, differential dc voltage is required between the inputs to force the output to zero volts.
  - This is called the Input Offset Voltage, V_{os}. Range between 2 mV or less.

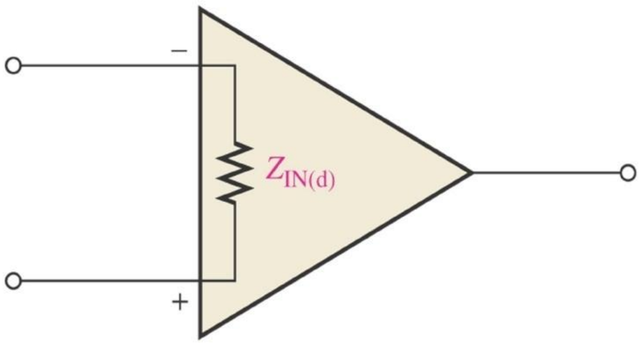
Op-Amp Parameters

- **Input Bias Current**
  - Ideally should be zero
  - The dc current required by the inputs of the amplifier to properly operate the first stage.
  - Is the average of both input currents

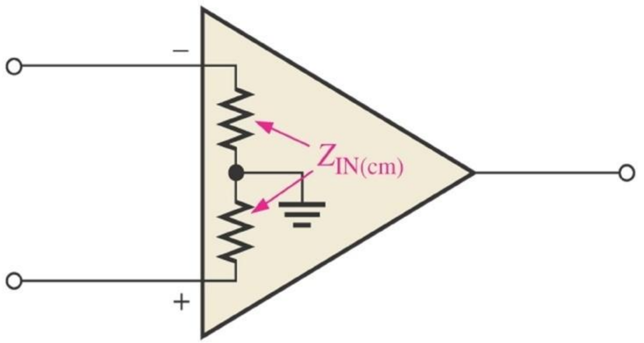


Op-Amp Parameters

- **Input Impedance**
  - Is the total resistance between the inverting and non-inverting inputs.
  - Differential input impedance : total resistance between the inverting and non-inverting inputs
  - Common-mode input impedance: total resistance between each input and ground



