Operational Amplifiers and Applications

MODULE 03

Introduction to Operational Amplifier :-

An operational amplifier is a high gain electronic voltage amplifier with two inputs and a single output. Operational amplifiers (op-amp) were used to primarily perform mathematical operations such as addition, subtraction, integration and differentiation.

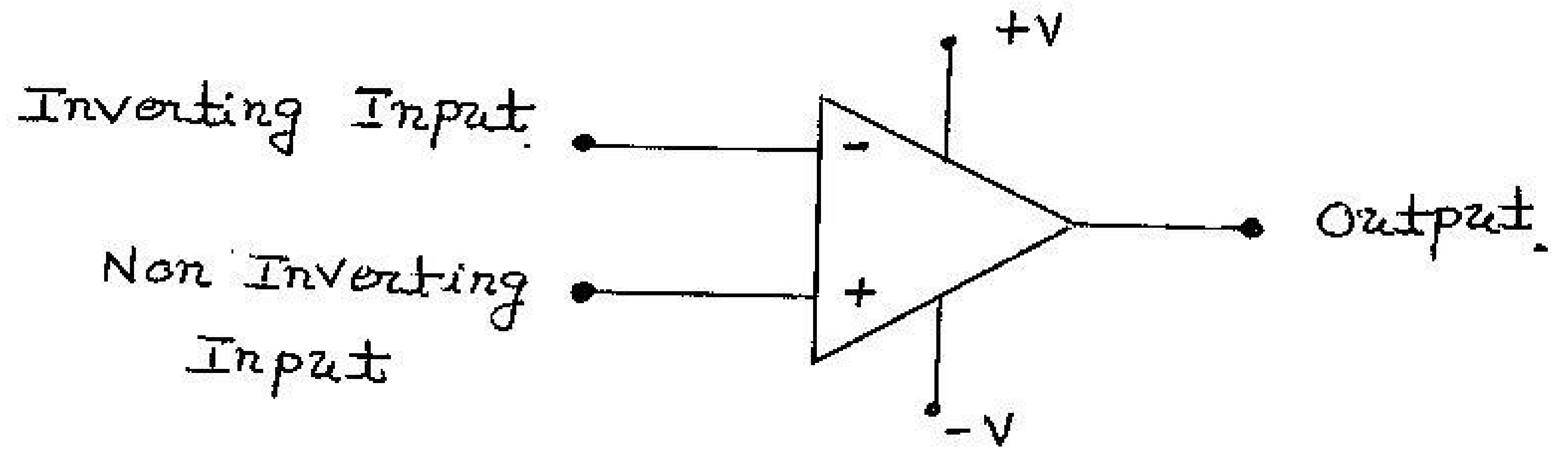


Figure above shows the circuit symbol of op-amp. It has two input terminals, the inverting input and the non inverting input, and one output terminal. Most op-amps Work with two dc supply voltages, one positive and the other negative as shown in the figure.

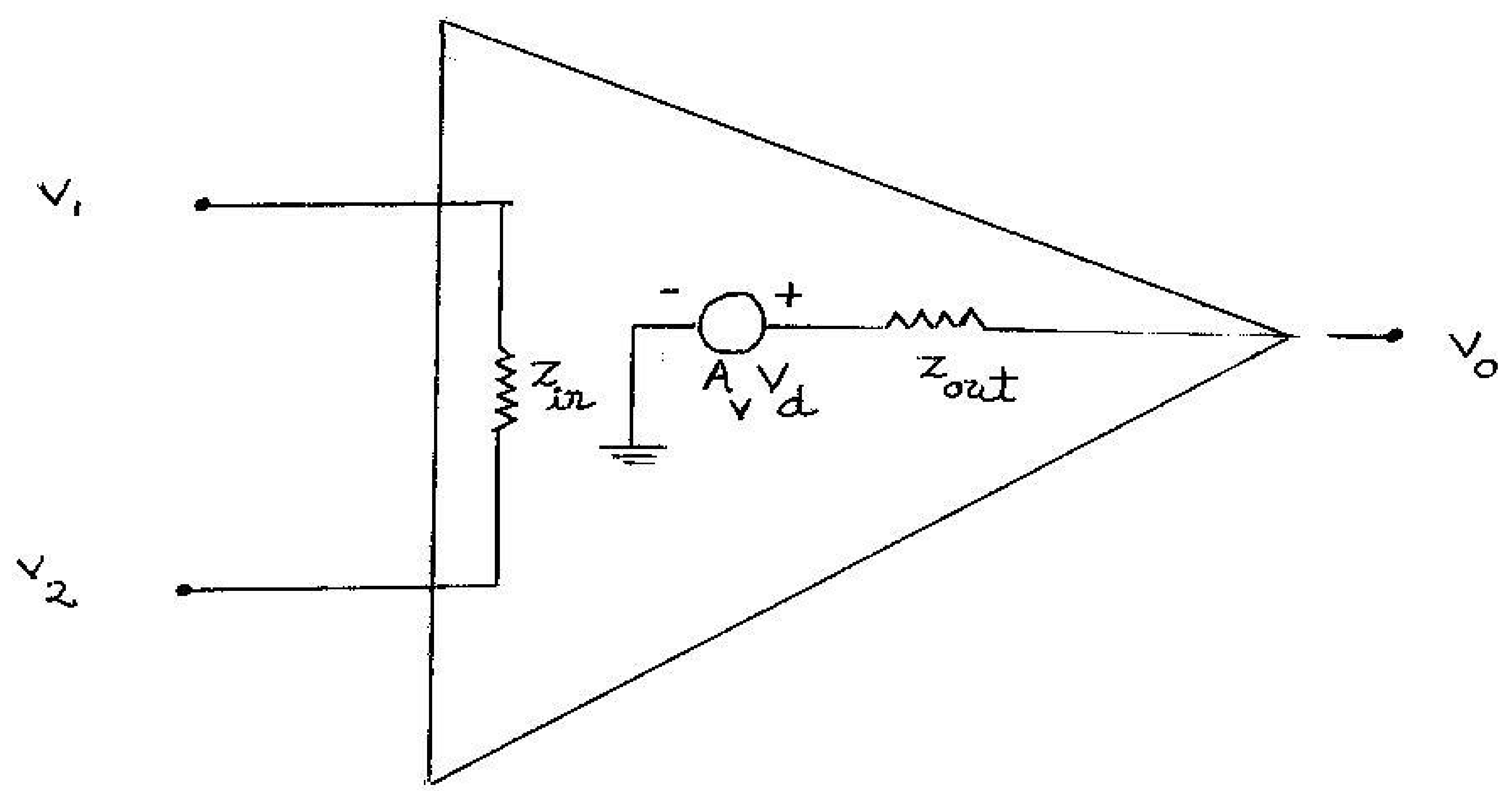


Figure above shows the equivalent circuit of op-amp. The output voltage V_o is given by

$$V_o = A_V V_d$$

$$= A_V (V_1 \sim V_2)$$

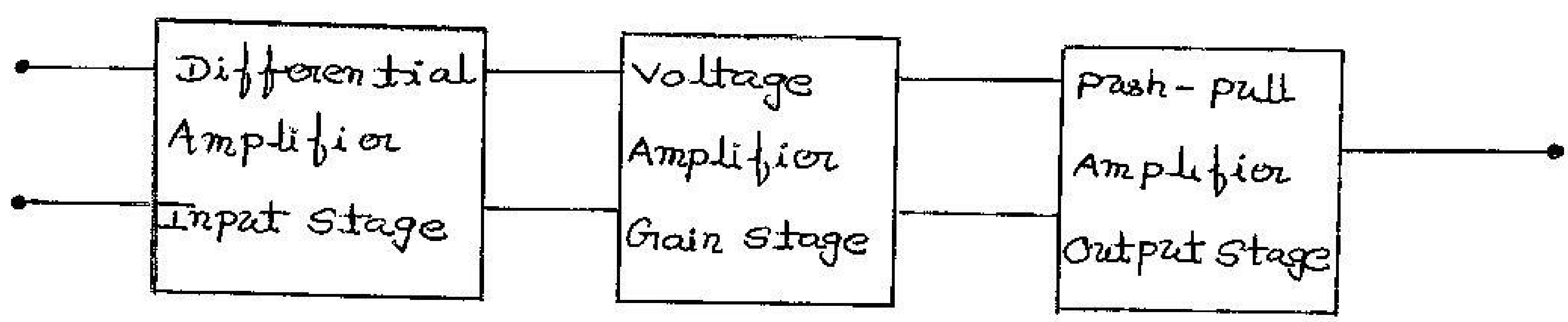
where,

A_V = open loop voltage gain

V_d = difference between the voltage at input terminals

Therefore op-amp amplifies the difference between the input voltages. The Z_{in} is the input impedance of the op-amp. The Z_{out} is the output impedance of the op-amp.

Internal Block Diagram of an op-amp



A typical op-amp contains the following three stages:

1. Input Stage :- The input stage requires high input impedance and low output impedance. The requirement

is achieved by using a differential amplifier. The function of the differential amplifier is to amplify the difference between the input signals. This stage provides most of the Voltage gain required.

2. Gain Stage :- The overall gain requirement of the op-amp is very high. The input stage alone cannot provide such a high gain. The main function of the gain stage is to provide the additional gain required. The gain stage practically contain a chain of cascaded amplifiers.

