
UA741CN
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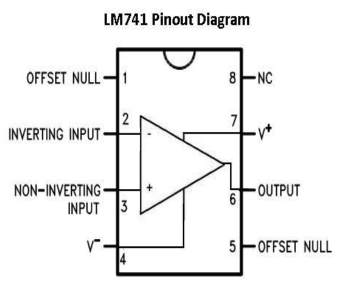
3.1 Introduction

- The integrated-circuit *operational-amplifier* is the fundamental building block for many electronic circuits. An op-amp is a multi-stage, direct coupled, high gain negative feedback amplifier used to amplify AC and DC input signals. It was initially used for basic mathematical operations such as addition, subtraction, multiplication, differentiation and integration in analog computers.
- The main applications of op-amp:
  Active filters, oscillators, peak detector, comparators, voltage regulators, precision rectifiers, instrumentation and control systems, pulse generators, square wave generators etc.
- For the design of all these circuits the op-amp is manufactured with many numbers of integrated transistors, diodes, one or two capacitors and resistors.
- By connecting external resistors, voltage gain and band width of an op-amp can be adjusted.
- The op-amp is an extremely compact; multi-tasking, low cost, highly reliable and temperature stable integrated circuit. In an ideal op-amp no current flows into either input offering infinite input resistance. The output acts as a voltage source with a very low resistance.
- In a practical op-amp (µA 741) the input current is in the order of pico - amps (10^{-12}) amp, or less.



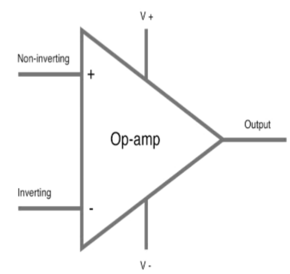


Fig. 3.1 (a) Basic pin-out of Op-amp **(b) circuit symbol**

OPAMP PARAMETERS

$$\text{CMRR} = \frac{A_d}{A_c} = 20\log_{10}\frac{A_d}{A_c}\,(\text{dB})$$

1. Common-Mode Rejection Ratio:

It is the ability of amplifier to reject the common-mode signals (unwanted signals) while amplifying the differential signal (desired signal).

It is defined as the *ratio of differential gain to the common mode gain*, measured in dB.

When both the inputs of the OPAMP has same voltages, then the output of it should be zero *($V_o = V_2 - V_1 = 0$; i.e, $V_1 = V_2$)* or the OPAMP should be rejecting the signal.

The function of the CMMR is used to reduce the noise on the transmission lines.

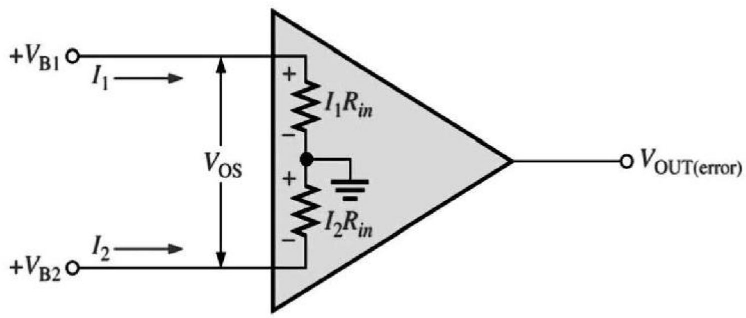
Ideal value : ∞	Practical Value: **90dB 120dB**

2. Open-loop voltage gain, (A_{ol}):
It is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components.

Ideal value : ∞	Practical Value: **2 10^{5}**

3. Input Offset Voltage:
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.

Ideal value : **0**	Practical Value: **2mV**

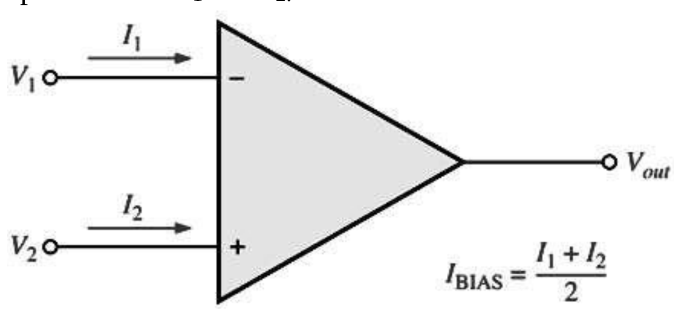


4. Input Offset Current
It is the difference of input bias currents I_1 and I_2.

$I_{os} = |I_1 - I_2|$ $\quad$ $V_{os} = I_1R_{in} - I_2R_{in} = (I_1 - I_2)R_{in}$

