or
$$v_1 = \frac{q}{C}. \qquad (14.23)$$

Differentiating with respect to time, we obtain

$$\frac{dv_1}{dt} = \frac{1}{C}\frac{dq}{dt} = \frac{i}{C} \qquad (14.24)$$

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

$$v_o = -CR\frac{dv_1}{dt} \qquad (14.25)$$

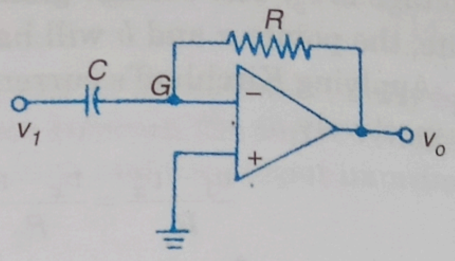

Fig. 14.13 Differentiator.

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 $i = v_1/R$. 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,

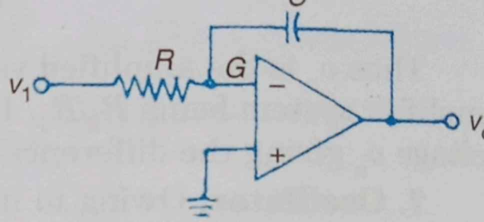

Fig. 14.14 Integrator.

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

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).

10. Voltage-to-current converter: If the output current of a device is proportional to its input signal voltage, the device is called a voltage-to-current converter. The noninverting amplifier circuit of Fig. 14.7, redrawn in Fig. 14.15, can serve as a voltage-to-current converter, the load resistance R_L replacing the resistance R_f. If i_L is the current through R_L, we have

$$i_L = \frac{v_1}{R_1} \qquad (14.27)$$

the point G having the input voltage v_1 due to the infinite gain of the OP AMP. Observe that the current i_L does not depend on the load resistance R_L and is proportional to the input voltage v_1. Voltage-to-current converters are used in analog-to-digital converters and in driving the deflection coils of cathode ray tubes in television.

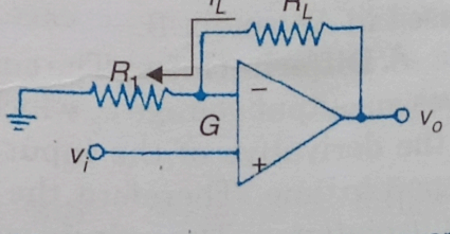

Fig. 14.15 Voltage-to-current converter.

11. Current-to-voltage converter: If the output voltage of a device is proportional to its input signal current, the device is termed a current-to-voltage converter. Figure 14.16 shows the circuit diagram of a current-to-voltage converter. The input signal current i_s can be provided by the output current (independent of the load) of a photocell or a photomultiplier tube. Since the point G serves as a virtual ground, the current through the resistance R_s must be zero. The whole input signal current i_s flows through the feedback resistor R_f to produce the output voltage v_o. We have

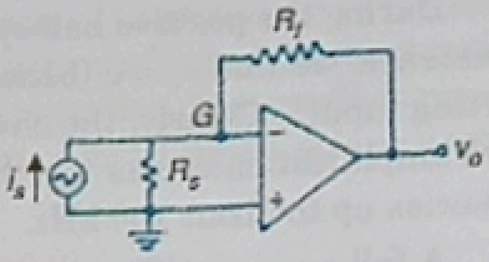

Fig. 14.16 Current-to-voltage converter.

$$v_o = -i_s R_f \tag{14.28}$$

Thus the output voltage v_o is proportional to the input current i_s, the proportionality constant being $-R_f$.

12. Logarithmic amplifier: If the feedback resistor R_f in the circuit of Fig. 14.6 is replaced by a diode, we obtain a *logarithmic amplifier* giving an output voltage v_o that changes as the logarithm of the input voltage v_1. The circuit of a logarithmic amplifier is shown in Fig. 14.17.

