14.5 OPERATIONAL AMPLIFIERS

The operational amplifier (abbreviated OP AMP) is the best known example of a general-purpose linear integrated circuit. The IC OP AMP was developed by Robert Widlar in 1964. Basically, the OP AMP is a direct-coupled high-gain differential-input amplifier. The significance of the term 'operational' is that the OP AMP can perform mathematical operations such as summation, subtraction, integration, and differentiation. Such operations are important in analog computers. In addition, the OP AMPs can be used in signal amplification, wave forming, servocontrols, impedance transformation, active filters, oscillators, voltage regulators, analog-to-digital and digital-to-analog converters, to mention but a few. IC OP AMPs are useful in communication equipment, instrumentation, and data processing.

The advantage of OP AMPs is that negative feedback can be applied. The performance of the OP AMP with negative feedback is controlled by the feedback elements independent of the characteristics of the transistors and other elements that constitute the OP AMP. As the feedback elements are usually passive, the circuit operation is very stable and predictable. The IC OP AMPs are inexpensive and have temperature stabilisation. The user of the device need not know the detailed internal circuit configuration of the OP AMP. He simply needs to be acquainted with its terminal properties, so that by connecting external circuit components he can use the OP AMP for a specific purpose.

Circuit Symbol: Figure 14.4 shows the circuit representation of an operational amplifier. It has two input terminals (marked a and b) and one output terminal (marked c). Terminal a is known as the *inverting input terminal* and is labelled '–'. The significance of the negative sign is that a signal applied at the terminal a appears at the terminal c with its polarity reversed.

Terminal b is called the *noninverting input terminal* and is labelled '+'. A signal applied to the terminal b appears at the terminal c with the same polarity. The output voltage at c is proportional to the *difference* of the two signal voltages applied at the two input terminals simultaneously. The constant of proportionality gives the *open-loop voltage gain* (A) of the operational amplifier. A is a real constant, and for an ideal amplifier A approaches infinity for all frequencies.

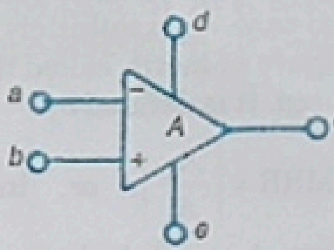

Fig. 14.4 Circuit symbol of a basic OP AMP.

The power supply voltages which are usually balanced with respect to ground are applied to the terminals d and e. The terminals d and e are, however, often omitted in schematic circuits.

OP AMP Characteristics: The ideal OP AMP has the following properties:

1. An infinite voltage gain.
2. An infinite input impedance.
3. Zero output impedance.
4. An infinite bandwidth.
5. Characteristics not drifting with temperature.
6. Perfect balance, i.e. the output voltage is zero when equal voltages are applied to the two input terminals.

For a practical OP AMP, the dc or the low-frequency voltage gain is typically 10^3 to 10^6. The bandwidth is finite, the voltage gain being constant up to several hundred kilohertz and then decreasing with increase in frequency. The input impedance is between 150 kiloohm and a few hundred meg ohm. The output impedance lies in the range 0.75 to 100 ohm. The practical OP AMPs do not have a prefect balance and their characteristics also change somewhat with temperature.

Common-mode rejection ratio. An OP AMP is basically a differential amplifier with signal voltages v_1 and v_2 each measured with respect to ground, applied to the noninverting terminal b and the inverting terminal a, respectively (Fig. 14.4). The output voltage appearing at the terminal c is v_o, measured with respect to ground. In practice, the *difference signal* v_d $(= v_1 - v_2)$ and also the average signal, called the *common-mode signal* v_c $\left(= \dfrac{v_1 + v_2}{2}\right)$ are amplified to produce the output voltage. We have

$$v_o = A_1 v_1 + A_2 v_2 \tag{14.1}$$

where A_1 is the voltage gain when the terminal a is grounded and A_2 is that when the terminal b is grounded. Now

$$v_1 = v_c + \frac{1}{2} v_d \tag{14.2}$$

and

$$v_2 = v_c - \frac{1}{2} v_d \tag{14.3}$$

Using Eqs. (14.2) and (14.3) in (14.1) we get

$$v_o = \frac{1}{2}(A_1 - A_2)\, v_d + (A_1 + A_2)\, v_c = A_d v_d + A_c v_c \tag{14.4}$$

