Fig. 31.23

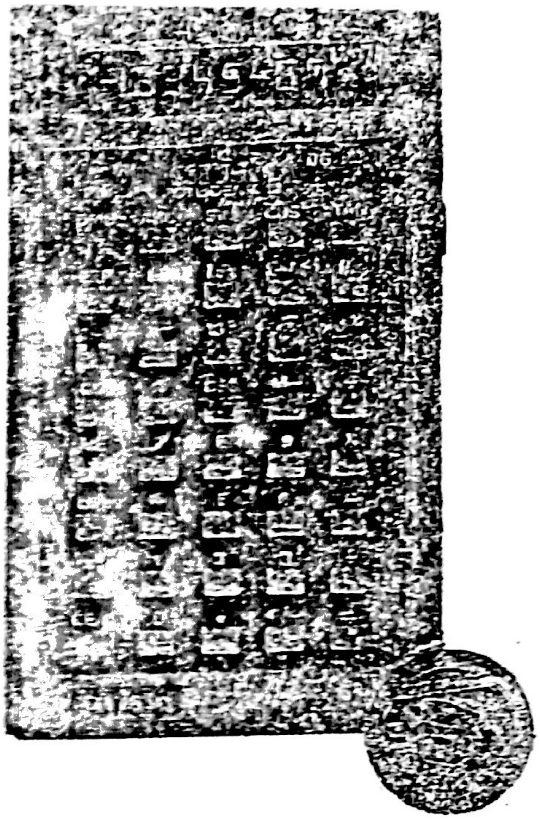


Fig. 31.24

2. There is no need for isolation technique for enhancement MOSFET devices since each source and drain region is isolated from the other by the P-N junctions formed within the N-type substrate. This fact is shown in Fig. 31.25 where two P-channel E-MOSFETs have been fabricated from the same substrate.

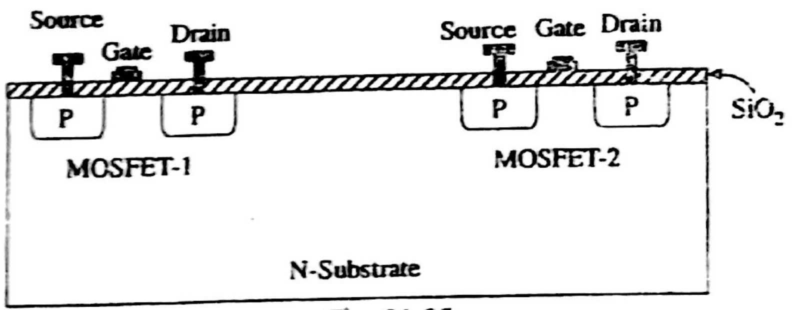


Fig. 31.25

3. The packing density of MOS ICs is at least ten times more than that for bipolar ICs. Also, a MOS resistor occupies less than 1 per cent of the area of a conventional diffused resistor. This high packing density makes MOS ICs especially suited for LSI and VLSI.

The main disadvantage of MOS ICs is *their slower operating speed as compared to bipolar ICs*. Hence, they do not compete with bipolar ICs in ultrahigh-speed applications.

However, due to their (*i*) low cost (*ii*) low power consumption and (*iii*) high packing density, MOS ICs are widely used for LSI and VLSI chips such as calculator chips, memory chips and microprocessors (μP).

31.18. What is an OP-AMP ?

It is a very high-gain, high-r_{in} directly-coupled negative-feedback amplifier which can amplify signals having frequency ranging from **0 Hz to a little beyond 1 MHz.** They are made with different internal configurations in linear ICs. An OP-AMP is so named because it was originally designed to perform mathematical operations like summation, subtraction, multiplication, differentiation and integration etc., in analog computers. Present day usage is much wider in scope but the popular name OP-AMP continues.

Typical uses of OP-AMP are : scale changing, analog computer operations, in instrumentation and control systems and a great variety of phase-shift and oscillator circuits. The OP-AMP is available in three different packages (*i*) standard dual-in-line package (DIP) (*ii*) TO-5 case and (*iii*) the flat-pack.

Although an OP-AMP is a complete amplifier, it is so designed that external components (resistors, capacitors etc.) can be connected to its terminals to change its external characteristics. Hence, it is relatively easy to tailor this amplifier to fit a particular application and it is, in fact, due to this versatility that OP-AMPs have become so popular in industry.

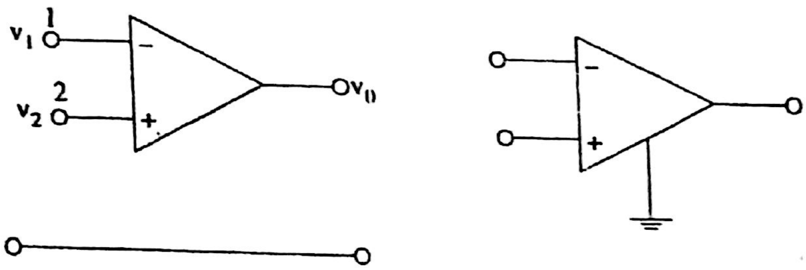
An OP-AMP IC may contain two dozen transistors, a dozen resistors and one or two capacitors.

