OPERATIONAL AMPLIFIER

Block diagram

- An op-amp is a multi-stage , direct coupled, high gain differential amplifier.
- An op-amp can be conveniently divided into four main blocks:
  - Input stage
  - Intermediate stage
  - Level shifting stage
  - Output stage

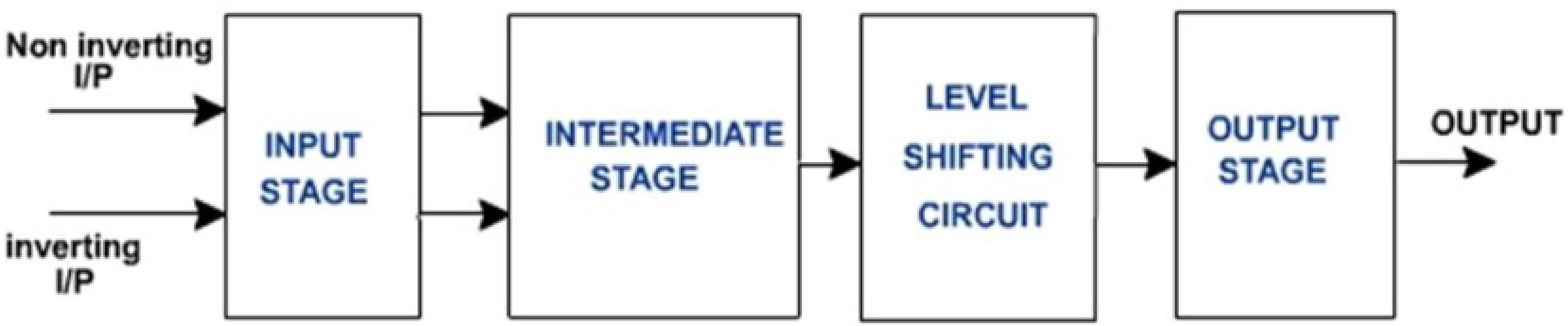


Fig. 1: Block diagram of a typical op-amp

Block diagram

- **Input stage:** It consists of a dual input, balanced output differential amplifier. Its function is to amplify the difference between the two input signals. It provides high differential gain, high input impedance and low output impedance.

- **Intermediate stage:** The overall gain requirement of an op-amp is very high. Since the input stage alone cannot provide such a high gain, intermediate stage is used to provide the required additional voltage gain.

Block diagram

- **Level shifting circuit:** Due to direct coupling used between the first and second stages, the input of level shifting stage is an amplified signal with some non-zero dc level. Level shifting stage is used to bring dc level to zero volts with respect to gnd.

- **Output stage:** The level shifted signal is then fed to the output stage where a push-pull amplifier is used that increases the output voltage swing of the signal and also increases the current supplying capability of the op-amp. It also ensures that the output resistance of op-amp is low.

Op-amp basics

- The op-amp is designed to sense the difference between the voltage signals applied at its two input terminals, multiplied by a number A(called as gain of op-amp), causing the resulting voltage A $(V_1 - V_2)$ to appear at its output terminal.

- The main use of an op-amp is to amplify ac and dc input signals and was initially used for basic mathematical operations such as addition, subtraction, multiplication, differentiation and integration.

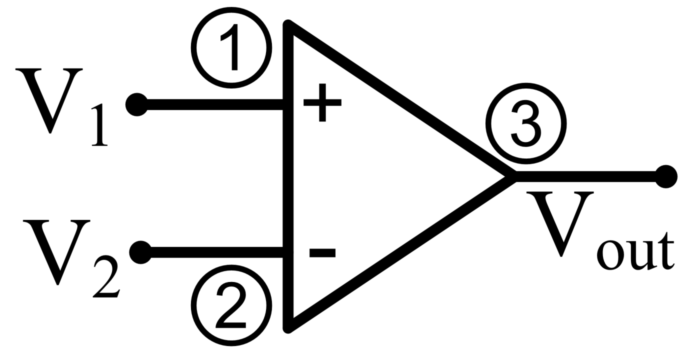
Op-amp basics

- Nowadays , the application of op-amp's varies from ac and dc signal amplification to use in active filters, oscillators, comparators, voltage regulators, instrumentation and control systems, pulse generators, square wave generators and many more electronic circuits.

- For the design of all these circuits the op-amp's are manufactured with integrated transistors, diodes, capacitors and resistors, thus making it an extremely compact, multi tasking, low cost, highly reliable and temperature stable integrated circuit.

Op-amp basics

- The schematic symbol of an op-amp is shown below:



- The above shown symbol is the most widely used op-amp symbol for all electronic circuits.
  - ❖ V_1 (Volts) – Non-inverting input voltage
  - ❖ V_2 (Volts) – Inverting input voltage
  - ❖ V_{out} (Volts) – Output voltage

Where $\boxed{V_{out} = A\,(V_1 - V_2)}$

Ideal characteristics

Key features of an ideal op-amp:

1. The **input impedance** of an ideal op-amp is supposed to be **infinite**.
   - The ideal op-amp is not supposed to draw any input current , i.e. the signal current into its input terminals are zero.

2. The **output impedance** of an ideal op-amp is supposed to be **zero**.
   - Voltage between output terminal and ground is independent of the current drawn from output terminal i.e. output terminal is supposed to act as the output terminal of an ideal voltage source.

Ideal characteristics

3. From the output expression i.e. $V_{out} = A (V_1 - V_2)$, we conclude that
   - Output is **in phase** (i.e. has the same sign) with V_1.
   - Output is **out of phase** (i.e. has the opposite sign) with V_2.
   - Hence, terminal 1 is called as non-inverting input terminal and terminal 2 is called as inverting input terminal.

4. **Common-mode rejection:** Op-amp responds only to the difference signal $(V_1 - V_2)$ and hence ignores any signal common to both the inputs i.e. if $V_1 = V_2$, then the output will ideally be **zero**.
   - From this we conclude that an ideal op amp has zero common-mode gain or infinite common-mode rejection.

Ideal characteristics

5. The ideal op-amp has **infinite bandwidth.**
   - The ideal op-amp has a gain A that remains constant down to zero frequency and up to infinite frequency.
   - That is, ideal op amps will amplify signals of any frequency with equal gain, and are thus said to have infinite bandwidth.

6. The ideal op-amp should have a **gain A** whose value is very large and **ideally infinite**.

One may ask: If the gain A is infinite, how are we going to use the op amp?

The answer is very simple: In almost all applications the op amp will *not* be used alone in a so-called open-loop configuration. Rather, we will use other components to apply feedback to close the loop around the op amp.

Ideal characteristics

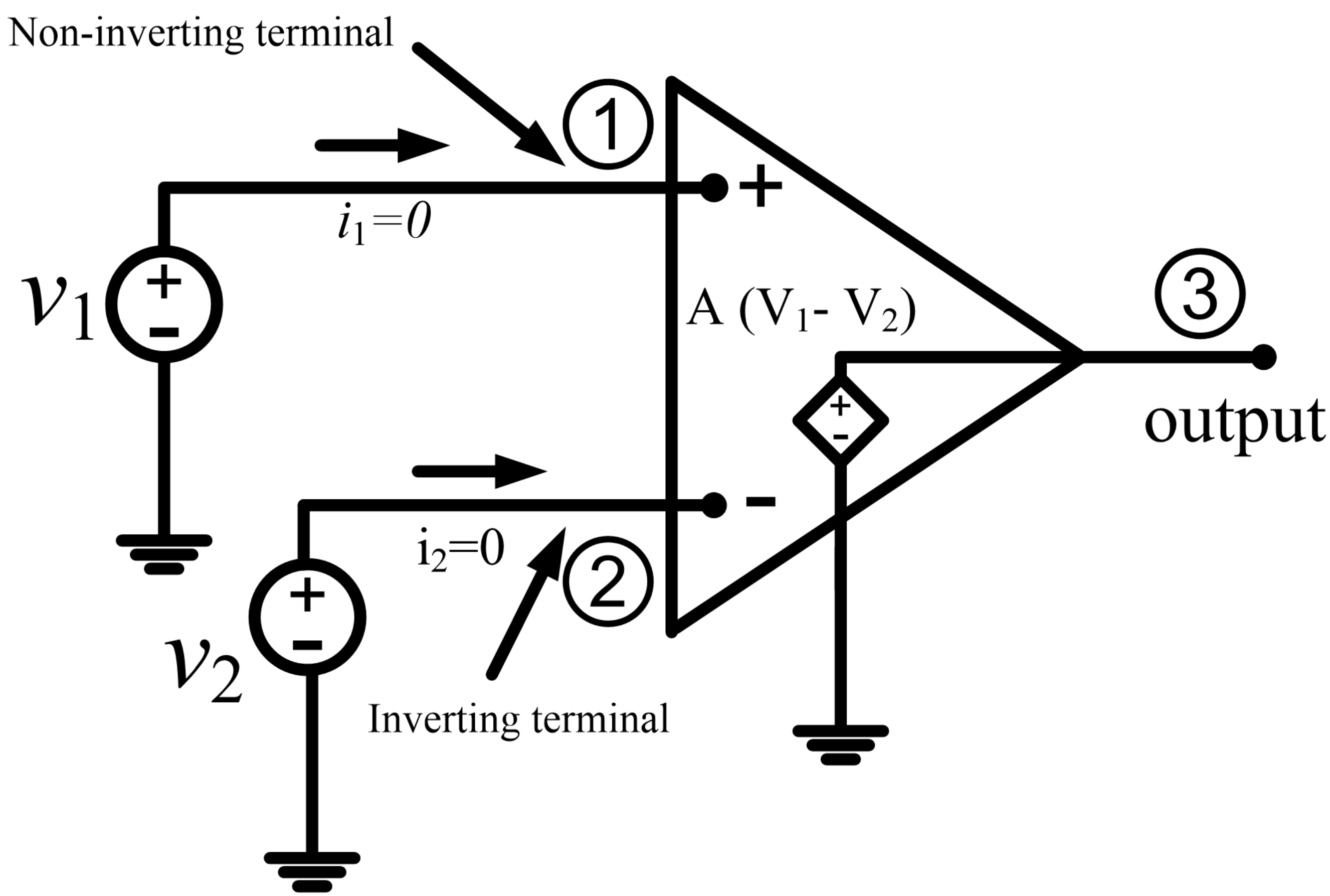


Fig.: Equivalent circuit of the ideal op-amp

Ideal characteristics

Final summary:

Characteristics	value
Input impedance	Infinite
output impedance	Zero
Common-mode rejection ratio	Infinite
Bandwidth	Infinite
Open-loop gain	Infinite

Important concept

- Output voltage of op-amp is A (V_1- V_2) where ideally A should be infinite. So,

$$V_1 - V_2 = \frac{V_o}{A} = 0$$

- That is, if A approaches infinity, the voltage V_1 approaches and ideally equals V_2.
- We conclude this as the two input terminals are **"tracking each other in potential".** It is also called that **"virtual short circuit"** exists between the two input terminals.