Ideal value : **0**	Practical Value: **20nA**

5. Input Bias Current
Input bias current is the current required by the inputs of the opamp to properly operate the first stage. It is defined as the average of both input currents I_1 and I_2.



Ideal value : **0**	Practical Value: **80nA**

6. Input Impedance: R_i **:**

It 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 inputs ($I_{IN} = 0$).
The ideal op-amp rules: 1. The differential input voltage is zero. $V_d = V_2 - V_1 = 0$

2. No current flowing into the input terminals.

$$R_{in} = \frac{V_d}{I_{in}} = \frac{V_d}{0\ \mathrm{A}} = \infty\ \Omega$$

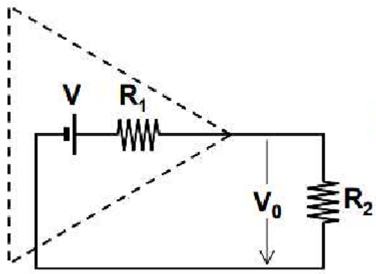
The larger the resistance of a device, the smaller the current that it demands. It determines the loading effect on the previous stage.

Ideal value : ∞	Practical Value:

7. Output Impedance: R_O

Op-amps are supposed to have zero output impedance, or very low means, the output voltage won't change, just in case the output current changes.

The ideal op-amp acts as a perfect internal voltage source with no internal resistance. This internal resistance is in series with the load, reducing the output voltage available to the load.



$$V_0 = \frac{VR_2}{R_1 + R_2}$$

Ideal value : **0**	Practical Value: **-**

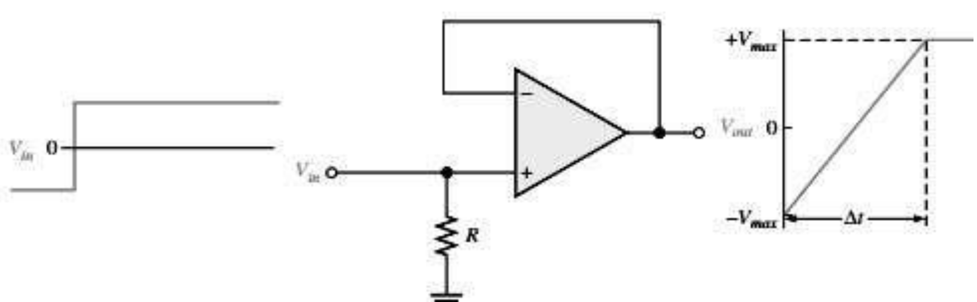
8. Slew Rate: SR = $dV_{o\,(max)}/dt$

Slew rate is defined as the *rate of change of maximum output voltage with respect to time*. The higher the value (in V/µs) of slew rate, the faster the op-amp responds.

$$SR = \left.\frac{dv_O}{dt}\right|_{max} \qquad V/\mu\sec$$

Slew rate describes how fast the output voltage responds to an immediate change in input voltage. It is particularly important parameter in applications where the output is required to switch from one level to another quickly.

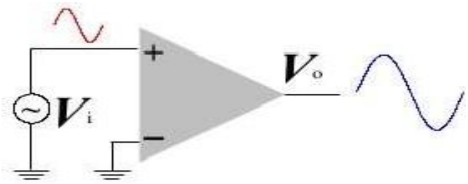
The power bandwidth maximum frequency is related to the slew rate and the peak output voltage by **SR = 2πf $V_{p\,(max)}$.** Where V_p is the peak voltage of the output signal and f is its frequency in Hz.