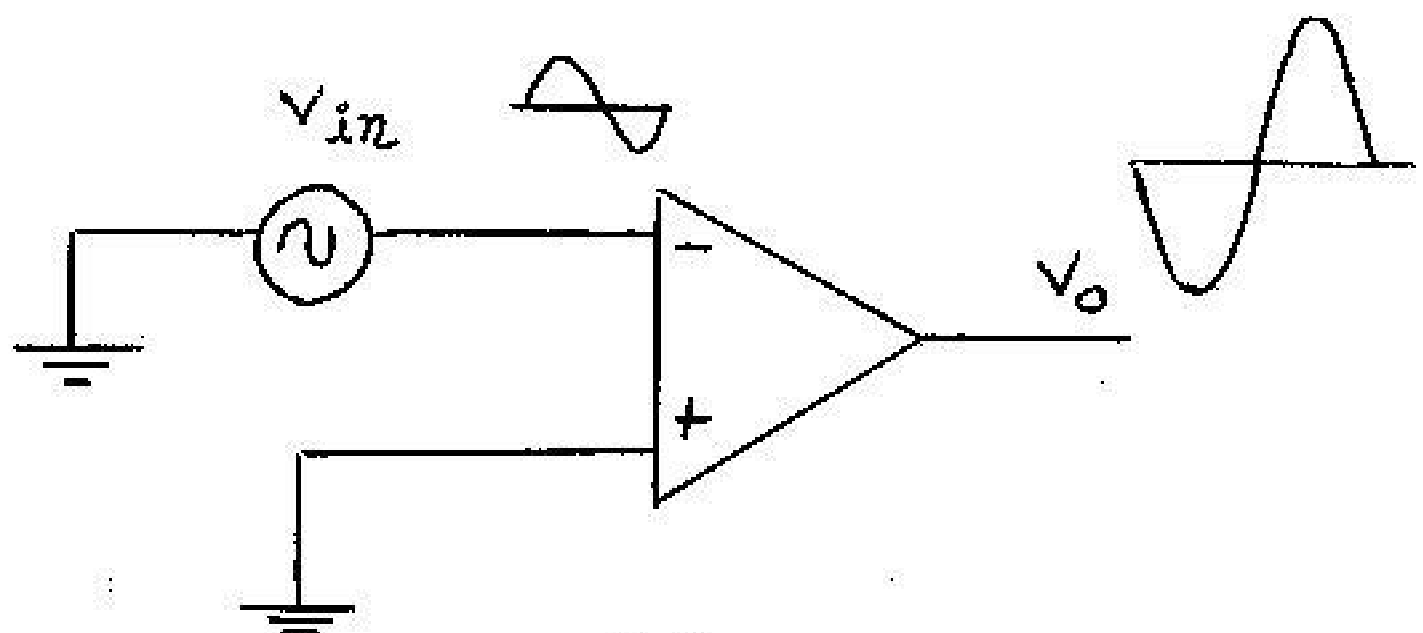
3. Output Stage :- The basic requirement of this stage is low output impedance and high current sourcing capability. The push pull amplifier meets the requirements and is used in the output stage.

Op-amp Input Signal Modes :-

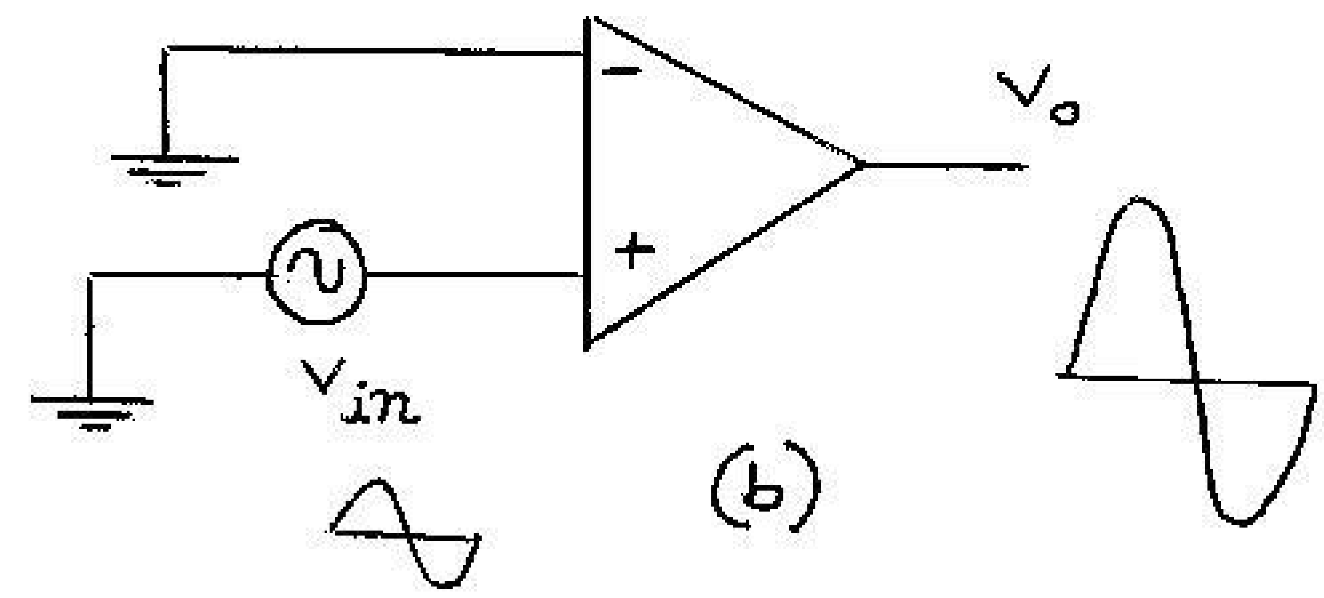
For op-amps we have two input signal modes. They are the differential mode and common mode.

In the differential mode either one signal is applied to an input with the other input grounded or two opposite polarity signals are applied to the inputs.

In the single ended differential mode, one input is grounded and a signal voltage is applied to the other input as shown in the figure below:



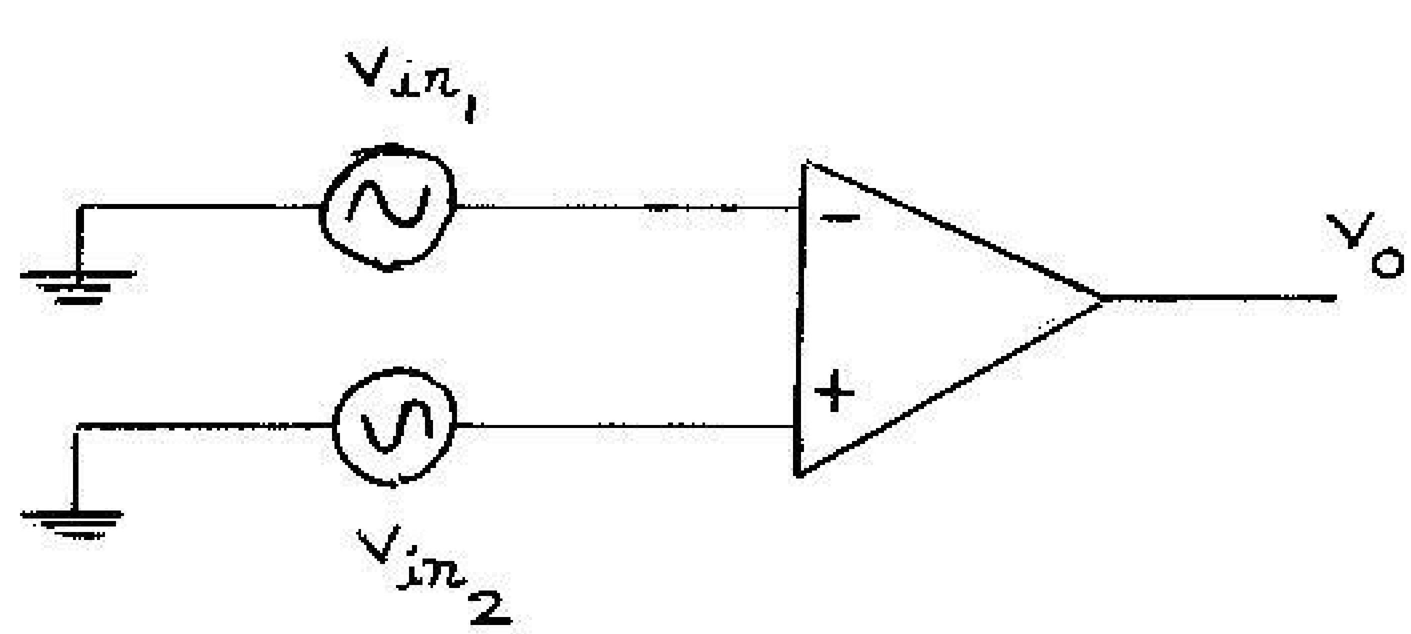
(a)