Important concept

A **virtual short circuit** means that whatever voltage is at 2 will automatically appear at 1 because of the infinite gain A. But terminal 2 happens to be connected to ground, we speak of terminal 1 as being a **virtual ground**— that is, having zero voltage but not physically connected to ground.

Here the word *virtual* should be emphasized, and one should *not* make the mistake of physically shorting terminals 1 and 2 together while analyzing a circuit.

Practical op-amp characteristics

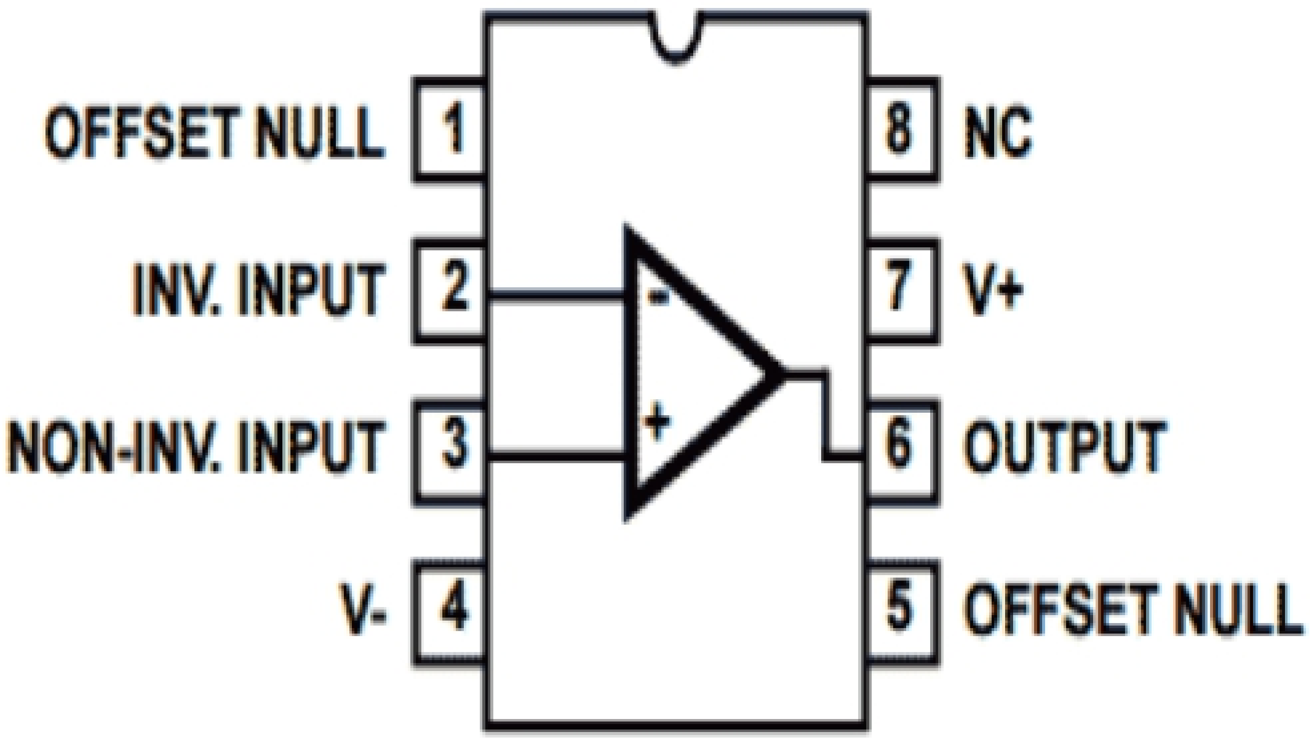
Practical op-amp characteristics varies from ideal op-amp characteristics

Characteristics	Ideally	practically
Input impedance	Infinite	$\approx 10^6 \Omega$
output impedance	Zero	In Ω
Common-mode rejection ration	Infinite	$\approx 10^0$ dB
Bandwidth	Infinite	$\approx 10^6$ MHz
Open-loop gain	Infinite	$\approx 10^6$

Pin diagram

There are 8 pins in a common op-amp IC

- Pin 1 is Offset null.
- Pin 2 is Inverting input terminal.
- Pin 3 is a non-inverting input terminal.
- Pin 4 is negative voltage supply (VCC)
- Pin 5 is offset null.
- Pin 6 is the output voltage.
- Pin 7 is positive voltage supply (+VCC)
- Pin 8 has no connection



Inverting amplifier

- Op-amps are not used alone, rather, the op-amp is connected to passive components in a feedback circuit.

- There are two such basic circuit configurations employing an op-amp and two resistors:
  - The inverting configuration
  - The non-inverting configuration

Inverting amplifier

Figure below depicts the circuit diagram for inverting configuration.

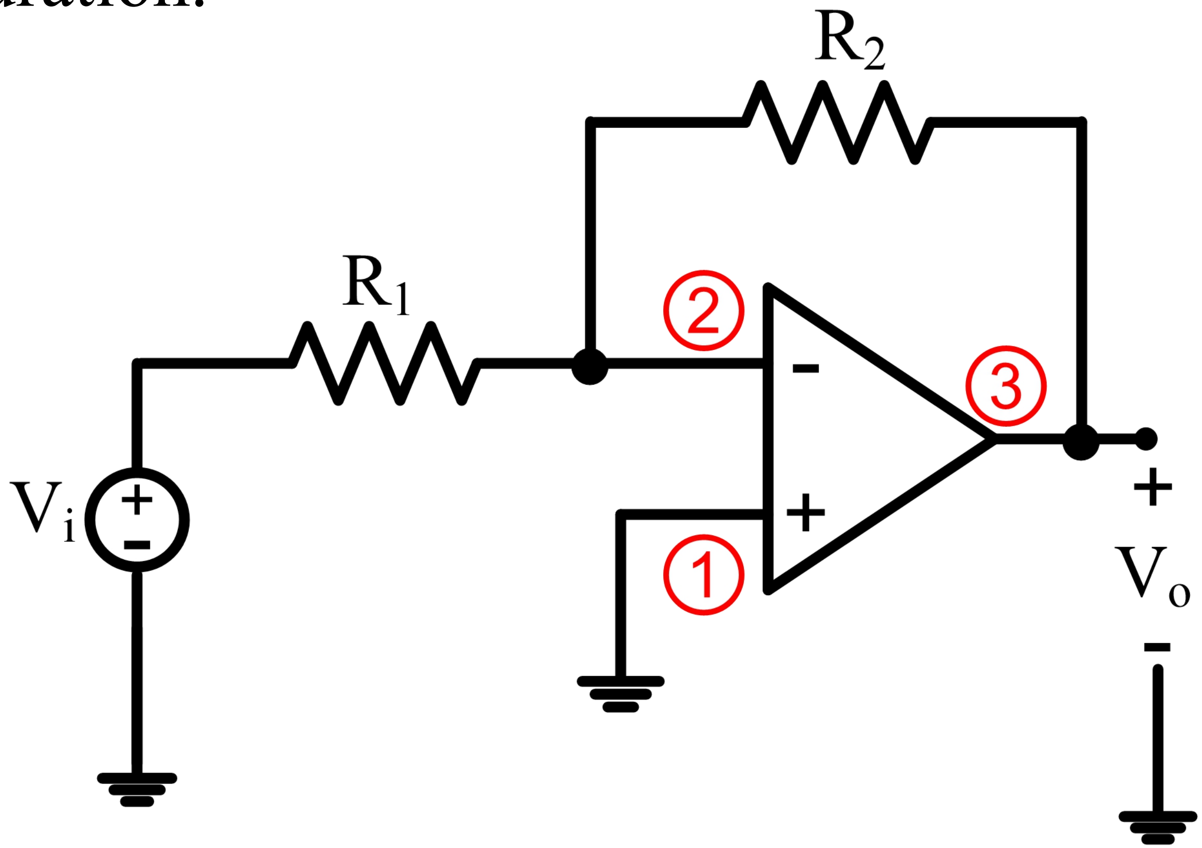


Fig.: Inverting amplifier

Inverting amplifier

- It consists of one op-amp and two resistors R_1 and R_2.
- Resistor R_2 is connected from the output terminal of the op-amp, and back to the inverting or negative input terminal.
- R_2 is seen as applying negative feedback as it is connected between negative terminal and output terminal.

Inverting amplifier

- Terminal 1 is grounded.
- Resistor R_1 and is connected between terminal 2 and an input signal source with a voltage v_{in}.
- Overall output of the circuit is taken at the output terminal i.e. between output terminal and ground.

Inverting amplifier

We will now analyze the previous circuit to determine the closed-loop gain.

- Closed loop gain G, is defined as:

$$G = \frac{V_o}{V_i}$$

- From the concept of virtual short circuit, since terminal 2 is grounded thus, $V_1 = 0$ & $V_2 = 0$.
- On applying ohm's law across R_1, we get-

$$i_1 = \frac{V_i - V_1}{R_1} = \frac{V_i - 0}{R_1} = \frac{V_i}{R_1}$$

Inverting amplifier

- This current cannot flow through the op-amp because an ideal op-amp draws zero current.
- It follows that i_1 will have to flow through R_2 to low-impedance terminal 3. Thus,

$$V_o = V_i - i_1 R_2 = 0 - \frac{V_i}{R_1} R_2$$

which is the closed loop gain of the inverting configuration.