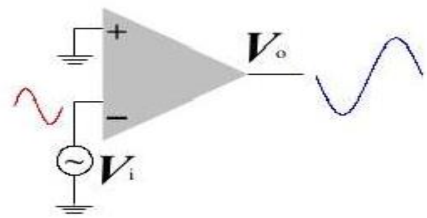


Ideal value : ∞	Practical Value: **0.5 µV/sec**

3.3 Operation Modes of OPAMP

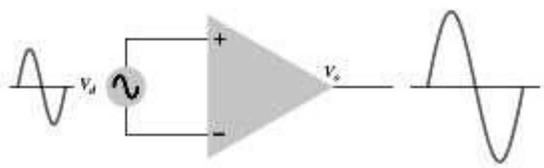
1. Single-ended input





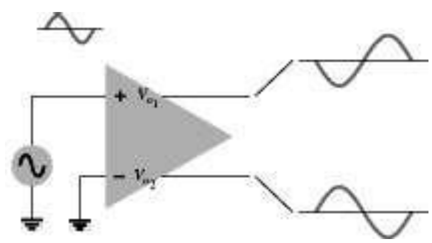
- Only one input is applied with input signal while the other is connected to ground.
- The input applied to the plus input results in an output having the same polarity as input.
- The input applied to the minus input results in an output being opposite in phase to the applied signal.

2. Differential (Double-ended) input



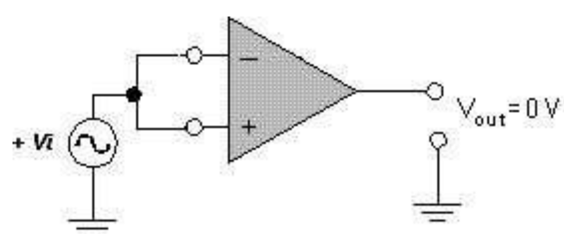
- When signal is applied between both inputs, it is referred to as double-ended input.
- The amplified output is in phase with the difference between the two inputs.
- This is the reason that this mode is called *differential input*.

3. Double-ended output



- The op-amp can also be operated with opposite outputs.
- The figure shows a single-ended input with a double-ended output.
- The signal applied to the plus input results in two amplified output of opposite polarity.

4. Common-mode



- When the same input signals are applied to both inputs, common-mode operation results.
- Ideally, the output is zero due to the two opposite output components.
- This means that signals common to both inputs will be suppressed, referred to as common-mode rejection.

Ideal Op-Amp Properties

- Infinite input impedance (500k-2MΩ
- Zero output impedance (20-100 Ω)

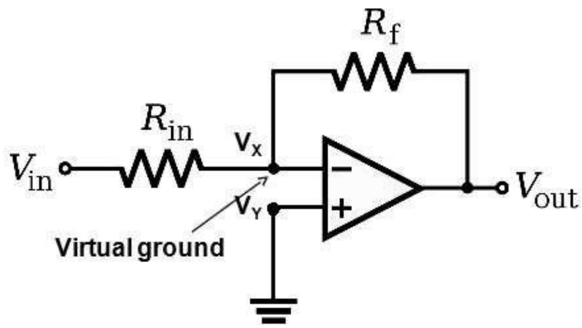
  Infinite open-loop gain (20k to 200k)

  Infinite bandwidth

  Zero noise contribution

  Zero DC output offset

Concept of Virtual Ground



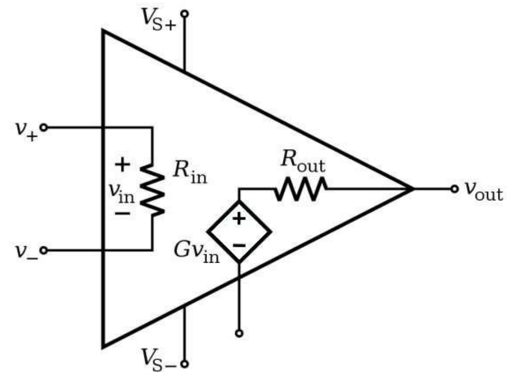


Fig. 3.2 (a) Illustration of virtual ground (b) Equivalent circuit of an Ideal op-amp

In an ideal Op-Amp (its equivalent circuit is shown in fig. 3.2(b)), when input voltages are equal output will be zero. Suppose, non-inverting terminal (+) is physically grounded (V_Y = 0) as shown in fig. 3.2(a). Though the inverting terminal (-) is not grounded, it also stays at 0V. i.e., V_X = 0V. This phenomenon is known as *virtual ground* of op-amp. This is because, since the input impedances of an ideal op-amp is infinite ($R_i = \infty$). There is no current flow into the two terminals. Hence, V_X = V_Y.