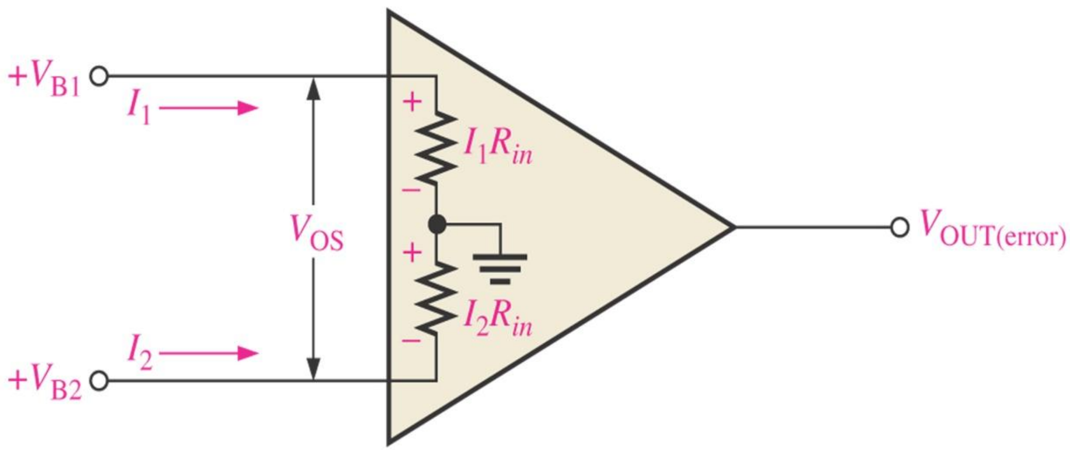
(a) Differential input impedance



(b) Common-mode input impedance

Op-Amp Parameters

- **Input Offset Current**
  - Is the difference of input bias currents



Input offset current

$$I_{os} = \left|I_1 - I_2\right|$$

Thus, error

$$V_{out(error)} = A_v I_{os} R_{in}$$

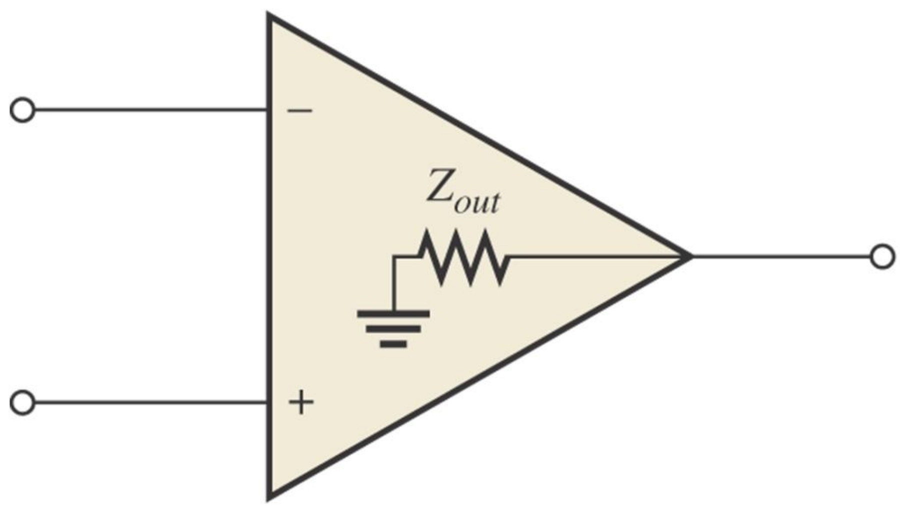
Offset voltage

$$V_{os} = I_1 R_{in} - I_2 R_{in} = \left(I_1 - I_2\right) R_{in}$$

$$V_{os} = I_{os} R_{in}$$

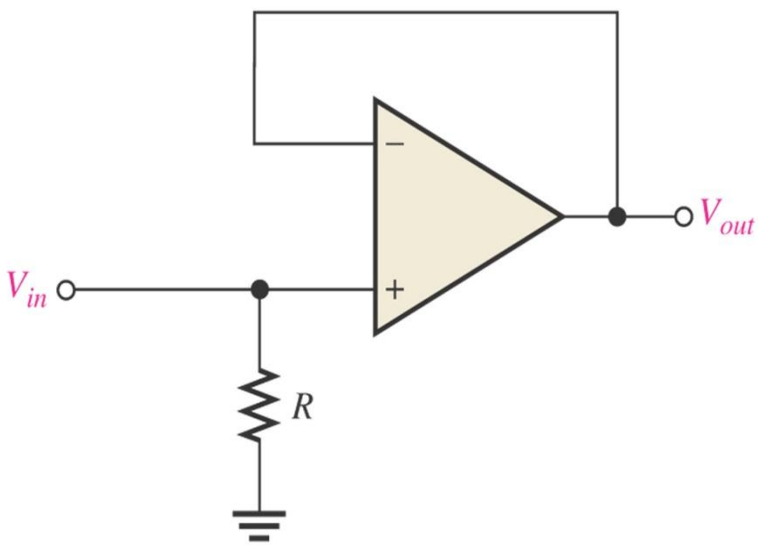
Op-Amp Parameters

- **Output Impedance**
  - Ideally should be zero
  - Is the resistance viewed from the output terminal of the op-amp. In reality, it is non-zero.

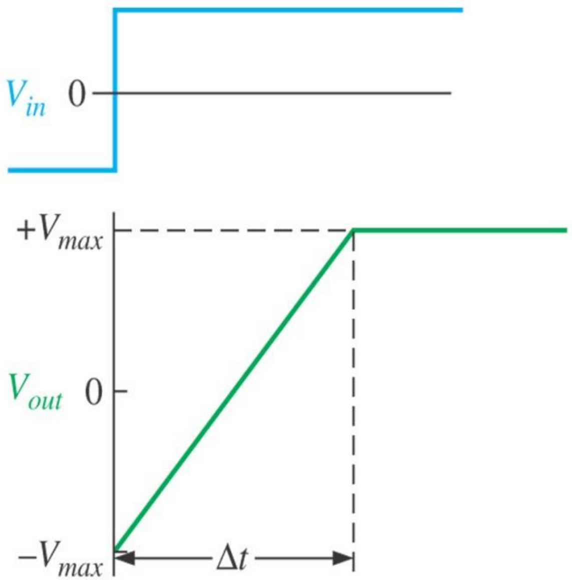


Op-Amp Parameters

- **Slew Rate**
  - Is the maximum rate of change of the output voltage in response to a step input voltage.