where

$$A_d = \frac{1}{2}(A_1 - A_2) \tag{14.5}$$

and

$$A_c = A_1 + A_2 \tag{14.6}$$

A_d is the voltage gain for the difference signal and A_c is that for the common-mode signal. In the ideal case, A_d is infinitely large while A_c is zero. In practice, the situation is not truly ideal, and a figure of merit, called the *common-mode rejection ratio* (CMRR) of the OP AMP has to be introduced. It is defined by

$$\text{CMRR} = \left|\frac{A_d}{A_c}\right|, \quad \text{or, in dB,} \quad \text{CMRR} = 20 \log_{10}\left|\frac{A_d}{A_c}\right| \text{ dB} \tag{14.7}$$

Since A_d needs to be large and A_c very small, the amplifier must be so designed that the CMRR is much larger than unity. Ideally, the CMRR is infinitely large.

Offset error voltages and current: An ideal OP AMP is perfectly balanced, i.e. $v_o = 0$ when $v_1 = v_2$. In practice, an OP AMP shows an unbalance due to a mismatch of the built-in transistors following the inverting and the noninverting input terminals. This mismatch gives unequal bias currents flowing through the input terminals. Thus an input offset voltage has to be applied between the two input terminals to balance the output.

The *input bias current* is half the sum of the individual currents entering the two input terminals of a balanced amplifier [Fig. 14.5(*a*)]. The input bias current is $i_B = (i_{b1} + i_{b2})/2$, when $v_o = 0$. The *input offset current* i_{i0} is the difference between the individual currents entering the input terminals of a balanced amplifier [Fig. 14.5(*a*)]. Thus $i_{io} = i_{b1} - i_{b2}$, when $v_o = 0$.

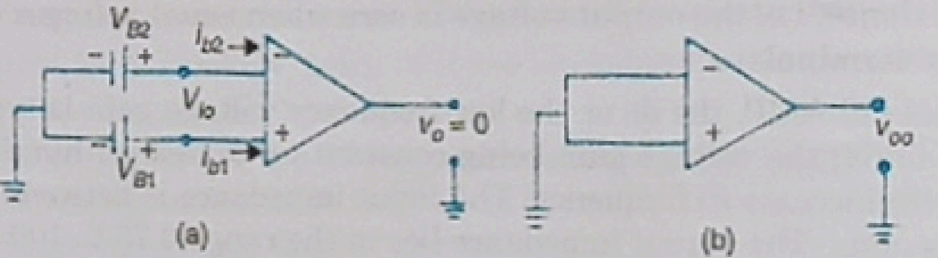

Fig. 14.5 (a) Input offset voltage (b) Output offset voltage.

The *input offset voltage* v_{io} is the voltage to be applied between the input terminals to balance the amplifier [Fig. 14.5(*a*)]. The *output offset voltage* v_{oo} is the voltage at the output terminal when the two input terminals are grounded [Fig. 14.5(*b*)]. Practical OP AMPs have arrangements to balance the offset voltage. Ideally, $i_{b1} = i_{b2}$, and i_{io}, v_{io} and v_{oo} are zero.

If a change δV of the supply voltages effects a change δv_{io} of the input offset voltage, the *power supply rejection ratio* (PSRR) is defined by PSRR = $\delta V/\delta v_{io}$, or, in dB, PSRR = 20 $\log_{10} (\delta V/\delta v_{io})$. In the ideal case, PSRR goes to infinity.

14.7 OP AMP APPLICATIONS

We give below some useful applications of the OP AMP. In these applications, all voltages are measured with respect to ground. The OP AMPs generally require balanced DC supplies (such as +15 V and −15V) with respect to ground to energise the circuit. These supply voltages are connected externally to the proper pins of the OP AMP, and are not shown in the schematic circuits discussed below.

When the magnitude of the output signal voltage is less than the magnitude of the power supply voltage, the OP AMP is said to be in the *linear region* because the input voltage–output voltage relationship is then linear. Usually, the OP AMP is operated in the linear region. If the magnitude of the output voltage equals the magnitude of the power supply voltage, the OP AMP is said to be in the *saturated region*. In this region, the output voltage does not increase with the input voltage, but, remains constant at the supply voltage.