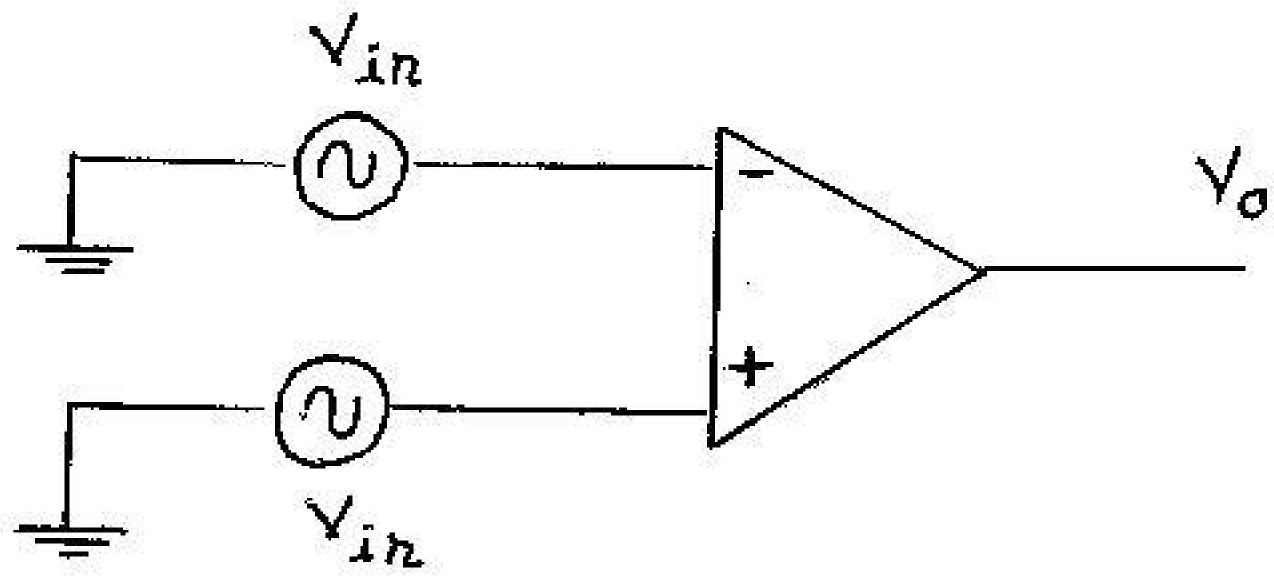
(b)

In the case when the signal voltage is applied to the inverting input as in figure (a), an inverted amplified signal voltage appears at the output. In case, when the signal voltage is applied to the non inverting input as in figure (b), a non inverted amplified signal voltage appears at the output.

In the double ended differential mode, two opposite polarity signals are applied to the inputs as shown in figure below: The difference between the two input voltages are amplified and appears at the output.



In common mode, the two signal voltages of same phase, frequency and magnitude are applied to the two inputs as shown in the figure below.



When equal input signals are applied to both inputs, they tend to cancel resulting in a zero output voltage. This action is called common mode rejection.

Op-amp Parameters :-

1. Common Mode Rejection Ratio :- Unwanted signals or noise appearing with same polarity on both lines of input are common mode signals and are cancelled by the op-amp and donot appear on the output. The measure of the op-amp's ability to reject common mode signals is expressed in terms of Common Mode Rejection Ratio (CMRR). The CMRR is defined as follows :

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

where A_{ol} is the open loop differential gain and the A_{cm} is the common mode gain.

Practical op-amps exhibit a very small common mode voltage gain and a very high differential mode voltage gain. The higher the differential gain with respect to the common mode gain the better the performance of the op-amp in terms of common mode rejection. In other words, higher the value of CMRR the lower will be the value of common mode gain.

2. <u>Maximum Output Voltage Swing</u> $V_{o(p-p)}$:- This parameter indicates the maximum limit of the peak output voltage. The ideal limit is $\pm V_{cc}$, where $+V_{cc}$ and $-V_{cc}$ are the DC supply voltage of the op-amp. For practical opamps the limit approaches the ideal value i,e if $\pm V_{cc} = \pm 12V$, then $V_{o(p-p)} \simeq \pm 10V$.

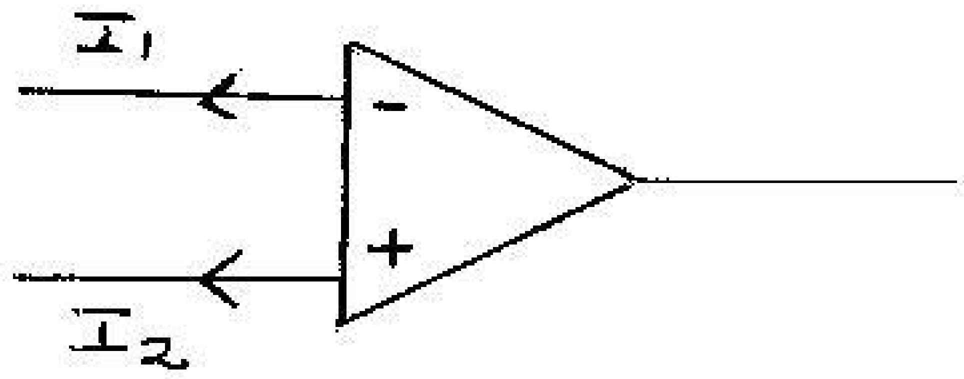
3. <u>Input Offset Voltage</u> :- The op-amp produces a small output voltage for zero input voltage. The input offset voltage V_{os} is the differential DC voltage between the input required to force the output to zero volts. Typical values of input offset voltage are in the range of 2 mV or less.

4. <u>Input Bias Current</u> :- The differential amplifier at the input stage of the op-amp has two inputs. The two input terminals are nothing but the base terminals

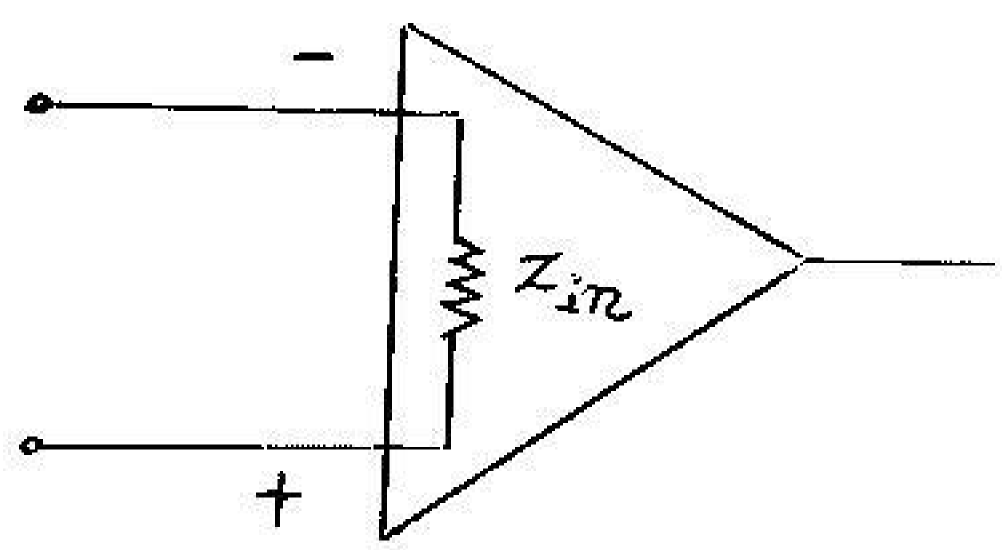
[illegible]

of the two transistors. Thus the input currents are the base currents. The input bias current is the DC current supplied by the inputs of the amplifier to properly operate the input stage. The input bias current is defined as the average of the two base currents.

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



5. Input Impedance :- The input impedance in the differential mode is the total resistance between the inverting and the non inverting inputs as shown below:

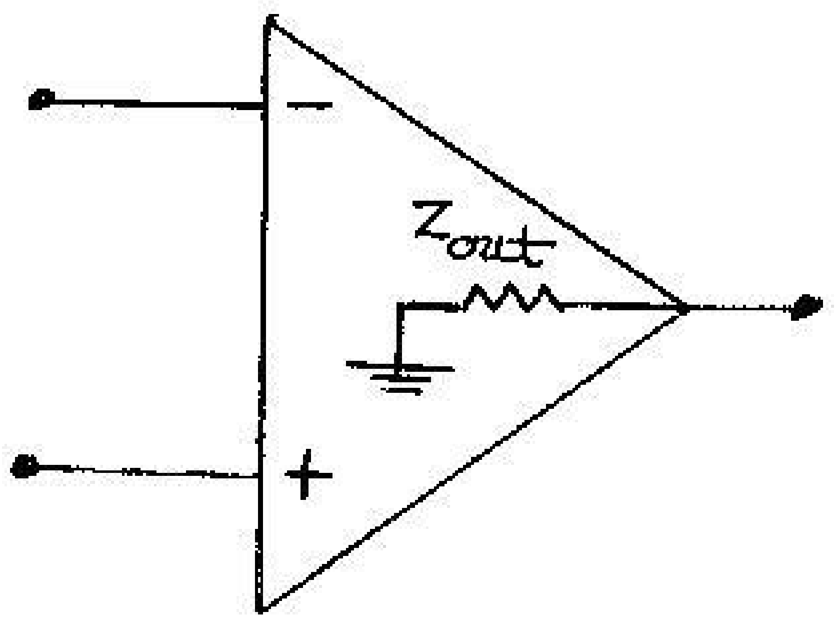


The input impedance in differential mode is obtained by the ratio of change in the differential input voltage and change in the bias current.