Example of OP-AMPs

1. μA 709—is a high-gain operational amplifier constructed on a single silicon chip using planar epitaxial process.
   It is intended for use in dc servo systems, high-impedance analog computers and in low-level instrumentation applications.
   It is manufactured by Semiconductors Limited, Pune.
2. [LM 108 – LM 208]— Manufactured by Semiconductors Ltd., Mumbai.
3. CA 741 CT and CA 741 T—these are high-gain operational amplifiers which are intended for use as (*i*) comparator, (*ii*) integrator, (*iii*) differentiator, (*iv*) summer, (*v*) dc amplifier, (*vi*) multivibrator, and (*vii*) bandpass filter.
   Manufactured by Bharat Electronics Ltd. (BEL), Bangalore.

31.19. OP-AMP Symbol

Standard triangular symbol for an OP-AMP is shown in Fig. 31.26 (*a*) though the one shown in Fig. 31.26 (*b*) is also used often. In Fig. 31.26 (*b*), **the common ground line has been omitted.** It also does not show other necessary connections such as for dc power and feedback etc.



(*a*) (*b*)

Fig. 31.26

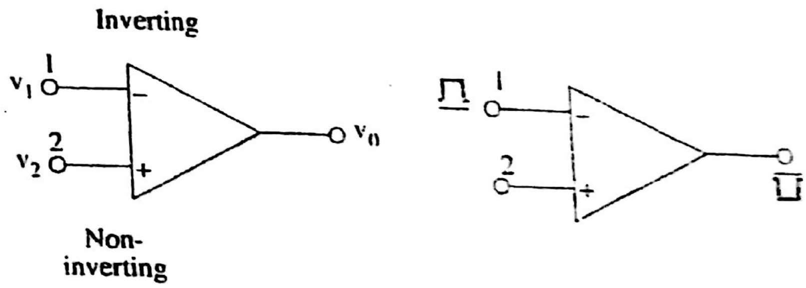
The OP-AMP's input can be single-ended or double-ended (or differential input) depending on whether input voltage is applied to one input terminal only or to both. Similarly, amplifier's output can also be either single-ended or double-ended. The most common configuration is *two input terminals and a single output.*

All OP-AMPs have a minimum of five terminals

1. inverting input terminal,
2. non-inverting input terminal,
3. output terminal,
4. positive bias supply terminal,
5. negative bias supply terminal.

31.20. Polarity Conventions

In Fig. 31.26 (*b*), the input terminals have been marked with minus (–) and plus (+) signs. These are meant to **indicate the inverting and non-inverting terminals only** [Fig. 31.27 (*a*)]. It simply means that a signal applied at negative input terminal will appear amplified but **phase-inverted at the output terminal** as shown in Fig. 31.27 (*b*). Similarly, signal applied at the positive input terminal will appear amplified and **in-phase** at the output. Obviously, these plus and minus polarities **indicate phase reversal only**. It does not mean that voltage v_1 and v_2 in Fig. 31.27 (*a*) are negative and positive respectively. Additionally, it also does not imply that



(*a*) (*b*)

Fig. 31.27

positive input voltage has to be connected to the plus-marked non-inverting terminal 2 and negative input voltage to the negative-marked inverting terminal 1. In fact, the amplifier can be used 'either way up' so to speak. It may also be noted that all input and output voltages are referred to a common reference usually the ground shown in Fig. 31.26 (*a*).

31.21. Ideal Operational Amplifier

When an OP-AMP is operated without connecting any resistor or capacitor from its output to any one of its inputs (*i.e.*, without feedback), it is said to be in the **open-loop condition.** The word 'open loop' means that *feedback path or loop is open.* The specifications of an OP-AMP under such condition are called open-loop specifications.

An ideal OP-AMP (Fig. 31.28) has the following characteristics:

1. its open-loop gain A_v is *infinite i.e.*, $A_v = -\infty$;
2. its input resistance R_i (measured between inverting and non-inverting terminals) is *infinite i.e.*, $R_i = \infty$ ohm;
3. its output resistance R_0 (seen looking back into output terminals) is *zero i.e.*, $R_0 = 0\ \Omega$;
4. it has *infinite bandwidth i.e.*, it has flat frequency response from dc to infinity.

Though these characteristics cannot be achieved in practice, yet an ideal OP-AMP serves as convenient reference against which real OP-AMPs may be evaluated.

Following additional points are worth noting:

1. Infinite input resistance means that input current $i = 0$ as indicated in Fig. 31.28.
   It means that an ideal OP-AMP is a voltage-controlled device.
2. $R_o = 0$ means that v_o is not dependent on the load resistance connected across the output.
3. Though for an ideal OP-AMP $A_v = \infty$, for an actual one, it is extremely high *i.e.*, about 10^6. However, it does not mean that 1 V signal will be amplified to 10^6 V at the output. Actually, the maximum value of v_0 is limited by the bias supply voltage, typically $\pm$ 15 V. With $A_v = 10^6$ and $v_0 = 15\ V_2$ the maximum value of input voltage is limited to $15/10^6 = 15\ \mu$V. Though 1 V cannot become 1 million volt in the OP-AMP, 1 μV can certainly become 1 V.

