(ii) In order to find differential voltage gain, we should first find d.c. emitter current.

$$\text{Tail current, } I_E = \frac{V_{EE} - V_{BE}}{R_E} = \frac{(12 - 0.7)V}{200\ \text{k}\Omega} = 0.0565\ \text{mA}$$

The d.c. emitter current in each transistor is

$$I_{E1} = I_{E2} = I_E/2 = 0.0565\ \text{mA}/2 = 0.0283\ \text{mA}$$

$$\therefore \quad \text{a.c. emitter resistance, } r'_e = \frac{25\ \text{mV}}{I_{E1}} = \frac{25\ \text{mV}}{0.0283} = 883.4\ \Omega$$

$$\therefore \quad \text{Differential voltage gain, } A_{DM} = \frac{R_C}{2r'_e} = \frac{100\ \text{k}\Omega}{2 \times 883.4\ \Omega} = 56.6$$

$$\therefore \quad CMRR_{dB} = 20 \log_{10} \frac{A_{DM}}{A_{CM}} = 20 \log_{10} \frac{56.6}{0.25} = \mathbf{47.09\ dB}$$

25.15 Operational Amplifier (OP- Amp)

Fig. 25.38 shows the block diagram of an operational amplifier (*OP*-amp). The input stage of an *OP*- amp is a differential stage followed by more stages of gain and a class *B* push-pull emitter follower.

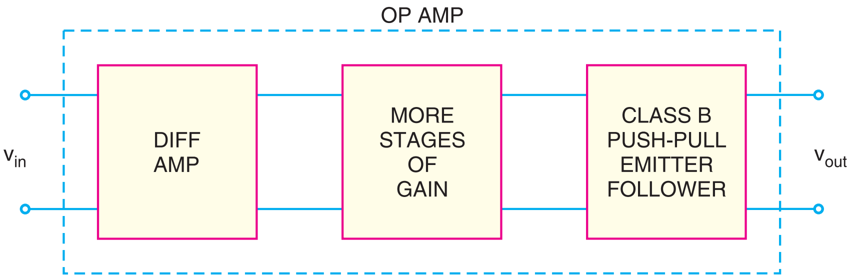


Fig. 25.38

The following are the important properties common to all operational amplifiers (*OP*-amps):

(i) An operational amplifier is a multistage amplifier. The input stage of an *OP*-amp is a differential amplifier stage.

(ii) An inverting input and a noninverting input.

(iii) A high input impedance (usually assumed infinite) at both inputs.

(iv) A low output impedance (< 200 Ω).

(v) A large open-loop voltage gain, typically 10^5.

(vi) The voltage gain remains constant over a wide frequency range.

(vii) Very large *CMRR* (> 90 dB).

25.16 Schematic Symbol of Operational Amplifier

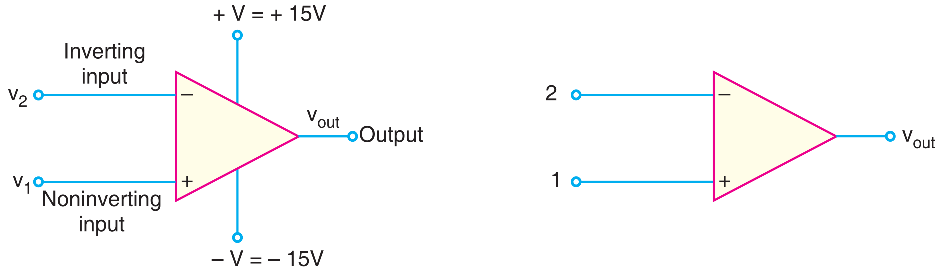
Fig.25.39(*i*) shows the schematic symbol of an operational amplifier. The following points are worth noting :

(i) The basic operational amplifier has *five terminals: two terminals for supply voltages +V and –V; two input terminals (inverting input and noninverting input) and one output terminal.

* Two other terminals, the *offset null terminals*, are used to ensure zero output when the two inputs are equal. These are normally used when small d.c. signals are involved.

(*ii*) Note that the input terminals are marked + and –. These are not polarity signs. The – sign indicates the *inverting input* while the + sign indicates the *noninverting input*. A signal applied to plus terminal will appear in the same phase at the output as at the input. A signal applied to the minus terminal will be shifted in phase 180° at the output.

(*iii*) The voltages v_1, v_2 and v_{out} are node voltages. This means that they are always measured w.r.t. ground. The differential input v_{in} is the difference of two node voltages v_1 and v_2. We normally do not show the ground in the symbol.



(*i*) (*ii*)

Fig. 25.39

(*iv*) For the sake of *simplicity, + *V* and – *V* terminals are often omitted from the symbol as shown in Fig. 25.39(*ii*). The two input leads are always shown on the symbol regardless of whether they are both used.

(*v*) In most cases, if only one input is required for an *OP*-amp circuit, the input not in use will be shown connected to ground. A single-input *OP*-amp is generally classified as either inverting or noninverting.

(*vi*) The *OP*-amp is produced as an integrated circuit (*IC*). Because of the complexity of the internal circuitry of an *OP*-amp, the *OP*-amp symbol is used exclusively in circuit diagrams.

25.17 Output Voltage From OP-Amp

The output voltage from an *OP*-amp for a given pair of input voltages depends mainly on the following factors:

1. The voltage gain of *OP*-amp.
2. The polarity relationship between v_1 and v_2.
3. The values of supply voltages, +*V* and –*V*.

1. Voltage gain of OP-amp. The *maximum* possible voltage gain from a given OP-amp is called *open-loop voltage gain* and is denoted by the symbol A_{OL}. The value of A_{OL} for an *OP*-amp is generally greater than 10,000.