Inverting amplifier

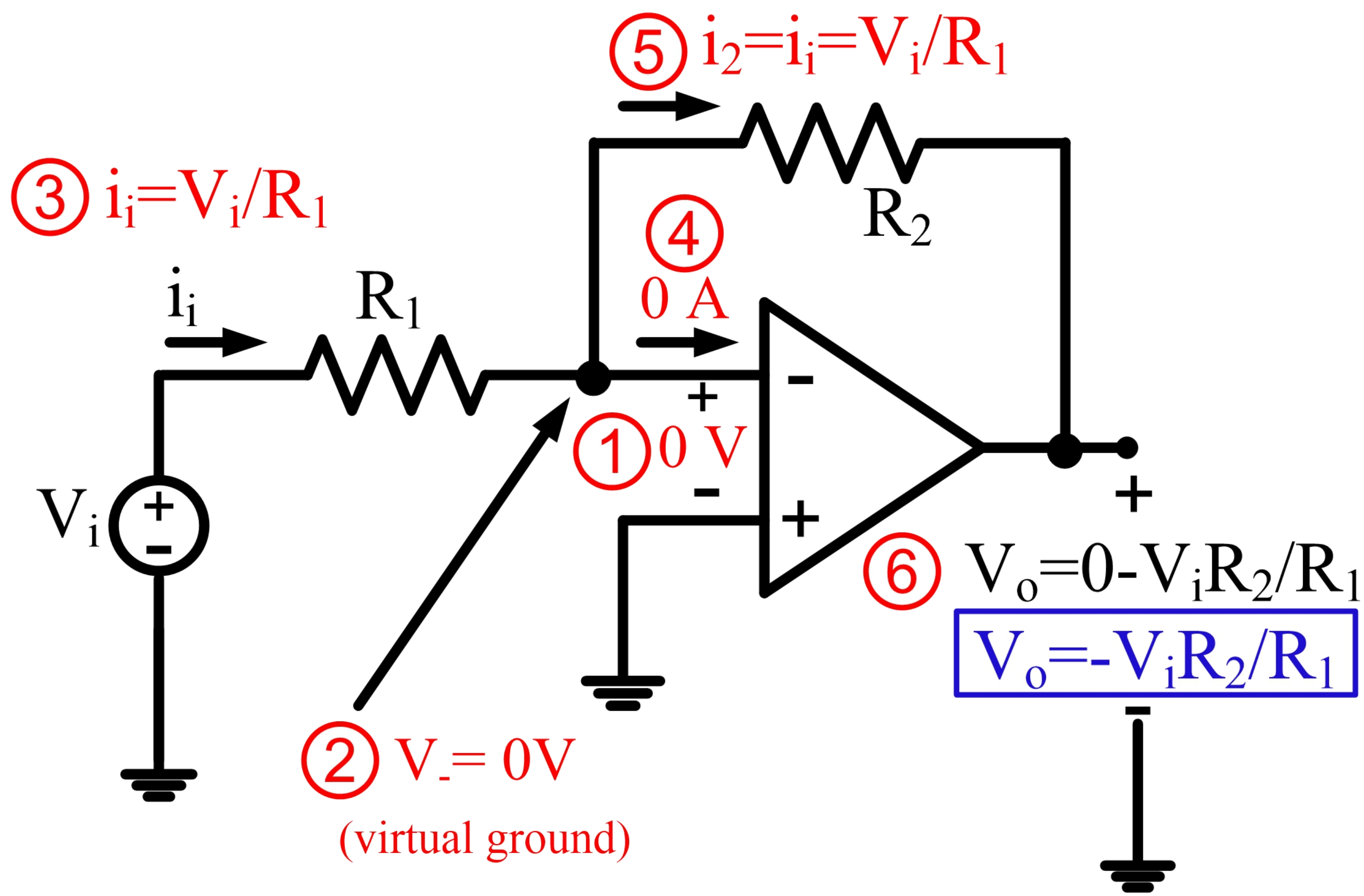
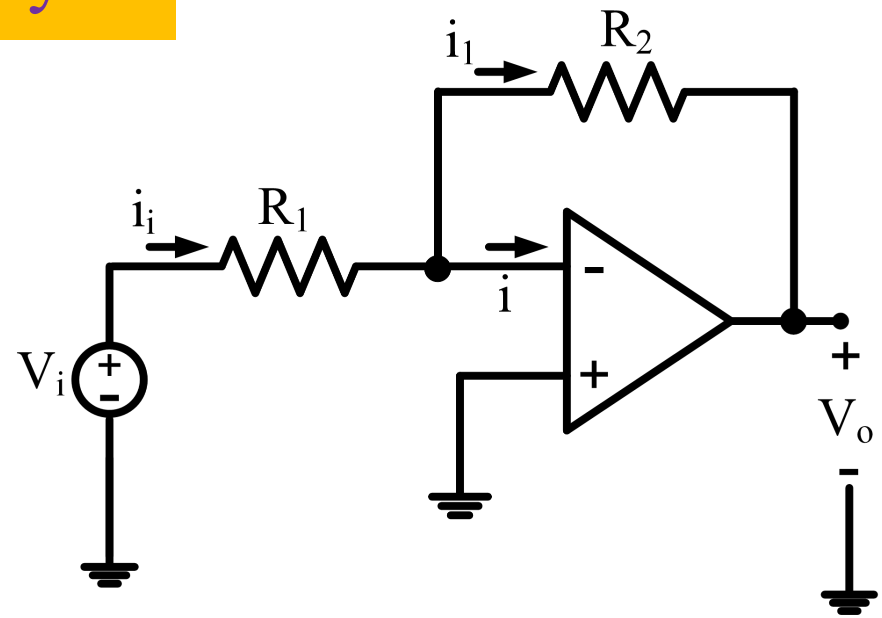


Fig.: Analysis of the inverting configuration

The circled number indicated order of analysis steps.

Inverting amplifier

Detailed analysis



$$i_i = i + i_1$$

Since, i = 0;

So, $i_i = i_1$

and, $i_i = \dfrac{V_i - V_-}{R}$

Due to virtual ground, $V_- = 0$

So, $i_i = \dfrac{V_i}{R}$

Thus, $i_1 = i_i = \dfrac{V_i}{R}$

and $V_o = 0 - i_1 R_2 \quad \Rightarrow V_o = -\dfrac{V_i R_2}{R_1}$

Inverting amplifier

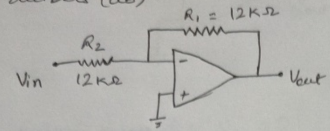
- Thus, closed-loop gain is ratio of two resistances R_1 and R_2 i.e. the closed-loop gain depends entirely on external passive components.
- The minus sign means that the closed-loop amplifier provides signal inversion.
- Input resistance of closed-loop inverting amplifier is simply equal to R_1.

$$R_i = \frac{V_i}{i_i} = \frac{V_i}{V_i / R_1} = R_1$$

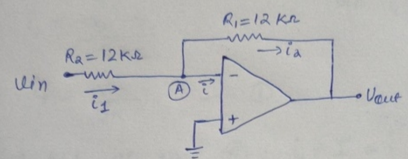
- Output resistance of closed-loop inverting amplifier is zero.

Numerical on inverting amplifier

Q1 Calculate overall voltage gain of the amplifier circuit shown in figure; both as a ratio and as a figure in units of decibels (dB).



Soln:



due to virtual ground, $V_- = 0$

$$i_1 = \frac{V_{in} - V_-}{R_2}$$

$$i_1 = \frac{V_{in}}{12K\Omega} \quad \text{— (1)}$$

using KCL at node (A) : $i_1 = i + i_2$

and since, $i = 0$, so, $i_1 = i_2$

and

$$i_2 = \frac{(V_-) - V_{out}}{R_1}$$

$$i_2 = \frac{-V_{out}}{R_1} \quad \text{— (2)}$$

since, $i_1 = i_2 \Rightarrow$ equating (1) & (2)

$$\frac{V_{in}}{12K} = \frac{-V_{out}}{12K}$$

So, $A_v = \frac{V_{out}}{V_{in}} = -\frac{12K}{12K} = -1$

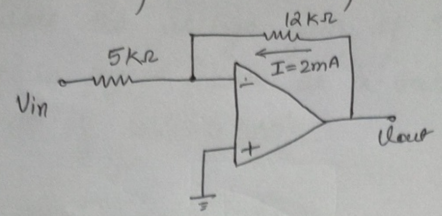
$$\boxed{|A_v| = 1}$$

$$A_v\Big|_{dB} = 20\log_{10}(|A_v|) = 20\log_{10}(1)$$

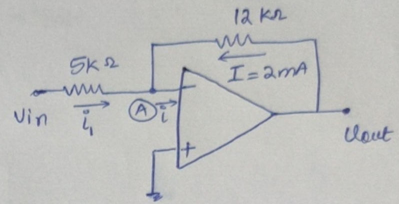
$$\boxed{A_v|_{dB} = 0}$$

Numerical on inverting amplifier

Q2 Determine both input and output voltage in this circuit.



Solⁿ: Due to virtual ground: $V_- = 0$



and $i_1 = \dfrac{V_{in} - V_-}{5k\Omega}$

so, $i_1 = \dfrac{V_{in}}{5K}$ — (1)

applying KCL at node (A): $i_1 + I = i$

where $i = 0$.

$\Rightarrow \quad i_1 = -I$

i.e. $i_1 = -2mA$. — (2)

equating (1) & (2); $\dfrac{V_{in}}{5K} = -2mA$

$\Rightarrow \boxed{V_{in} = -10\,V}$

also, $I = \dfrac{V_{out} - 0}{12k\Omega}$

$\Rightarrow V_{out} = 2mA \times 12k\Omega$

$\boxed{V_{out} = 24\,V}$

Non-Inverting amplifier

- Figure below depicts the circuit diagram for non-inverting configuration.