3.4 Op-amp Application circuits

3.4.1 Inverting operational Amplifier

The basic circuit for the inverting op-amp circuit is shown in the fig. 3.3. Input signal V_{in} is applied to the inverting terminal of the circuit through R_{in} , and resistor R_F is connected between the output and the inverting input. The non-inverting input is connected to ground.

- Output V_{out} is inverted version (180° phase shift) of input V_{in}, but amplified as shown in the fig. 3.3 (c). The ratio R_F / R_{in} controls the closed loop gain (A_{CL}).

Virtual ground concept:

1. No input current flows into the (-) terminal and
2. V_X always equals to V_Y.

Therefore, all input current I_{in} flows towards the output (V_{out}) through R_F. See fig. 3.4.

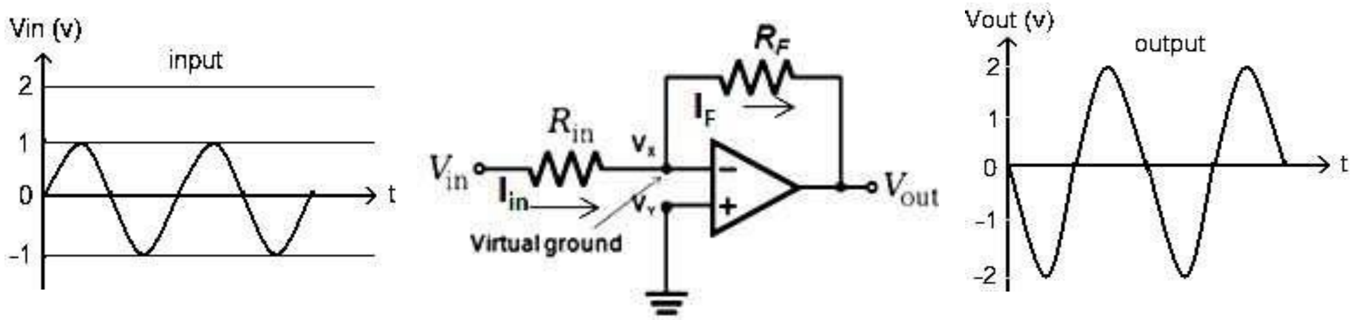


Fig. 3.3 Inverting op amp (a) Input wave form (b) Inverting op amp circuit (c) Output wave form

Analysis: Apply KCL at node V_X

$I_{in} = I_F$ using nodal analysis in the direction of current flow,

$\frac{V_{in}-V_X}{R_{in}} = \frac{V_X-V_{out}}{R_F}$ since, $V_X = V_Y = 0$

$\frac{V_{in}-0}{R_{in}} = \frac{0-V_{out}}{R_F}$ or $\frac{V_{in}}{R_{in}} = \frac{-V_{out}}{R_F}$

$\frac{V_{out}}{V_{in}} = \frac{-R_F}{R_{in}}$ $\frac{V_{out}}{V_{in}} = A_{CL} = \frac{-R_F}{R_{in}}$

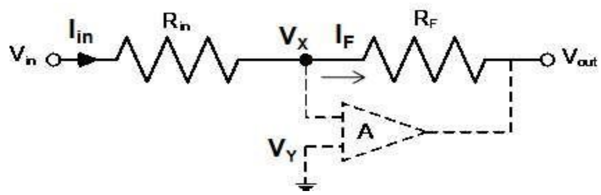


Fig. 3.4 Virtual ground concept

Closed Loop Gain $A_{CL} = \frac{-R_F}{R_{in}}$

Output Voltage $V_{out} = - V_{in}\left[\frac{R_F}{R_{in}}\right]$

[**NOTE**: 1. Minus (-) indicates output is inverted version of input.