The volt-ampere characteristic of the diode is given by Eq. (5.5), viz.

$$i = I_s\left[\exp\left(\frac{ev_f}{\eta k_B T}\right) - 1\right]$$

Here i is the diode current for the forward voltage v_f. If $e\,v_f/(\eta\, k_B\, T) >> 1$ or, $i >> I_s$, we have

$$i \approx I_s \exp\left(\frac{ev_f}{\eta k_B T}\right)$$

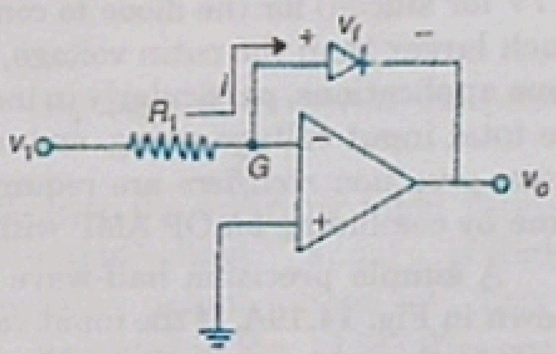

Fig. 14.17 A logarithmic amplifier for positive input voltage v_1

or,
$$\ln\left(\frac{i}{I_s}\right) = \frac{ev_f}{\eta k_B T}$$

or,
$$v_f = \frac{\eta k_B T}{e} \ln\left(\frac{i}{I_s}\right)$$

Since G is a virtual ground in Fig. 14.17, we have $i = v_1/R_1$ and the output voltage is

$$v_o = -v_f = -\frac{\eta k_B T}{e} \ln\left(\frac{v_1}{I_s R_1}\right).$$

Hence v_o responds to the logarithm of v_1.

13. Half-wave rectifier: The half-wave rectifier circuit of Fig. 14.18 operates in the fol-

current and the load voltage are also zero.

14. Peak detector: In the peak detector circuit (Fig. 14.20), *if* the input voltage v_i is larger than the output voltage v_0, the OP AMP output voltage v is positive. Hence the diode D is forward biased and it conducts. The circuit now acts as a voltage follower, so that $v = v_i$, and the capacitor C is charged by the amplifier output current through D to the voltage v_i. If v_i now drops below the capacitor voltage v_o, the OP AMP output voltage v is negative and the diode D turns OFF. The capacitor cannot discharge, and holds at any instant of time t the most positive value of the input voltage v_i prior to t (Fig. 14.21). After the operation, the circuit is reset by activating the gate of a MOSFET connected across the capacitor. The MOSFET acts as a switch to discharge the capacitor.

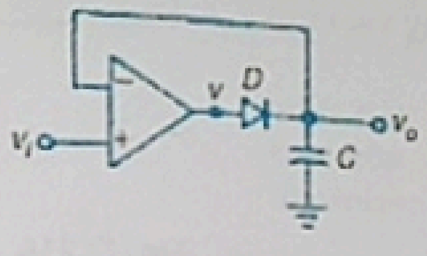

Fig. 14.20 Peak detector

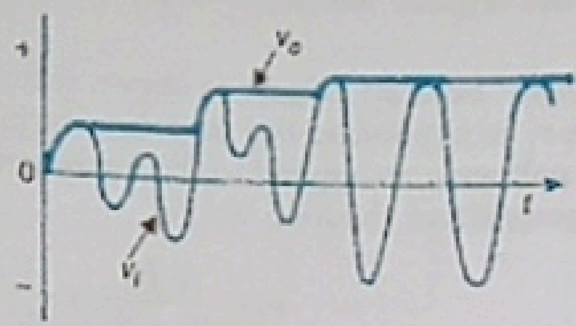

Fig. 14.21 Input and output voltage waveforms

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 $v_d = v_1 - v_2 \approx 0$.

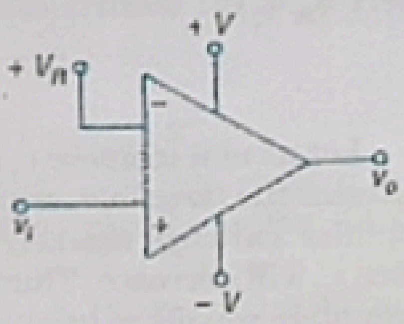

Fig. 14.21 (i) An OP AMP comparator.

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 $-V$.