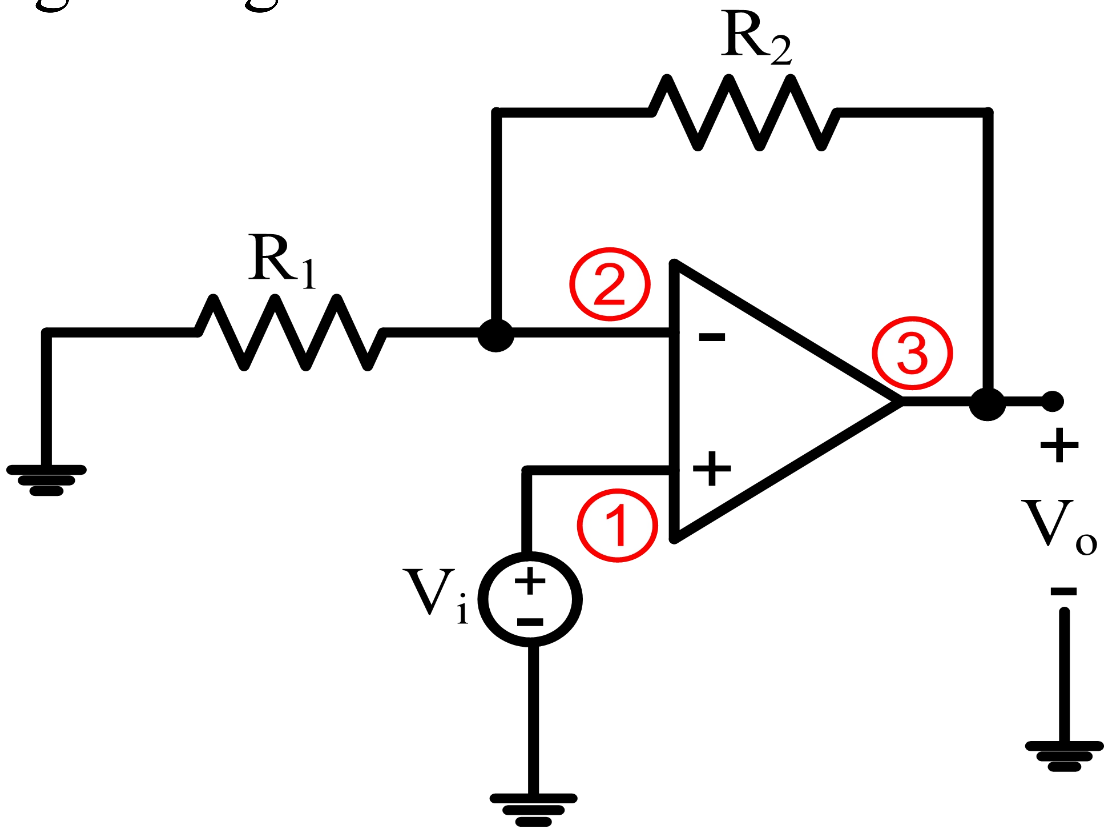


Fig.: Non-inverting amplifier

Non-Inverting amplifier

- It also consists of one op-amp and two resistors R_1 and R_2.
- Resistor R_2 is connected from the output terminal of the op-amp, and back to the inverting or negative input terminal.
- R_2 is seen as applying negative feedback as it is connected between negative terminal and output terminal.

Non-Inverting amplifier

- At terminal 1 an input signal source with a voltage v_{in} is applied.
- Resistor R_1 and is connected between terminal 2 and ground.
- Overall output of the circuit is taken at the output terminal i.e. between output terminal and ground.

Non-Inverting amplifier

We will now analyze the previous circuit to determine the closed-loop gain.

- The current flowing through R_1 can be determined as v_i/R_1
- Because of the infinite input impedance of the op-amp, the current v_i/R_1 will flow through R_2.

Non-Inverting amplifier

- Now the output voltage can be determined from

$$V_o = V_i + \left(\frac{V_i}{R_1} \right) R_2$$

which yields

$$\frac{V_o}{V_i} = 1 + \left(\frac{R_2}{R_1} \right)$$

which is the open loop gain of the no-inverting configuration.

Non-Inverting amplifier

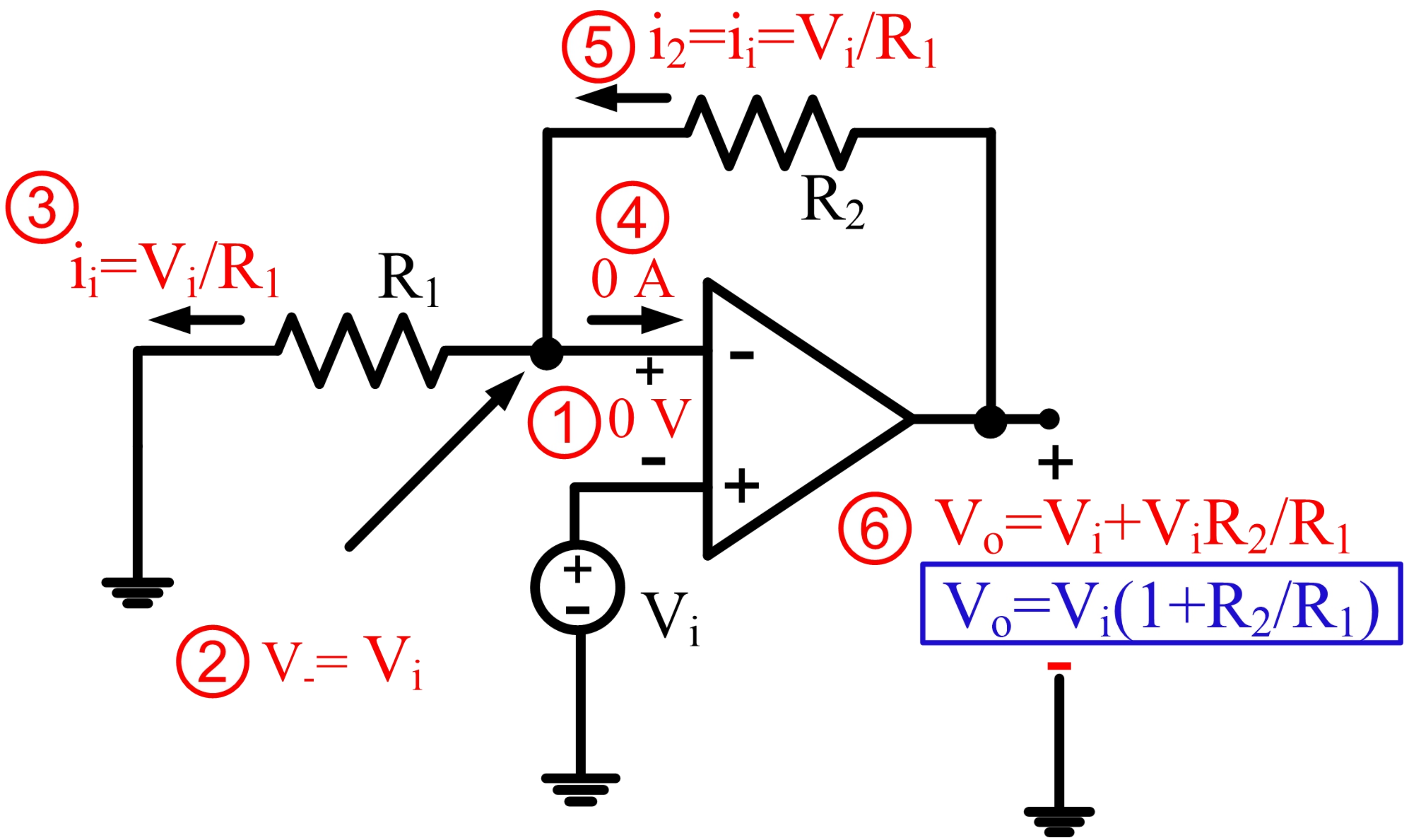


Fig.: Analysis of the non-inverting configuration

The circled number indicated order of analysis steps.

Non-Inverting amplifier

Detailed analysis

$$i_1 + i = i_2$$

Since, i = 0;

So, $i_1 = i_2$

and, $i_1 = \dfrac{V_- - 0}{R}$

due to virtual short, $V_- = V_i$

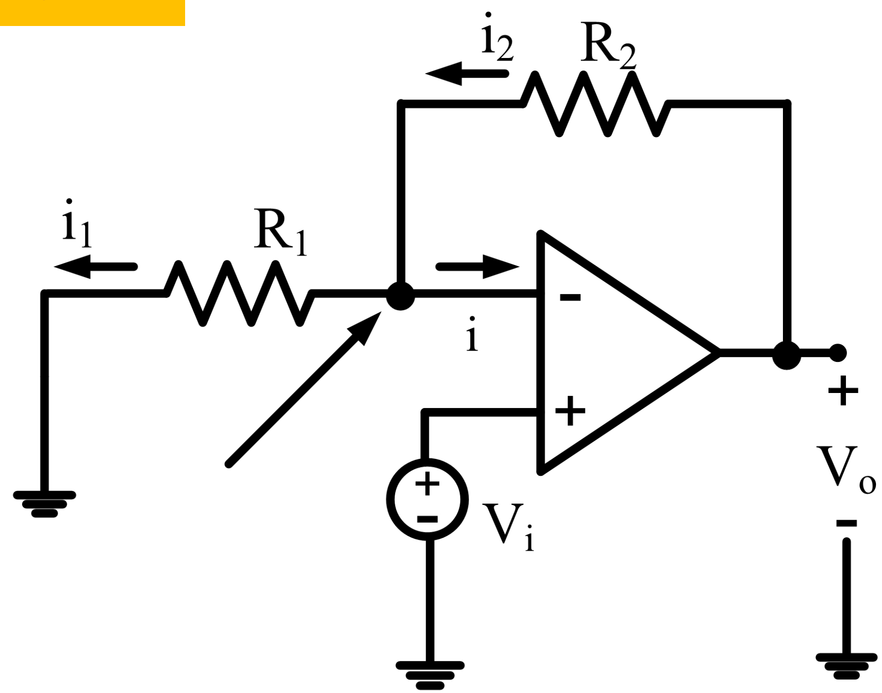
so, $i_1 = \dfrac{V_i}{R}$

thus, $i_2 = i_1 = \dfrac{V_i}{R_1}$

and

$$V_o = V_i + i_2 R_2$$

$$\Rightarrow V_o = V_i + \frac{V_i R_2}{R_1} \quad \Rightarrow V_o = V_i\left(1 + \frac{R_2}{R_1}\right)$$

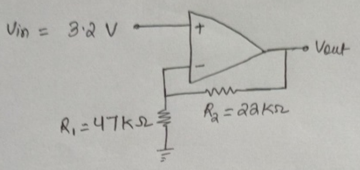


Non-Inverting amplifier

- Thus, the closed-loop gain depends entirely on external passive components.
- Since the gain of the non-inverting configuration is positive and hence the name non-inverting.
- Input resistance of closed-loop non-inverting amplifier is infinite
- Output resistance of closed-loop non-inverting amplifier is zero.