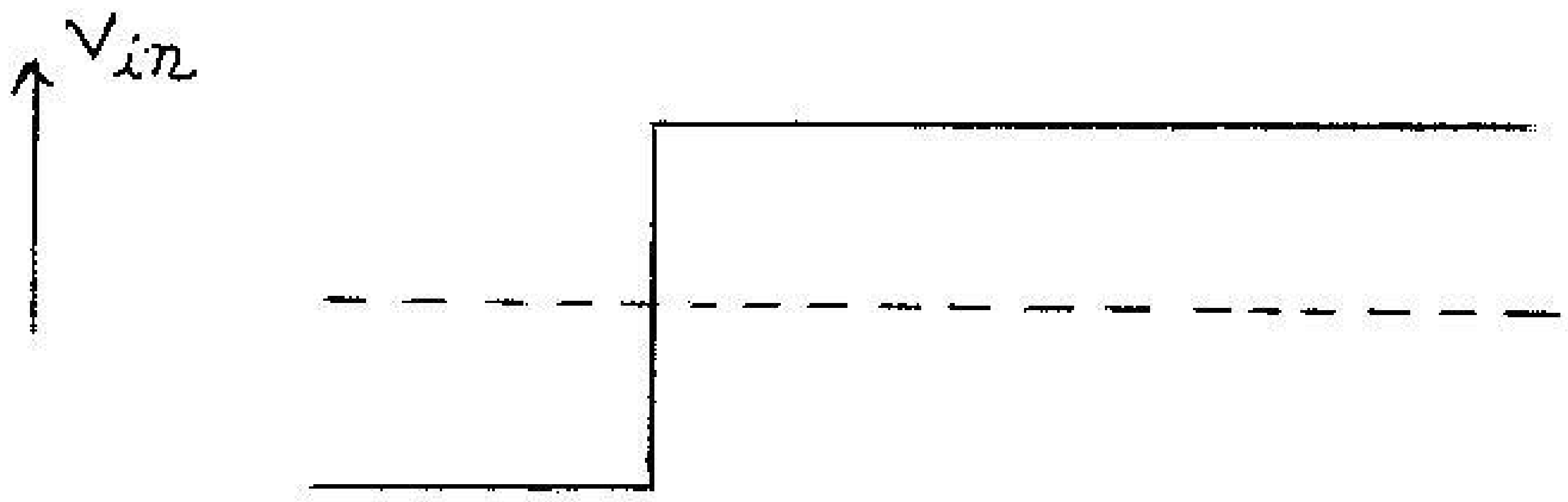
6. Input offset current :- The input offset current is the difference of the input bias currents expressed as an absolute value.

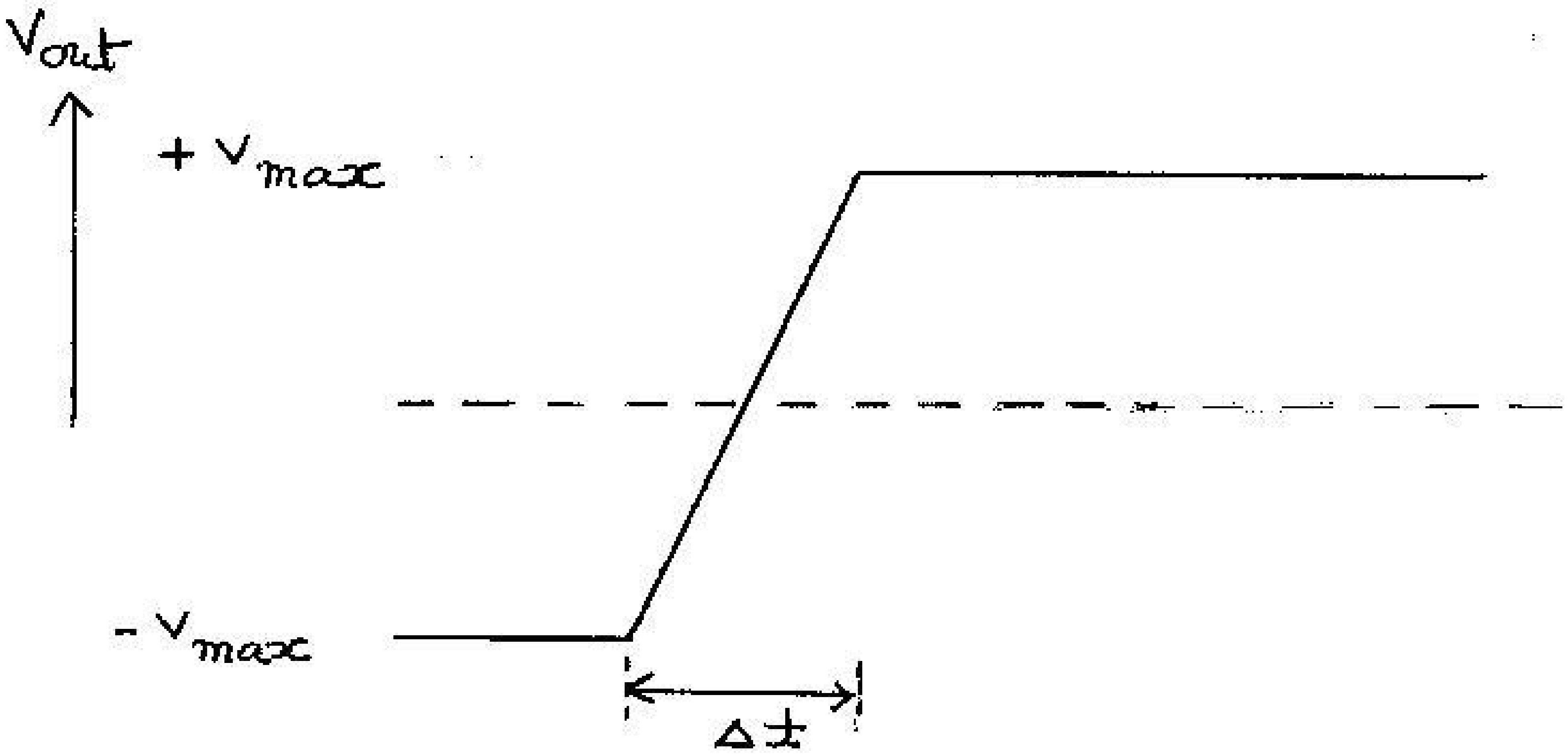
$$I_{OS} = |I_1 - I_2|$$

7 <u>Output Impedance :-</u> The output impedance is the resistance viewed from the output terminal of the op-amp as shown below :



8 <u>Slew Rate :-</u> The maximum rate of change of the output voltage in response to a step input voltage is called the slew rate of the op-amp.





A certain time interval Δt, is required for the output voltage to go from $-V_{max}$ to $+V_{max}$ when step input is applied.

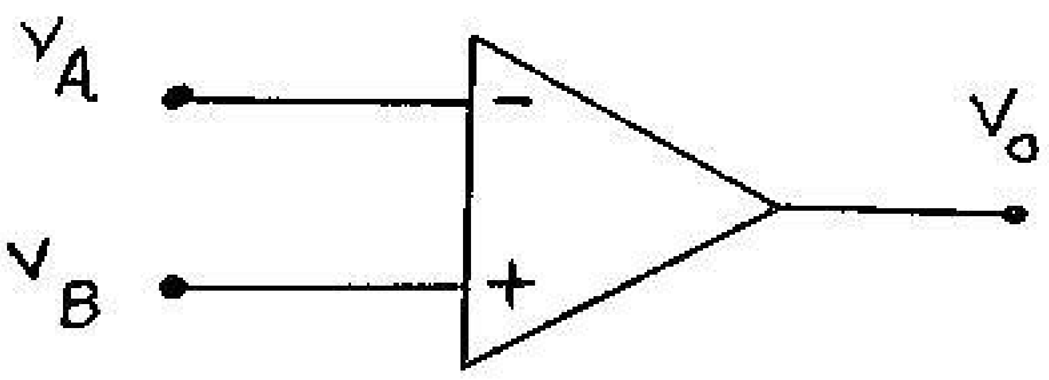
$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

Characteristics of an ideal op-amp

An ideal op-amp exhibits the following characteristics

1. Infinite voltage gain
2. Infinite input impedance
3. Zero output impedance
4. Zero input offset voltage
5. Zero input offset current
6. Infinite CMRR
7. Infinite Slew rate
8. Infinite Bandwidth.