2. $\frac{R_F}{R_i}$ is a scaling factor, the gain A_{CL} depends on the selection of R_F and R_i values]

3.4.2 Non-inverting operational Amplifier

- The basic circuit for the non-inverting op amp circuit is shown in the fig. 3.5. Input signal V_{in} is applied to the non-inverting (+) terminal of the circuit and resistor R_F is connected between the output and the inverting terminal. The inverting (-) input is connected to ground via R_{in}.
- Output V_{out} is non-inverted version (0° phase shift) of input V_{in}, but amplified. The ratio R_F / R_{in} controls the closed loop gain (A_{CL}). Always A_{CL} is greater than 1.

Virtual ground concept:

1. No current flows into the input terminal (+) and
2. V_X always equals V_Y. Therefore, $V_X = V_Y = V_{in}$, also current flows from output (V_{out}) through R_F reaching ground. See fig. 3.6

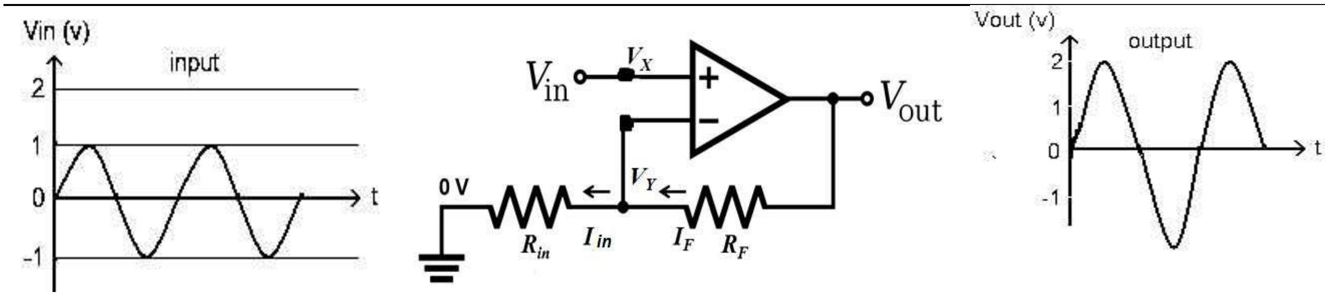


Fig. 3.5 Non-inverting op-amp (a) Input wave form (b) circuit (c) Output wave form

Analysis:

Apply KCL at node V_Y

using nodal analysis in the direction of current flow,

$$I_{in} = I_F$$

$$\frac{V_Y - 0}{R_{in}} = \frac{V_{out} - V_Y}{R_F} \qquad \text{since, } V_X = V_Y = V_{in}$$

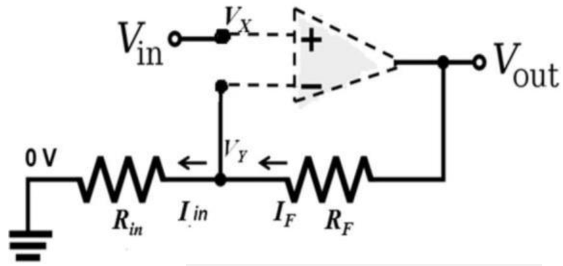


Fig. 3.6 Virtual ground concept

$$\frac{V_{in}}{R_{in}} = \frac{V_{out} - V_{in}}{R_F}$$

$$\frac{V_{in}}{R_{in}} = \frac{V_{out}}{R_F} - \frac{V_{in}}{R_F}$$

$$V_{in}\left[\frac{1}{R_{in}} + \frac{1}{R_F}\right] = \frac{V_{out}}{R_F}$$

$$\frac{V_{out}}{V_{in}} = R_F\left[\frac{R_F + R_{in}}{R_F\,R_{in}}\right]$$

$$\frac{V_{out}}{V_{in}} = \left[\frac{R_F}{R_{in}} + 1\right] \quad OR \quad V_{out} = V_{in}\left[\frac{R_F}{R_{in}} + 1\right]$$

Closed loop gain $A_{CL} = \frac{V_{out}}{V_{in}} = \left[\frac{R_F}{R_{in}} + 1\right]$
Output voltage $V_{out} = V_{in}\left[\frac{R_F}{R_{in}} + 1\right]$

3.4.3 Summing OPAMP

- The inverting summing or adder op-amp circuit for three inputs is shown in the fig. 3.7.
- The output voltage, Vo is proportional to the algebraic sum of the input voltages, V_1, V_2, V_3. Because effectively it adds individual input voltage signals.
- Input signals V_1, V_2 and V_3 are applied to the inverting (-) input of the op-amp through input resistors R_1, R_2 and R_3, respectively. Thus, I_1, I_2 and I_3 are input currents flow through them.