Numerical on non-inverting amplifier

Q Calculate the voltage gain of the amplifier circuit shown in figure, both as a ratio and as a figure in units of decibels (dB).

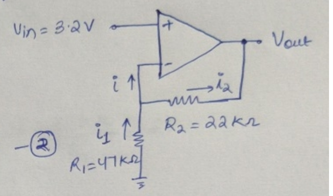


Soln:

Due to virtual short, $V_- = V_{in} = 3.2V$

Now, $i_1 = \frac{0 - V_{in}}{R_1} = \frac{-3.2\,V}{47k\Omega}$

$i_1 = -68.09\,\mu A$ — ①



also, $i_2 = \frac{V_{in} - V_{out}}{R_2} = \frac{3.2 - V_{out}}{22k\Omega}$ — ②

equating ① & ②

$$\frac{3.2 - V_{out}}{22k\Omega} = -68.09\,\mu A$$

$\Rightarrow$ $V_{out} = 3.2 + (68.09 \times 10^{-6} \times 22 \times 10^3)$

$V_{out} = (3.2 + 1.49)\,V$

$V_{out} = 4.69\,V$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{4.69}{3.2} = 1.465$$

$A_v|_{dB} = 20\log_{10}(1.465)$

$\boxed{A_v|_{dB} = 3.33\,dB}$

Alternatively: as it is a non-inverting configuration,

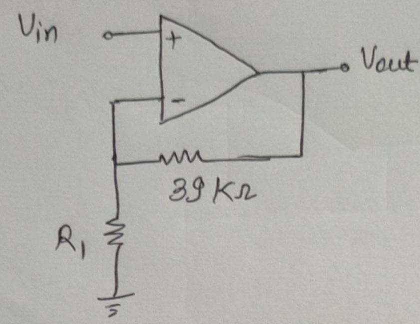
$$A_v = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} = \left(1 + \frac{22k\Omega}{47k\Omega}\right)$$

$A_v = (1 + 0.468)$

$\boxed{A_v = 1.468}$

Numerical on non-inverting amplifier

Q Calculate the necessary resistor value (R_1) in this circuit to give it a voltage gain of 30.



Solⁿ: As it is a non-inverting configuration, its gain is given by: $A_v = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$

where $A_v = 30$ (given)

so, $1 + \frac{39\,K\Omega}{R_1} = 30 \Rightarrow \frac{39\,K\Omega}{R_1} = 29$

$\Rightarrow R_1 = \frac{39\,K\Omega}{29}$

$\Rightarrow \boxed{R_1 = 1.34\,K\Omega}$

Unity follower

It is called by several names such as unity follower or unity-gain follower or voltage follower.

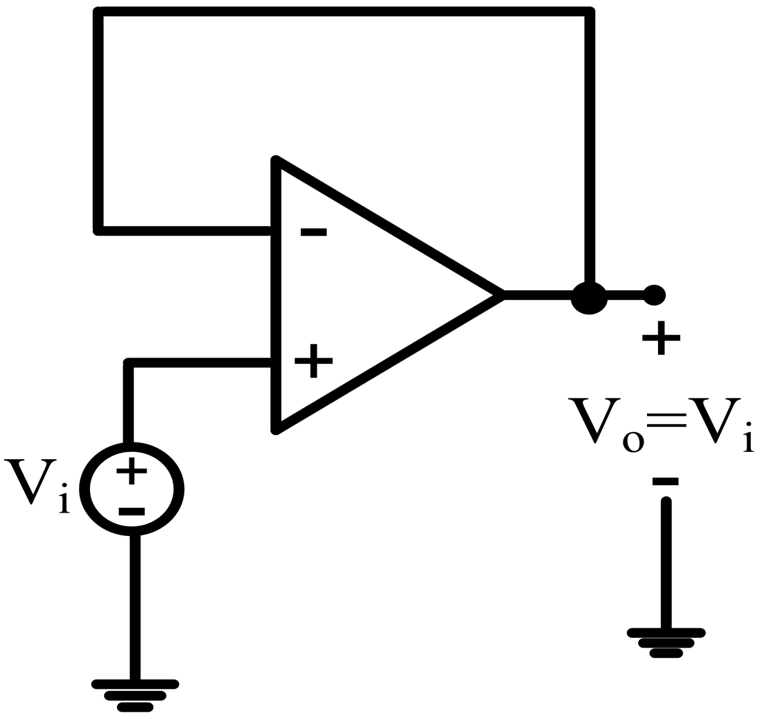


Fig: Unity-gain follower

Unity follower

- The property of high input impedance is a very desirable feature of the non-inverting configuration.
- It enables using this circuit as a buffer amplifier.
- Buffer amplifier is used:
  - To connect a source with a high impedance to a low-impedance load.
  - Buffer amplifier does not provide any voltage gain.
  - Rather, it is used mainly as an impedance transformer.

Unity follower

- To obtain the unity-gain amplifier **as** shown in previous fig., we may take R_1 and R_2 of non-inverting configuration as ∞ and 0 respectively.

- This circuit is commonly referred to as a **voltage follower as the output follows the input.**

Summing amplifier

It is a very important application of the inverting configuration.

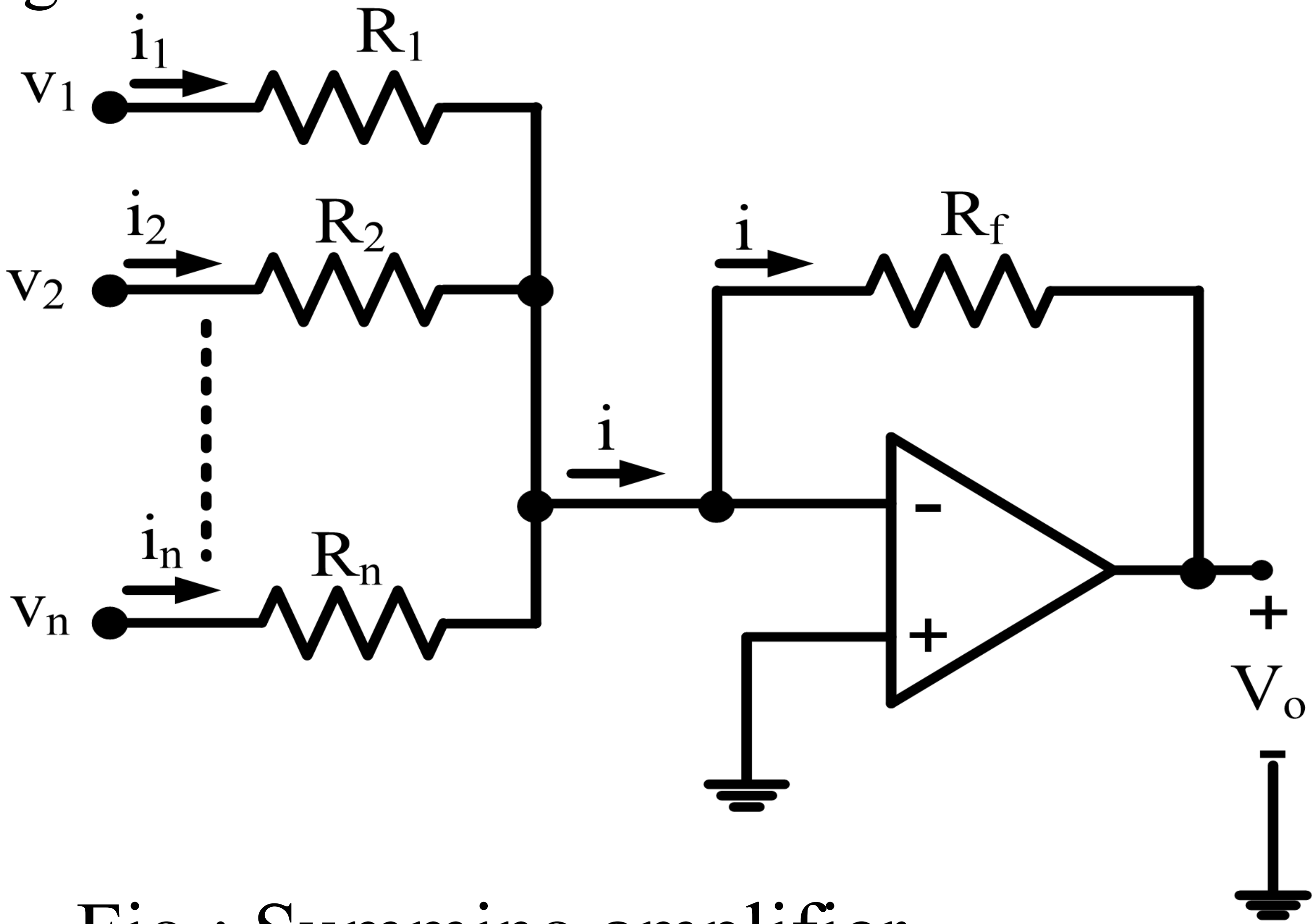


Fig.: Summing amplifier

Summing amplifier

- R_f is the negative feedback path resistance
- v_1, v_2……v_n are number of input signals applied through corresponding resistors R_1, R_2……R_n
- Input signals are being applied to inverting terminal of op-amp.