The term open-loop indicates a circuit condition where there is *no feedback path from the output to the input of OP-amp.* The *OP*-amps are almost always operated with negative feedback *i.e.*, a part of the output signal is fed back in phase opposition to the input. Such a condition is

* Since two or more *OP*-amps are often contained in a single *IC* package, eliminating these terminals on the symbol eliminates unnecessary duplication.

illustrated in Fig. 25.40. Here R_i is the input resistance and R_f is the feedback resistor. Consequently, the voltage gain of *OP* amplifier is reduced. When a feedback path is present such as R_f connection in Fig. 25.40, the resulting circuit gain is referred to as *closed-loop voltage gain* (A_{CL}). The following points may be noted :

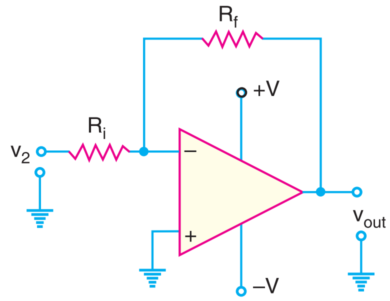


Fig. 25.40

(*i*) The maximum voltage gain of given OP-amp is A_{OL}. Its value is generally greater than 10,000.

(*ii*) The actual gain (A_{CL}) of an OP-amplifier is reduced when negative feedback path exists between output and input.

2. OP-Amp Input/Output Polarity Relationship. The polarity relationship between v_1 and v_2 will determine whether the *OP*-amp output voltage polarity is positive or negative. There is an easy method for it. We know the differential input voltage v_{in} is the difference between the non-inverting input (v_1) and inverting input (v_2) *i.e.*,

$$v_{in} = v_1 - v_2$$

When the result of this equation is *positive*, the OP-amp output voltage will be *positive*. When the result of this equation is *negative*, the output voltage will be *negative*.

Illustration. Let us illustrate *OP*-Amp input/output polarity relationship with numerical values.

(*i*) In Fig. 25.41(*i*), v_1 = + 4V and v_2 = + 2V so that $v_{in} = v_1 - v_2$ = (+ 4V) – (+ 2V) = 2V. Since v_{in} is *positive*, the *OP*-amp output voltage will be *positive*.

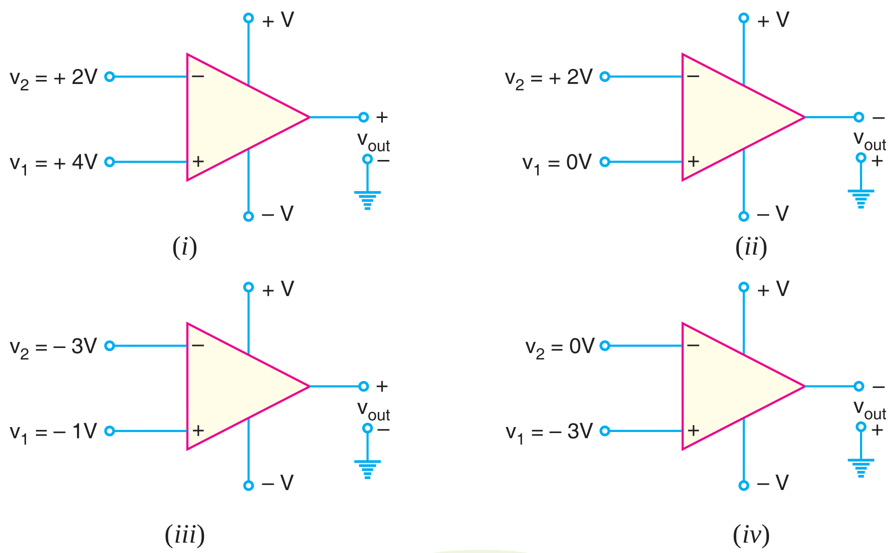


Fig. 25.41

(*ii*) In Fig. 25.41 (*ii*), v_1 = 0*V* and v_2 = + 2*V* so that $v_{in} = v_1 - v_2$ = (0*V*) – (+2*V*) = –2*V*. Since v_{in} is *negative*, the *OP*-amp output voltage will be *negative*.

(*iii*) In Fig. 25.41 (*iii*), v_1 = –1*V* and v_2 = –3*V* so that $v_{in} = v_1 - v_2$ = (–1*V*) – (–3*V*) = 2*V*. Clearly, the *OP*-amp output voltage will be *positive*.

(*iv*) In Fig. 25.41 (*iv*), v_1 = –3*V* and v_2 = 0*V* so that $v_{in} = v_1 - v_2$ = (–3*V*) – (0V) = –3V. Therefore, the *OP*-amp output voltage will be *negative*.

3. Supply Voltages. The supply voltages for an *OP*-amp are normally equal in magnitude and opposite in sign *e.g.*, ± 15V, ± 12V, ± 18*V*. These supply voltages determine the limits of output voltage of *OP*-amp. These limits, known as *saturation voltages*, are generally given by;

$$+ V_{sat} = + V_{supply} - 2V$$
$$- V_{sat} = - V_{supply} + 2V$$

Suppose an *OP*-amplifier has $V_{supply} = \pm 15V$ and open-loop voltage gain $A_{OL} = 20{,}000$. Let us find the differential voltage v_{in} to avoid saturation.

$$V_{sat} = V_{supply} - 2 = 15 - 2 = 13V$$

$$\therefore \quad V_{in} = \frac{V_{sat}}{A_{OL}} = \frac{13V}{20,000} = 650\ \mu V$$

If the differential input voltage V_{in} exceeds this value in an *OP*-amp, it will be driven into saturation and the device will become non-linear.

Note : Although input terminals of an *OP*-amp are labeled as + and –, this does not mean you have to apply positive voltages to the + terminal and negative voltages to the –terminal. Any voltages can be applied to either terminal. The true meaning of the input terminal labels (+ and –) is that a *positive voltage applied to the + terminal drives the output voltage towards +V of d.c. supply; a positive voltage applied to the – terminal drives the output voltage towards –V of d.c. supply.