(a) Test circuit

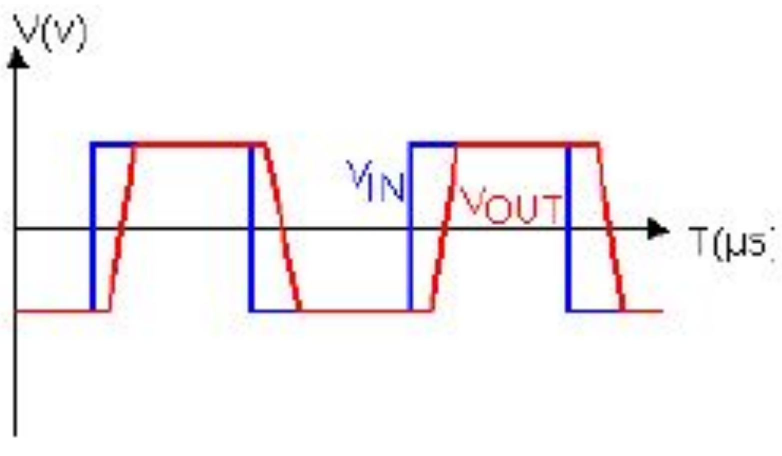


(b) Step input voltage and the resulting output voltage

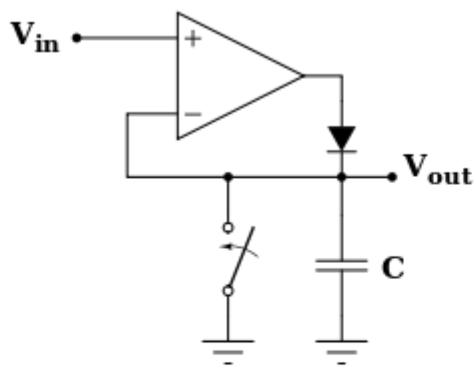
$$SlewRate = \frac{\Delta V_{out}}{\Delta t} \qquad \text{where} \quad \Delta V_{out} = +V_{\max} - (-V_{\max})$$

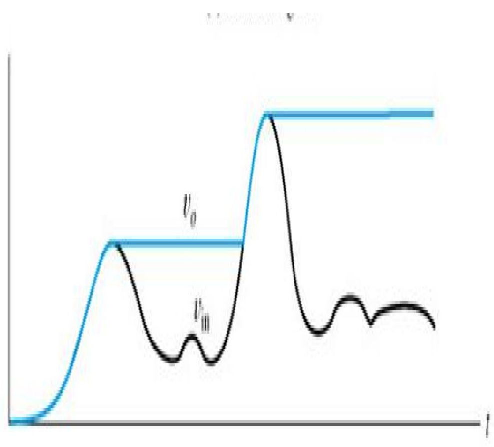
Op-Amp Parameters

- Slew Rate
  - It’s a measure of how fast the output can “follow” the input signal.



Peak detector:





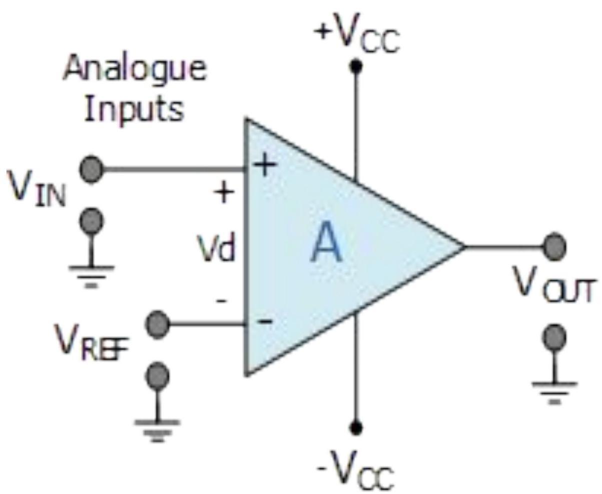
(b) Typical waveforms

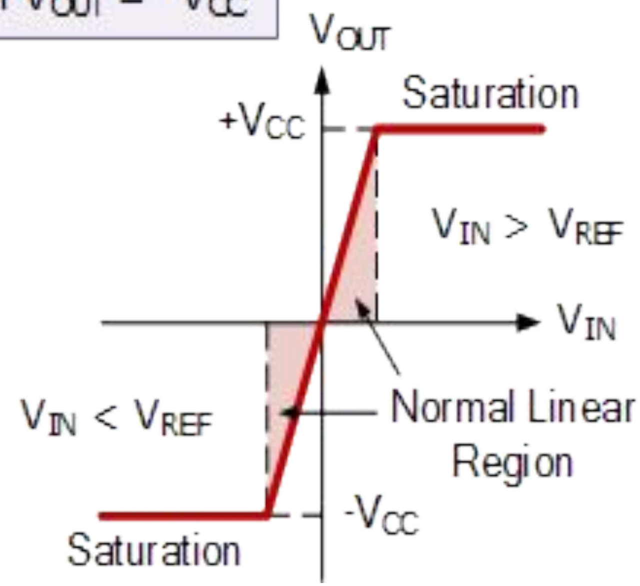
- The function of a peak detector is to compute the peak value of the input.
- The circuit follows the voltage peaks of a signal and stores the highest value on a capacitor.The highest peak value is stored until the capacitor is discharged.
- $V_{out} < V_{in}$; D ON and C charges to peak value of input, (i.e) voltage follower.
- $V_{out} < V_{in}$; D OFF and C holds the peak value of input.
- The circuit can be reset, capacitor voltage can be made zero by connecting low leakage MOSFET switch across the capacitor.
- Applications: Measurement and instrumentation, Amplitude modulation.

Comparator: A circuit which compares a signal voltage applied at one input of an op amp.

If $V_{IN} > V_{REF}$ then $V_{OUT} = +V_{CC}$

If $V_{IN} < V_{REF}$ then $V_{OUT} = -V_{CC}$

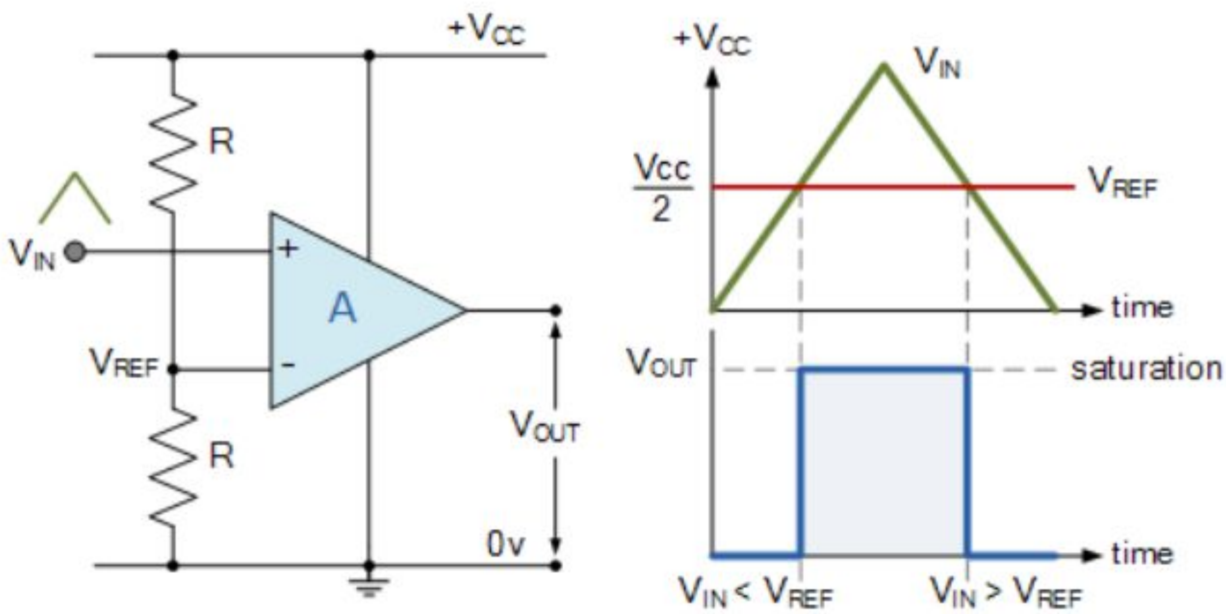




Positive Voltage Comparator

The basic configuration for the positive voltage comparator, also known as a non-inverting comparator circuit detects when the input signal, V_{IN} is ABOVE or more positive than the reference voltage, V_{REF} producing an output at V_{OUT} which is HIGH as shown.