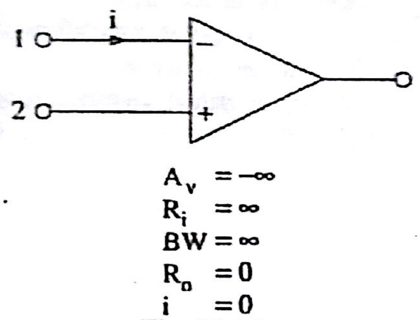


Fig. 31.28

31.22. Virtual Ground and Summing Point

In Fig. 31.29 is shown an OP-AMP which employs *negative feedback* with the help of resistor R_f which feeds a portion of the output to the input.

Since input and feedback currents are algebraically added at point *A*, it is called the **summing point.**

The concept of **virtual** ground arises from the fact that input voltage v_i at the inverting terminal of the OP-AMP is forced to such a small value that, for all practical purposes, it may be assumed to be zero. Hence, point *A* is essentially at ground voltage and is referred to as *virtual ground.* Obviously, *it is not the actual ground,* which, as seen from Fig. 31.29, is situated below.

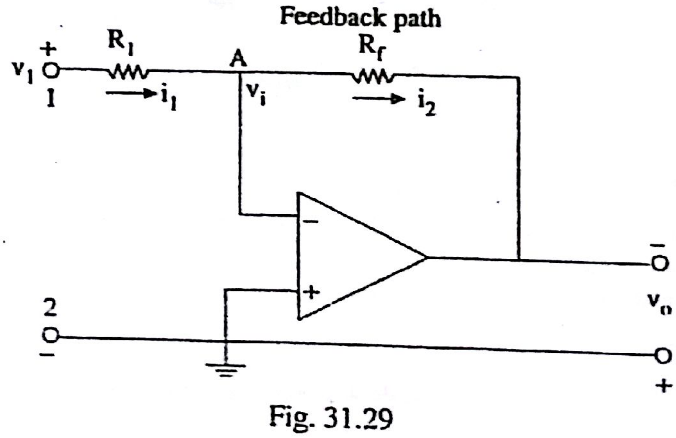


Fig. 31.29

31.23. Why V_i is Reduced to almost Zero ?

When v_1 is applied, point *A* attains some positive potential and at the same time v_o is brought into existence. Due to negative feedback, some fraction of the output voltage is fed back to point *A* antiphase with the voltage already existing there (due to v_1).

The algebraic sum of the two voltages is almost zero so that $v_i = 0$. Obviously, v_i will become exactly zero when **negative feedback voltage at A is exactly equal to the positive voltage produced by v_1 at A.**

Another point worth considering is that there exists a virtual short between the two terminals of the OP-AMP because $v_i = 0$. It is virtual because no current flows (remember $i = 0$) despite the existence of this short.

31.24. OP-AMP Applications

We will consider the following applications:

1. as scaler or linear (*i.e.*, small-signal) constant-gain amplifier; both inverting and non-inverting,
2. as unity follower,
3. Adder or Summer,
4. Subtractor,
5. Integrator,
6. Differentiator,
7. Comparator.

Now, we will discuss the above circuits one by one assuming an ideal OP-AMP.

31.25. Linear Amplifier

We will consider the functioning of an OP-AMP as a constant-gain amplifier both in the inverting and non-inverting configurations.

(a) Inverting Amplifier or Negative Scale

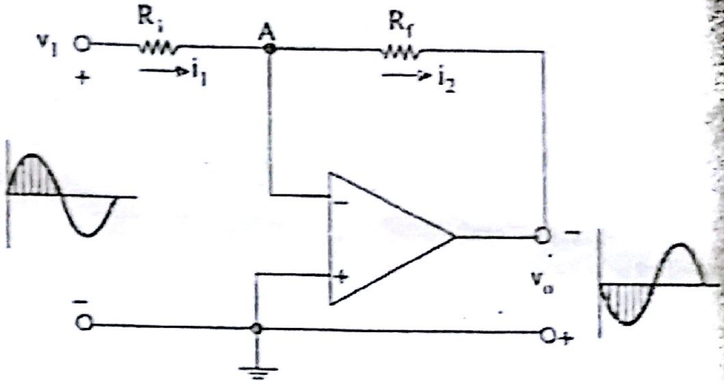


Fig. 31.30

As shown in Fig. 31.30, non-inverting terminal has been grounded whereas R_1 connects the input signal v_1 to the inverting input. A feedback resistor R_f has been connected from the output to the inverting input.