Summing amplifier

- For ideal op-amp, there will be a virtual ground appearing at its negative input terminal.
- Ohm's law tells us that the currents i_1, i_2……i_n are given by:

$$i_1 = \frac{v_1}{R_1}, i_2 = \frac{v_2}{R_2} \ldots\ldots, i_n = \frac{v_n}{R_n}$$

- All these currents sum together to produce the current i; that is:

$$i = i_1 + i_2 \ldots\ldots + i_n$$

$$i = \frac{v_1}{R_1} + \frac{v_2}{R_2} + \ldots\ldots + \frac{v_n}{R_n}$$

Summing amplifier

- This current will flow through R_f as no current flows into the input terminals of an ideal op-amp.
- So the output voltage V_{out} may now be determined by using ohm's law:

$$v_{out} = 0 - iR_f = -iR_f$$

$$v_{out} = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \ldots.. + \frac{R_f}{R_n} v_n \right)$$

$$v_{out} = -R_f \left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \ldots.. + \frac{v_n}{R_n} \right)$$

$$\text{If } R_1 = R_2 = \ldots = R_n = R_s$$

$$\boxed{v_{out} = -\frac{R_f}{R_s}(v_1 + v_2 + \ldots + v_n)}$$

Summing amplifier

- That is, the output voltage is a weighted sum of the input signals v_1, v_2……v_n.
- This circuit is therefore called as a **weighted summer.**
- Each summing coefficient may be independently adjusted by adjusting the corresponding ‘feed-in’ resistor (R_1 to R_n).

Summing amplifier

- The previous weighted summer has the constraint that all the summing coefficients are of the same sign.
- There can be an occasional need for summing signals with opposite signs.
- Such a function can be implemented using two op-amps as shown in fig. of next slide.
- Analysis can be done assuming ideal op-amps.

Summing amplifier

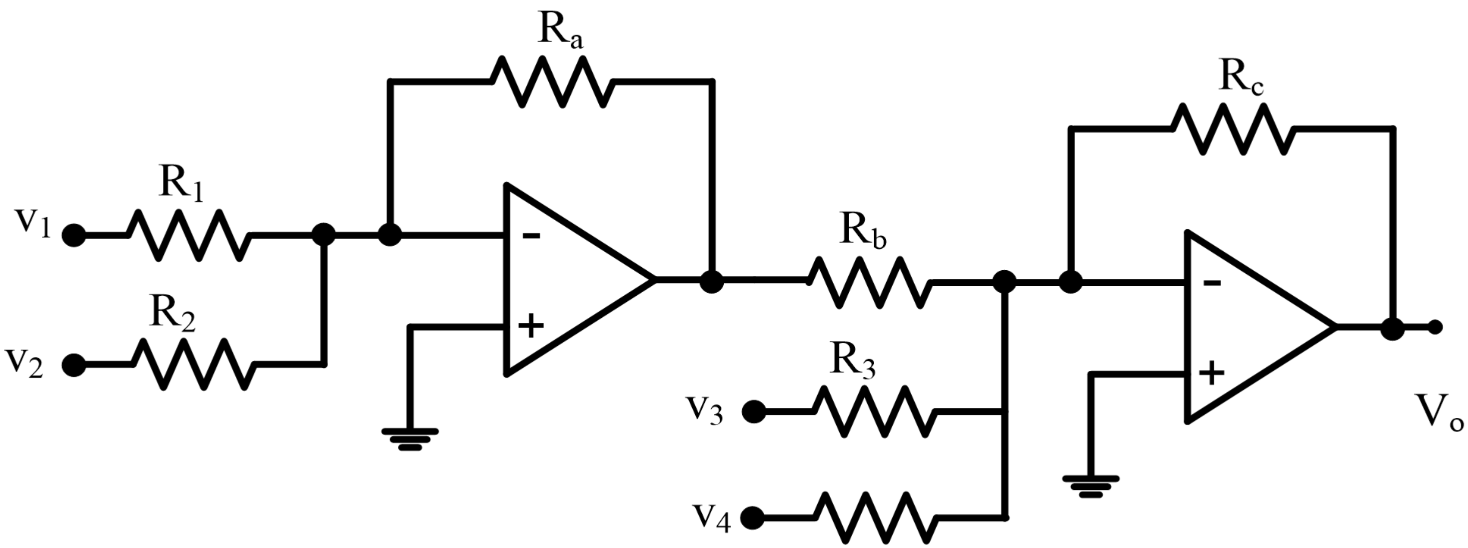


Fig.: A weighted summer capable of implementing summing coefficients of both signs.

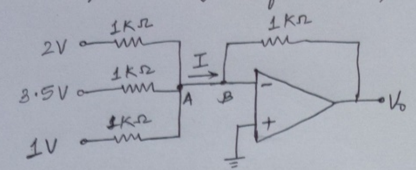
The output voltage is given by

$$v_o = v_1\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) + v_2\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) - v_3\left(\frac{R_c}{R_3}\right) - v_4\left(\frac{R_c}{R_4}\right)$$

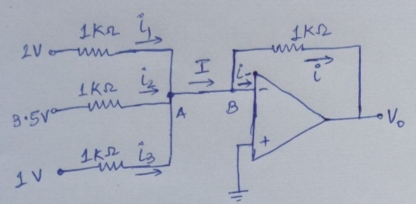
Students are encouraged to derive this equation by themselves

Numerical on summing amplifier

Q Determine the amount of current from point A to point B and also the output voltage of the op-amp.



Soln:



Here, $i_1 = \frac{2V}{1K\Omega} = 2mA$

$i_2 = \frac{3.5V}{1K\Omega} = 3.5mA$

$i_3 = \frac{1V}{1K\Omega} = 1mA$

$I = i_1 + i_2 + i_3$

so, $I = (2 + 3.5 + 1)mA = 6.5mA \Rightarrow \boxed{I = 6.5mA}$

applying KCL at node B

$I = i_- + i$

where $i_- = 0$

so, $I = i$

and $i = \frac{-V_{out}}{1K\Omega}$

$\Rightarrow V_{out} = -i \times 1K\Omega$

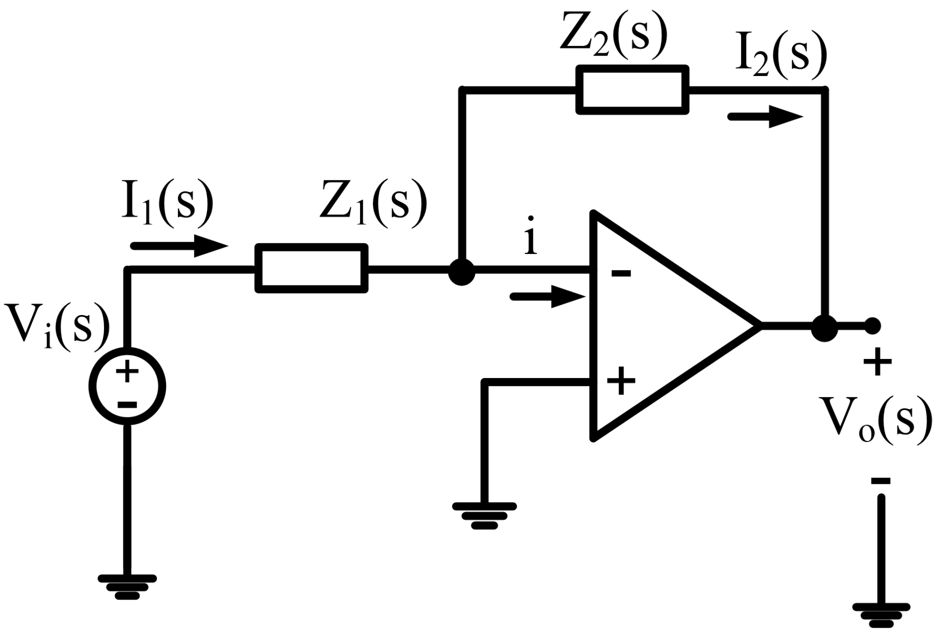
$\Rightarrow \boxed{V_{out} = 6.5V}$

Integrator & differentiator

- The op-amp circuit applications we have studied thus far utilized resistors in the op-amp feedback path and in connecting the signal source to the circuit, that is, in the feed-in path.
- As a result circuit operation has been (ideally) independent of frequency.
- By allowing the use of capacitors together with resistors in the feedback and feed-in paths of op-amp circuits, we open the door to a very wide range of useful and exciting applications of the op amp.

Inverting configuration with general impedances

- Consider the inverting closed-loop configuration with impedances $Z_1(s)$ and $Z_2(s)$ replacing resistors R_1 and R_2 respectively.
- The resulting circuit is shown in fig. below.
- For an ideal op amp, the closed-loop gain or the closed-loop transfer function is:



$$I_1(s) = i + I_2(s)$$

since, i=0;

so, $I_1(s) = I_2(s)$

and, $I_1(s) = \dfrac{V_i - V_-}{Z_1(s)}$

due to virtual ground, $V_- = 0$

so, $I_1(s) = \dfrac{V_i(s)}{Z_1(s)}$

thus, $I_2(s) = I_1(s) = \dfrac{V_i(s)}{Z_1(s)}$

and $V_o(s) = 0 - I_2(s) Z_2(s)$

$$\Rightarrow V_o(s) = -\frac{V_i(s) Z_2(s)}{Z_1(s)}$$

$$\boxed{\frac{V_o(s)}{V_i(s)} = -\frac{Z_2(s)}{Z_1(s)}}$$

Integrator

- By placing a capacitor in the feedback path (i.e., in place of Z_2 in previous figure) and a resistor at the input (in place of Z_1), we obtain the circuit of integrator as shown in figure here.