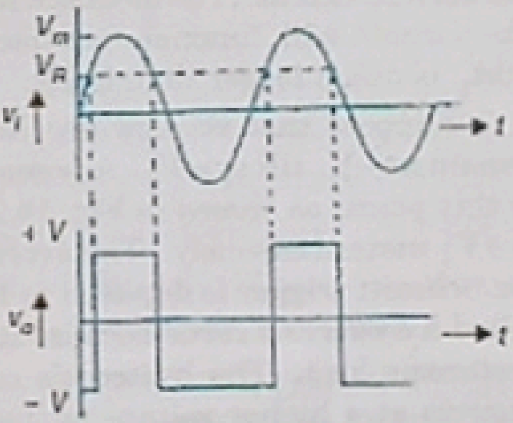

Fig. 14.21 (ii) Input and output voltages of the comparator.

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.

14.8 THE SCHMITT TRIGGER

With a positive or *regenerative* feedback, an OP AMP circuit can be constructed to switch from one voltage level to another, showing the phenomenon of *hysteresis* or *backlash*. Such a circuit is called a *regenerative comparator*, or more commonly, a *Schmitt trigger* after the original developer of the circuit using vacuum tubes.

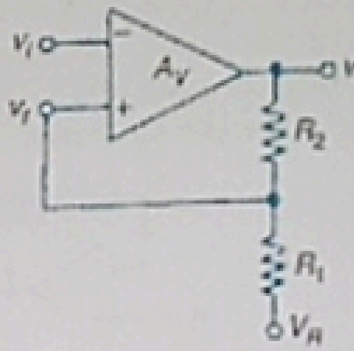

Fig. 14.21A An OP AMP Schmitt trigger.

An OP AMP Schmitt trigger is shown inFig. 14.21A. The input voltage v_i is applied to the inverting terminal, whereas the feedback voltage v_f is applied to the noninverting terminal. From the superposition theorem we get

$$v_f = \frac{v_o R_1}{R_1 + R_2} + \frac{V_R R_2}{R_1 + R_2}$$

If v_i is small or negative such that $v_i << v_f$, then the amplifier will saturate giving $v_o = V_A$, where V_A is the positive saturation voltage. So,

$$v_f = \frac{V_A\, R_1}{R_1 + R_2} + \frac{V_R\, R_2}{R_1 + R_2} = V_1 \text{ (say)}.$$

Let us now increase v_i in the positive direction. Then v_o will remain unchanged at V_A till v_i attains the *threshold, critical,* or *trigger voltage* V_1. At this trigger voltage, the output of the amplifier switches regeneratively to $v_o = -V_A$. This is because as v_i just exceeds V_1, v_0 and hence v_f will decrease. Thus $(v_i - v_f)$ increases to decrease v_o further. This cumulative action takes place rapidly to bring v_o immediately to $-V_A$. The output voltage v_o is held at $-V_A$ so long as $v_i > V_1$. Figure 14.21B(*a*) shows this transfer characteristic.

For $v_i > V_1$, we have

$$v_f = \frac{V_R\, R_2}{R_1 + R_2} - \frac{V_A\, R_1}{R_1 + R_2} = V_2 \text{ (say)}.$$

The switching action occurs only if the amplification is sufficiently large so that small changes in v_f are amplified to the desired extent. The feedback factor here is $\beta = R_1/(R_1 + R_2)$. The circuit will function satisfactorily provided the loop gain $-\beta A_V$ is much larger than unity.

Suppose that we now decrease v_i. Then the output will remain at $-V_A$ till $v_i = V_2$. A regenerative transition will occur at this point, as shown in Fig. 14.21B(*b*) so that v_o will switch to $+V_A$ instantaneously. The overall transfer characteristic of the Schmitt trigger is depicted in Fig. 14.21B(*c*). This curve is called a *hysteresis curve* because it has the form of a magnetic hysteresis loop. The hysteresis curve shows that the circuit triggers at a higher voltage for increasing input signals than for decreasing input signals.

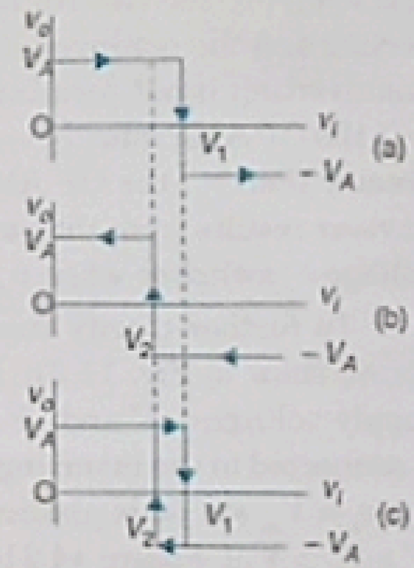

Fig. 14.21B Transfer characteristic of the Schmitt trigger for (a) increasing v_i, and (b) decreasing v_i. (c) The overall input-output curve exhibiting hysteresis.