Gain

Since point A is at ground potential*, $i_1 = \dfrac{v_{in}}{R_1} = \dfrac{v_1}{R_1}$

$$i_2 = \frac{-v_o}{R_f} \qquad \text{— please note – ve sign}$$

Using KCL (Art. 3.2) for point A,

$$i_1 - (-i_2) = 0 \quad \text{or} \quad \frac{v_1}{R_1} + \frac{v_o}{R_f} = 0 \quad \text{or} \quad \frac{v_0}{R_f} - \frac{v_1}{R_1} \quad \text{or} \quad \frac{v_0}{v_1} = -\frac{R_f}{R_1}$$

$$\therefore \quad A_v = -\frac{R_f}{R_1} \quad \text{or} \quad A_v = -K \qquad \text{Also,} \quad v_o = -Kv_{in}$$

It is seen from above, that closed-loop gain of the inverting amplifier depends on the ratio of the two external resistors R_1 and R_f and is independent of the amplifier parameters.

It is also seen that the OP-AMP works as a negative scaler. It scales the input *i.e.*, it multiplies the input by a minus constant factor K.

(b) Non-inverting Amplifier or Positive Scaler

This circuit is used when there is need for an output which is equal to the input multiplied by a positive constant. Such a positive scaler circuit which uses negative feedback but provides an output that equals the input multiplied by a positive constant is shown in Fig. 31.31.

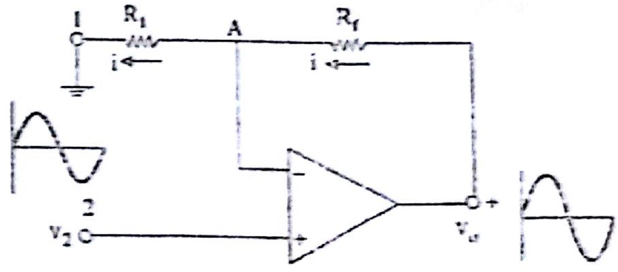


Fig. 31.31

* If not, then $i_1 = \dfrac{v_1 - v_i}{R_1}$ and $i_2 = \dfrac{v_0 - v_1}{R_f}$.

Since input voltage v_2 is applied to the non-inverting terminal, the circuit is also called **non-inverting amplifier**.

Here, polarity of v_o is the same as that of v_2 *i.e.*, both are positive.

Gain

Because of virtual short between the two OP-AMP terminals, voltage across R_1 is the input voltage v_2. Also, v_0 is applied across the series combination of R_1 and R_f

$$\therefore \quad v_{in} = v_2 = iR_1 \, ; \qquad v_0 = i(R_1 + R_f)$$

$$\therefore \quad A_v = \frac{v_o}{v_{in}} = \frac{i(R_1 + R_f)}{iR_1} \quad \text{or} \quad A_v = \frac{R_1 + R_f}{R_1} = \left(1 + \frac{R_f}{R_1}\right)$$

Alternative Derivation

As shown in Fig. 31.32, let the currents through the two resistors be i_1 and i_2.

The voltage across R_1 is v_2 and that across R_f is $(v_o - v_2)$.

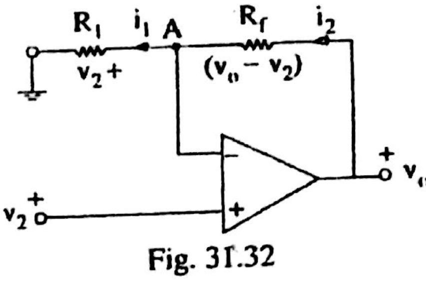


Fig. 31.32

$$\therefore \quad i_1 = \frac{v_2}{R_1} \quad \text{and} \quad i_2 = \frac{v_o - v_2}{R_f}$$

Applying KCL to junction A, we have

$$(-i_1) + i_2 = 0 \quad \text{or} \quad \frac{-v_2}{R_1} + \frac{(v_o - v_2)}{R_f} = 0$$

$$\therefore \quad \frac{v_o}{R_f} = v_2\left(\frac{1}{R_1} + \frac{1}{R_f}\right) = v_2 \frac{R_1 + R_f}{R_1 R_f}$$

$$\therefore \quad \frac{v_o}{v_2} = \frac{R_1 + R_f}{R_1} \quad \text{or} \quad A_v = 1 + \frac{R_f}{R_1}$$

—as before

Example 31.1. *Calculate (i) input impedance and (ii) the voltage gain of the OP-AMP amplifier circuit of Fig. 31.33.*

Solution. (*i*) The input impedance of the OP-AMP amplifier is very high and when negative feedback is used, the impedance is increased even further. Hence, input impedance of a non-inverting OP-AMP amplifier can be thought of as infinite.

(*ii*) The voltage gain is given by

$$A_v = 1 + \frac{R_f}{R_1} = 1 + \frac{15}{3.5} = \mathbf{5.3}$$

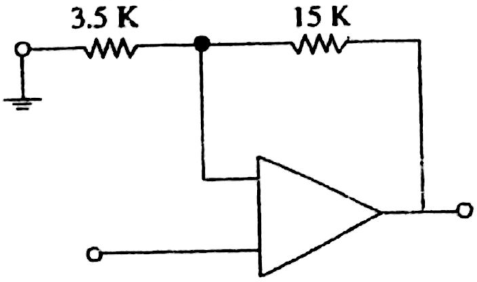


Fig. 31.33

Example 31.2. *For the inverting amplifier of Fig. 31.30, $R_1 = 1K$ and $R_f = 1M$. Assuming an ideal OP-AMP amplifier, determine the following circuit values :*

(a) voltage gain, (b) input resistance , (c) output resistance.