Concept of virtual ground



Let V_A and V_B be the voltage at the input terminals. We know that

$$V_o = A_v (V_A - V_B)$$

The A_V is the differential voltage gain and its ideal value is infinity

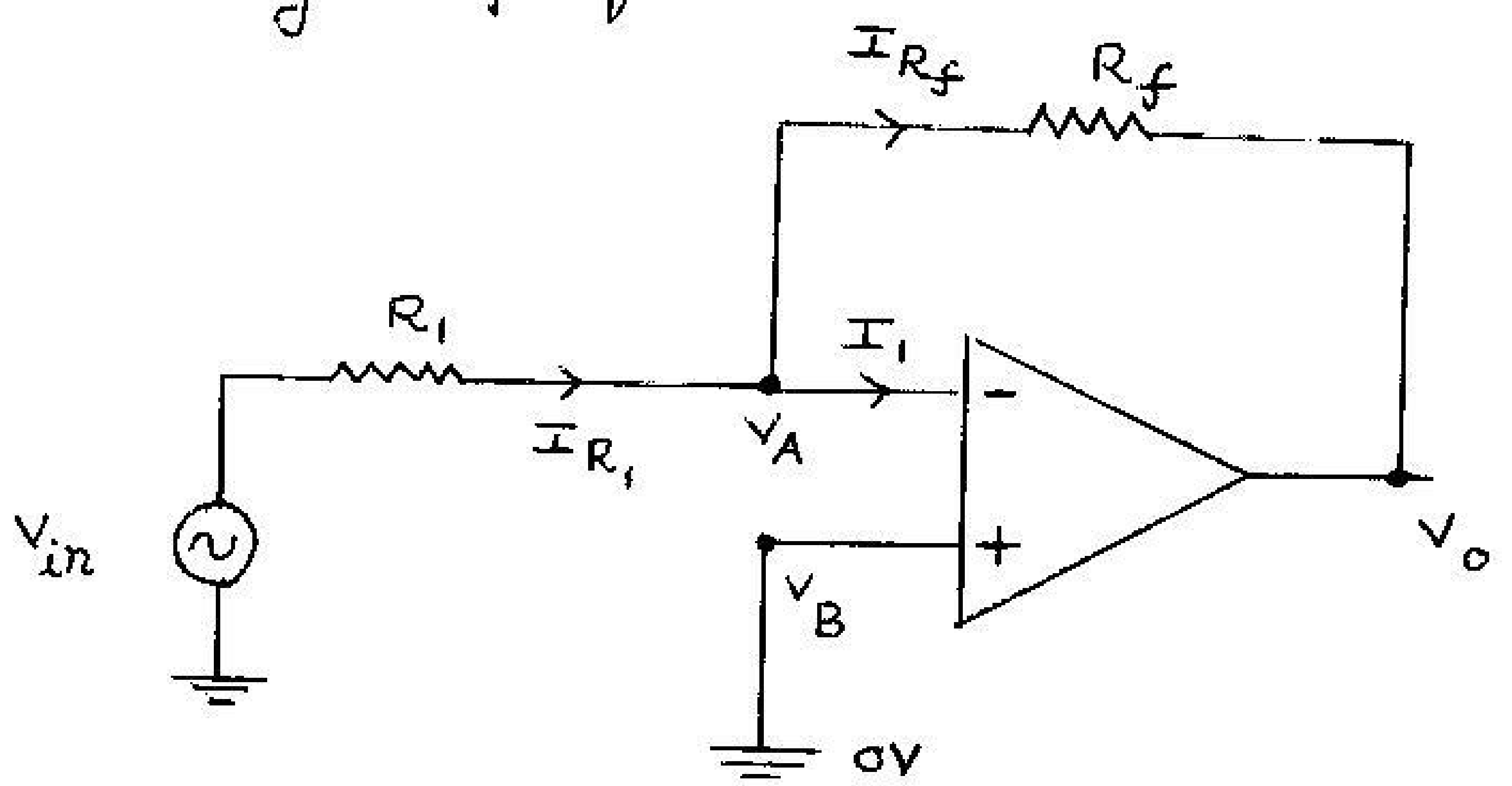
$$A_V = \infty = \frac{V_o}{V_A - V_B}$$

$$\Longrightarrow \quad V_A - V_B = 0$$

This concept is called as virtual ground.

Op-amp as an inverting amplifier

An inverting amplifier is a circuit whose output is amplified and inverted with respect to the input. Figure below shows the circuit diagram of an inverting amplifier.



By the concept of virtual ground, we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have,

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_1 = 0$

Hence $I_{R_1} = I_{R_f}$

$$\frac{V_{in} - V_A}{R_1} = \frac{V_A - V_o}{R_f}$$

Substituting $V_A = 0V$ we have

$$\frac{V_{in}}{R_1} = \frac{-V_o}{R_f}$$

$$\therefore \boxed{V_o = -\left(\frac{R_f}{R_1}\right) V_{in}}$$

The term (R_f/R_1) is called the gain of the inverting amplifier. The negative sign indicates that the output is inverted with respect to the input.

Op-amp as an inverting adder (summer)

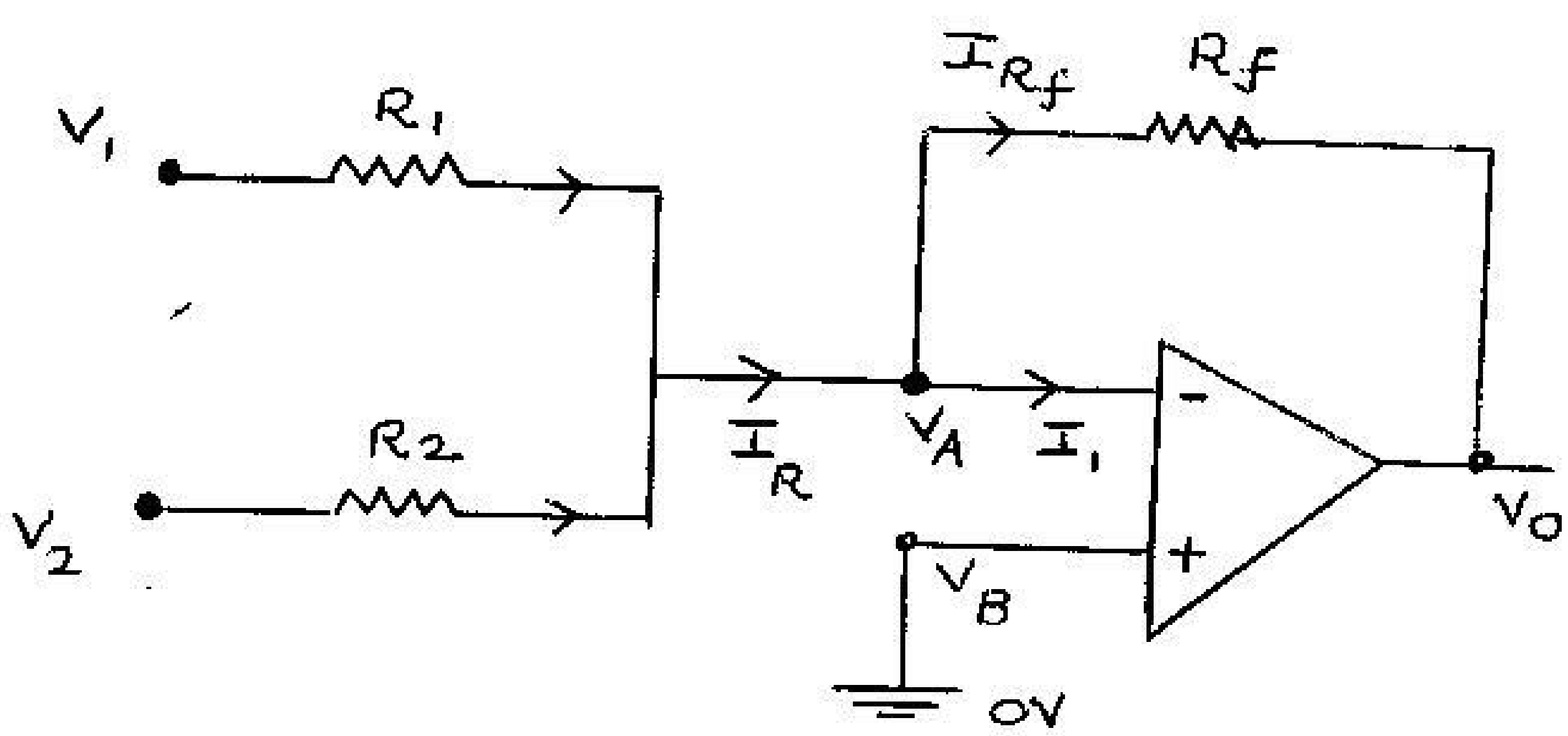


Figure above shows the circuit diagram of an inverting adder. By the concept of virtual ground we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have,

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_1 = 0$

Hence

$$I_R = I_{R_f}$$

$$\frac{V_1 - V_A}{R_1} + \frac{V_2 - V_A}{R_2} = \frac{V_A - V_o}{R_f}$$

Substituting $V_A = 0$ we have

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = \frac{-V_o}{R_f}$$

$$\therefore \quad V_o = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2\right]$$