1. Inverting amplifier: A basic inverting amplifier using an OP AMP connected with an input resistance R_1 and a feedback resistance R_f is shown in Fig. 14.6. Since R_f connects the output terminal to the inverting input terminal, it provides a *negative feedback*. The noninverting input terminal is grounded. The input and the output voltages are v_1 and v_o, respectively. Let v be the voltage at the inverting input terminal. As the open-loop gain A of the OP AMP is very high, and the output voltage v_o is finite due to negative feedback, we have $v = v_o/A \to 0$ as $|A| \to \infty$. Therefore, the inverting input terminal is practically at the ground potential. Thus, though the point G is not actually connected to ground it is held *virtually* at ground potential, whatever be the magnitudes of v_1 and v_o.

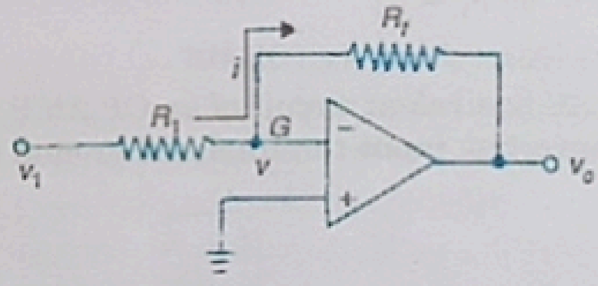

Fig. 14.6 Inverting amplifier

There is an important difference between an 'actual ground' and a 'virtual ground'. When a terminal is actually grounded, any amount of current can flow to ground through the terminal. Thus an actual ground can serve as a 'sink' for infinite current. But the input impedance of an OP AMP being infinite, no current can flow into the OP AMP through the virtual ground. So a virtual ground cannot serve as a sink for current.

The current i through the resistance R_1 is

$$i = \frac{v_1 - v}{R_1} \tag{14.8}$$

Assuming that the OP AMP is an ideal one with an infinite input impedance, the current i passes through R_f and not into the OP AMP. Kirchhoff's current law at the point G gives

$$\frac{v_1 - v}{R_1} = \frac{v - v_o}{R_f} \tag{14.9}$$

As the point G is a *virtual ground*, $v \approx 0$. Hence Eq. (14.9) reduces to

$$\frac{v_1}{R_1} = -\frac{v_o}{R_f} \tag{14.10}$$

The ratio of the output voltage v_0 and the input voltage v_1 is the *closed-loop gain* of the amplifier. So, the closed-loop gain of the inverting amplifier is

$$\frac{v_o}{v_1} = -\frac{R_f}{R_1} \tag{14.11}$$

Thus the closed-loop voltage gain is the ratio of the feedback resistance R_f to the input resistance R_1. The negative sign signifies that the output voltage is *inverted* with respect to the input voltage.

The input resistance of the amplifier system is

$$R_{in} = \frac{v_1}{i} = \frac{v_1}{(v_1 - v)/R_1} \approx R_1 \tag{14.12}$$

using Eq. (14.8) and noting that $v \approx 0$. It should be noted that R_{in} refers to the entire amplifier system and not to the OP AMP which has an infinite input impedance. The output resistance of the inverting amplifier is very small.

2. Phase shifter: Let the resistances R_1 and R_f in the circuit of Fig. 14.6 be replaced respectively by the impedances Z_1 and Z_f which have equal magnitudes but different phase angles. Hence

$$\frac{v_o}{v_1} = -\frac{Z_f}{Z_1} = -\frac{|Z_f| \exp(j\theta_f)}{|Z_1| \exp(j\theta_1)} = \exp[j(\pi + \theta_f - \theta_1)] \tag{14.13}$$

Since $|Z_f| = |Z_1|$ and $\exp(j\pi) = -1$. The angles θ_f and θ_1 are respectively the phase angles of Z_f and Z_1. Equation (14.13) shows that v_o leads v_1 by $(\pi + \theta_f - \theta_1)$, but $|v_o| = |v_1|$. Obviously, the circuit shifts the phase of a sinusoidal input voltage leaving its magnitude unaltered. The phase shift can be anything between 0° and 360°.