25.18 A.C. Analysis of OP-Amp

The basic *OP*-amp has two input terminals and one output terminal. The input terminals are labeled as + (noninverting input) and –(inverting input). As discussed earlier, a signal applied to the non-inverting input (+) will produce an output voltage that is in phase with the input voltage. However, a signal applied to the inverting input (–) will produce an output voltage that is 180° out of phase with the input signal.

(*i*) Practical OP–amp. Fig. 25.42 shows the a.c. equivalent circuit of a practical *OP*-amp. The characteristics of a practical OP-amp are : *very high voltage gain, very high input impedance* and *very low output impedance*. The input voltage v_{in} appears between the two input terminals and the output voltage is $A_v v_{in}$ taken through the output impedance Z_{out}. The consequences of these properties of a practical OP–amp are :

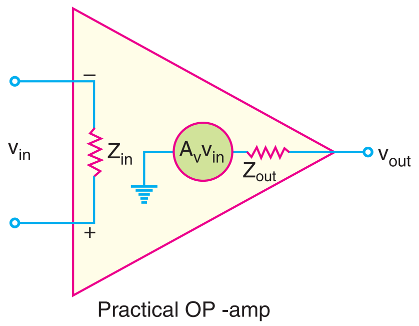


Fig. 25.42

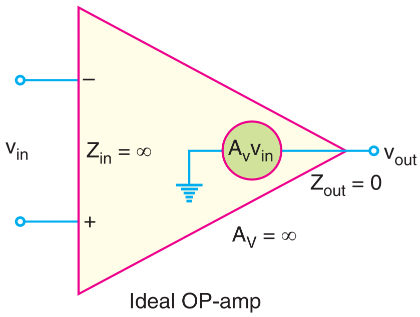


Fig. 25.43

* Note that positive and negative are relative terms. Thus if +4V is applied at +input terminal and +2V at – input terminal, then + terminal is at more positive potential. Therefore, the output voltage will swing towards +V of d.c. supply.

(a) Since the voltage gain (A_v) of a practical *OP*-amp is very high, an extremely small input voltage (v_{in}) will produce a large output voltage (v_{out}).

(b) Since the input impedance (Z_{in}) is very high, a practical OP-amp has very small input current.

(c) Since the output impedance (Z_{out}) of a practical OP-amp is very low, it means that output voltage is practically independent of the value of load connected to OP-amp.

(ii) Ideal OP-amp. Fig. 25.43 shows the a.c. equivalent circuit of an ideal OP-amp. The characteristics of an ideal OP-amp are : *infinite voltage gain, infinite input impedance* and *zero output impedance*. The consequences of these properties of an ideal *OP*-amp are :

(a) Since the voltage gain (A_v) of an ideal *OP*-amp is infinite, it means that we can set $v_{in} = 0V$.

(b) Since the input impedance (Z_{in}) is infinite, an ideal *OP*-amp has zero input current.

(c) Since the output impedance (Z_{out}) of an ideal *OP*-amp is zero, it means the output voltage does not depend on the value of load connected to *OP*-amp.

We can sum up the values of parameters of a practical *OP*-amp and an ideal *OP*-amp as under :

Practical *OP*-amp	**Ideal *OP*-amp**
$Z_{in} = 2\ \text{M}\Omega$	$Z_{in} \to \infty$ (Open circuit)
$A_v = 1 \times 10^5$	$A_v \to \infty$
$Z_{out} = 100\ \Omega$	$Z_{out} = 0\Omega$

25.19 Bandwidth of an OP-Amp

All electronic devices work only over a limited range of frequencies. This range of frequencies is called **bandwidth.** Every *OP*-amp has a bandwidth *i.e.*, the range of frequencies over which it will work properly. The bandwidth of an *OP*-amp depends upon the closed-loop gain of the *OP*-amp circuit. One important parameter is **gain-bandwidth product (GBW).** It is defined as under :

$$A_{CL} \times f_2 = f_{unity} = \text{GBW}$$

where A_{CL} = closed-loop gain at frequency f_2

f_{unity} = frequency at which the closed-loop gain is unity

It can be proved that the gain-bandwidth product of an OP-amp is constant. Since an *OP*-amp is capable of operating as a d.c. amplifier, its bandwidth is ($f_2 - 0$). The gain-bandwidth product of an OP-amp is an important parameter because it can be used to find :

(i) The maximum value of A_{CL} at a given value of f_2.

(ii) The value of f_2 for a given value of A_{CL}.

Example 25.21. *An OP-amp has a gain-bandwidth product of 15 MHz. Determine the bandwidth of OP-amp when A_{CL} = 500. Also find the maximum value of A_{CL} when f_2 = 200 kHz.*

Solution.
$$f_2 = \frac{f_{unity}}{A_{CL}} = \frac{15\text{MHz}}{500} = 30\text{ kHz}$$

Since the *OP*-amp is capable of operating as a d.c. amplifier, bandwidth *BW* = **30 kHz.**

$$A_{CL} = \frac{f_{unity}}{f_2} = \frac{15\text{MHz}}{200\text{ kHz}} = \mathbf{75 \text{ or } 37.5\text{ db}}$$

Example 25.22. *An OP-amp has a gain-bandwidth product of 1.5 MHz. Find the operating bandwidth for the following closed-loop gains* (*i*) A_{CL} = 1 (*ii*) A_{CL} = 10 (*iii*) A_{CL} = 100.

Solution. Bandwidth, $BW = \dfrac{GBW}{A_{CL}}$

(*i*) For $A_{CL} = 1$, $BW = \frac{1.5 \text{ MHz}}{1} = $ **1.5 MHz**

(*ii*) For $A_{CL} = 10$, $BW = \frac{1.5 \text{ MHz}}{10} = $ **150 kHz**

(*iii*) For $A_{CL} = 100$, $BW = \frac{1.5 \text{ MHz}}{100} = $ **15 kHz**

From this example, we conclude that :

(*a*) The higher the gain (A_{CL}) of an *OP*-amp, the narrower its bandwidth.