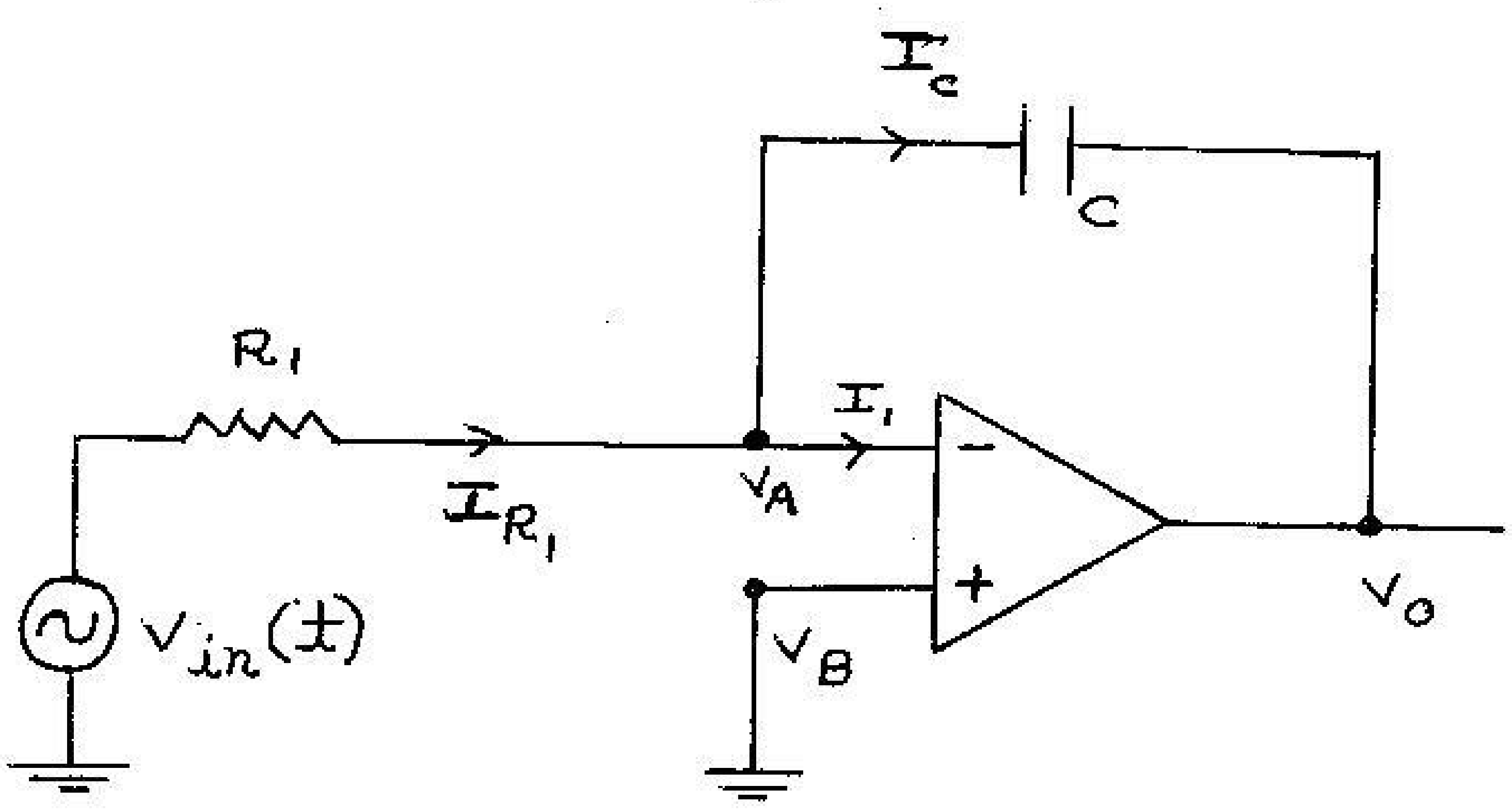
If $R_1 = R_2 = R_f$ is chosen, then we have,

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

Since the output of the circuit is equal to negative of sum of input voltages, the circuit is called as the inverting summer

op-amp as an integrator :-

An integrator is a circuit, in which the output voltage is proportional to the integral of the input voltage. Figure below shows the circuit diagram of the integrator using op-amp



By the concept of virtual ground, we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have

$$V_A = 0\ V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_1 = 0$.

Hence $$I_{R_1} = I_C$$

$$\frac{V_{in} - V_A}{R_1} = C \frac{d}{dt}(V_A - V_o)$$

Substituting $V_A = 0$, we have

$$\frac{V_{in}(t)}{R_1} = -c\,\frac{dV_o}{dt}$$

or $$\frac{dV_o}{dt} = \frac{-1}{R_1 C}\, V_{in}(t)$$

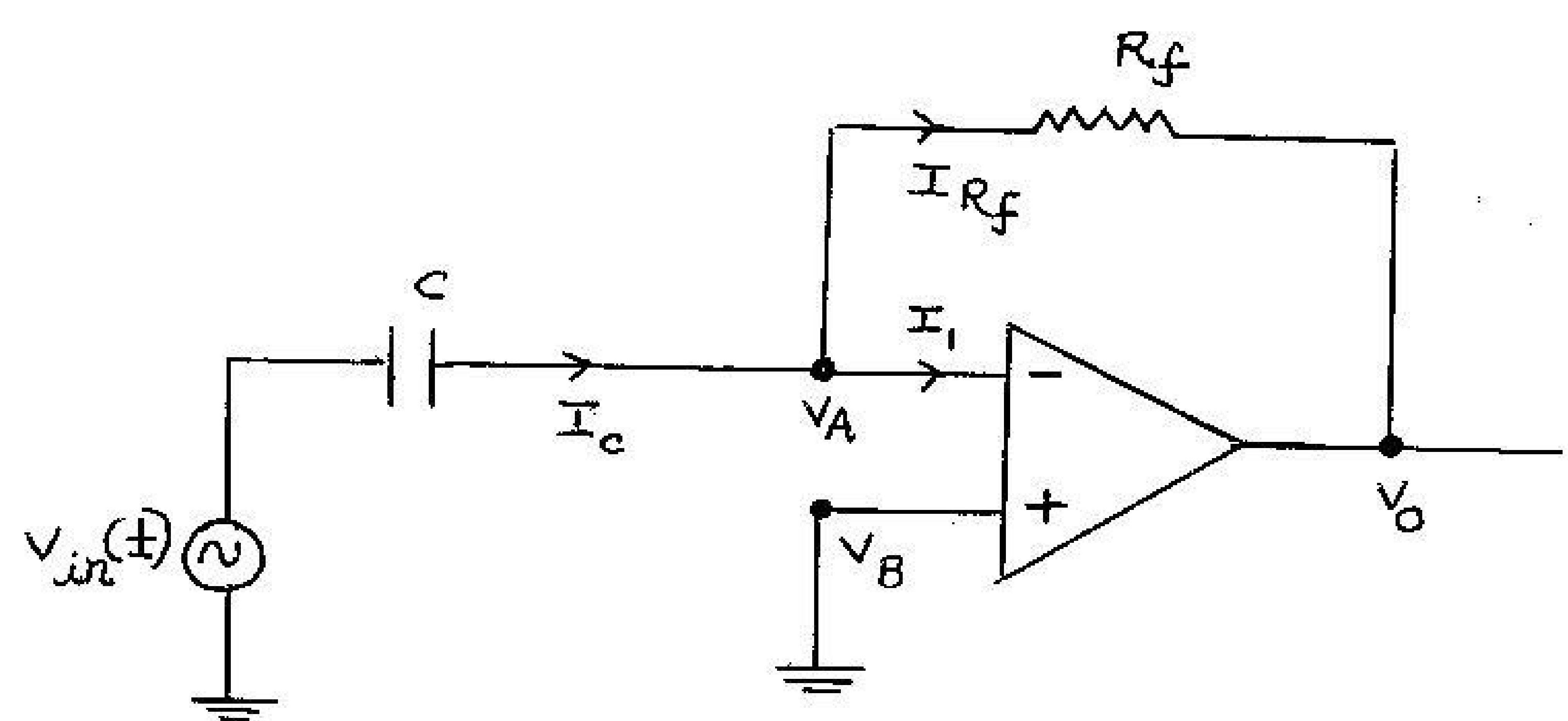
Integrating on both sides w.r.t t

$$V_o = -\frac{1}{R_1 C}\int_0^t V_{in}(t)\, dt$$

---

op-amp as a differentiator

A differentiator is a circuit, in which the output voltage is proportional to the time derivative of the input voltage. Figure shows the circuit diagram of a differentiator using op-amp.