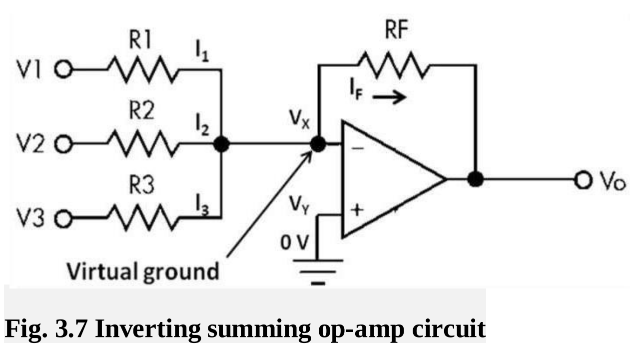


Fig. 3.7 Inverting summing op-amp circuit

- R_F is connected between the V_o and the (-) input. The non-inverting input is connected to ground.

  Virtual ground concept:

  - 1. No input current flows into the (-) terminal and
  - 2. V_X always equals V_Y. Therefore, all input currents flow towards output (V_{out}) through R_F.

Analysis: Apply KCL at node V_X, using nodal analysis in the direction of current flow,

$$I_1 + I_2 + I_3 = I_F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, $I_1 = \frac{V_1 - V_X}{R_1}$, $I_2 = \frac{V_2 - V_X}{R_2}$, $I_3 = \frac{V_3 - V_X}{R_3}$ and $I_F = \frac{V_X - V_o}{R_F}$

Then eqn (1) becomes, $\frac{V_1 - V_X}{R_1} + \frac{V_2 - V_X}{R_2} + \frac{V_3 - V_X}{R_3} = \frac{V_X - V_o}{R_F}$ since, $V_X = V_Y = 0$

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

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{-V_o}{R_F}$$

$$V_o = -R_F\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$ if $R_1 = R_2 = R_3 = R_F = R$

$V_o = -(V_1 + V_2 + V_3)$ ≡ output voltage is proportional to the algebraic sum of the input voltages, V_1, V_2, V_3.

Voltage follower OPAMP

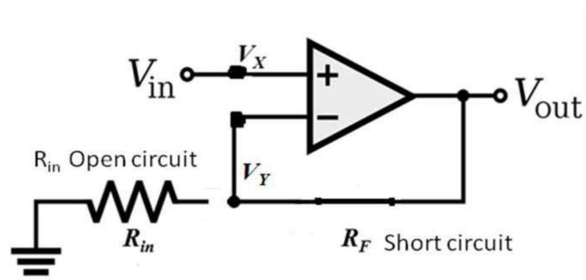


Fig. 3.8 (a) Voltage follower op-amp (b) resembled circuit of non-inverting op-amp

- Output voltage V_{out} follows the input voltage V_{in} so the circuit is named as op-amp voltage follower.
- The output is connected directly back to the (-) inverting input so that the feedback is 100% and V_{in} is exactly equal to V_{out} . It is shown in the fig. 3.8(a).
- If voltage V_{in} increases, voltage V_{out} increases. On the other hand, if voltage V_{in} decreases, voltage V_{out} also decreases. It provides an effective isolation of the output from the signal source that eliminating the loading effect of the second circuit from the first circuit. Because the input impedance of the op amp is very high, draws very little power from the signal source, avoiding loading effects. This circuit is useful for the first stage.

Properties of Voltage Follower

- Voltage gain = 1
- Input impedance $R_{in} = \infty$
- Output impedance $R_{out} = 0$
- Effective isolation of the output from the signal source.

To Prove Voltage gain, $\frac{V_{out}}{V_{in}} = A_V = 1$

Voltage follower is resembles to that of non-inverting opamp, in which input impedance R_{in} is open circuited (= ∞) and output impedance R_{out} is short circuited (= 0). See fig. 3.8(b).