3. Scale changer: Let $R_f/R_1 = K$ (a real constant) in the circuit of Fig. 14.6. The output voltage can be written as

$$v_o = -K v_1. \tag{14.14}$$

Thus the output voltage scale is obtained by multiplying the input voltage scale by $-K$, called the *scale factor*. Using precision resistors, accurate values of K can be achieved. The inverting amplifier can then serve as a *scale changer*. A low voltage can be accurately measured by amplifying the voltage by the scale changer and dividing the amplified voltage by the scale factor.

4. Noninverting amplifier: Figure 14.7 depicts the circuit diagram of a noninverting amplifier. The input voltage v_1 is applied to the noninverting terminal. Since the voltage gain of the OP AMP is infinite, the potential of the point G is also v_1. The current flowing into the OP AMP is negligible, its input impedance being very large. Hence, applying Kirchhoff's current law at the point G we obtain

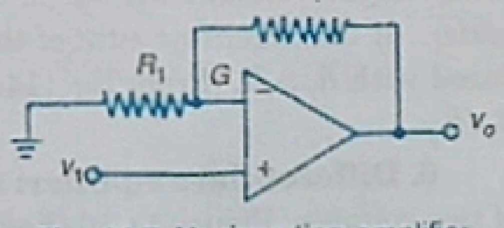

Fig. 14.7 Noninverting amplifier.

$$\frac{v_o - v_1}{R_f} = \frac{v_1}{R_1} \tag{14.15}$$

or

$$\frac{v_o}{v_1} = 1 + \frac{R_f}{R_1} \tag{14.16}$$

which is the voltage gain of the amplifier system. The voltage gain is greater than unity by a factor R_f/R_1. As the gain is positive, there is no phase difference between the input voltage v_1 and the output voltage v_o. The input impedance of the circuit is high and the output impedance is low.

In the circuit of Fig. 14.7, if $R_f = 0$ and $R_1 = \infty$, the circuit reduces to that of Fig. 14.8. Equation (14.16) shows that the voltage gain in this case is unity. Therefore, the circuit of Fig. 14.8 is referred to as a *unity-gain buffer* or a *voltage follower*. This circuit offers a high input impedance and a low output impedance, and therefore can be employed as an impedance matching device between a high-impedanace source and a low-impedance load.

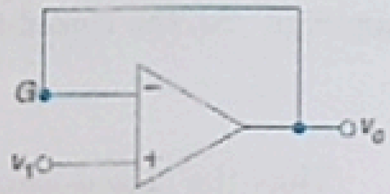

Fig. 14.8 A voltage follower

5. Adder or summing amplifier: Figure 14.9 gives the circuit diagram of an adder or a summing amplifier. The same reasoning as in the case of the inverting amplifier shows that the point G is a virtual ground, i.e. G is at ground potential. The input impedance of the OP AMP being infinite, the sum of the currents $i_1, i_2, ..., i_n$ will be equal to i_o, by Kirchhoff's current law. That is,

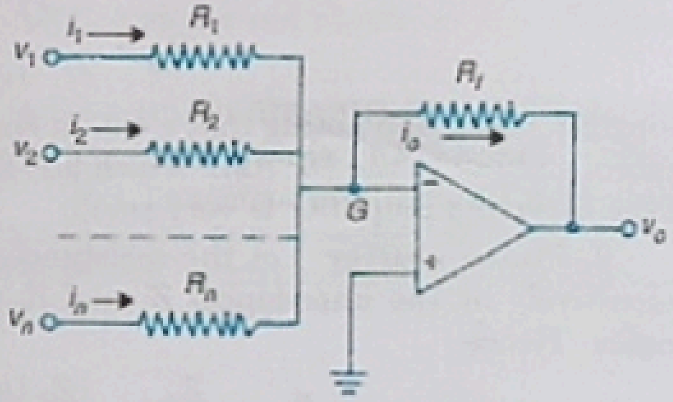

Fig. 14.9 Summing amplifier

$$i_1 + i_2 + ... + i_n = i_o$$

or

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + ... + \frac{v_n}{R_n} = -\frac{v_o}{R_f}$$

or

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + ... + \frac{R_f}{R_n}v_n\right) \tag{14.17}$$