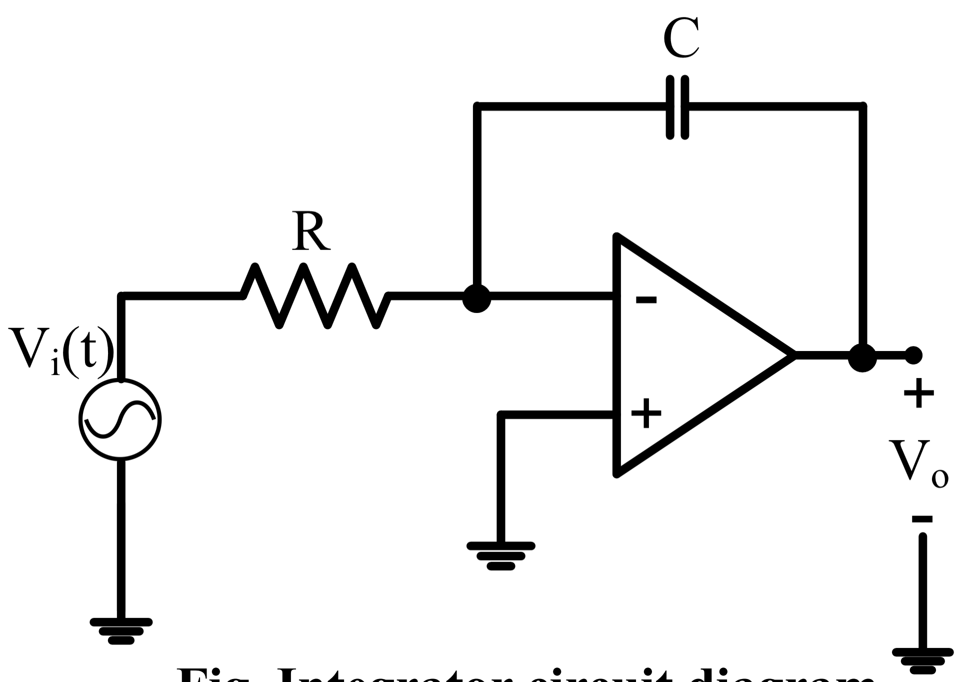
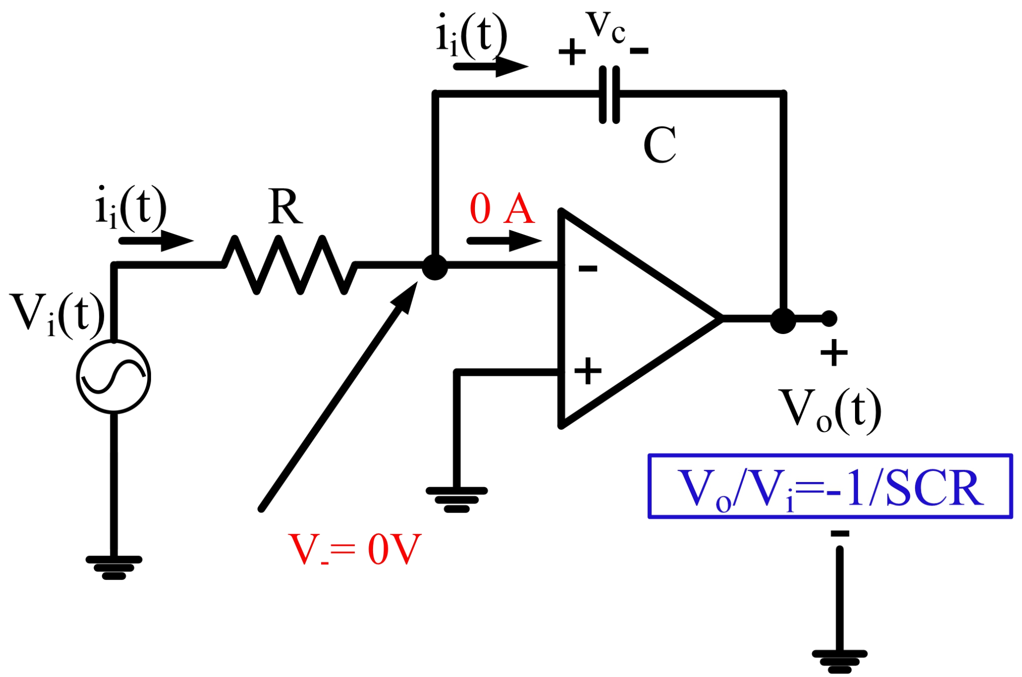


Fig. Integrator circuit diagram

Integrator

- Let the input be a time-varying function $v_i(t)$.
- The virtual ground at the inverting op-amp input causes $v_i(t)$ to appear across *R,* and thus the current $i_i(t)$ will be $v_i(t)$ /*R.*
- This current flows through the capacitor C, causing charge to accumulate on C.



Integrator

- If we assume that the circuit begins operation at time $t = 0$, then at an arbitrary time t the current $i_i(t)$ will have deposited on C a charge equal to $\int_0^t i_1(t)dt$.
- Thus the capacitor voltage $v_c(t)$ will change by $\frac{1}{C}\int_0^t i_1(t)dt$.
- If the initial voltage on C (at $t = 0$) is denoted V_c, then

$$v_c(t) = V_c + \frac{1}{C}\int_0^t i_1(t)dt$$

Integrator

- Now the output voltage $v_o(t) = -v_c(t)$; thus,

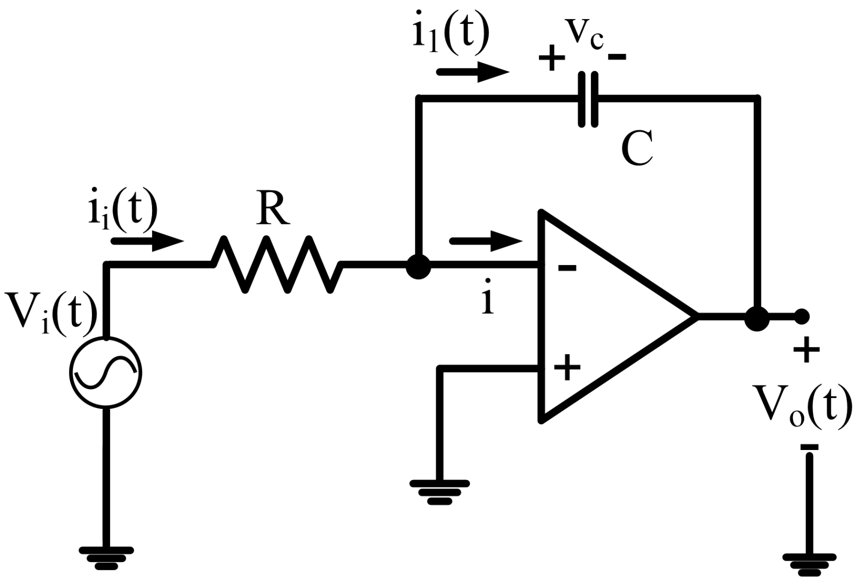
$$v_o(t) = -V_c - \frac{1}{CR}\int_0^t v_i(t)\,dt$$

- Thus the circuit provides an output voltage that is proportional to the time-integral of the input, with V_c being the initial condition of integration and *CR* the **integrator time-constant.**

- There is a negative sign attached to the output voltage, and thus this integrator circuit is also said to be an inverting integrator.

Integrator

Detailed analysis



$$i_i(t) = i + i_1(t)$$

since, i=0, so, $i_i(t) = i_1(t)$

and, $i_i(t) = \dfrac{V_i(t)}{R}$

voltage $v_c(t)$ is developed across capacitor C:

$$V_c(t) = \frac{1}{C}\int_0^t i_1(t)dt$$

assuming initial voltage on C as V_c

$$v_c(t) = V_c + \frac{1}{C}\int_0^t i_1(t)dt$$

$$\Rightarrow v_c(t) = V_c + \frac{1}{C}\int_0^t \frac{V_1(t)}{R}dt$$

$$\Rightarrow v_c(t) = V_c + \frac{1}{RC}\int_0^t V_1(t)dt$$

also, $v_o(t) = 0 - v_c(t)$

$$\boxed{v_o(t) = -V_c - \frac{1}{CR}\int_0^t v_i(t)dt}$$

Integrator

The operation of the integrator circuit can be described alternatively in the frequency domain by substituting $Z_1(s)=R$ and $Z_2(s)=1/SC$ to obtain the transfer function:

$$I_i(s) = i + I_1(s)$$

since, i=0; $I_i(s) = I_1(s)$

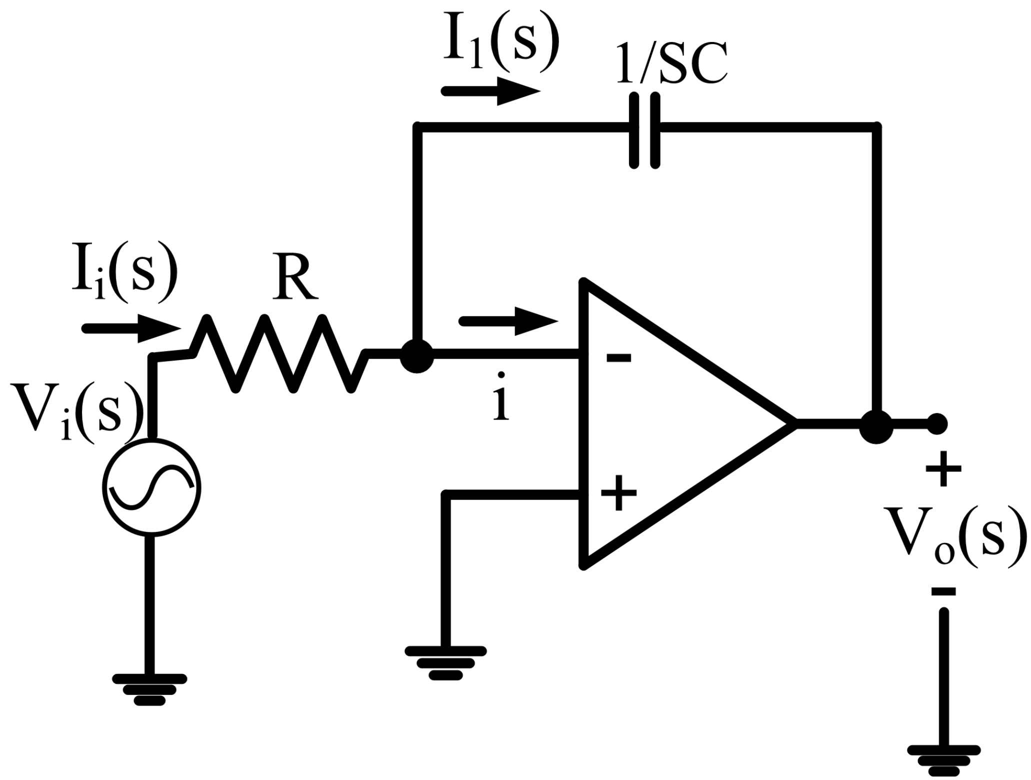
and, $I_i(s) = \dfrac{V_i(s)}{R}$

thus, $I_1(s) = I_i(s) = \dfrac{V_i(s)}{R}$

and $V_o(s) = 0 - \dfrac{I_1(s)}{SC}$

$$\Rightarrow V_o(s) = -\frac{V_i(s)}{SRC}$$

$$\boxed{\frac{V_o(s)}{V_i(s)} = -\frac{1}{SRC}}$$



Differentiator

- Interchanging the location of the capacitor and the resistor of the integrator circuit results in the circuit of differentiator.
- 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".
- 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 dependent on the rate of change of the input signal.