(*b*) The lower the gain of an *OP*-amp, the wider its bandwidth.

25.20 Slew Rate

The slew rate of an *OP*-amp is a measure of *how fast the output voltage can change* and is measured in volts per microsecond (V/μs). If the slew rate of an *OP*-amp is 0.5V/μs, it means that the output from the amplifier can change by 0.5 V every μs. Since frequency is a function of time, the *slew rate can be used to determine the maximum operating frequency of the OP-amp* as follows:

$$\text{Maximum operating frequency, } f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}}$$

Here V_{pk} is the peak output voltage.

Example 25.23. *Determine the maximum operating frequency for the circuit shown in Fig. 25.44. The slew rate is 0.5 V/μs.*

Solution. The maximum peak output voltage(V_{pk}) is approximately *8*V*. Therefore, maximum operating frequency (f_{max}) is given by;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\, V/\mu s}{2\pi \times 8}$$

$$= \frac{500 \text{ kHz}}{2\pi \times 8} \quad (\because 0.5 \text{ V/μs} = 500 \text{ kHz})$$

$$= \mathbf{9.95 \text{ kHz}}$$

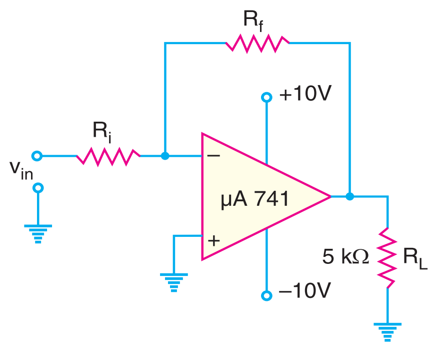


Fig. 25.44

While 9.95 kHz may not seem to be a very high output frequency, you must realise that the amplifier was assumed to be operating at its maximum output voltage. Let us see what happens when peak output voltage is reduced (See example 25.24).

Example 25.24. *The amplifier in Fig. 25.44 is being used to amplify an input signal to a peak output voltage of 100 mV. What is the maximum operating frequency of the amplifier?*

Solution. The maximum operating frequency (f_{max}) of the amplifier is given by;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\, V/\mu s}{2\pi \times 0.1} \quad (\because 100 \text{ mV} = 0.1\text{V})$$

$$= \frac{500 \text{ kHz}}{2\pi \times 0.1} = \mathbf{796 \text{ kHz}} \quad (\because 0.5\text{V/μs} = 500 \text{ kHz})$$

The above examples show that an *OP*-amp can be operated at a much higher frequency when being used as a small-signal amplifier than when being used as a large-signal amplifier.

* $+V_{sat} = +V_{supply} - 2 = 10 - 2 = 8V$

25.21 Frequency Response of an OP-Amp

The operating frequency has a significant effect on the operation of an *OP*-amp. The following are the important points regarding the frequency response of an *OP*-amp :

(*i*) The maximum operating frequency of an *OP*-amp is given by;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}}$$

Thus, the *peak output voltage limits the maximum operating frequency.*

(*ii*) When the maximum operating frequency of an *OP*-amp is exceeded, the result is a distorted output waveform.

(*iii*) Increasing the operating frequency of an *OP*-amp beyond a certain point will :

(*a*) Decrease the maximum output voltage swing.

(*b*) Decrease the open-loop voltage gain.

(*c*) Decrease the input impedance.

(*d*) Increase the output impedance.

25.22 OP-Amp with Negative Feedback

An *OP*-amp is almost always operated with negative feedback *i.e.*, a part of the output is fed back in phase opposition to the input (See Fig. 25.45). The reason is simple. The open-loop voltage gain of an *OP*-amp is very high (usually greater than 100,000). Therefore, an extremely small input voltage drives the *OP*-amp into its saturated output stage. For example, assume v_{in} = 1mV and A_{OL} = 100,000. Then,

$$v_{out} = A_{OL}\, v_{in} = (100{,}000) \times (1 \text{ mV}) = 100 \text{ V}$$

Since the output level of an *OP*-amp can never reach 100 V, it is driven deep into saturation and the device becomes non-linear.

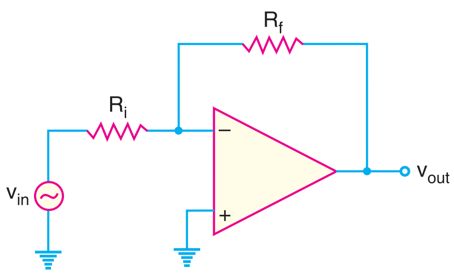


Fig. 25.45

With negative feedback, the voltage gain (A_{CL}) can be reduced and controlled so that OP-amp can function as a linear amplifier. In addition to providing a controlled and stable gain, negative feedback also provides for control of the input and output impedances and amplifier bandwidth. The table below shows the general effects of negative feedback on the performance of OP-amps.

	Voltage gain	Input Z	Output Z	Bandwidth
Without negative feedback	A_{OL} is too high for linear amplifier applications	Relatively high	Relatively low	Relatively narrow
With negative feedback	A_{CL} is set by the feedback circuit to desired value	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

25.23 Applications of OP-Amps

The operational amplifiers have many practical applications. The *OP*-amp can be connected in a large number of circuits to provide various operating characteristics. In the sections to follow, we shall discuss important applications of *OP*-amps.

25.24 Inverting Amplifier

An *OP* amplifier can be operated as an inverting amplifier as shown in Fig. 25.46. An input signal v_{in} is applied through input resistor R_i to the minus input (inverting input). The output is fed back to the same minus input through feedback resistor R_f. The plus input (noninverting input) is grounded. Note that the resistor R_f provides the **negative feedback*. Since the input signal is applied to the inverting input (–), the output will be inverted (*i.e.* 180° out of phase) as compared to the input. Hence the name inverting amplifier.