Solution. It should be noted that we will be calculating values *of the circuit* and not *for the OP-AMP proper.*

(*a*) $A_v = -\dfrac{R_f}{R_1} = -\dfrac{1000\text{ K}}{1\text{ K}} = \mathbf{-1000.}$

(*b*) Because of virtual ground at A, $R_{in} = R_1 = \mathbf{1\ K.}$

(*c*) Output resistance of the circuit equals the output resistance of the OP-AMP *i.e.*, **zero ohm.**

31.26. Unity Follower

It provides a gain of unity without any phase reversal. It is very much similar to the emitter follower (Art. 21.8) except that its gain is very much closer to being exactly unity.

This circuit (Fig. 31.34) is useful as a buffer or isolation amplifier because it allows input voltage v_{in} to be transferred as output voltage v_o while at the same time preventing load resistance

R_L from loading down the input source. It is due to the fact that its $R_i = \infty$ and $R_o = 0$.

In fact, circuit of Fig. 31.34 can be obtained from that of Fig. 31.31 by putting

$$R_1 = R_f = 0$$

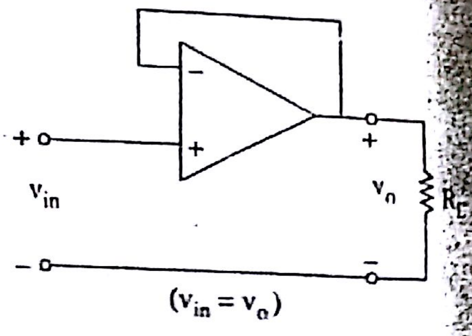


Fig. 31.34

31.27. Adder or Summer

The adder circuit provides an output voltage proportional to or equal to the algebraic sum of two or more input voltages each multiplied by a constant gain factor. It is basically similar to a scaler (Fig. 31.30) except that it has more than one input. Fig. 31.35 shows a three-input inverting adder circuit. As seen, *the output voltage is phase-inverted.*

Calculations

As before, we will treat point A as virtual ground

$$i_1 = \frac{v_1}{R_1} \quad \text{and} \quad i_2 = \frac{v_2}{R_2}$$

$$i_3 = \frac{v_3}{R_3} \quad \text{and} \quad i = -\frac{v_o}{R_f}$$

Applying KCL to point A, we have

$$i_1 + i_2 + i_3 + (-i) = 0$$

or
$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} - \left(\frac{-v_o}{R_f}\right) = 0$$

$\therefore$
$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

or
$$v_o = -(K_1v_1 + K_2v_2 + K_3v_3)$$

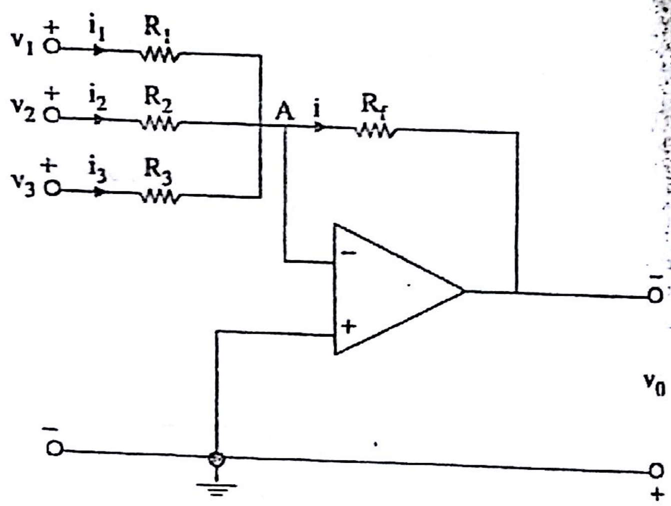


Fig. 31.35

The overall negative sign is unavoidable because we are using the inverting input terminal.

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

$$v_o = -\frac{R_f}{R}(v_1 + v_2 + v_3) = -K(v_1 + v_2 + v_3)$$

Hence, output voltage is proportional to (*not equal to*) the **algebraic sum** of the three input voltages.

If $R_f = R$, then output exactly equals the sum of inputs. However, if $R_f = R/3$,

then
$$v_o = -\frac{R/3}{R}(v_1 + v_2 + v_3) = -\frac{1}{3}(v_1 + v_2 + v_3)$$

Obviously, the output is equal *to the average of the three inputs.*

31.28. Subtractor

The function of a subtractor is to provide an output proportional to or equal to the difference of two input signals. As shown in Fig. 31.36, we have to apply the inputs at the inverting as well as non-inverting terminals.

Calculations

According to Superposition Theorem (Art. 4.2)

$$v_o = v_o' + v_o''$$

where v_o' is the output produced by v_1 and v_o'' is that produced by v_2.