The width of the hysteresis loop is given by

$$V_H = V_1 - V_2 = \frac{2R_1\, V_A}{R_1 + R_2}.$$

In order to reduce V_H, we have to make $R_1/(R_1 + R_2)$ small. But it cannot be reduced greatly, for otherwise the loop gain $-\beta A_V$ becomes small.

Suppose we have to design a Schmitt trigger for which $V_R = 3$ V, and $V_H = 0.03$ V, using an OP AMP for which $V_A = 5$ V and $A_V = -20000$. Then

$$V_H = 0.03 = \frac{2R_1 V_A}{R_1 + R_2} = \frac{10R_1}{R_1 + R_2}$$

or,
$$\frac{R_1}{R_1 + R_2} = 0.003.$$

The loop gain is $-\dfrac{A_V R_1}{R_1 + R_2} = 20000 \times 3 \times 10^{-3} = 60$. This is much larger than 1, and is therefore acceptable. Let us choose $R_1 = 100\ \Omega$. Solving for R_2 gives $R_2 = 33.23$ kΩ. We can use the commonly available resistance of 33 kΩ for R_2. For these parameter values, the high-level trigger voltage is $V_1 = 3.006$ V and the low-level trigger voltage is $V_2 = 2.976$ V. Note that these trigger voltages are primarily determined by the reference voltage V_R.

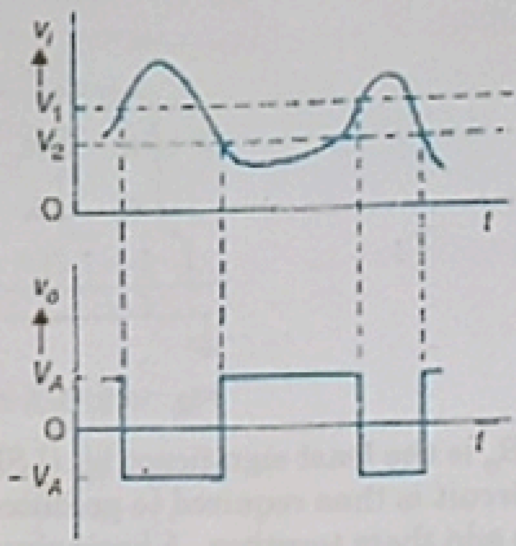

Fig. 14.21C Generation of square waves by the Schmitt trigger from an arbitrary input voltage waveform

An important application of the Schmitt trigger is to transform a slowly varying input voltage into a square wave voltage at the output. Consider the input signal v_i of Fig. 14.21C, plotted against time t. This signal is arbitrary but extends beyond V_1 and V_2. The output voltage v_o swings abruptly to $-V_A$ when the input voltage v_i exceeds V_1 and to $+V_A$ when v_i drops below V_2. The output voltage is thus a square wave of peak values $+V_A$ and $-V_A$ independent of the amplitude of the input voltage.

The Schmitt trigger is a comparator because the circuit compares an input voltage with the trigger levels V_1 and V_2 for the output voltage to swing between $-V_A$ and $+V_A$. It is a regenerative comparator because it employs positive or regenerative feedback.

Observation

When a practical OP AMP is connected as an amplifier with a closed loop gain, say, A_c and an input dc voltage of 1 volt is applied, the output voltage is expected to be A_c volt. In practice, the output voltage does not at once attain the final value of A_c volt, but takes some time to reach it owing to the inherent internal time constants of the OP AMP. The time rate of change of the closed-loop amplifier output voltage is called the *slew rate* of the OP AMP. It is a figure of merit, measured in volt per microsecond. A typical value of the slew rate for a monolithic OP AMP is 1 V/μs. For a faithful reproduction of the input signal, the output must change at a rate less than the slew rate. For an ideal OP AMP, the slew rate is infinitely large.