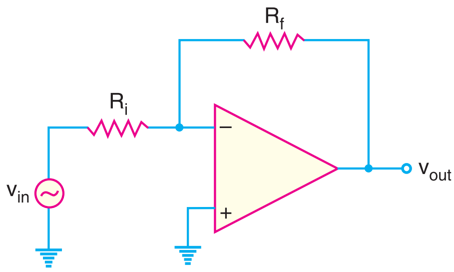


Fig. 25.46

Voltage gain. An OP-amp has an infinite input impedance. This means that there is zero current at the inverting input. If there is zero current through the input impedance, then there must be *no* voltage drop between the inverting and non-inverting inputs. This means that voltage at the inverting input (–) is zero (point *A*) because the other input (+) is grounded. The 0V at the inverting input terminal (point *A*) is referred to as **virtual ground.** This condition is illustrated in Fig. 25.47. The point *A* is said to be at virtual ground because it is at 0V but is not physically connected to the ground (*i.e.* $V_A = 0V$).

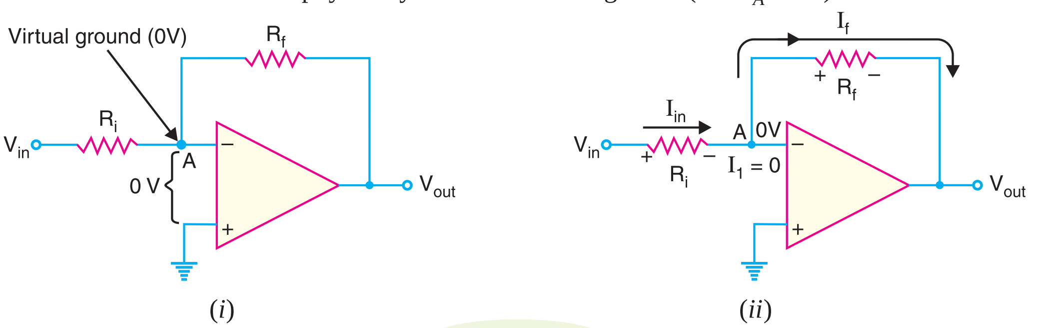


Fig. 25.47

Referring to Fig. 25.47 (*ii*), the current I_1 to the inverting input is zero. Therefore, current I_{in} flowing through R_i entirely flows through feedback resistor R_f. In other words, $I_f = I_{in}$.

Now $$I_{in} = \frac{\text{Voltage across } R_i}{R_i} = \frac{V_{in} - V_A}{R_i} = \frac{V_{in} - 0}{R_i} = \frac{V_{in}}{R_i}$$

and $$I_f = \frac{\text{Voltage across } R_f}{R_f} = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$, $$-\frac{V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

∴ Voltage gain, $$A_{CL} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

* The output voltage is 180° out of phase with the input. Since the voltage drop across R_f is of the opposite polarity to the applied voltage, the circuit is providing negative feedback.

The negative sign indicates that output signal is inverted as compared to the input signal. The following points may be noted about the inverting amplifier :

(*i*) The closed-loop voltage gain (A_{CL}) of an inverting amplifier is the ratio of the feedback resistance R_f to the input resistance R_i. *The closed-loop voltage gain is independent of the OP-amp's internal open-loop voltage gain.* Thus the negative feedback stabilises the voltage gain.

(*ii*) The inverting amplifier can be designed for unity gain. Thus if $R_f = R_i$, then voltage gain, $A_{CL} = -1$. Therefore, the circuit provides a unity voltage gain with 180° phase inversion.

(*iii*) If R_f is some multiple of R_i, the amplifier gain is constant. For example, if $R_f = 10\ R_i$, then $A_{CL} = -10$ and the circuit provides a voltage gain of exactly 10 along with a 180° phase inversion from the input signal. If we select precise resistor values for R_f and R_i, we can obtain a wide range of voltage gains. *Thus the inverting amplifier provides constant voltage gain*.

25.25 Input and Output Impedance of Inverting Amplifier

It is worthwhile to give a brief discussion about the input impedance and output impedance of inverting amplifier.

(*i*) **Input impedance.** While an *OP*-amp has an extremely high input impedance, the inverting amplifier does not. The reason for this can be seen by referring back to Fig. 25.47(*i*). As this figure shows, the voltage source "sees" an input resistance (R_i) that is going to virtual ground. Thus the input impedance for the inverting amplifier is

$$Z_i \simeq R_i$$

The value of R_i will always be much less than the input impedance of the *OP*-amp. Therefore, the overall input impedance of an inverting amplifier will also be much lower than the *OP*-amp input impedance.

(*ii*) **Output impedance.** Fig. 25.48 shows the inverting amplifier circuit. You can see from this figure that the output impedance of the inverting amplifier is the parallel combination of R_f and the output impedance of *OP*-amp itself.

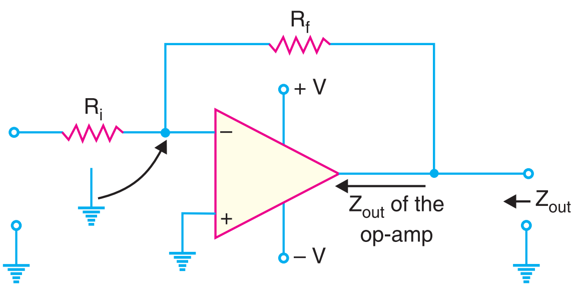


Fig. 25.48

The presence of the negative feedback circuit reduces the output impedance of the amplifier to a value that is less than the output impedance of *OP*-amp.

