CONTENTS

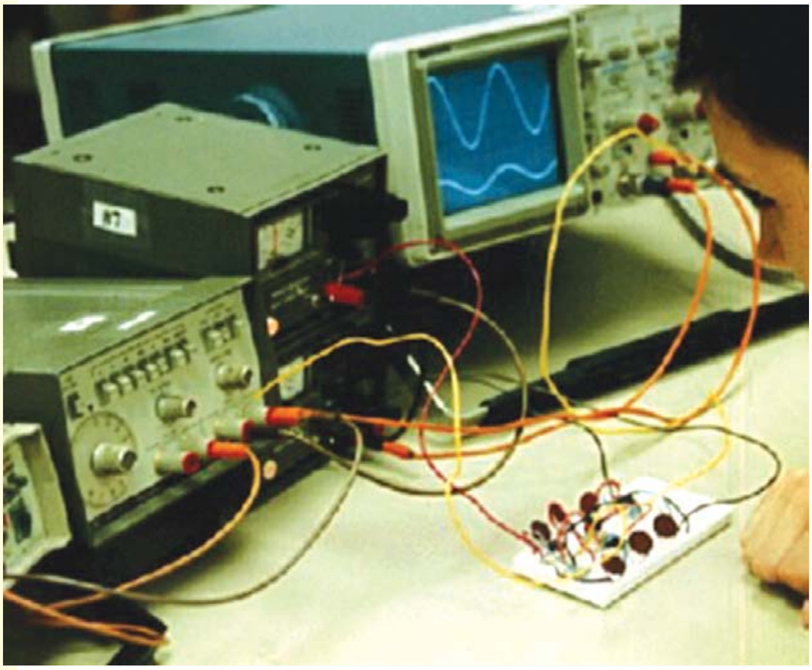
CHAPTER 68

OP-AMP AND ITS APPLICATIONS

Learning Objectives

- What is an OP-AMP?
- OP-AMP Symbol
- Polarity Conventions
- Ideal Operational Amplifier
- Virtual Ground and Summing Point
- Why V_i is Reduced to Almost Zero?
- OP-AMP Applications
- Linear Amplifier
- Unity Follower
- Adder or Summer
- Subtractor
- Integrator
- Differentiator
- Comparator
- Audio Amplifier
- OP-Amp Based Oscillator Circuits
- OP-Amp Based Wien Bridge Oscillator
- OP-Amp Based Crystal Oscillator
- A Triangular-wave Oscillator
- A Voltage- controlled Sawtooth Oscillator (VCO)
- A Square-wave Relaxation Oscillator
- High-impedance Voltmeter
- Active Filters
- Low-pass Filter
- High-pass Filter
- Band-pass Filter
- Notch Filter

CONTENTS



The operational amplifier was designed to perform mathematical operations. Although now superseded by the digital computer, op-amps are a common feature of modern analog electronics

68.1 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 (*DIL*) ***(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. Bombay,

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.

68.2. OP-AMP Symbol

Standard triangular symbol for an *OP-AMP* is shown in Fig. 68.1 (*a*) though the one shown in Fig. 68.1 (*b*) is also used often. In Fig. 68.1 (*b*), **the common ground line has been omitted.** It also does not show other necessary connections such as for dc power and feedback etc.

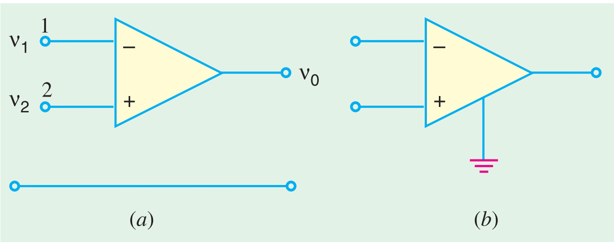


Fig. 68.1

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.

68.3. Polarity Conventions

In Fig. 68.1 (*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. 68.2]. 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. 68.2 (*b*). Similarly, signal applied at the positive input terminal will appear amplified and **inphase** 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. 68.2 (*a*) are negative and positive respectively. Additionally, it also does not imply that a ***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. 68.1 (*a*).

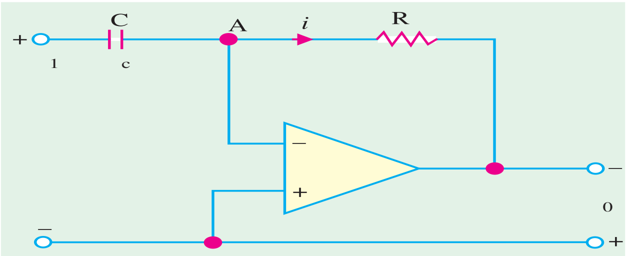


Fig. 68.2

68.4. 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 *OP-AMP* under such condition are called open-loop specifications.

An ideal *OP-AMP* (Fig. 68.3) 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 bandwith*** *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 a convenient reference against which real *OP-AMPs* may be evaluated.

Following additional points are worth noting :

1. infinte input resistance means that input current $i = 0$ as indicated in Fig. 68.3. It means that an ideal *OP-AMP* is a voltage-controlled device.
2. $R_0 = 0$ means that v_0 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 basis supply voltage, typically ± 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 μV. Though 1 μV in the *OP-AMP*, can certainly become 1 V.

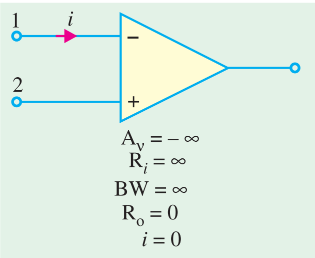


Fig. 68.3

68.5. Virtual Ground and Summing Point

In Fig. 68.4 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.

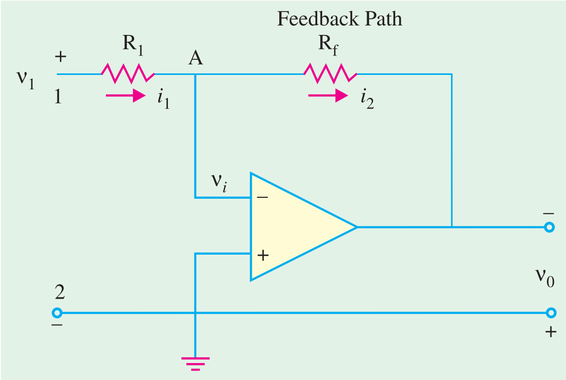


Fig. 68.4

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. 68.4, is situated below.

68.6. 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_0 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 $v_i \cong 0$. 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.

68.7. OP-AMP Applications

We will consider the following applications :

1. as scalar 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*.

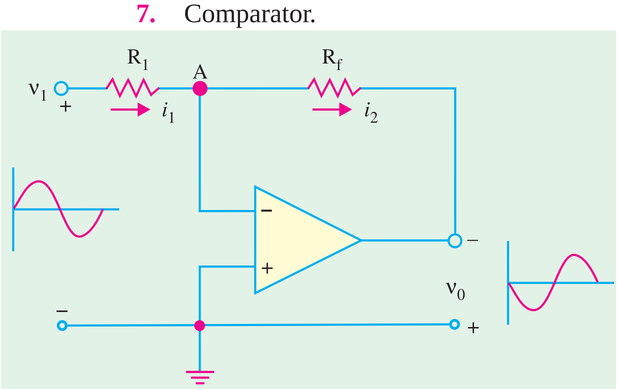


Fig. 68.5

68.8. Linear Amplifier

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

(*a*) Inverting Amplifier or Negative Scale.

As shown in Fig. 68.5, noninverting

terminal has been grounded, whereas R_1 connects the input signal v_1 to the inverting input. A feed-back resistor R_f has been connected from the output to the inverting input.

Gain

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

$$i_2 = \frac{-v_0}{R_f} \quad \text{Please note –ve sign}$$

Using KCL (Art. 2.2) for point A,

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

$$\therefore \quad A_v = -\frac{R_f}{R_1} \quad \text{or} \quad A_v = -K \quad \text{Also, } v_0 = -Kv_{in}$$

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. 68.6.

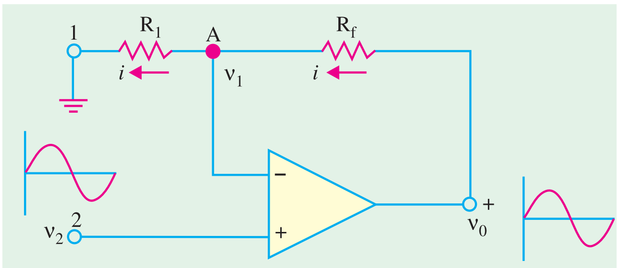


Fig. 68.6

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

Here, polarity of v_0 is the same as that 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.