If $R_1 = R_2 = ... = R_n = R$, Eq. (14.17) gives

$$v_o = -\frac{R_f}{R}(v_1 + v_2 + ... + v_n) \tag{14.18}$$

With $R_f = R$, Eq. (14.18) reduces to

$$v_o = -(v_1 + v_2 + ... + v_n) \tag{14.19}$$

This equation shows that the output voltage v_o is numerically equal to the algebraic sum of the input voltages $v_1, v_2, ..., v_n$. Hence the circuit is termed a *summing amplifier* or an *adder*. If the algebraic sum of the input voltages is very small, the output voltage v_o is measured with $R_f > R$. From Eq. (14.18), the desired sum is obtained accurately by dividing v_o by R_f/R_1.

6. Differential amplifier: A differential (or difference) amplifier amplifies the difference of two voltages. Figure 14.10 shows the circuit diagram of a differential amplifier. Suppose that the difference between the voltages v_2 and v_1 is to be amplified. The voltage v_2 is applied to the noninverting input terminal and v_1 to the inverting input terminal of the OP AMP through resistances. The output voltage is v_o. The voltage gain of the OP AMP being infinite, the points a and b will have the same potential, say, v_x. Applying Kirchhoff's current law at a and b, we obtain respectively

$$\frac{v_1 - v_x}{R_1} = \frac{v_x - v_o}{R_2} \tag{14.20}$$

and

$$\frac{v_2 - v_x}{R_1} = \frac{v_x}{R_2} \tag{14.21}$$

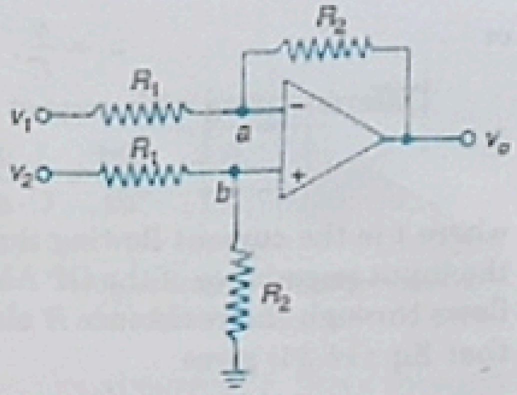

Fig. 14.10 Differential amplifier

where we have assumed that the input impedance of the OP AMP is infinite. Subtracting Eq. (14.20) from Eq. (14.21), we get

$$v_o = \frac{R_2}{R_1}(v_2 - v_1) \tag{14.22}$$

Thus v_o is the amplified version of the difference voltage $(v_2 - v_1)$, the voltage gain of the amplifier system being R_2/R_1. If $R_1 = R_2$, the circuit serves as a simple *subtractor*, the output voltage v_o giving the difference of the input voltages v_2 and v_1.

7. Oscillator: Owing to its high gain and wide bandwidth, the IC OP AMP can be used in oscillator circuits. Figure 14.11 shows the circuit diagram of a phase-shift RC oscillator using an OP AMP. The node G is a virtual ground, so that the voltage v_i is the feedback voltage to the input of the OP AMP. If v_o is the output voltage of the OP AMP, it can be shown that the frequency of oscillation is $f = 1/(2\sqrt{6}\,\pi RC)$, and that the voltage gain of the inverting amplifier v_o/v_i $(= -R_1/R)$ must be -29 for sustained oscillations. The resistor R_1 is varied to achieve the desired voltage gain, allowing for small deviations of the circuit parameter values.

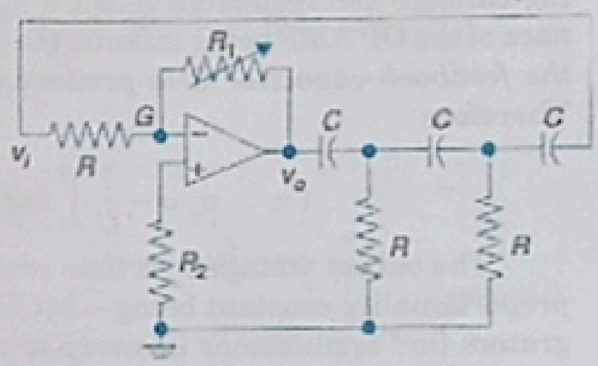

Fig 14.11 Phase-shift oscillator using OP AMP

The use of an OP AMP as the active element in the Wien-bridge oscillator circuit is shown in Fig. 14.12. The oscillation frequency is $f_o = 1/(2\pi RC)$. The principle of oscillation has been discussed in detail in Chapter 11. From Eq. (11.58) we find that the voltage gain A of the active element must be δ, where δ (a positive number greater than 3) is given by Eq. (11.54).