Example 25.25. *Given the OP-amp configuration in Fig. 25.49, determine the value of R_f required to produce a closed-loop voltage gain of –100.*

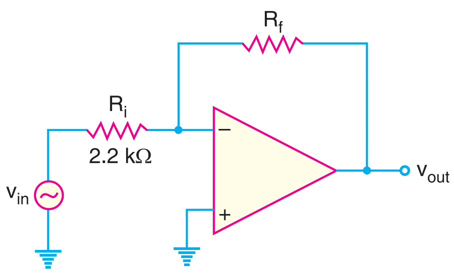


Fig. 25.49

Solution. $$A_{CL} = -\frac{R_f}{R_i} \quad \text{or} \quad -100 = -\frac{R_f}{2.2}$$

$$\therefore \quad R_f = 100 \times 2.2 = \mathbf{220\ k\Omega}$$

Example 25.26. *Determine the output voltage for the circuit of Fig. 25.50.*

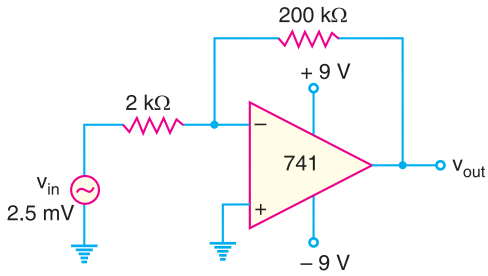


Fig. 25.50

Solution. $$A_{CL} = -\frac{R_f}{R_i} = -\frac{200\ k\Omega}{2\ k\Omega} = -100$$

$$\therefore \quad \text{Output voltage, } v_{out} = A_{CL} \times v_{in} = (-100) \times (2.5\ mV) = -250\ mV = \mathbf{-0.25\ V}$$

Example 25.27. *Find the output voltage for the circuit shown in Fig. 25.51.*

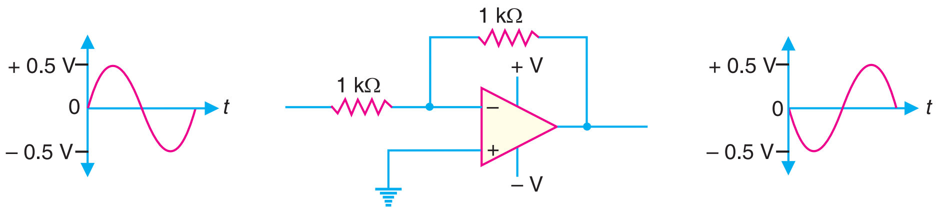


Fig. 25.51

Solution. Voltage gain, $$A_{CL} = -\frac{R_f}{R_i} = -\frac{1\ k\Omega}{1\ k\Omega} = -1$$

Since the voltage gain of the circuit is –1, the **output will have the same amplitude but with 180° phase inversion.**

Example 25.28. *Find the output voltage for the circuit shown in Fig. 25.52.*

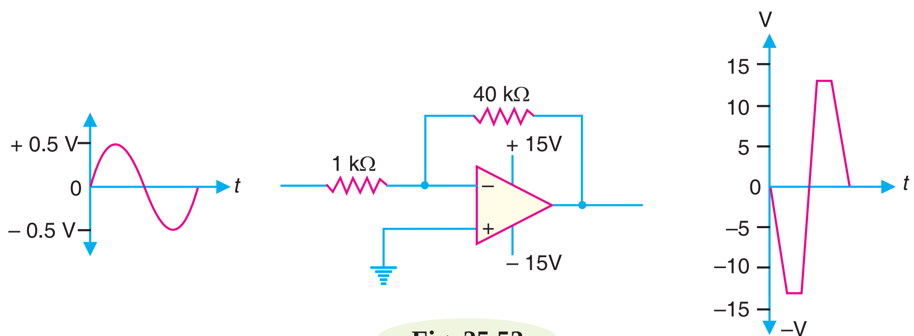


Fig. 25.52

Solution. Voltage gain, $$A_{CL} = -\frac{R_f}{R_i} = -\frac{40\ k\Omega}{1\ k\Omega} = -40$$

Note that the input signal is the same as in example 25.27 but now the voltage gain is –40 instead of –1. Since the supply voltages are ± 15 V, the *saturation occurs at ± 13 V. Since the output voltage far exceeds the saturation level, the *OP*-amp will be driven to deep saturation and it will behave as a non-linear amplifier. This means that the output will not have the same shape as input but will clip at the saturation voltage. Note that 180° phase inversion does occur.

Example 25.29. *For the circuit shown in Fig. 25.53, find (i) closed-loop voltage gain (ii) input impedance of the circuit (iii) the maximum operating frequency. The slew rate is 0.5V/μs.*

Solution.

(*i*) Closed-loop voltage gain, $A_{CL} = -\dfrac{R_f}{R_i} = -\dfrac{100\ \text{k}\Omega}{10\ \text{k}\Omega} = \mathbf{-10}$

(*ii*) The input impedance Z_i of the circuit is

$$Z_i \simeq R_i = \mathbf{10\ k\Omega}$$

(*iii*) To calculate the maximum operating frequency (f_{max}) for this inverting amplifier, we need to determine its peak output voltage. With values of V_{in} = 1 V_{pp} and A_{CL} = 10, the peak-to-peak output voltage is

$$V_{out} = (1V_{pp})\ (A_{CL})$$

$$= (1V_{pp}) \times 10 = 10\ V_{pp}$$

Therefore, the peak output voltage is

$$V_{pk} = 10/2 = 5\ \text{V}$$

$$\therefore \quad f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\ \text{V}/\mu\text{s}}{2\pi \times 5}$$

$$= \frac{500\ \text{kHz}}{2\pi \times 5} = \mathbf{15.9\ kHz}$$

$(\because\ 0.5\ \text{V}/\mu\text{s} = 500\ \text{kHz})$

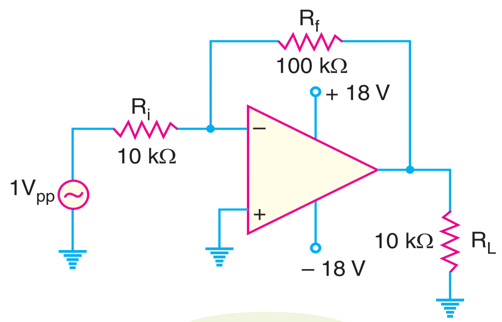


Fig. 25.53

Example 25.30. *You have the following resistor values available:*

1 kΩ; 5 kΩ ; 10 kΩ and 20 kΩ

Design the OP-amp circuit to have a voltage gain of –4.