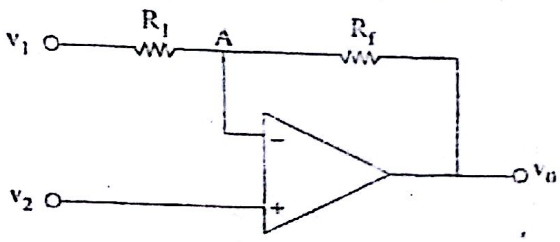


Fig. 31.36

$$\text{Now,} \quad v_o' = -\frac{R_f}{R_1} \cdot v_1 \qquad \text{— Art. 31.25 } (a)$$

$$v_o'' = \left(1 + \frac{R_f}{R_1}\right) v_2 \qquad \text{— Art. 31.26 } (b)$$

$$\therefore \quad v_o = \left(1 + \frac{R_f}{R_1}\right) v_2 - \frac{R_f}{R_1} v_1$$

Since $R_f \gg R_1$ and $R_f / R_1 \gg 1$, hence

$$v_o \equiv \frac{R_f}{R_1}(v_2 - v_1) = K(v_2 - v_1)$$

Further, if $R_f = R_1$, then

$$v_o = (v_2 - v_1) = \text{difference of the two input voltages.}$$

Obviously, if $R_f \neq R_1$, then a scale factor is introduced.

Example 31.3. *Find the output voltage of an OP-AMP inverting adder for the following sets of input voltages and resistors. In all cases, $R_f = 1M$.*

$$v_1 = -3\ V,\ v_2 = +3\ V,\ v_3 = +2\ V;\ R_1 = 250\ K,\quad R_2 = 500\ K,\ R_3 = 1\ M$$

Solution. $v_o = -(K_1 v_1 + K_2 v_2 + K_3 v_3)$

$$K_1 = \frac{R_f}{R_1} = \frac{1000\ K}{250\ K} = 4,\ K_2 = \frac{1000}{500} = 2,\ K_3 = \frac{1\ M}{1\ M} = 1$$

$$\therefore \quad v_o = -[(4 \times -3) + (2 \times 3) + (1 \times 2)] = \mathbf{+4\ V}$$

Example 31.4. *In the subtractor circuit of Fig. 31.36, $R_1 = 5\ K$, $R_f = 10\ K$, $v_1 = 4\ V$ and $v_2 = 5\ V$. Find the value of output voltage.*

$$\textbf{Solution.} \quad v_o = \left(1 + \frac{R_f}{R_1}\right) v_1 - \frac{R_f}{R_1} v_2 = \left(1 + \frac{10}{5}\right) 4 - \frac{10}{5} \times 5 = \mathbf{+2\ V}$$

31.29. Integrator

The function of an integrator is to provide an output voltage which is proportional to the integral of the input voltage.

A simple example of integration is shown in Fig. 31.37 where input is dc level and its integral is a *linearly-increasing ramp output.*

The actual integrating circuit is shown in Fig. 31.38. This circuit is similar to the scaler circuit of Fig. 31.29 except that **the feedback component is a capacitor C instead of a resistor R_f.**

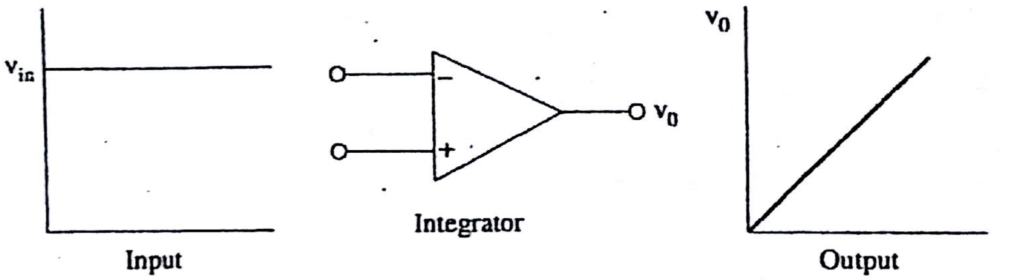


Fig. 31.37

Calculations

As before, point A will be treated as virtual ground.

$$i_1 = \frac{v_1}{R};\quad i_2 = -\frac{v_o}{X_C} = -\frac{v_o}{1/j\omega C} = -\frac{v_o}{1/sC} = -sC\,v_o$$

where $\quad s = j\,\omega$ in the Laplace notation.

$$\text{Now} \quad i_1 = i_2 \qquad \text{— Art. 31.20 } (a)$$

$$\therefore \quad \frac{v_1}{R} = -sCv_o$$

$$\therefore \quad \frac{v_o}{v_{in}} = \frac{v_o}{v_1} = -\frac{1}{sCR} \qquad \text{—(i)}$$