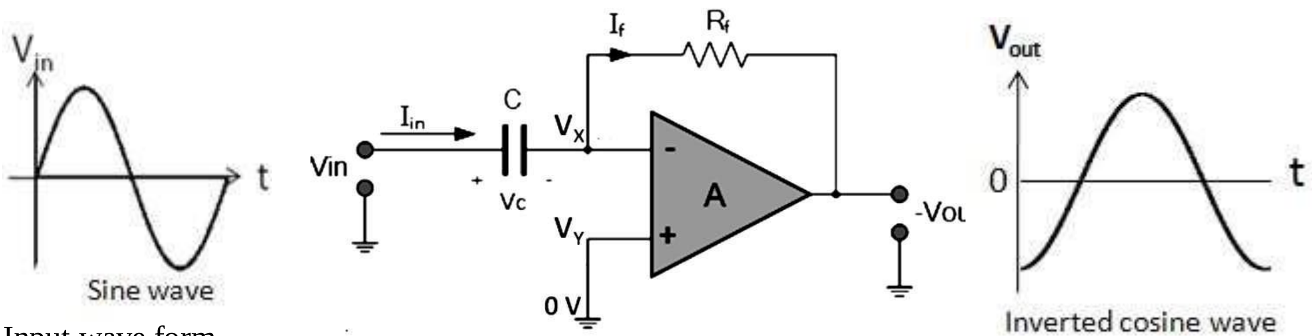
$$\frac{V_{out}}{V_{in}} = A_V = \left[\frac{R_F}{R_1} + 1\right]$$

$$\frac{V_{out}}{V_{in}} = A_V = \left[\frac{0}{\infty} + 1\right] = 1$$

Advantage: provides current and power gain.
Applications: The voltage follower is often used as buffers for logic circuits, impedance matching.

3.4.5 Differentiator op-amp

- Differentiator produces output voltage (V_{out}) is proportional to the rate of change of the input voltage V_{in}. If input is a sine wave output of a differentiator is a (inverted) cosine wave. See the fig.3.9.
- A differentiator with the only RC network is called a passive differentiator, whereas a differentiator with an op-amp is called an active differentiator.
- Advantages of active differentiator: have higher output voltage and lower output resistance than passive RC differentiators.
- An op-amp differentiator is an inverting amplifier, which uses a capacitor C in series with the input voltage V_{in} and a feedback resistor R_f is connected between V_{out} and inverting (-) input. The non-inverting input terminal of the op-amp is connected to ground as shown in the fig.3.9.
- For DC input, capacitor C behaves like an open-circuit. Also, attenuates low frequency signals and allows only high frequency signals at the output. In other words, circuit behaves like a high-pass filter.



Input wave form

Output wave form

Fig. 3.9 Differentiator op-amp

Analysis:
From the fig.3.9, since, the node V_Y is at ground potential the node V_X is virtually grounded.

i.e. $V_x = V_y = 0$.

Therefore, the current flowing into the op-amp internal circuit is zero, effectively all of the current flows through the resistor R_f.

From the input side, the current $I_{in} = C\,[d(V_{in} - V_x) / dt] = C\,[dV_{in} / dt]$…………………………(1)

From the output side, the current $I_F = (V_x - V_{out}) / R_f = -\{V_{out} / R_f\}$ …………………………(2)

Equating the (1) & (2) equations $I_{in} = I_F$

$$C\{dV_{in} / dt\} = - V_{out} / R_f$$

$$V_{out} = - R_f \, C\{dV_{in} / dt\}$$

The output V_{out} is R_f C times the differentiation of the input voltage. The product R_f C is called as the RC time constant of the differentiator circuit. The negative sign indicates the output is out of phase by 180^o with respect to the input.

Applications:

- Wave shaping circuits
- To operate on triangular and rectangular signals.