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

$$\therefore \quad A_v = \frac{v_0}{v_{in}} = \frac{i(R_1 + R_f)}{iR_1} \quad \text{or} \quad A_v = \frac{R_1 + R_f}{R_1} = \left(1 + \frac{R_f}{R_1}\right)$$

Alternative Derivation

As shown in Fig. 68.7, 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 $(v_0 - v_2)$.

$$\therefore \quad i_1 = \frac{v_2}{R_1} \quad \text{and} \quad i_2 = \frac{v_0 - v_2}{R_f}$$

Applying KCL to junction A, we have

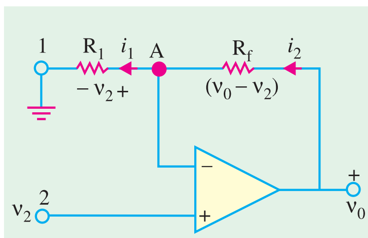


Fig. 68.7

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

$$(-i_1) + i_2 = 0 \quad \text{or} \quad \frac{v_2}{R_1} + \frac{(v_0 - v_2)}{R_f} = 0$$

$$\therefore \quad \frac{v_0}{R_f} = v_2\left(\frac{1}{R_1} + \frac{1}{R_f}\right) = v_2\,\frac{R_1 + R_f}{R_1 R_f}$$

$$\therefore \quad \frac{v_0}{v_2} = \frac{R_1 + R_f}{R_1} \quad \text{or} \quad A_v = 1 + \frac{R_f}{R_1} \qquad \text{—as before}$$

Example 68.1. *For the inverting amplifier of Fig. 68.5, R_1 = 1 K and R_f = 1 M. 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*) $$A_v = -\frac{R_f}{R_1} = -\frac{1000\,K}{1\,K} = \mathbf{-1000}$$

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

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

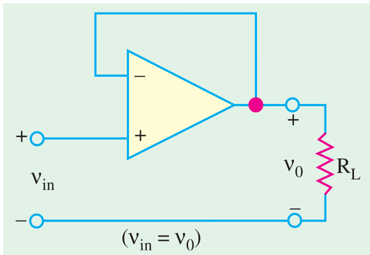


Fig. 68.8

68.9. Unity Follower

It provides a gain of unity without any phase reversal. It is very much similar to the emitter follower (Art 68.8) except that its gain is very much closer to being exactly unity.

This circuit (Fig. 68.8) is useful as a buffer or isolation amplifier because it allows, input voltage v_{in} to be transferred as output voltage v_0 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 $R_0 = 0$.

In fact, circuit of Fig. 68.8 can be obtained from that of Fig. 68.6 by putting

$$R_1 = R_f = 0$$

68.10. Adder to 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. 68.5) except that it has more than one input. Fig. 68.9 shows a three-input inverting adder circuit. As seen, *the* ***output voltage is phase-inverted.***

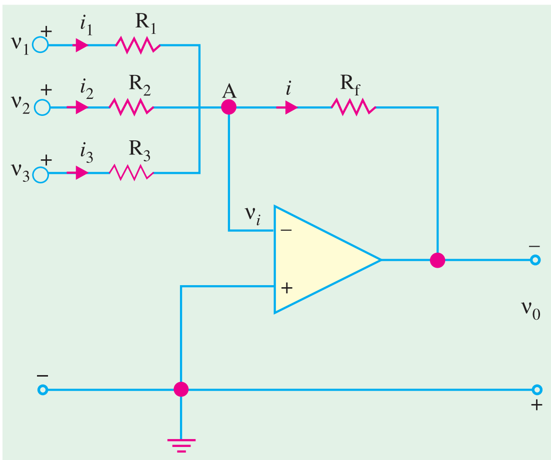


Fig. 68.9

Calculations

As before, we will treat point A as virtual ground

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

$$i_3 = \frac{v_3}{R_3} \quad \text{and} \quad i = -\frac{v_0}{R_f}$$

Applying KCI to point A, we have

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

or $$\frac{v_1}{R_1}+\frac{v_2}{R_2}+\frac{v_3}{R_3}-\left(\frac{-v_0}{R_f}\right)=0$$

$\therefore$ $$v_0=-\left(\frac{R_f}{R_1}v_1+\frac{R_f}{R_2}v_2+\frac{R_f}{R_3}v_3\right)$$

or $$v_0=-(K_1v_1+K_2v_2+K_3v_3)$$

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

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

$$v_0 = -\frac{R_f}{R}(v_1+v_2+v_3)=-K(v_1+v_2+v_3)$$

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

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

then $$v_0 = -\frac{R/3}{R}(v_1+v_2+v_3) = -\frac{1}{3}(v_1+v_2+v_3)$$

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

68.11. 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. 68.10 we have to apply the inputs at the inverting as well as non-inverting terminals.

Calculations

According to Superposition Theorem (Art. 2.17) $v_0 = v_0' + v_0''$

where v_0' is the output produced by v_1 and v_0'' is that produced by v_2.

Now, $$v_0' = -\frac{R_f}{R_1}\cdot v_1 \quad \text{...Art 67.37 }(a)$$

$$v_0'' = \left(1+\frac{R_f}{R_1}\right)v_2 \quad \text{...Art 67.37 }(b)$$

$\therefore$ $$v_0 = \left(1+\frac{R_f}{R_1}\right)v_2 - \frac{R_f}{R_1}\cdot v_1$$

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

$$v_0 \cong \frac{R_f}{R_1}(v_2-v_1) = K(v_2-v_1)$$

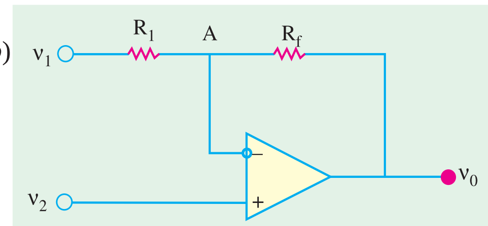


Fig. 68.10

Further, If $R_f = R_1$, then

$$v_0 = (v_2 - v_1) = \text{difference of the two input voltages}$$

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

Example 68.2. *Find the output voltages of an OP-AMP inverting adder for the following sets of input voltages and resistors. In all cases, R_f = 1 M.*

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

[Electronic Engg. Nagpur Univ. 1991]

Solution. $$v_0 = -(K_1v_1+K_2v_2+K_3v_3)$$

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

$\therefore \qquad v_0 = -[(4 \times -3) + (2 \times 3) + (1 \times 2)] = +\ \mathbf{4V}$

Example 68.3. *In the subtractor circuit of Fig. 68.10, R_1 = 5 K, R_f = 10 K, v_1 = 4 V and v_2 = 5 V. Find the value of output voltage.*

Solution. $$v_0 = \left(1 + \frac{R_f}{R_1}\right)v_1 - \frac{R_f}{R_1}v_2 = \left(1 + \frac{10}{5}\right)4 - \frac{10}{5} \times 5 = +\ \mathbf{2V}$$

Example 68.4. *Design an OP-AMP circuit that will produce an output equal to – (4 v_1 + v_2 + 0·1 v_3). Write an expression for the output and sketch its output waveform when v_1 = 2 sin ωt, v_2 = + 5 V dc and v_3 = –100 V dc.* **[Banglore University 2001]**

Solution. $$v_0 = -\left[\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right] \qquad ...(1)$$

and also $$v_0 = -(4\,v_1 + v_2 + 0{\cdot}1\,v_3) \qquad ...(2)$$

Comparing equations **(1)** and **(2)**, we find,

$$\frac{R_f}{R_1} = 4, \quad \frac{R_f}{R_2} = 1, \quad \frac{R_f}{R_3} = 0{\cdot}1$$

Therefore if we assume R_f = 100 *K*, then R_1 = 25 *K*, R_2 = 100 *K* and R_3 = 10 *K*. With there values of R_1, R_2 and R_3, the *OP-AMP* circuit is as shown in Fig. 68.11(*a*)