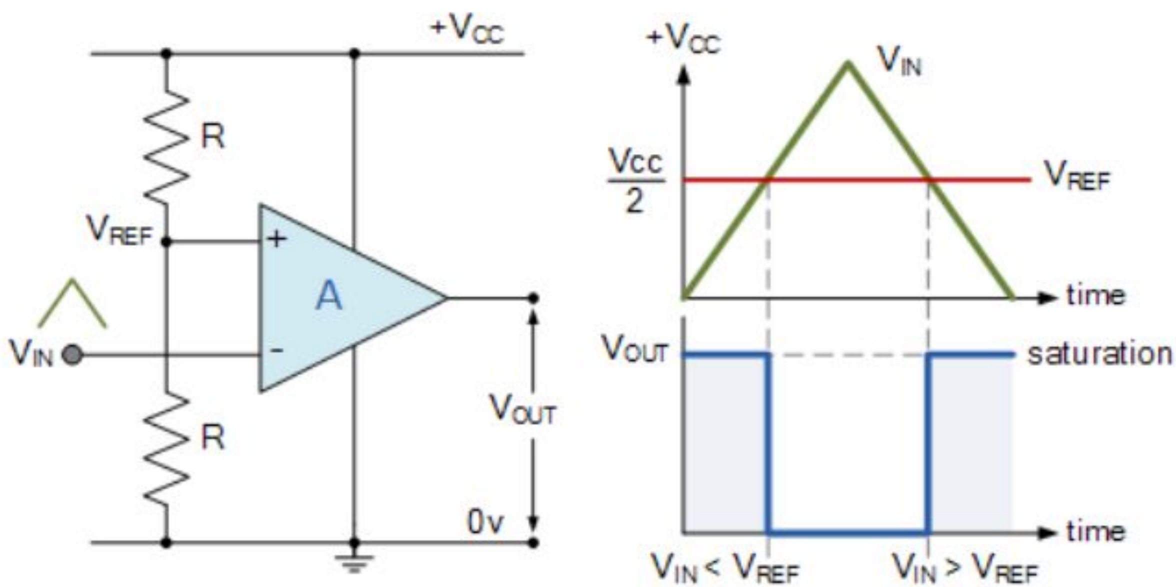
Non-inverting Comparator Circuit



Negative Voltage Comparator

The basic configuration for the negative voltage comparator, also known as an inverting comparator circuit detects when the input signal, V_{IN} is BELOW or more negative than the reference voltage, V_{REF} producing an output at V_{OUT} which is HIGH as shown.

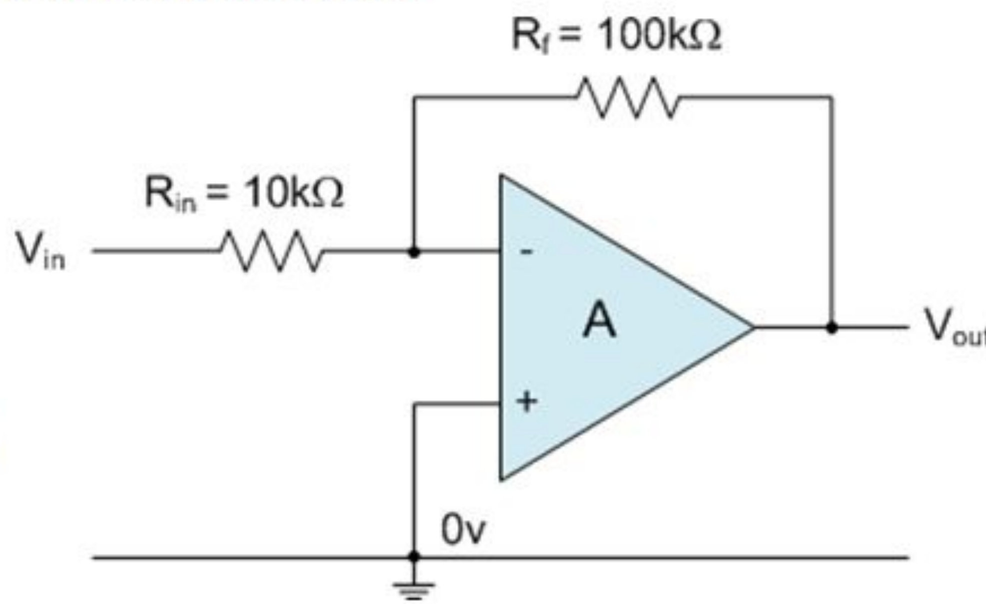
Inverting Comparator Circuit



Example Problems

Example No1

Find the closed loop gain of the given inverting amplifier circuit.