LC oscillators with OP AMPs are discussed in Appendix B.

8. Differentiator: The circuit of Fig. 14.13 gives an output voltage v_o which is proportional to the derivative of the input voltage v_1 with respect to time. Therefore, the circuit is termed a *differentiator*. The infinite voltage gain of the OP AMP makes G a virtual ground. The charge on the capacitor C is therefore $q = Cv_1$

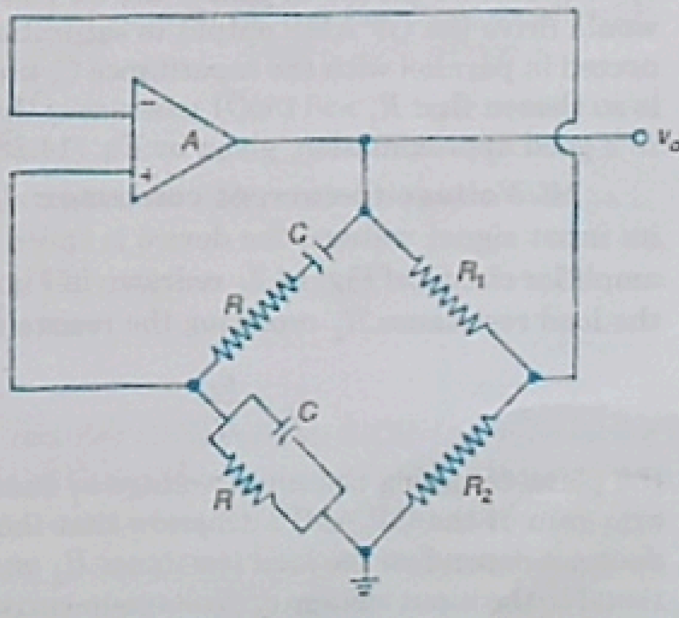

Fig 14.12 Wien-bridge oscillator using OP AMP

or

$$v_1 = \frac{q}{C}. \tag{14.23}$$

Differentiating with respect to time, we obtain

$$\frac{dv_1}{dt} = \frac{1}{C}\frac{dq}{dt} = \frac{i}{C} \tag{14.24}$$

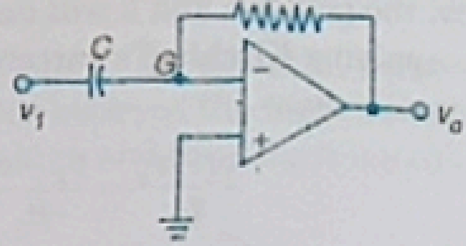

Fig. 14.13 Differentiator

where i is the current flowing through the capacitor. Since the input impedance of the OP AMP is infinite, the current i flows through the resistance R also. Therefore, $i = -v_o/R$, so that Eq. (14.24) gives

$$v_o = -CR\frac{dv_1}{dt} \tag{14.25}$$

Obviously, the output voltage v_o is proportional to the time derivative of the input voltage v_I, the proportionality constant being $-CR$.

9. Integrator: If the positions of R and C in the circuit of Fig. 14.13 are interchanged, the resulting circuit, depicted in Fig. 14.14, is an integrator. As the gain of the OP AMP is infinite, the point G is a virtual ground. The current i flowing through the resistance R is $i = v_I/R$. The input impedance of the OP AMP being infinite, the current i flows through *the feedback capacitor C to produce the output voltage* v_o. Therefore,

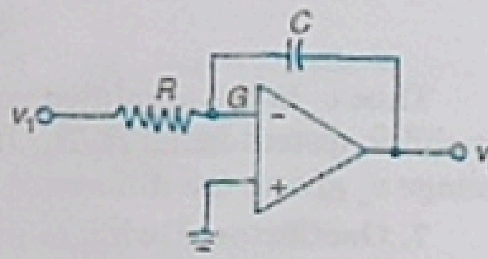

Fig. 14.14 Integrator.

$$v_o = -\frac{1}{C}\int_0^t i\,dt = -\frac{1}{CR}\int_0^t v_1\,dt. \tag{14.26}$$

The output voltage v_o is thus proportional to the time integral of the input voltage v_I, the proportionality constant being $-1/(CR)$. Hence the circuit is referred to as an *integrator*. Integrators find applications in sweep or ramp generators, in filters, and in simulation studies in analog computers.