By the concept of virtual ground, we have

$$V_A - V_B = 0$$

Since V_B is grounded, $V_B = 0V$. Thus we have

$$V_A = 0V$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_1 = 0$

Hence $I_C = I_{R_f}$

$$C \frac{d}{dt}\{V_{in}(t) - V_A\} = \frac{V_A - V_o}{R_f}$$

Substituting $V_A = 0$ we have,

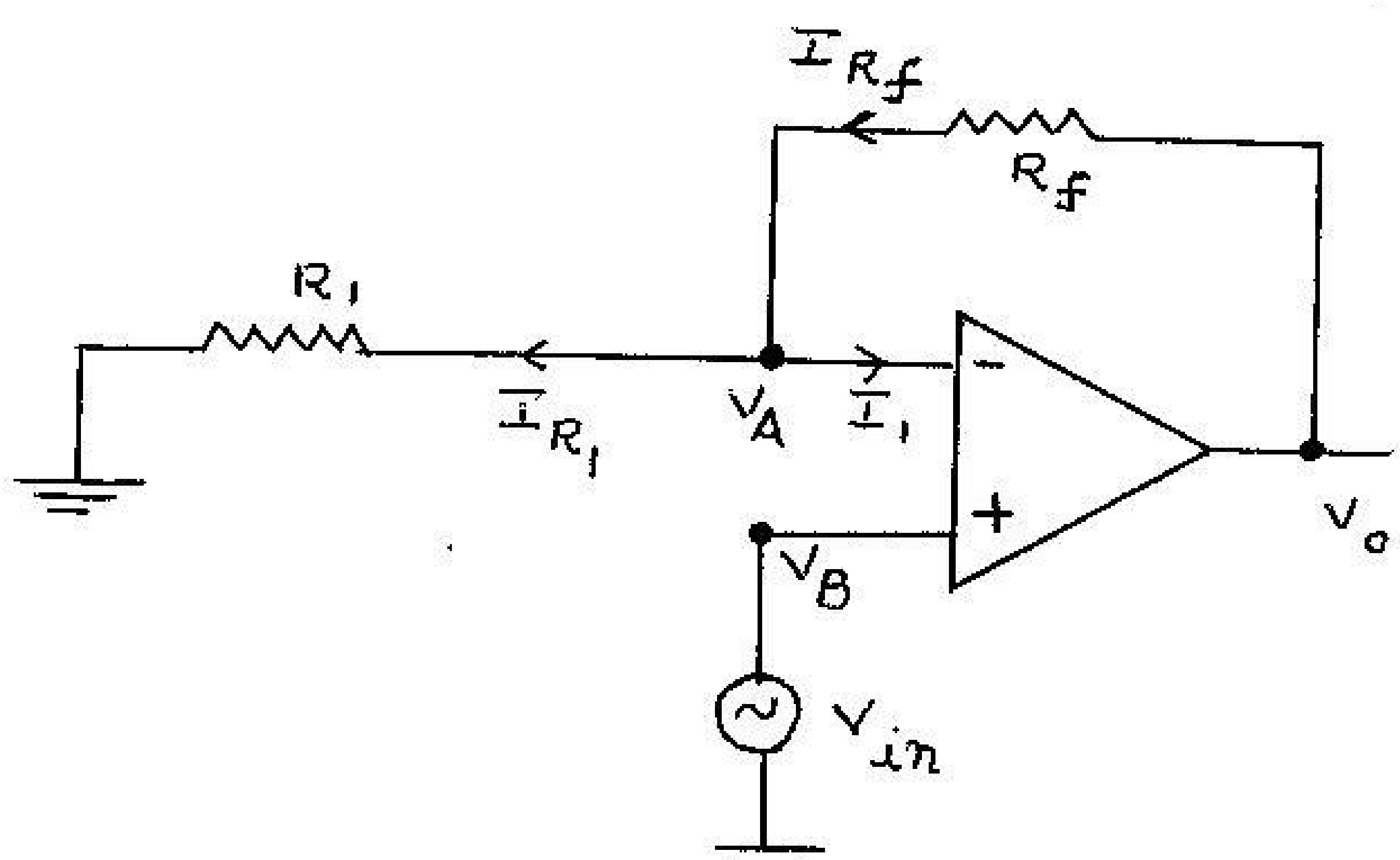
$$C \frac{d}{dt} V_{in}(t) = \frac{-V_o}{R_f}$$

or

$$V_o = -R_f C \frac{d}{dt} V_{in}(t)$$

Op-amp as a non inverting amplifier :-

Figure below shows the circuit diagram of a non inverting amplifier.



By the Concept of virtual ground we have

$$V_A - V_B = 0$$

Since V_B is maintained at a voltage V_{in} we have

$$V_A = V_B = V_{in}$$

Since the op-amp has infinite input impedance, it does not draw any current. Hence $I_1 = 0$.

Hence

$$I_{R_f} = I_{R_1}$$

$$\frac{V_o - V_A}{R_f} = \frac{V_A - 0}{R_1}$$

$$\frac{V_o}{R_f} = \frac{V_A}{R_f} + \frac{V_A}{R_1} = V_A \left[\frac{1}{R_f} + \frac{1}{R_1}\right]$$

Substituting $V_A = V_{in}$ we have

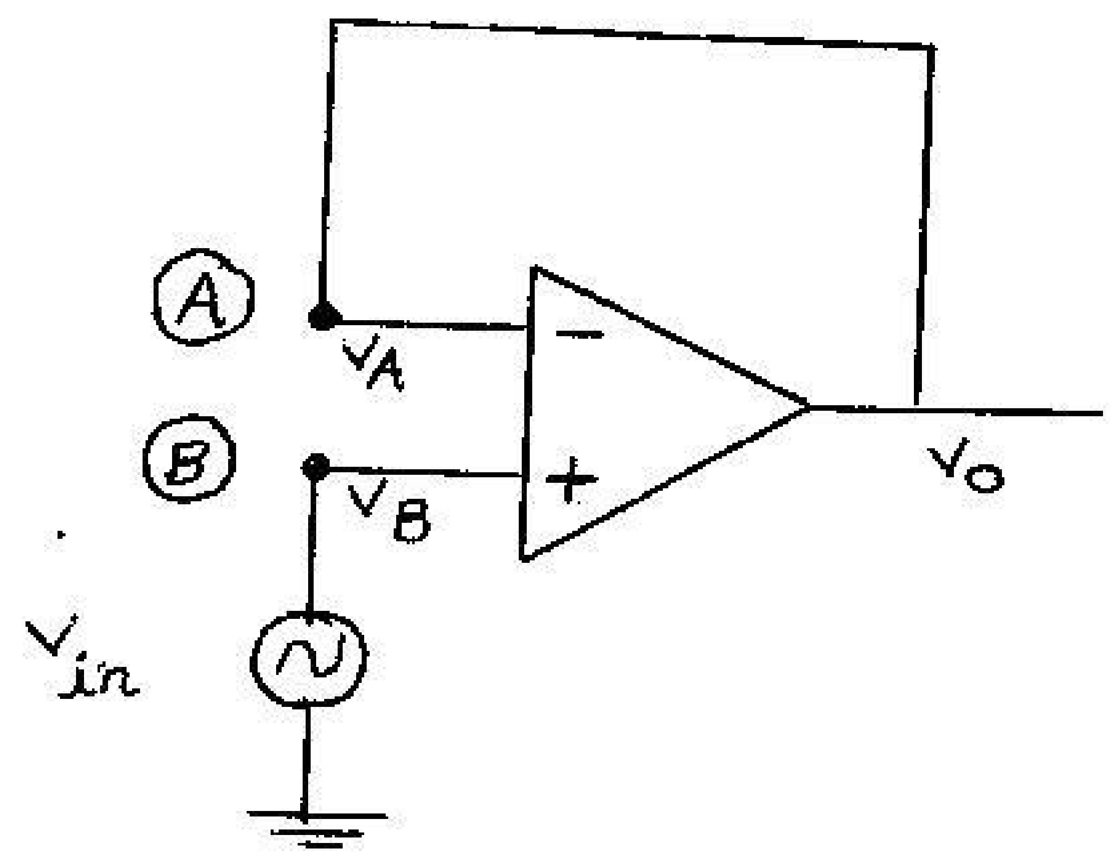
$$\frac{V_o}{R_f} = V_{in}\left[\frac{1}{R_f} + \frac{1}{R_1}\right]$$

$$\therefore \quad V_o = V_{in}\left(1 + \frac{R_f}{R_1}\right).$$

The term $\left(1 + \frac{R_f}{R_1}\right)$ is called gain of the non inverting amplifier.

op-amp as a voltage follower :-

A voltage follower is a circuit in which output voltage is : same as the input voltage. Figure below shows the circuit of voltage follower.



The node B is maintained at a potential V_{in}. So

$V_B = V_{in}$

By the concept of virtual ground we have

$$V_A - V_B = 0$$

Since V_B is equal to V_{in}, we have

$$V_A = V_{in}$$

The node A is directly connected to the output. Hence

$V_o = V_A$

$$\therefore \quad V_o = V_{in}$$

Thus the output voltage is equal to the input voltage

op-amp as a comparator :-

A comparator is a circuit which compares a signal voltage applied at one input of the op-amp with a known reference voltage at other input.