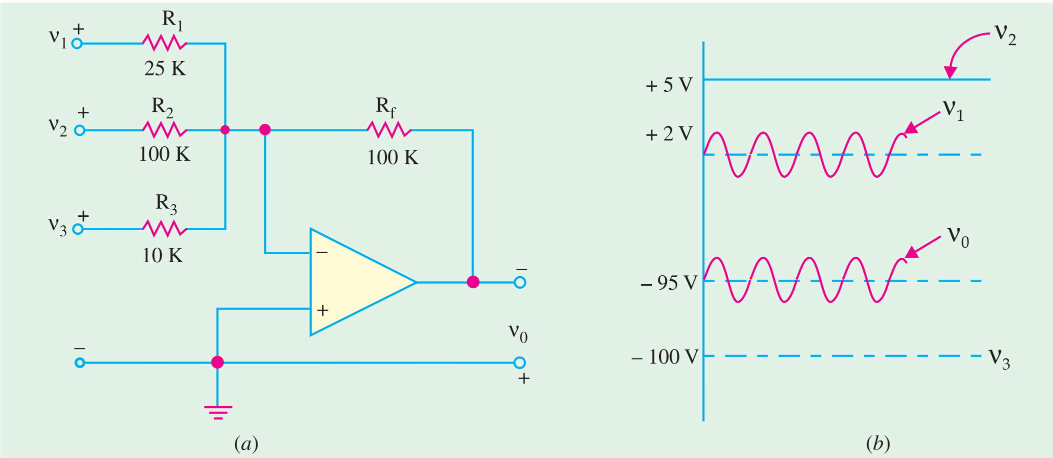


Fig. 68.11

With the given values of v_1 = 2 sin ω*t*, v_2 = + 5V, v_3 = – 100 V dc, the output voltage, v_0 = 2 sin ω*t* + 5 – 100 = 2 sin ω*t* – 95 V. The waveform of the output voltage is sketched as shown in Fig. 68.11 (*b*).

68.12. Integrator

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

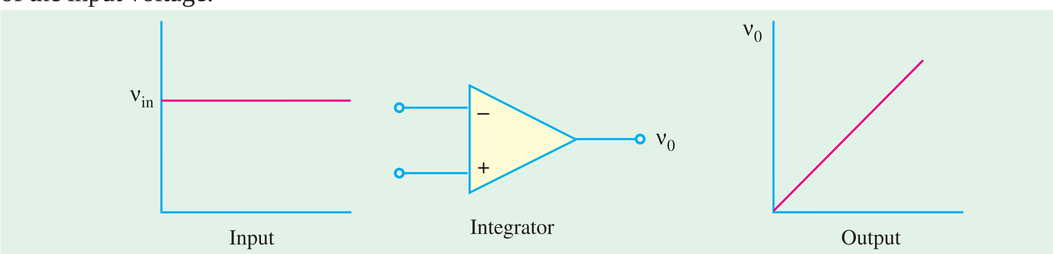


Fig. 68.12

A simple example of integration is shown in Fig. 68.12 where input is dc level and its integral is ***a linearly-increasing ramp output.*** The actual integration circuit is shown in Fig. 68.13. This circuit is similar to the scaler circuit of Fig. 68.5 except that **the feedback component is a capacitor C instead of a resistor R_f.**

Calculations

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

$$i_1 = \frac{v_1}{R} \; ; \; i_2 = -\frac{v_0}{X_C} = -\frac{v_0}{1/j\omega C} = -\frac{v_0}{1/sC} = -s\,C\,v_0$$

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

Now $\quad i_1 = i_2 \quad$ ...Art. 68.26 (a)

$$\therefore \quad \frac{v_1}{R} = -s\,Cv_0$$

$$\therefore \quad \frac{v_0}{v_{in}} = \frac{v_0}{v_1} = -\frac{1}{s\,CR} \quad \text{...}(i)$$

$$\therefore \quad A_v = -\frac{1}{s\,CR}$$

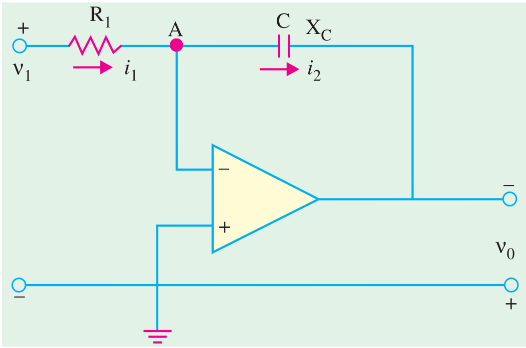


Fig. 68.13

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

$$v_0\,(t) = -\frac{1}{40\,\pi}(\cos 2000\,\pi t - 1)$$

It is seen from above that output (right-hand side expression) 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 solve differential equations and to set up a wide variety of electrical circuit analogs of physical system operation. For example, let

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

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

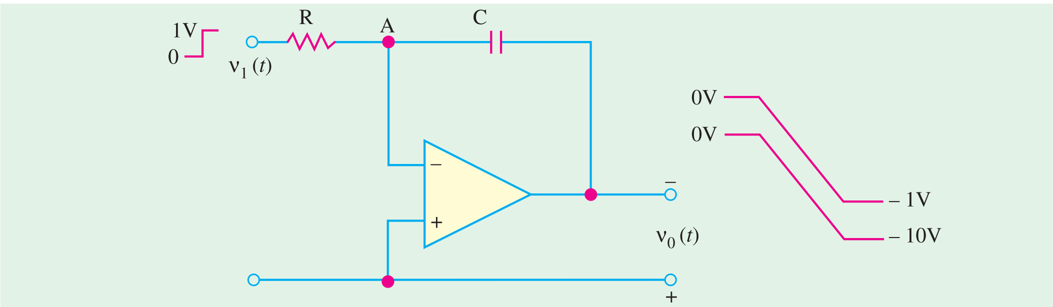


Fig. 68.14

As shown in Fig. 68.14 the input is a step voltage, whereas output is a ramp (or linearly-changing voltages) with a scale multiplier of –1. However, when R = 100 K, then

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

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

It is also shown in Fig. 68.14. Of course, we can integrate more than one input as shown below in Fig. 68.15. With multiple inputs, the output is given by

$$v_0(t) = -\left[K_1 \int v_1(t)\,dt + K_2 \int v_2(t)\,dt + k_3 \int v_3(t)\,dt\right]$$

where $K_1 = \dfrac{1}{CR_1},\ K_2 = \dfrac{1}{CR_2}$ and $K_3 = \dfrac{1}{CR_3}$

Fig. 68.15 (*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. 68.15 (*b*) indicates only the scale factor for each input.

Example 68.5. *A 5-mV, 1-kHz sinusoidal signal is applied to the input of an OP-AMP integrator of Fig. 64.37 for which R = 100 K and C = 1 μF. Find the output voltage.*

[Electronic & Comm. Engg. Kurukshetra Univ. 1990]

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

The equation for the sinusoidal voltage is

$$v_1 = 5 \sin 2\pi ft = 5 \sin 2000\,\pi t$$

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

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

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

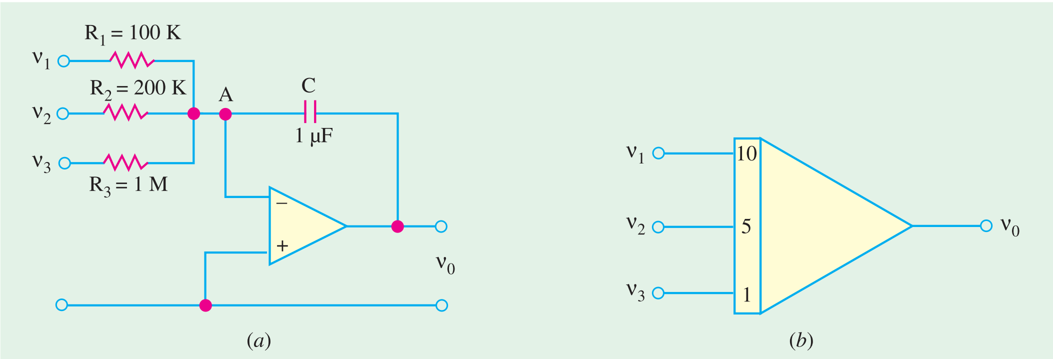


Fig. 68.15

68.13. Differentiator

Its function is to provide an output voltage which is ***proportional to the rate of the change of the input voltage.*** It is an inverse mathematical operation to that of an integrator. As shown in Fig. 68.16, when we feed a differentiator with linearly-increasing ramp input, we get a constant dc output.

Circuit

Differentiator circuit can be obtained by interchanging the resistor and capacitor of the integrator circuit of Fig. 68.13.