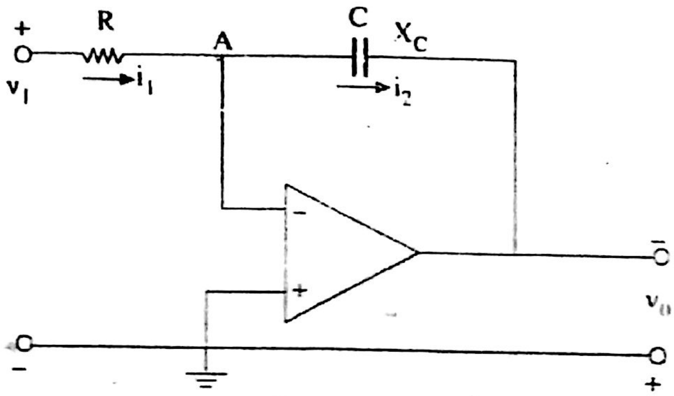


Fig. 31.38

$$\therefore \quad A_v = -\frac{1}{sCR}$$

Now, the expression of Eq. (*i*) can be written in time domain as

$$v_o(t) = -\frac{1}{CR}\int v_1(t)\ .\ dt$$

It is seen from above that output (right-hand side expressions) is an integral of the input, with an inversion and a scale factor of $1/CR$.

This ability to integrate a given signal enables an analog computer to solve differential equations and to set up a wide variety of electrical circuit analogs of physical system operations. For example, let

$$R = 1\ \text{M} \quad \text{and} \quad C = 1\ \mu\text{F. Then}$$

$$\text{scale factor} = -\frac{1}{CR} = -\frac{1}{10^6 \times 10^{-6}} = -1$$

As shown in Fig. 31.39, the input is a step voltage whereas output is a ramp (or linearly-changing voltage) with a scale multiplier of –1.

However, when $R = 100$ K, then

$$\text{scale factor} = -\frac{1}{10^5 \times 10^{-6}}$$
$$= -10$$

$$\therefore \quad v_0(t) = -10\int v_1(t).\ dt$$

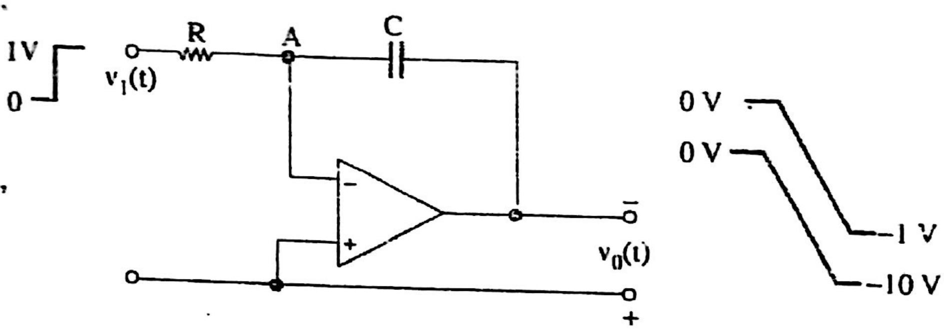


Fig. 31.39

It is also shown in Fig. 31.39. Of course, we can integrate more than one input as shown below in Fig. 31.40. With multiple inputs, the output is given by

$$v_o(t) = -[K_1\int v_1(t)\,dt + K_2\int v_2(t)\,dt + K_3\int v_3(t)\,dt]$$

$$\text{where} \quad K_1 = \frac{1}{CR_1},\quad K_2 = \frac{1}{CR_2} \quad \text{and} \quad K_3 = \frac{1}{CR_3}$$

Fig. 31.40 (*a*) shows a summing integrator as used in an analog computer. It shows all the three resistors and the capacitor. The analog computer representation of Fig. 31.40 (*b*) indicates only the scale factor for each input.

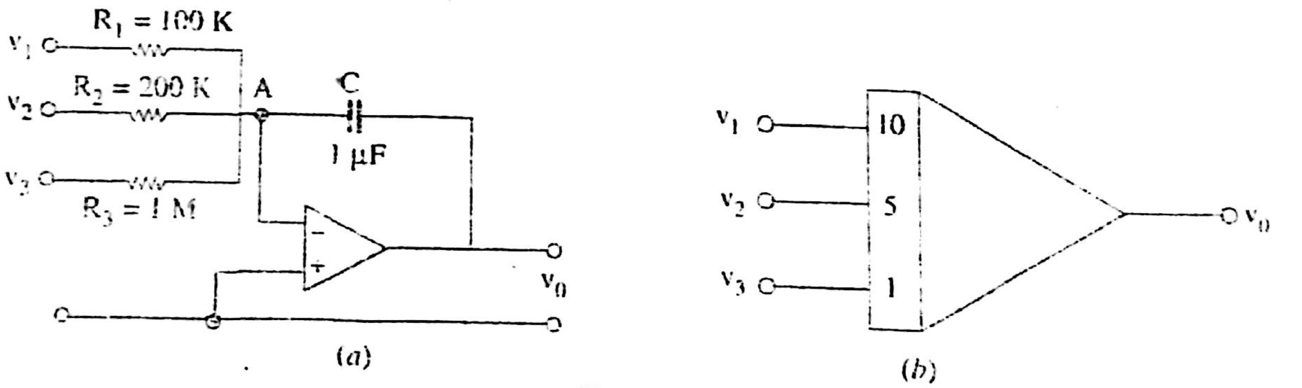


Fig. 31.40

Example 31.5. *A 5 mV, 1 kHz sinusoidal signal is applied to the input of an OP-AMP integrator of Fig. 31.38 for which R = 100 K and C = 1 μF. Find the output voltage.*