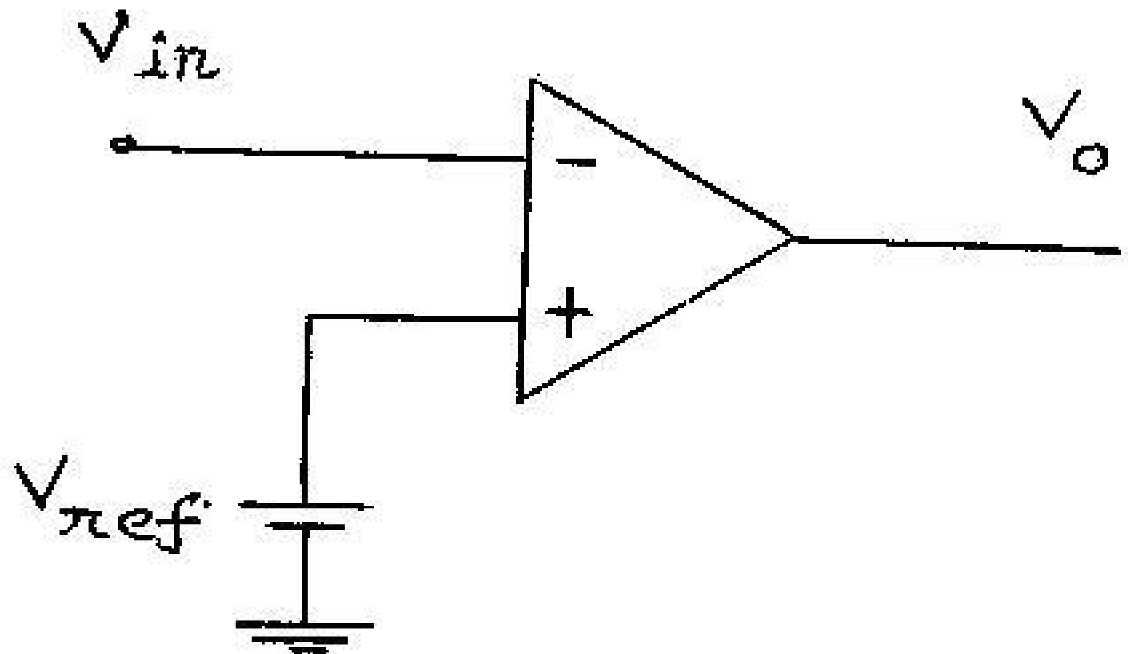
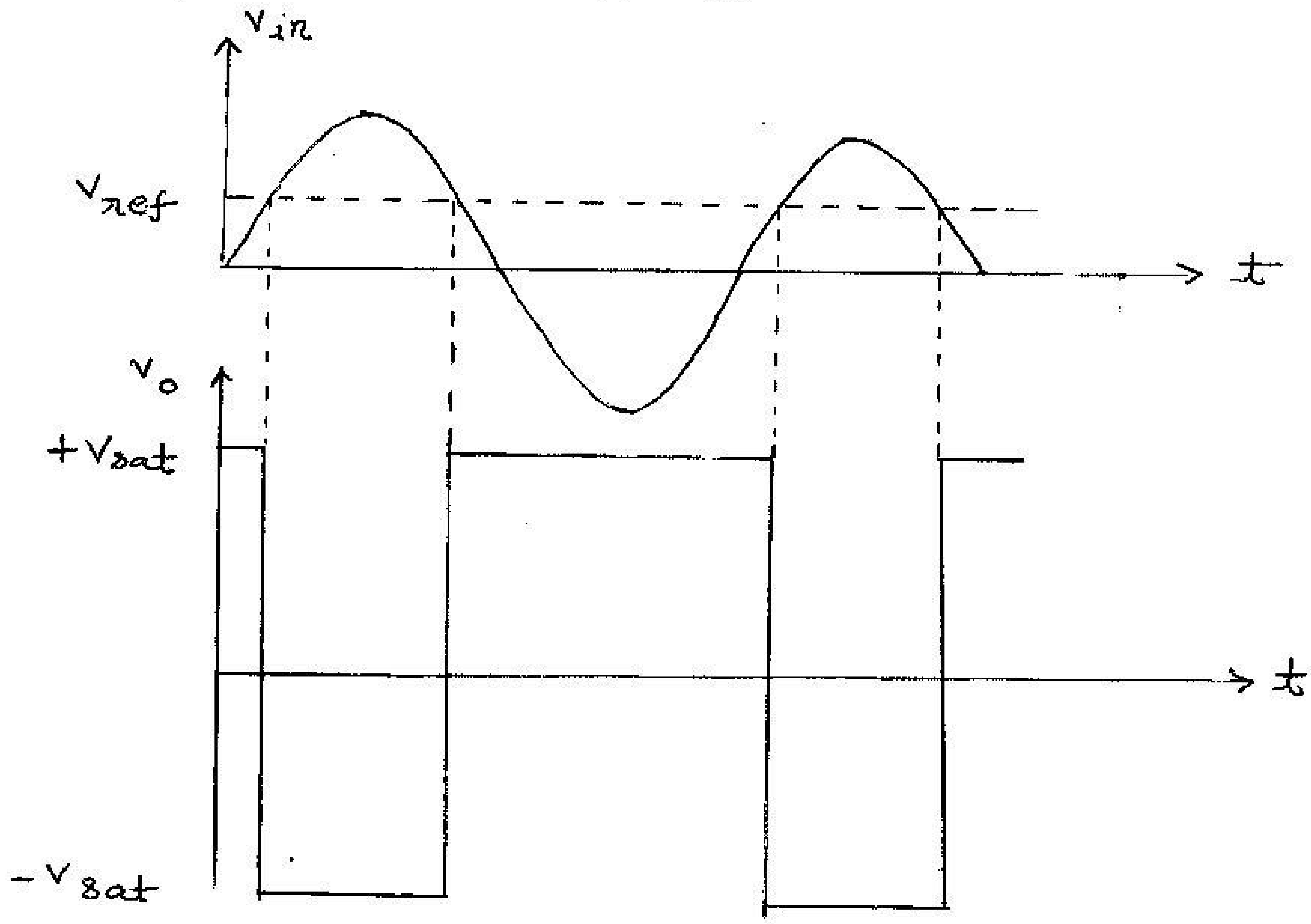


Figure shows the circuit diagram of an inverting comparator with the reference voltage V_{ref} applied at the noninverting input. The input signal is applied at the inverting input.

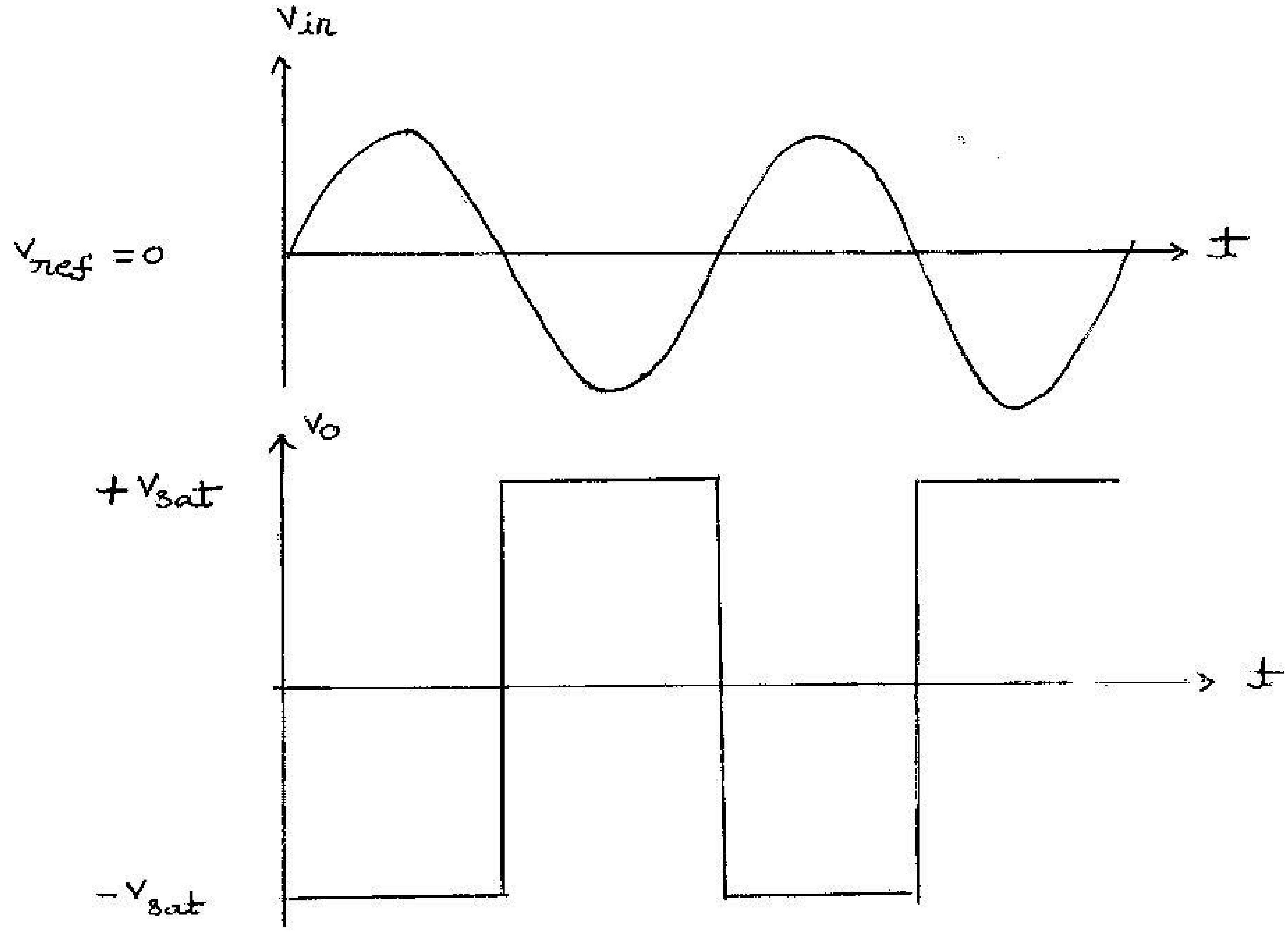
When the input voltage V_{in} is less than the reference voltage V_{ref}, the output voltage is at maximum negative level $-V_{sat}$ ($\simeq -V_{cc}$).

When the input voltage V_{in} is greater than the reference voltage V_{ref}, the output voltage is at maximum positive level $+V_{sat}$ ($\simeq V_{cc}$).

The input and output waveforms are shown below for $V_{ref} > 0$.



When Vref is set to zero, the comparator is called Zero crossing detector. The input and output waveforms are shown below.



Important questions

1. What is an op-amp? With a neat diagram explain the internal blockdiagram of an op-amp.

2. Explain the types of input modes of an op-amp

3. With reference to an op-amp, explain the following

(i) Common Mode Rejection Ratio

(ii) Input offset voltage

(iii) Slew rate.

4. With reference to an op-amp, explain the following

(i) Input bias current

(ii) Input offset current

(iii) Input impedance

(iv) Maximum Voltage swing

5. With a neat circuit diagram derive the expression for output voltage of an inverting op-amp.

6. With a neat circuit diagram derive the expression for output voltage of a non inverting op-amp

7. With a neat circuit diagram show that an op-amp could be used as a summer.

8. With a neat circuit diagram, explain how an op-amp could be used an integrator?

9. Explain how an op-amp can be used as a Voltage follower.

10. With a neat circuit diagram, explain how an op-amp could be used as a differentiator?

11. Explain op-amp as a Voltage comparator.