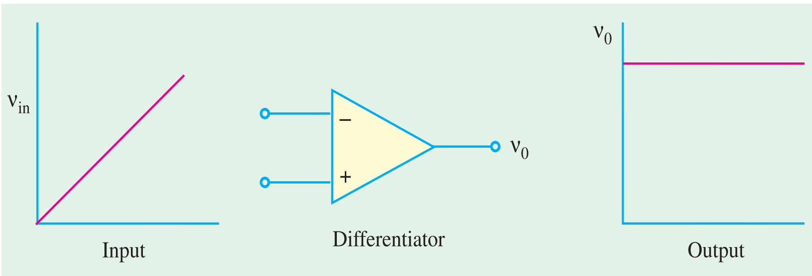


Fig. 68.16

Let i = rate of change of charge

$$= \frac{dq}{dt}$$

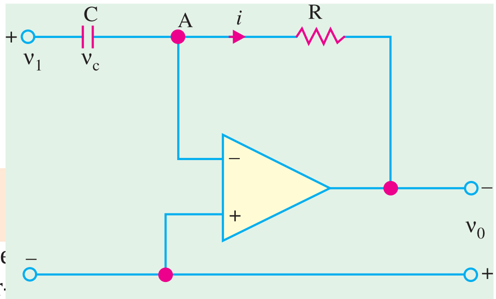


Fig. 68.17

Now, $q = C\nu_c$

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

Taking point A as virtual ground

$$\nu_0 = -iR = -\left(C\cdot\frac{d\nu_c}{dt}\right)R = -CR\cdot\frac{d\nu_c}{dt}$$

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

Example 68.6. *The input to the differentiator circuit of Fig. 68.17 is a sinusoidal voltage of peak value of 5 mV and frequency 1 kHz. Find out the output if R = 1000 K and C = 1 μF.*

Solution. The equation of the input voltage is

$\nu_1 = 5 \sin 2\pi \times 1000\, t = 5 \sin 2000\, \pi t$ mV

scale factor $= CR = 10^{-6} \times 10^5 = 0{\cdot}1$

$\nu_0 = 0{\cdot}1 \frac{d}{dt}(5 \sin 2000\, \pi t) = (0{\cdot}5 \times 2000\, \pi) \cos 2000\, \pi t = 1000\, \pi \cos 2000\, \pi t$ mV

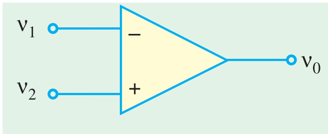


Fig. 68.18

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

68.14. Comparator

It is a circuit which compares two signals or voltage levels. The circuit is shown in Fig. 68.18 and (like that of the unity follower) is the simplest because it needs no additional external components.

If ν_1 and ν_2 are equal, then ν_0 should idealy be zero. Even if ν_1 differs from ν_2 by a very small amount, ν_0 is large because of amplifier's high gain. Hence, circuit of Fig. 68.18 can detect very small changes which is another way of saying that it compares two signals,

68.15. Audio Amplifier

As a matter of fact, in most communication receivers, the final output stage is the audio amplifier. The ideal audio amplifier will have the following characteristics :

1. High gain
2. Minimum distortion in the audio frequency range (*i.e.*, 20 Hz to 20 kHz range).
3. High input resistance (or impedance).
4. Low output resistance (or impedance) to provide optimum coupling to the speaker.

The use of *OP-AMP* is an audio amplifier will fullfill the requirements listed above very nicely. An *OP-AMP* audio amplifier is shown in Fig. 68.19.

Note that the *OP-AMP* is supplied only for $+V$ volt power supply, the $-V$ terminal is grounded. Because of this, the output will be between the limits of $(+V - 1)$ volts and $+1$ volt approximately. Also notice the use of a coupling capacitor C_2 between the *OP-AMP* and speaker. This capacitor is necessary to reference the speaker signal around ground. The capacitor C_s, is included in the V_{CC} line to prevent any transient current caused by the operation of *OP-AMP* from being coupled back to Q_1 through the power supply. The high gain requirements is accomplished by the combination of two amplifier stages. The high R_m/Low R_{out} of the audio amplifier is accomplished by the *OP-AMP* itself, as the low distortion characteristic.

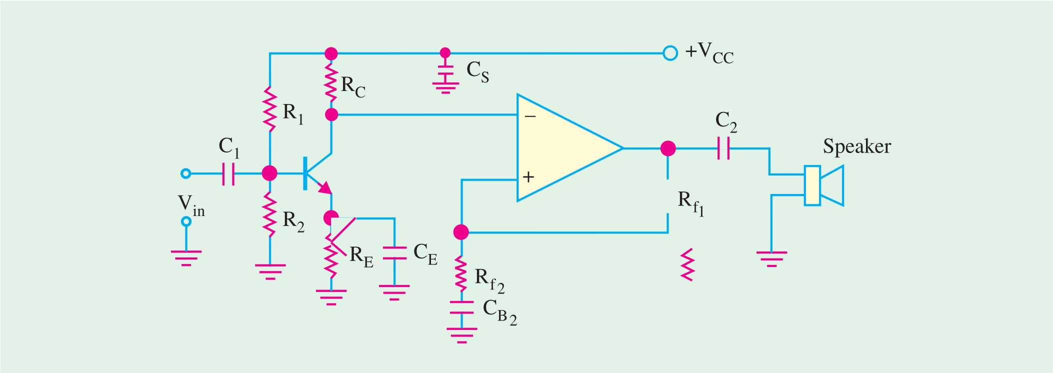


Fig. 68.19

68.16. OP-AMP Based Oscillator Circuits

We have already discussed about sinusoidal oscillators in Chapter 15. There we defined the oscillator as a circuit that produces an output waveform without any external signal source. The only input to an oscillator is the dc power supply. As such, the oscillator can be viewed as being a signal generator. We have also discussed in the same chapter, about the different types of oscillator circuits (like Wien Bridge oscillator, Colpitts Oscillator and Crystal Oscillator) using bipolar junction and field-effect transistor. Now we still study these oscillator circuits using *OP-AMP*.

68.17. OP-AMP Based Wien Bridge Oscillator

Fig. 68.20 shows the basic version of a Wien Bridge oscillator. The circuits uses an *OP-AMP* and *RC* bridge circuit. Note the basic bridge connection carefully. Resistors R_1, R_2 and capacitors $C_1$and C_2 form the frequency adjustment elements while resistors R_3 and R_4 form part of the feedback path. The *OP-AMP* output is connected as the bridge input as points '*A*' and '*C*'. The bridge circuit output at points '*B*' and '*D*' is the input to the *OP-AMP* shows an alternative way of connecting the *RC* bridge circuit to the *OP-AMP*. In a typical Wien Bridge oscillator, $R_1 = R_2 = R$, and $C_1 = C_2 = C$. This means that the two *RC* circuits will have the same cut-off frequency. The cut-off frequency is given by (1/2 π*RC*).

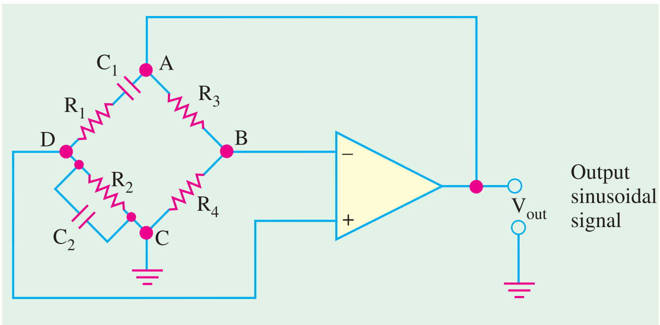


Fig. 68.20

Example 68.7. *Fig. 68.21 shows the circuit of a Wien-Bridge Oscillator using OP-AMP as an amplifier. Notice the components R_1, C_1, R_2, C_2, R_3 and R_4 are connected in the bridge configuration in the same way as shown in Fig. 68.22.*

Calculate the frequency of the Wien Bridge oscillator.