Using the previously found formula for the gain of the circuit

$$Gain = \frac{V_o}{V_{in}} = -\frac{R_f}{R_{in}}$$

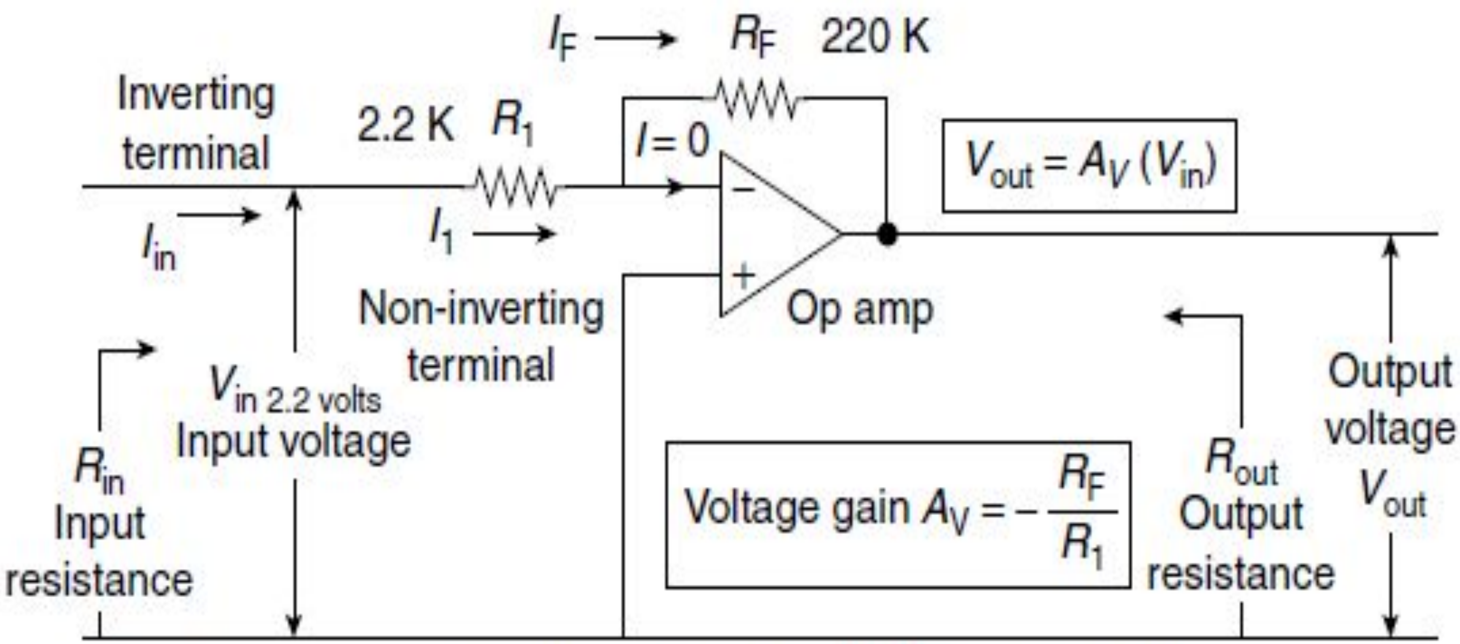
R_{in} = 10kΩ and R_f = 100kΩ.

Gain = $-R_f/R_{in}$ = 100k/10k = 10.

Therefore, the closed loop gain of the given inverting amplifier circuit is given **10** or **20dB**.

Example

For the operational amplifier circuit shown in Fig. , calculate input current, output voltage, and voltage gain for the given data in the circuit.



Operational Amplifier with Negative Feedback

Solution: Input current $I_1 = \dfrac{V_{in}}{R_1} = \dfrac{2.2\,\text{V}}{2.2\,\text{K}} = 1\ \text{mA}$

Total current passing through resistor R_1 will flow through feedback resistor R_F, because the current (I) through input port of op amp is zero. Inverting input terminal is at virtual ground. Therefore, the current drawn by op amp $I = 0$ mA.

Hence, $I_1 = I_F = 1$ mA.