Solution. Since the voltage gain is negative, the *OP*-amp is operating as an inverting amplifier.

Now, $$A_{CL} = -\frac{R_f}{R_i} = -4$$

We need to use resistors that have a ratio of 4 : 1. The two resistors which satisfy this requirement are : R_f = **20 kΩ** and R_i = **5kΩ.**

Example 25.31. *Fig. 25.54 shows an inverting OP-amp. Find the closed-loop gain if (i) R_{source} = 0Ω (ii) R_{source} = 1 kΩ.*

Solution. (*i*) When $R_{source} = 0\ \Omega$; $A_{CL} = -\dfrac{R_f}{R_i} = -\dfrac{100\ \text{k}\Omega}{1\ \text{k}\Omega} = \mathbf{-100}$

(*ii*) When R_{source} = 1 kΩ ; $A_{CL} = -\dfrac{R_f}{R_{source} + R_i} = -\dfrac{100\ \text{k}\Omega}{1\ \text{k}\Omega + 1\ \text{k}\Omega} = \mathbf{-50}$

Note that we have lost half of the voltage gain.

* $+V_{sat} = +V_{supply} - 2\ \text{V} = +15\ \text{V} - 2\ \text{V} = +13\ \text{V}$

$-V_{sat} = -V_{supply} + 2\ \text{V} = -15\ \text{V} + 2\ \text{V} = -13\ \text{V}$

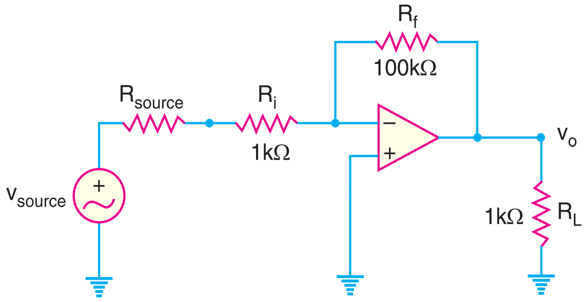


Fig. 25.54

25.26 Noninverting Amplifier

There are times when we wish to have an output signal of the same polarity as the input signal. In this case, the *OP*-amp is connected as noninverting amplifier as shown in Fig. 25.55. The input signal is applied to the noninverting input (+). The output is applied back to the input through the feedback circuit formed by feedback resistor R_f and input resistance R_i. Note that resistors R_f and R_i form a voltage divide at the inverting input (–). This produces **negative feedback* in the circuit. Note that R_i is grounded. Since the input signal is applied to the noninverting input (+), the output signal will be noninverted i.e., the output signal will be in phase with the input signal. Hence, the name non-inverting amplifier.

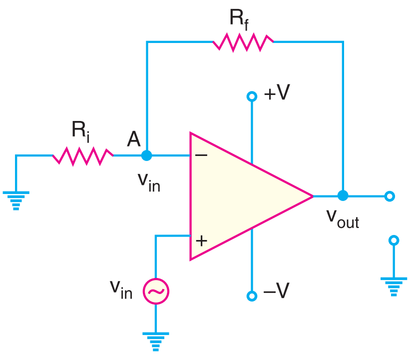


Fig. 25.55

Voltage gain. If we assume that we are not at saturation, the potential at point *A* is the same as V_{in}. Since the input impedance of *OP*-amp is very high, all of the current that flows through R_f also flows through R_i. Keeping these things in mind, we have,

$$\text{Voltage across } R_i = V_{in} - 0 \;;\; \text{Voltage across } R_f = V_{out} - V_{in}$$

Now $$\text{Current through } R_i = \text{Current through } R_f$$

or $$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

or $$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

or $$V_{in}(R_f + R_i) = V_{out} R_i$$

or $$\frac{V_{out}}{V_{in}} = \frac{R_f + R_i}{R_i} = 1 + \frac{R_f}{R_i}$$

$$\therefore \quad \text{Closed-loop voltage gain, } A_{CL} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_i}$$

The following points may be noted about the noninverting amplifier :

(*i*) $$A_{CL} = 1 + \frac{R_f}{R_i}$$

* If the output voltage increases, the voltage at the inverting input will also increase. Since the voltage being amplified is the difference between the voltages at the two input terminals, the differential voltage will decrease when the output voltage increases. Therefore, the circuit provides negative feedback.

The voltage gain of noninverting amplifier also depends upon the values of R_f and R_i.

(ii) The voltage gain of a non-inverting amplifier can be made equal to or greater than 1.

(iii) The voltage gain of a non-inverting amplifier will always be greater than the gain of an equivalent inverting amplifier by a value of 1. If an inverting amplifier has a gain of 150, the equivalent noninverting amplifier will have a gain of 151.

(iv) The voltage gain is positive. This is not surprising because output signal is in phase with the input signal.

Non-inverting operational amplifier.

25.27 Voltage Follower

The voltage follower arrangement is a special case of noninverting amplifier where all of the output voltage is fed back to the inverting input as shown in Fig. 25.56. Note that we remove R_i and R_f from the noninverting amplifier and short the output of the amplifier to the inverting input. The voltage gain for the voltage follower is calculated as under :

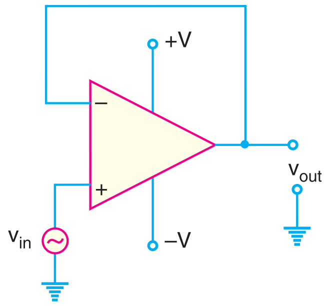


Fig. 25.56

$$A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{0}{R_i} = 1 \qquad (\because R_f = 0\Omega)$$

Thus the closed-loop voltage gain of the voltage follower is 1. The most important features of the voltage follower configuration are its *very high input impedance* and its *very low output impedance*. These features make it a nearly ideal buffer amplifier to be connected between high-impedance sources and low-impedance loads.