Solution. The frequency of oscillations,

$$f_0 = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 51\,K \times 0{\cdot}001\,\mu\text{F}} = \mathbf{3{\cdot}12\ kHz}$$

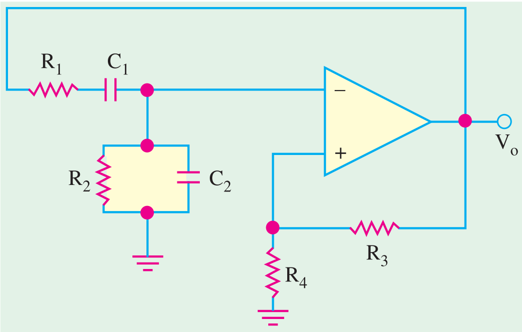


Fig. 68.21

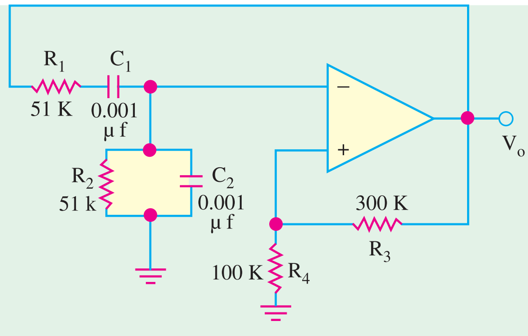


Fig. 68.22

68.18. OP-AMP Based Colpitts Oscillator

An *OP-AMP* based Colpitts oscillator is as shown in Fig. 68.23. Here the *OP-AMP* provides the basic amplification needed while a *LC* feedback network of Colpitts configuration sets the oscillator frequency.

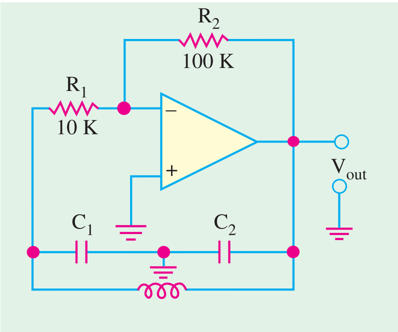


Fig. 68.23

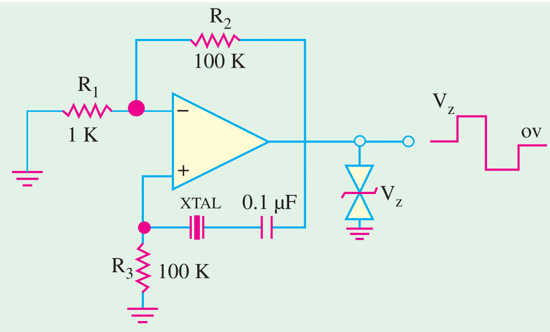


Fig. 68.24

68.19. OP-AMP Based Crystal Oscillator

An *OP-AMP* can be used in a crystal oscillator as shown in Fig. 68.24. The crystal is connected in the series resonant path and operates at the crystal series resonant frequency. The present circuit has high gain so that an output square-wave results are shown in the figure. A pair of Zener diodes is shown at the output to provide output amplitude at exactly the Zener voltage (V_Z).

68.20. A Triangular-Wave Oscillator

Fig. 68.25 shows an *OP-AMP* circuit to generate a triangular-wave from a square-wave. The circuit makes use of two *OP-AMP* : one of them is used as a comparator and the other as an integrator. The operation of the circuit is as given below :

To begin with, let us assume that the output voltage of the comparator is at its maximum negative level. This output is connected to the inverting input

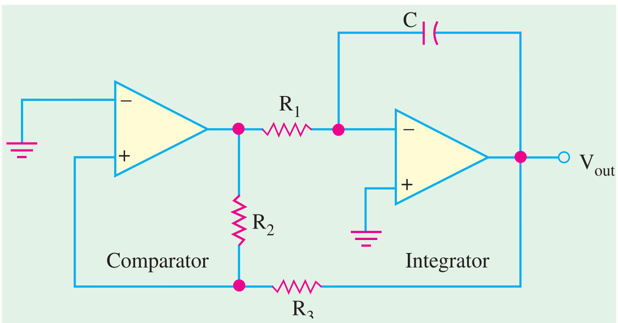


Fig. 68.25

of the integrator through resistor, R_1. This produces a positive-going ramp on the output of the integrator. When the ramp voltage reaches the upper trigger point (UTP), the comparator switches to its maximum positive level. This positive level causes the integrator ramp to change to a negative going direction. The ramp continues in this direction until the lower trigger point (LTP) of the comparator is reached. At this point, the comparator output switches back to its maximum negative level and the cycle repeats. This action is shown in Fig. 68.26.

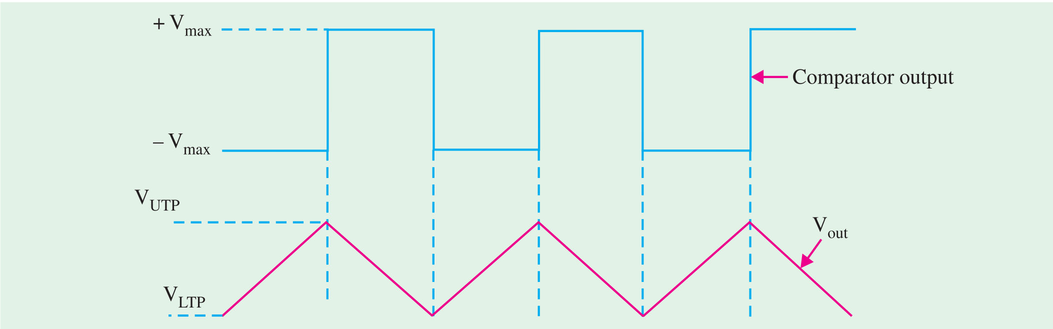


Fig. 68.26

Since the comparator produces square-wave output, therefore, circuit shown in Fig. 68.25 can be used as both a triangular-wave oscillator and a square-wave oscillator. Devices of this type are commonly known as function generator because they produce more than one output function. The output amplitude of the square-wave is set by the output swing of the comparator. While the output amplitude of the triangular-wave is set by the resistors R_2 and R_3 by establishing the UTP and LTP voltages according to the following formulas :

$$V_{\text{UTP}} = +V_{max}\left(\frac{R_3}{R_2}\right)$$

$$V_{\text{LTP}} = -V_{max}\left(\frac{R_3}{R_2}\right)$$

It may be noted that the comparator output levels, $+V_{max}$ are equal. The frequency of both waveforms depend on the $R_1\,C$ time constant as well as the amplitude-setting resistors R_2 and R_3. By varying R_1, the frequency of oscillation can be adjusted without changing the output amplitude.

$$f = \frac{1}{4\,R_1\,C}\left(\frac{R_2}{R_3}\right)$$

68.21. A Voltage-Controlled Sawtooth Oscillator (VCO)

The voltage-controlled oscillator (VCO) is an oscillator whose frequency can be changed by a variable dc control voltage. The VCOs can be either sinusoidal or nonsinusoidal. One way to build a voltage-controlled sawtooth oscillator is shown in Fig. 68.27 (*a*). This circuit makes use of an *OP-AMP* integrator that uses switching device called programmable unijunction transistor (abbreviated as PUT) in parallel with the feedback capacitor to terminate each ramp at a prescribed level and effectively "reset" the circuit.

The programmable unijunction transistor (PUT) is a three terminal device *i.e.*, it has an anode, a cathode and a gate terminal. The gate is always biased positively with respect to the cathode. When the anode voltage exceeds the gate voltage by approximately 0·7 V, the PUT turns on and acts as a forward biased diode. When the anode voltage falls below this level, the PUT turns off. Also, the value of current must be above the holding value to maintain conduction.