Output voltage $\quad V_{out} = -I_F \times R_F = 1 \times 10^{-3} \times 220 \times 10^3 = 220\ \text{V}$

Output voltage $\quad V_{out} = -I_F \times R_F = -I_{in} \times R_F = -\dfrac{V_{in}}{R_{in}} \times R_F$

Therefore, voltage gain $\quad A_V = \dfrac{V_{out}}{V_{in}} = -\dfrac{R_F}{R_{in}} = \dfrac{220\,\text{K}}{2.2\,\text{K}} = 100$

Example

Consider an operational amplifier with resistors $R_1 = 1\ \text{k}\Omega$ and $R_f = 99\ \text{k}\Omega$. When the two input terminals are grounded so that voltage $V_1 = 0$ and $V_2 = 0$. Calculate the output offset voltage $V_{out}(0)$, if there is an input offset voltage $V_{in}(0) = 2$ mV.

Solution:

Voltage gain
$$A_V = \left[1 + \frac{R_f}{R_1}\right] = \left[1 + \frac{99\,\text{k}\Omega}{1\,\text{k}\Omega}\right] = 100$$

Output offset voltage
$$V_{out}(0) = A_V \times V_{in}(0)\ \text{V} = 100 \times 2\ \text{mV} = 200\ \text{mV} = 0.2\ \text{V}.$$

Example

1. Calculate the voltage gain of an inverting op amp with $R_1 = 3.3\ \text{k}\Omega$ and resistor $R_2 = 33\ \text{k}\Omega$.
2. Calculate the output voltage when the input voltage = 0.5 V.
3. Calculate the total output offset voltage for input offset voltage = 0.05 V.

Solution:

1. Voltage gain of an inverting op amp $A_V = \left(\frac{R_2}{R_1}\right) = \frac{33 \times 10^3}{3.3 \times 10^3} = 10$
2. Output voltage = $V_{out} = A_V \times V_{in} = 10 \times 0.5 = 5$ V.
3. Output voltage due to offset voltage $V_{out}(0) = A_V (V_{in} + V_{in}(0))$

$$V_{out}(0) = 10\,(0.5 + 0.05) = 5.5\ \text{V}.$$

Example

1. Calculate the voltage gain of non-inverting op amp if $R_1 = 2.2\ \text{k}\Omega$ and resistor $R_2 = 22\ \text{k}\Omega$
2. Calculate output voltage for input voltage of 0.2 V.
3. Calculate the total offset voltage due to input offset voltage of 0.02 V.

Solution:

1. Voltage gain of non-inverting op amp = $A_{\text{V}} = \left(1 + \frac{R_2}{R_1}\right) = \left(1 + \frac{22 \times 10^3}{2.2 \times 10^3}\right) = 11$

2. Ideal output voltage with zero input offset voltage $V_{\text{out}} = A_{\text{V}} \times V_{\text{in}} = 11 \times 0.2 = 2.2$ V.
3. Output voltage with finite input offset voltage $V_{\text{out}}(0) = A_{\text{V}}(V_{\text{in}} + V_{\text{in}}(0))$

$$V_{\text{out}}(0) = A_{\text{V}}(V_{\text{in}} + V_{\text{in}}(0)) = 11 \times (0.2 + 0.02) = 11 \times 0.22 = 2.42 \text{ V.}$$

2. Slew rate SR = 0.5 V/μs.

Peak (maximum) value of output voltage = $V_{\max}$ (output) = 2 V.

Maximum frequency (Bandwidth) is calculated as in the following:

$$f_{\max} = \frac{\text{maximum slew rate without causing distortion in output signal}}{2\pi V_{\max}(\text{output})}$$

$$f_{\max} = \frac{0.5}{2\pi \times 2 \times 10^{-6}} = \frac{100 \times 10^3}{4\pi} = 7.96\ \text{kHz}$$

Example

An op amp has a slew rate of 2 V/μs. What is the maximum frequency of an output sinusoid of peak value 5 V at which the distortion sets in due to the slew rate limitation?

Solution: Slew rate SR = 2 V/μs.

Peak (maximum) value of output voltage = $V_{\max}$ (output) = 5 V.

Maximum frequency (bandwidth) $f_{\max}$ is calculated as in the following:

$$f_{\max} = \frac{\text{maximum slew rate without causing distortion in output signal}}{2\pi V_{\max}(\text{output})}$$

$$f_{\max} = \frac{2}{2\pi \times 5 \times 10^{-6}} = \frac{100 \times 10^3}{5\pi} = 6.365\ \text{kHz}$$