3.4.6 Integrator op-amp

- Integrator produces output voltage V_{out}, is proportional to the integral of the input voltage V_{in}. If input is a square wave, output of an integrator is a triangular (inverted) wave. See the fig.3.10. Integrator with the only RC network is called a passive integrator, whereas an integrator with an op-amp is called an active integrator. Advantages of *active integrator*: have higher output voltage and lower output resistance than passive RC integrators.
- An op-amp integrator is an inverting amplifier, which uses a resistor R_{in} in series with the input voltage V_{in} and a capacitor C is connected between V_{out} and inverting (-) input as feedback. The non-inverting input terminal of the op-amp is connected to ground as shown in the fig.3.10.
- For DC input, capacitor C behaves like an open-circuit. Also, attenuates high frequency signals and allows only low frequency signals at the output. In other words, circuit behaves like a low-pass filter.

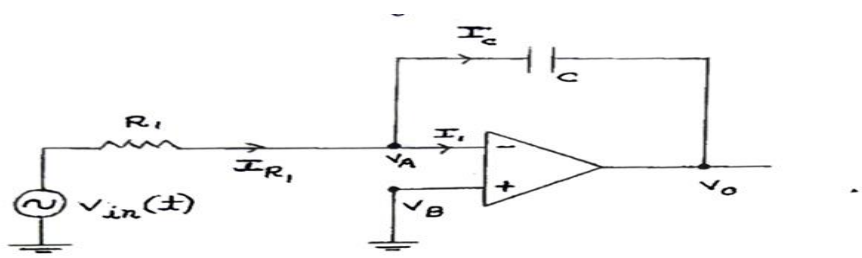


Fig. 3.10 Integrator op-amp

Analysis: From the fig.3.10, since, the node V_Y is at ground potential the node V_X is virtually grounded. i.e. $V_x = V_y = 0$. Therefore, the current flowing into input terminals is zero, effectively all of the current flows through the capacitor C.

From the input side, the current $I_{in} = \frac{V_{in}-V_X}{R_{in}} = \frac{V_{in}}{R_{in}}$ ………………………… (1)

From the output side, the current $I_F = C\,[d(V_X - V_{out}) / dt] = - C\,[dV_{out} / dt]$ …………………… (2)

Equating the (1) & (2) equations: $I_{in} = I_F$

$$\frac{V_{in}}{R_{in}} = - C\,[d(V_{out})/dt] \quad \text{………………………………….(3)}$$

Integrating both side equation(3) $\int \frac{V_{in}}{R_{in}}\, dt = -C \int \frac{d(Vout)}{dt}\, dt$

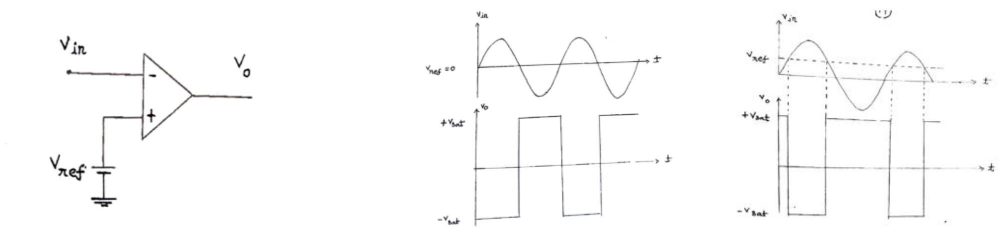
$$V_{out} = -\frac{1}{CR_{in}}\int V_{in}\, dt$$

The output V_{out} is CR_{in} times the integration of the input voltage V_{in}. The product CR_{in} is called as the RC time constant of the integrator circuit. The negative sign indicates the output is out of phase by 180° with respect to the input.

3.4.7 Comparator OPAMP

OPAMP voltage comparator compares the magnitudes of two voltage inputs and determines which is the larger of the two.

- Referring the fig.3.11, assume ($V_{IN} < V_{REF}$).
- As the non-inverting (positive) input of the comparator is less than the inverting (negative) input, the output will be the negative supply voltage, -Vcc resulting in a negative saturation of the output.



- When ($V_{IN} > V_{REF}$), the output voltage rapidly switches HIGH towards the positive supply voltage, +Vcc resulting in a positive saturation of the output.

- Suppose the input voltage V_{IN}, is decreased slightly less than V_{REF}, the op-amp's output switches back to its negative saturation voltage acting as a threshold detector.
- Then it is seen that the op-amp voltage comparator is a device whose output is dependent on the value of the input voltages.