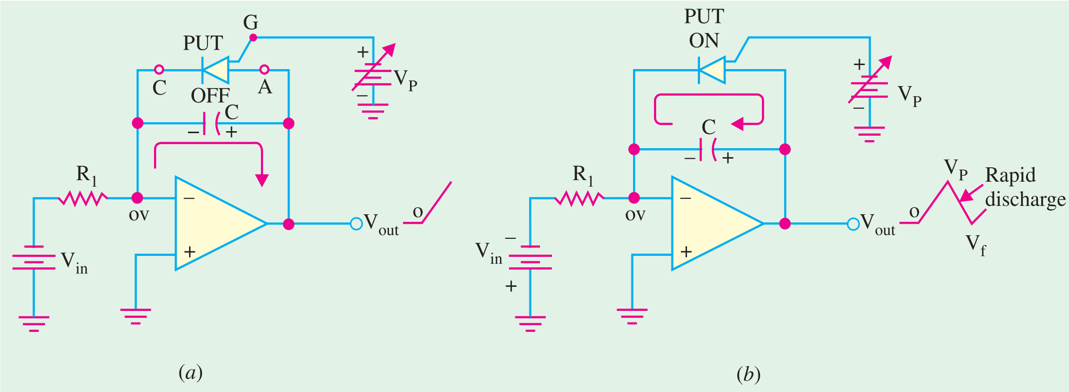


Fig. 68.27

The operation of the circuit may be explained as below. The negative dc input voltage, $-V_{IN}$, produces a positive-going ramp on the output. During the time that ramp is increasing the circuit acts as a regular integrator. When the ramp voltage (*i.e.*, voltage at PUT anode) exceeds the gate voltage by 0·7 V, the PUT turns on. This forces the capacitor to discharge rapidly as shown in Fig. 68.27 (*b*). However, the capacitor does not discharge completely to zero because of the PUT's forward voltage, V_F. Discharging of the capacitor continues until the current through PUT drops below the holding value. At this point, the PUT turn off and capacitor begins to charge again, thus generating a new output ramp. The cycle repeats and the resulting output is a repetitive sawtooth waveform as shown in the figure. It may be noted that the sawtooth amplitude and period can be adjusted by varying the PUT gate voltage.

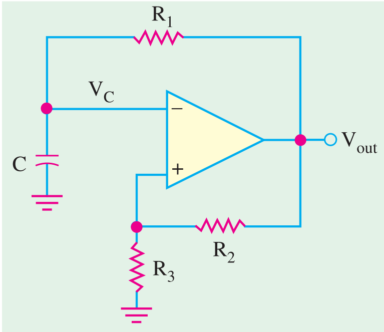


Fig. 68.28

The frequency of smooth curve is given by the relation :

$$f = \frac{|V_{IN}|}{R_1\,C}\left(\frac{1}{V_P - V_F}\right)$$

It is evident from the above equation that the frequency depends upon the time constant "$R_1\,C$" of the integrator and the peak voltage set by the PUT. The time period of the sawtooth wave is the reciprocal of the frequency, *i.e.*,

$$T = \frac{V_P - V_F}{|V_{IN}|/R_1 C}$$

68.22. A Square-wave Relaxation Oscillator

Fig. 1.28 shows the circuit of a basic relaxation oscillator. Its operation depends upon charging and discharging of a capacitor. Notice that the *OP-AMP*'s inverting input is the capacitor voltage and the noninverting input is a portion of the output fed-back through resistors R_2 and R_3.

When the circuit is first turned on, the capacitor is uncharged. Because of this, the inverting input is at 0 V. This makes the output a positive maximum, and capacitor begins to charge towards V_{out} through R_1. When the capacitor voltage reaches a value equal to the feedback voltage on the noninverting input, the switches to the maximum negative stage. At this point, the capacitor begins to discharge from $+V_f$ toward $-V_f$. When the capacitor voltage reaches $-V_f$ the *OP-AMP* switches back to the maximum positive state. This action continues to repeat and a square wave input is obtained as shown in Fig. 68.29.

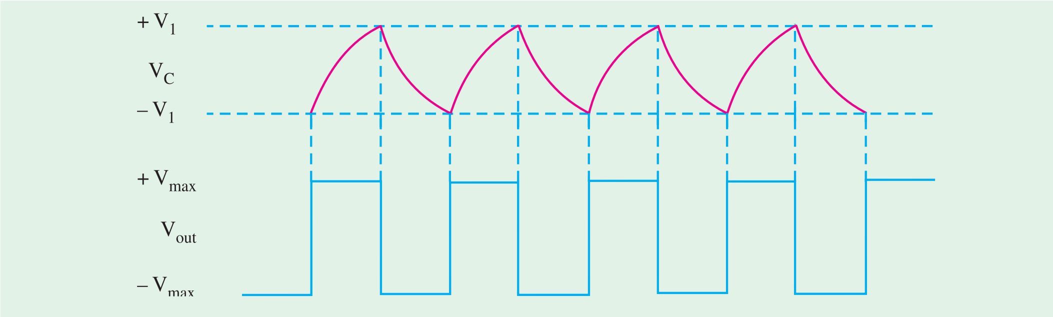


Fig. 68.29

68.23. High-impedance Voltmeter

Fig. 68.30 shows the circuit of a high impedance voltmeter. In such a circuit, the closed loop-gain depends on the internal resistance of the meter R_M. The input voltage will be amplified and the output voltage will cause a proportional current to flow through the meter. By adding a small series potentiometer in the feedback loop, the meter can be calibrated to provide a more accurate reading.

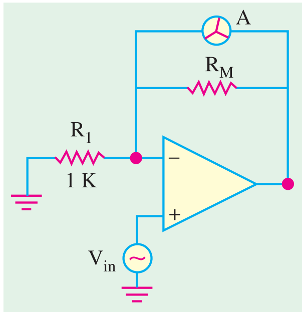


Fig. 68.30

The high input impedance of the *OP-AMP* reduces the circuit loading that is caused by the use of the meter. Although this type of circuit would cause some circuit loading, it would be much more accurate than a VOM (Volt-Ohm-Meter) with an input impedance of 20 K/V.

68.24. Active Filters

We have already discussed in Chapter 10, about tuned amplifiers. Such amplifiers are designed to amplify only those frequencies that are within certain range. As long as the input signal is within the specified range, it will be amplified. If it goes outside of this frequency range, amplification will be drastically reduced. The tuned amplifier circuits using *OP-AMP* are generally referred to as active filters. Such circuits do not require the use of inductors. The frequency response of the circuit is determined by resistor and capacitor values.

A filter circuit can be constructed using passive components like resistors and capacitors. But an active filter, in addition to the passive components makes use of an *OP-AMP* as an amplifier. The amplifier in the active filter circuit may provide voltage amplification and signal isolation or buffering.

There are four major types of filters namely, low-pass, filter-high-pass filter, and band-pass filter and band-stop or notch filter. All these four types of filters are discussed one by one in the following pages.

68.25. Low-Pass Filter

A filter that provides a constant output from dc up to a cut-off frequency (f_{OH}) and then passes no signal above that frequency is called an ideal low-pass filter. The ideal response of a low-pass filter is as shown in Fig. 68.31 (*a*). Notice that the response shows that the filter has a constant output (indicated by a horizontal line AB) from dc or zero frequency up to a cutt-off frequency (f_{OH}). And beyond f_{OH}, the output is zero as indicated by the vertical line 'BC' in the figure.

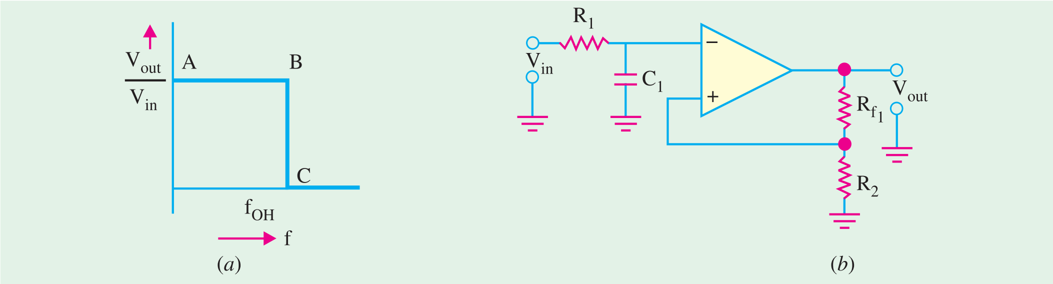


Fig. 68.31

Fig. 68.31 (*b*) shows the circuit of a low-pass active filer using a single resistor and capacitor. Such a ricuit is also referred to as first-order (or single-pole) low-pass filter. It is called first-order because it makes use of a single resistor and a capacitor. The response of such a first-order low pass filter is as shown in Fig. 68.32. Notice that the response below the cut-off frequency (f_{OH}) shows a constant gain (indicated by a horizontal line 'AB')

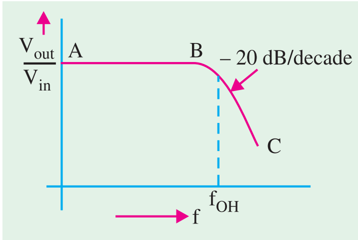


Fig. 68.32

However, beyond the cut-off frequency, the gain does not reduce immediately to zero as expected in Fig. 68.31 (*a*) but reduces with a slope of 20 dB/decade (means that the output voltage reduces by a factor of 100 when the fequency increases by a factor of 10). The voltage gain for a low-pass filter below the cut-off frequency (f_{OH}) is given by the relation.

$$A_v = 1 + \frac{R_3}{R_1}$$

And the cut-off frequency is determined by the relation

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

It is possible to connect two sections of the filter together as shown in Fig. 68.33 (*a*). Such a circuit is called second-order (or two-pole) low pass filter. Fig. 68.33 configuration of the second-order low-pass filter.