...tion. Scale factor $= -\dfrac{1}{CR} = \dfrac{1}{10^5 \times 10^{-6}} = -10$

The equation for the sinusoidal voltage is

$$v_1 = 5 \sin 2\pi f t = 5 \sin 2000 \pi t$$

Obviously, it has been assumed that at $t = 0$, $v_1 = 0$

$$\therefore \quad v_0(t) = -10 \int_0^t 5 \sin 2000 \pi t = -50 \left| \frac{-\cos 2000 \pi t}{2000} \right|_0^t$$

$$= \frac{1}{40\pi} (\cos 2000 \pi t - 1)$$

31.30. Differentiator

Its function is to provide an output voltage which *is proportional to the rate of change of the input voltage*. It is an inverse mathematical operation to that of an integrator. As shown in Fig. 31.41, when we feed a differentiator, we get a constant dc output.

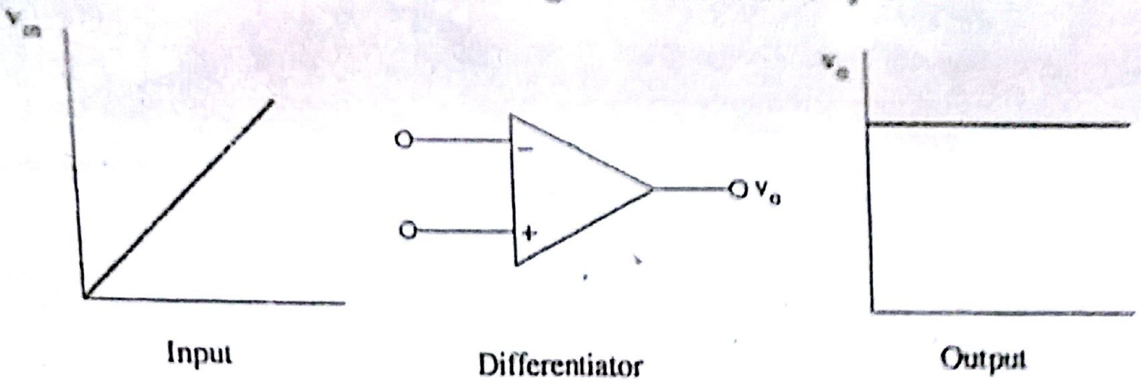


Fig. 31.41

Circuit

Differentiator circuit can be obtained *by interchanging the resistor and capacitor of the integrator circuit of Fig. 31.38.*

Let $\quad i$ = rate of change of charge $= \dfrac{dq}{dt}$

Now, $q = Cv_c$

$$\therefore \quad i = \frac{d}{dt}(Cv_c) = C\frac{dv_c}{dt}$$

Taking point A as virtual ground

$$v_0 = -iR = -\left(C \cdot \frac{dv_c}{dt}\right)R$$

$$= -CR \cdot \frac{dv_c}{dt}$$

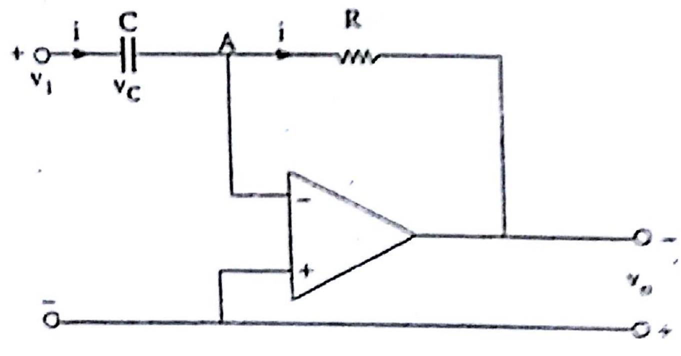


Fig. 31.42

As seen, output voltage is proportional to the derivate of the input voltage, the constant of proportionality (*i.e.*, scale factor) being ($-CR$).

Example 31.7. *The input to the differentiator circuit of Fig. 31.42 is a sinusoidal voltage of peak value 5 mV and frequency 1 kHz. Find out the output if R = 100 K and C = 1 μF.*

Solution. The equation of the input voltage is

$$v_1 = 5 \sin 2\pi \times 1000t = 5 \sin 2000 \pi t \text{ mV}$$

scale factor $= CR = 10^{-6} \times 10^5 = 0.1$

$$v_0 = 0.1 \frac{d}{dt}(5 \sin 2000 \pi t) = (0.5 \times 2000 \pi) \cos 2000 \pi t$$

$$= 1000 \pi \cos 2000 \pi t \text{ mV}$$

As seen, output is a cosinusoidal voltage of frequency 1 kHz and peak value 1000π mV.