The basic integrator circuit of Fig. 14.14 has the drawback that since the capacitor is an open circuit for dc, the dc gain of the OP AMP circuit is infinite. So, any dc voltage at the input would drive the OP AMP output to saturation. To avoid this possibility, a resistance R_1 is connected in parallel with the capacitance C, which limits the dc gain of the circuit. The value of R_1 is so chosen that $R_1 >> |1/\omega C|$ where ω is the angular frequency of the input signal. Then v_o is, to a good approximation, given by Eq. (14.26).

15. Voltage comparator: A *voltage comparator* (or simply a *comparator*) is a device used for the comparison of two voltage levels. The output of the comparator indicates which of the two input voltages is greater. Hence it is a switching device, giving an output voltage when one input voltage is larger, and another output voltage when the other input voltage is larger. An OP AMP can be used as a comparator by operating it in the open-loop condition and applying the two voltages to be compared to the inverting and the noninverting inputs. If the voltage to the noninverting input terminal (v_1) slightly exceeds the voltage to the inverting input terminal (v_2), the OP AMP quickly switches to the maximum positive output voltage V, and if v_2 is slightly greater than v_1, the OP AMP switches to the maximum negative output voltage $-V$. This behaviour results from the very large open-loop gain, and is illustrated in Fig. 14.5C. The output voltage v_o switches when $v_d = v_1 - v_2 \approx 0$.

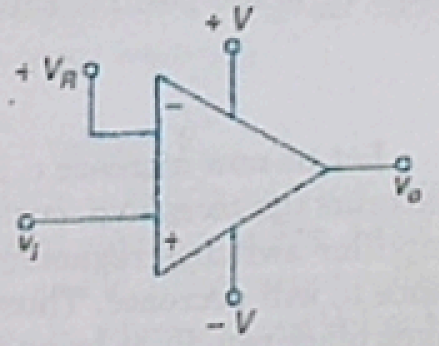

Fig. 14.21 (i) An OP AMP comparator.

To further clarify the behaviour of the comparator we show in Fig. 14.21(i) an open-loop OPAMP with supply voltages $+V$ and $-V$. A dc source of voltage $+V_R$ is connected to the inverting input and a sinusoidal voltage $v_i = V_m \sin \omega t$ is applied to the noninverting input ($V > V_m > V_R$). Figure 14.21(ii) displays the comparator output voltage v_o. The output voltage v_o switches to $+V$ whenever v_i exceeds V_R. v_o stays at V as long as $v_i > V_R$. When v_i drops below V_R, the comparator output switches to $-V$.

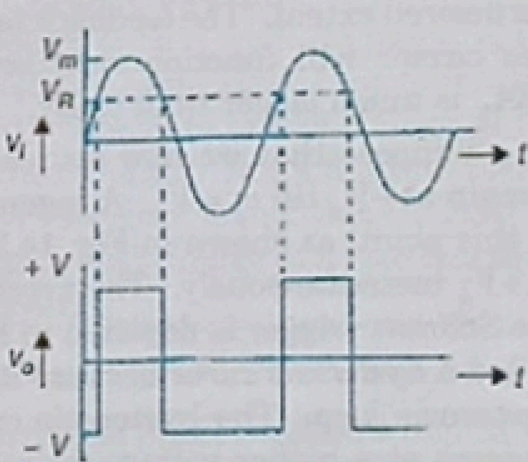

Fig. 14.21 (ii) Input and output voltages of the comparator

Sometimes the inverting or the noninverting input terminal is grounded. The comparator then acts as a *zero-crossing detector*. If the inverting input is grounded, the output voltage v_0 switches to the maximum positive voltage V when the voltage v_i to the noninverting input is slightly positive. When v_i is slightly negative, v_o switches to $-V$. If the noninverting input is grounded, the reverse action takes place.

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