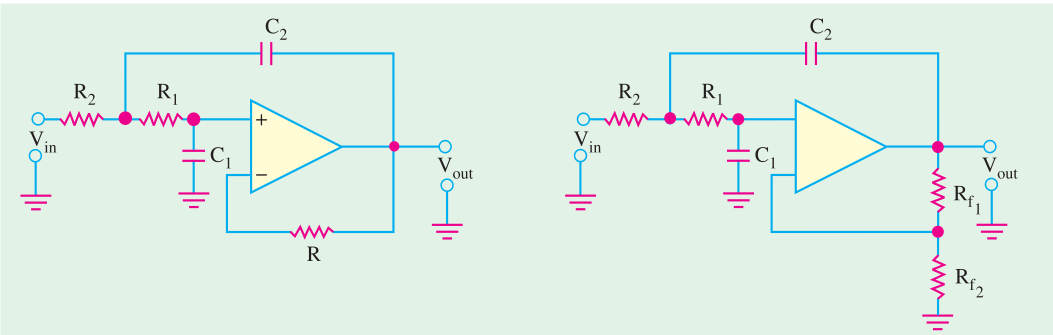


Fig. 68.33

Each circuit shown in Fig. 68.33 has two RC circuits, $R_1 - C_1$ and $R_2 - C_2$. As the operating frequency increases beyond f_2, each circuit will be dropping the closed-loop gain by 20 dB, giving a total roll-off rate of 40 dB/decade when operated above f_2. The cut-off frequency for each of the circuit is given by,

$$f_2 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

68.26. High-pass Filter

As a matter of a fact, there is very little difference between the high-pass filter and the low-pass filter. Fig. 68.34 (*a*) shows the circuit of a first order (or single-pole) high-pass filter and Fig. 68.34 (*b*), the circuit of a second-order (or two-pole) high-pass filter. Notice that the only thing that has changed is the position of the capacitors and resistors. The value of cut-off frequencies f_1 and f_2 is obtained by using the same equations we used for low-pass filter.

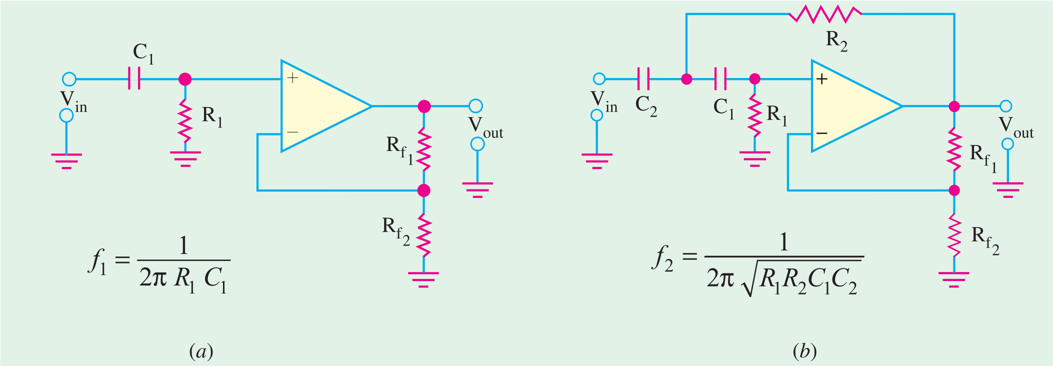


Fig. 68.34

Fig. 68.35 shows the gain versus frequency response of a high-pass filter. Notice that the solid line indicates the ideal response while the dashed line, corresponds to the actual response of the filter circuit. The ideal curve indicates that the filter has a zero output for the frequencies below f_{OL} (indicated by the line 'AB'). And beyond f_{OL}, it has a constant output. The actual response curve may correspond to the roll-off gain by 20 dB/decade for first order to 40 dB/decade for second-order low-pass filters.

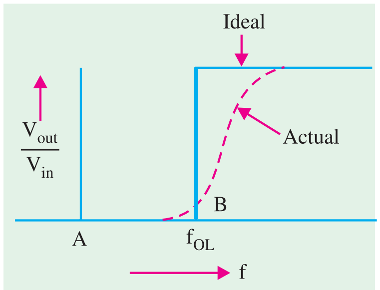


Fig. 68.35

68.27. Band-pass Filters

A band-pass filter is the one that is designed to pass all frequencies within its bandwith. A simple way to construct a band-pass filter is to cascade a low-pass filters and a high-pass filter as shown in Fig. 68.36. The first stage of the band-pass filter will pass all frequencies that are below its cutt-off value, f_2. All the frequencies passed by the first stage will head into the second stage. This stage will pass all frequencies above its value of f_1. The result of this circuit action is as shown in Fig. 68.37. Note that the only frequencies that all will pass through the amplifier are those that fall within the pass band of both amplifiers. The values of f_1 and f_2 can be obtained by using the relations, $1/2\pi R_1 C_1$ and, $1/2\pi R_2 C_2$. Then bandwith,

$$BW = f_2 - f_1$$

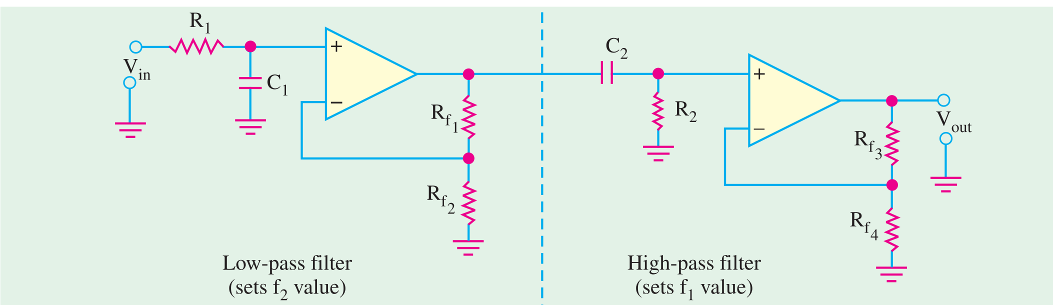


Fig. 68.36

And the centre frequency,

$$f_0 = f_1 \cdot f_2$$

The Quality-factor (or Q-factor) of the band-pass filter circuit.

$$Q = \frac{f_0}{BW}$$

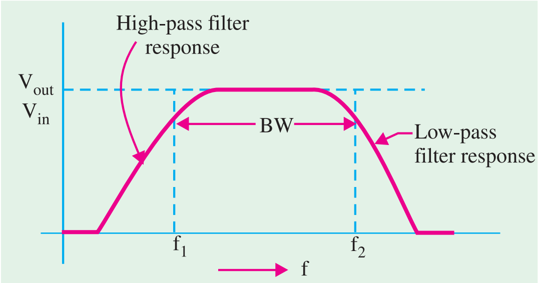


Fig. 68.37

68.28. Notch Filter

The notch filter is designed to block all frequencies that fall within its bandwidth Fig. 68.38 (*a*) shows a block diagram and 68.38 (*b*), the gain versus frequency response curve of a multistage notch filter.

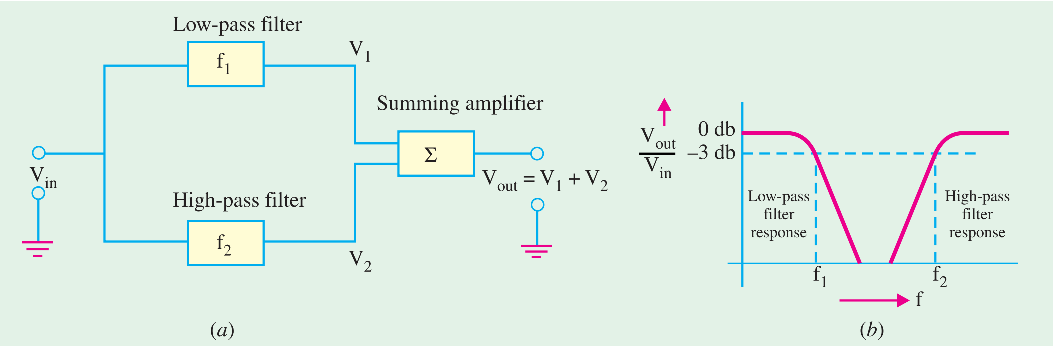


Fig. 68.38

The block diagram shows that the circuit is made up of a high-pass filter, a low-pass filter and a summing amplifier. The summing amplifier produces an output that is equal to a sum of the filter output voltages. The circuit is designed in such a way so that the cut-off frequency, f_1 (which is set by a low-pass filter) is lower in value than the cut-off frequency, f_2 (which is set by high-pass filter). The gap between the values of f_1 and f_2 is the bandwidth of the filter.