Differentiator

- Let the input be a time-varying function $v_i(t)$.
- The virtual ground at the inverting input terminal of the op-amp causes $v_i(t)$ to appear across *C*.
- Thus the current $i_i(t)$ through C will be $C(dv_i/dt)$.

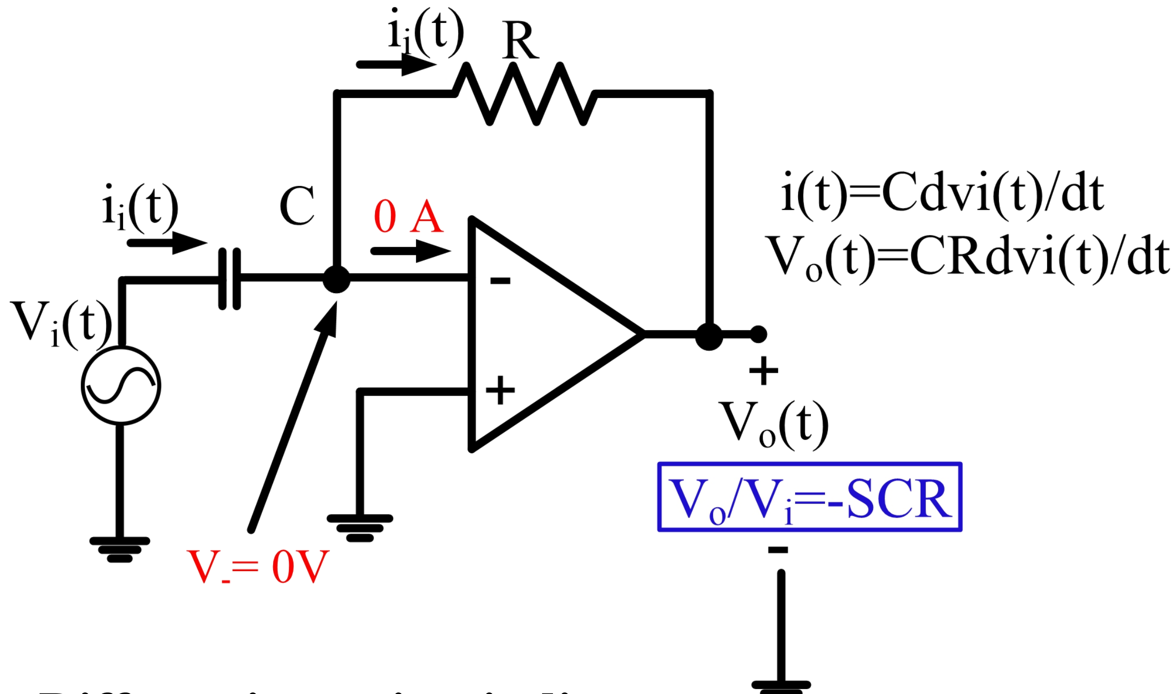


Fig. Differentiator circuit diagram

Differentiator

- This current also flows through the feedback resistor *R* providing at the op-amp output a voltage $v_o(t)$,

$$v_o(t) = -CR\frac{dv_i(t)}{dt}$$

- Thus, the circuit provides an output voltage that is proportional to the time-derivative of the input.
- The minus sign (–) indicates a 180^o phase shift because the input signal is connected to the inverting input terminal of the operational amplifier.
- *CR* is called as the **differentiator time-constant.**

Differentiator

Detailed analysis

$$i_i(t) = i + i_1(t)$$

Since, i = 0;

So, $i_i(t) = i_1(t)$

and, $i_i(t) = C\dfrac{dv_i(t)}{dt}$

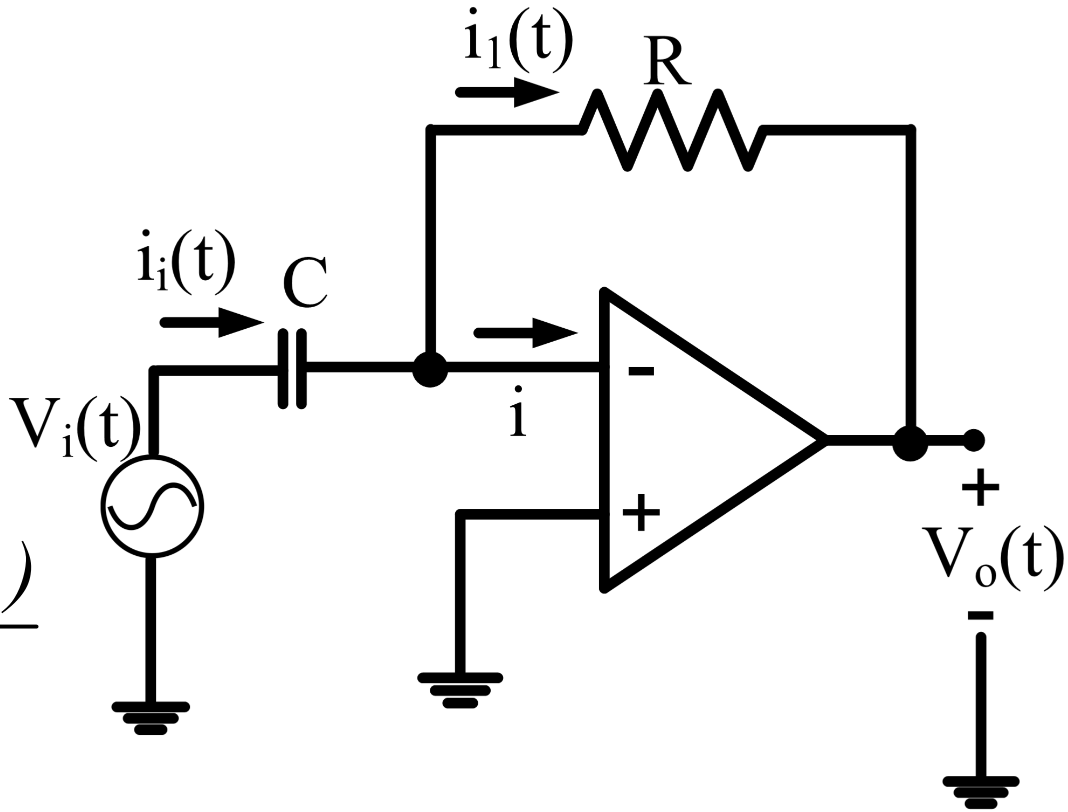
thus,

$$i_1(t) = i_i(t) = C\frac{dv_i(t)}{dt}$$

also,

$$v_o(t) = 0 - i_1(t)R$$

$$\Rightarrow v_o(t) = -RC\frac{dv_i(t)}{dt}$$



Differentiator

The operation of the integrator circuit can be described alternatively in the frequency domain by substituting $Z_1(s)=1/SC$ and $Z_2(s)=R$ to obtain the transfer function:

$I_i(s) = i + I_1(s)$

since, i=0;

so, $I_i(s) = I_1(s)$

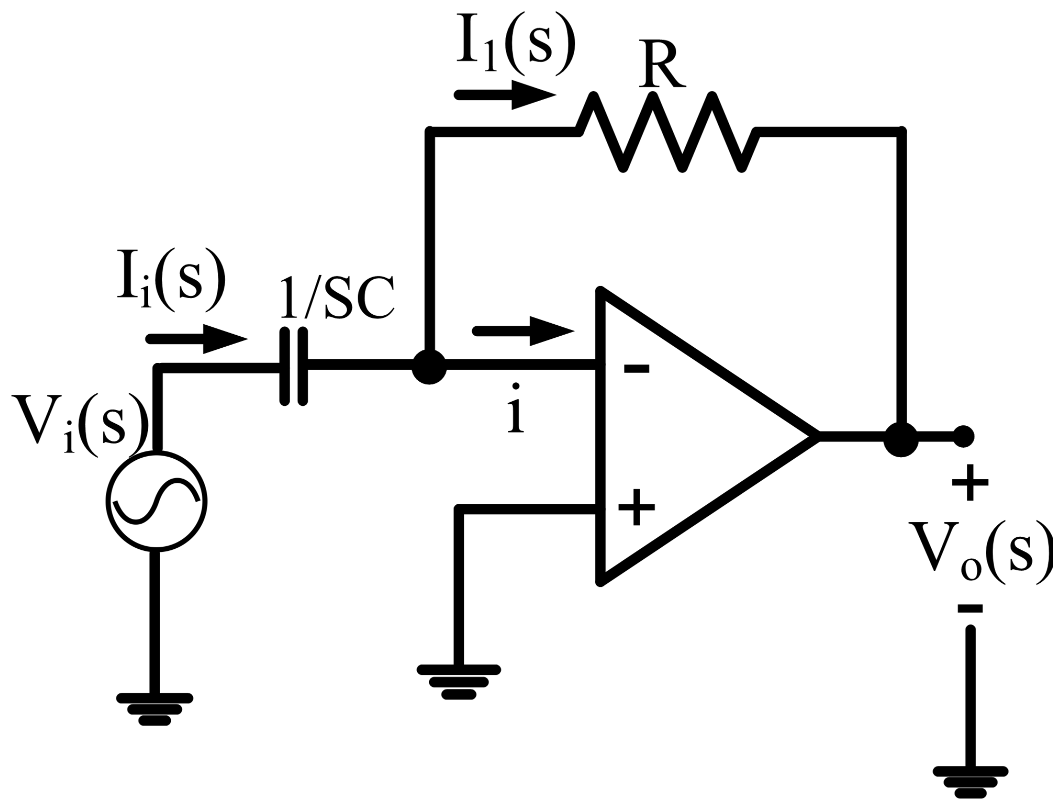
and, $I_i(s) = V_i(s)SC$

thus, $I_1(s) = I_i(s) = V_i(s)SC$

and $V_o(s) = 0 - I_1(s)R$

$$\Rightarrow V_o(s) = -SRCV_i(s)$$

$$\boxed{\frac{V_o(s)}{V_i(s)} = -SRC}$$



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 dependent upon the RC time constant of the Resistor/Capacitor combination.