When the circuit input frequency is lower than f_1, the input signal will pass through low-pass filter to the summing amplifier. Since the input frequency is below the cut-off frequency of the high-pass filter, v_2 will be zero. Thus the output from the summing amplifier will equal the output from the low-pass filter. When the circuit input frequency is higher than f_2, the input signal will pass through the high-pass filter to the summing amplifier. Since the input frequency is above the cut-off frequency of the low-pass filter, v_1 will zero. Now the summing amplifier output will equal the output from the high-pass filter.

It is evident from the above discussion that frequencies below f_1 and those above f_2, have been passed by the notch filter. But when the circuit frequency between f_1 and f_2, neither of the filters will produce an output. Thus v_1 and v_2 will be both zero and the output from the summing amplifier will also be zero.

The frequency analysis of the notch filter is identical to the band-pass filter. Fisrt, determine the cut-off frequencies of the low-pass and the high-pass filters. Then using these calculated values, determine the bandwidth, center frequency and Q values of the circuit.

Tutorial Problems No. 68

1. Determine the maximum allowable value of v_{in} for the circuit shown in Fig. 68.39. Assume that the gain of the amplifier is 200. **(40 mV)**

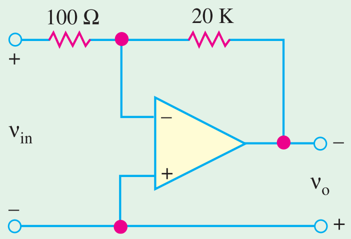


Fig. 68.39

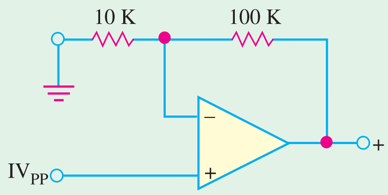


Fig. 68.40

2. For the non-inverting amplifier shown in Fig. 68.40, find the voltage gain of the circuit. **(11)**

3. Determine the value of output voltage for the summing circuit shown in Fig. 68.41. **(3·52 V)**

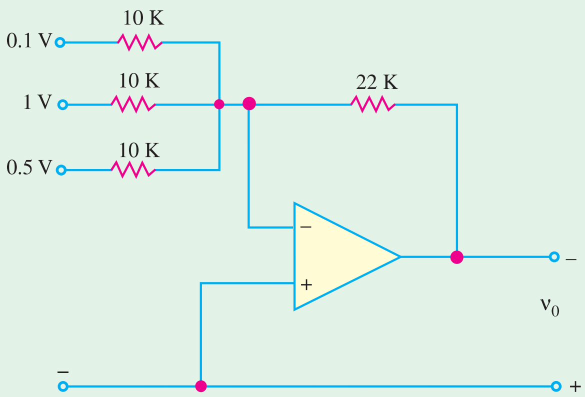


Fig. 68.41

OBJECTIVE TESTS – 68

1. An OP-AMP can be classified as .... amplifier.
(*a*) linear
(*b*) low-r_{in}
(*c*) positive feedback
(*d*) *RC*-coupled.

2. An ideal OP-AMP has
(*a*) infinite A_v
(*b*) infinite R_i
(*c*) zero R_0
(*d*) all the above.

3. OP-AMP have become very popular in industry mainly because
(*a*) they are dirt cheap
(*b*) their external characteristics can be changed to suit any application
(*c*) of their extremely small size
(*d*) they are available in different packages.

4. Since input resistance of an ideal OP-AMP is infinte
(*a*) its output resistance is zero
(*b*) its output voltage becomes independent of load resistance
(*c*) its input current is zero
(*d*) it becomes a current-controlled device.

5. The gain of an actual OP-AMP is around
(*a*) 1,000,000 (*b*) 1000
(*c*) 100 (*d*) 10,000

6. When an input voltage of 1 V is applied to an OP-AMP having $A_v = 10^6$ and bias supply of + 15 V, the output voltage available is
(*a*) 15×10^6 V (*b*) 10^6 V
(*c*) 15 μV (*d*) 15 V.

7. An inverting amplifier has $R_f = 2$ M and $R_1 = 2$ K, Its scale factor is

(*a*) 1000 (*b*) −1000
(*c*) 10^{-3} (*d*) -10^{-3}

8. In an inverting amplifier, the two input terminals of an ideal OP-AMP are at the same potential because

(*a*) the two input terminals are directly shorted internally
(*b*) the input impedance of the OP-AMP is infinity
(*c*) common-mode rejection ratio is infinity
(*d*) the open-loop gain of the OP-AMP is infinity.

9. The open-loop gain of an operational amplifier is 10^5. An input signal of 1 mV is applied to the inverting input with the non-inverting input connected to the ground. The supply voltages are ±10 V. The output of the amplifier will be

(*a*) + 100 V
(*b*) – 100 V
(*c*) + 10 V (approximately)
(*d*) – 10 V (approximately)

10. The output voltage of the circuit shown in Fig. 68.42 is

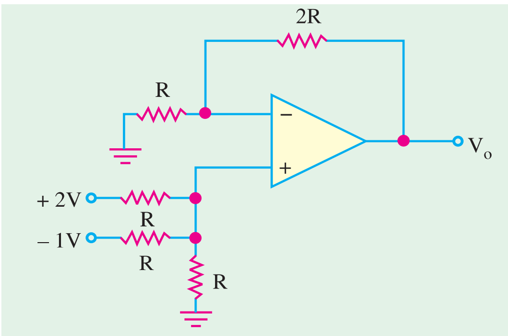


Fig. 68.42

(*a*) 1·0 V (*b*) 1·5 V
(*c*) 2·0 V (*d*) 2·5 V

11. In the circuit shown in Fig. 68.43, the value of output, v_0 is

(*a*) + 3 V (*b*) – 3 V
(*c*) – 7 V (*d*) + 7 V

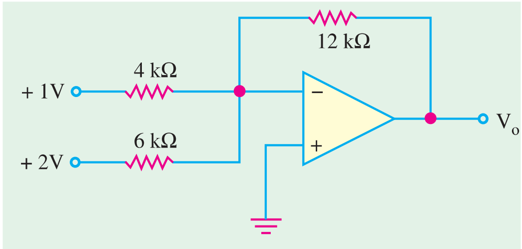


Fig. 68.43

12. When in a negative scaler, both R_1 and R_f are reduced to zero, the circuit functions as

(*a*) integrator (*b*) subtractor
(*c*) comparator (*d*) unity follower.

13. The two input terminals of an OP-AMP are known as

(*a*) positive and negative
(*b*) differential and non-differential
(*c*) inverting and non-inverting
(*d*) high and low.

14. The purpose of comparator is to

(*a*) amplify an input voltage
(*b*) detect the occurrence of a changing input voltage
(*c*) maintain a constant output when the dc input voltage changes.
(*d*) produce a change in input voltage when an input voltage equals the reference voltage.

15. The OP-AMP comparator circuit uses

(*a*) positive feedback
(*b*) negative beedback
(*c*) regenerative feedback
(*d*) no feedback

16. The feedback path in an OP-AMP integrator consists of

(*a*) a resistor
(*b*) a capacitor
(*c*) a resistor and a capacitor in series
(*d*) a resistor and a capacitor in parallel.

17. The feedback path in an OP-AMP differentiator consists of

(*a*) a resistor
(*b*) a capacitor
(*c*) a resistor and a capacitor in series
(*d*) a resistor and a capacitor in parallel.

ANSWERS

1. (*a*) **2.** (*d*) **3.** (*b*) **4.** (*c*) **5.** (*a*) **6.** (*d*) **7.** (*b*) **8.** (*b*) **9.** (*b*) **10.** (*c*) **11.** (*d*) **12.** (*d*)
13. (*c*) **14.** (*d*) **15.** (*d*) **16.** (*b*) **17.** (*a*)

GO To FIRST