Example 25.32. *Calculate the output voltage from the noninverting amplifier circuit shown in Fig. 25.57 for an input of 120 µV.*

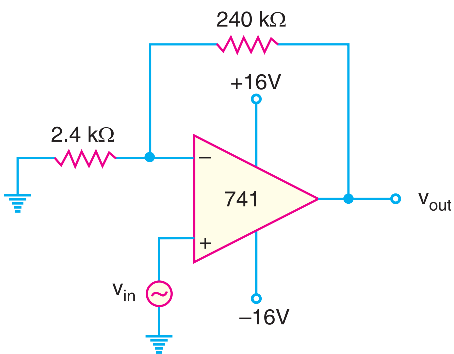


Fig. 25.57

Solution. Voltage gain, $A_{CL} \;=\; 1+\dfrac{R_f}{R_i}=1+\dfrac{240\text{ k}\Omega}{2.4\text{ k}\Omega}=1+100=101$

Output voltage, $v_{out} \;=\; A_{CL}\times v_{in}=(101)\times(120\ \mu\text{V})=$ **12.12 mV**

Example 25.33. *For the noninverting amplifier circuit shown in Fig. 25.58, find the output voltage for an input voltage of (i) 1 V (ii) –1 V.*

Solution. Voltage gain, $A_{CL} \;=\; 1+\dfrac{R_f}{R_i}=1+\dfrac{10\text{ k}\Omega}{1\text{ k}\Omega}=1+10=11$

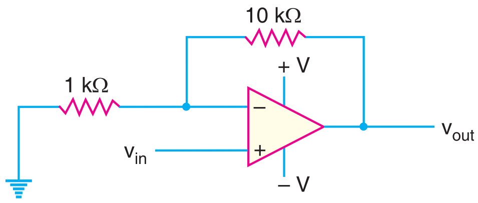


Fig. 25.58

(i) For v_{in} = 1 V ; $v_{out} = A_{CL}\times v_{in} = 11\times 1\text{ V} =$ **11 V**

(ii) For v_{in} = –1 V ; $v_{out} = A_{CL}\times v_{in} = 11\times(-1\text{ V}) =$ **– 11 V**

Example 25.34. *For the noninverting amplifier circuit shown in Fig. 25.59, find peak-to-peak output voltage.*

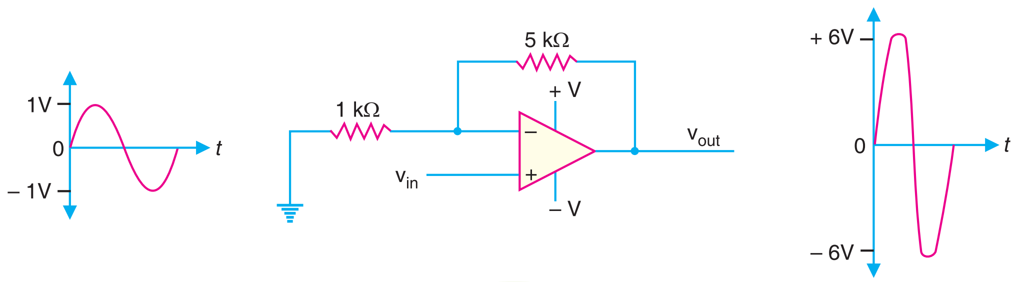


Fig. 25.59

Solution. The input signal is 2 *V* peak-to-peak.

Voltage gain, $A_{CL} \;=\; 1+\dfrac{R_f}{R_i}=1+\dfrac{5\text{ k}\Omega}{1\text{ k}\Omega}=1+5=6$

∴ Peak-to-peak output voltage $= A_{CL}\times v_{inpp} = 6\times 2 =$ **12 V**

Example 25.35. *For the noninverting amplifier circuit shown in Fig. 25.60, find (i) closed-loop voltage gain (ii) maximum operating frequency. The slew rate is 0.5 V/µs.*

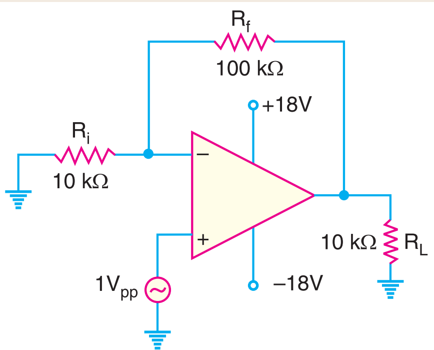


Fig. 25.60

Solution.

(*i*) Voltage gain, $A_{CL} = 1 + \dfrac{R_f}{R_i} = 1 + \dfrac{100\text{ k}\Omega}{10\text{ k}\Omega} = 1 + 10 = \mathbf{11}$

(*ii*) To determine the value of maximum operating frequency (f_{max}), we need to calculate the peak output voltage for the amplifier. The peak-to-peak output voltage is

$$v_{out} = A_{CL} \times v_{in} = 11 \times (1V_{pp}) = 11V_{pp}$$

∴ Peak output voltage, $V_{pk} = 11/2 = 5.5\text{ V}$

$$\therefore \quad f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\text{ V/}\mu\text{s}}{2\pi \times 5.5}$$

$$= \frac{500\text{ kHz}}{2\pi \times 5.5} = \mathbf{14.47\text{ kHz}} \qquad (\because 0.5\text{ V/}\mu\text{s} = 500\text{ kHz})$$

Example 25.36. *Determine the bandwidth of each of the amplifiers in Fig. 25.61. Both OP-amps have an open-loop voltage gain of 100 dB and a unity-gain bandwidth of 3MHz.*

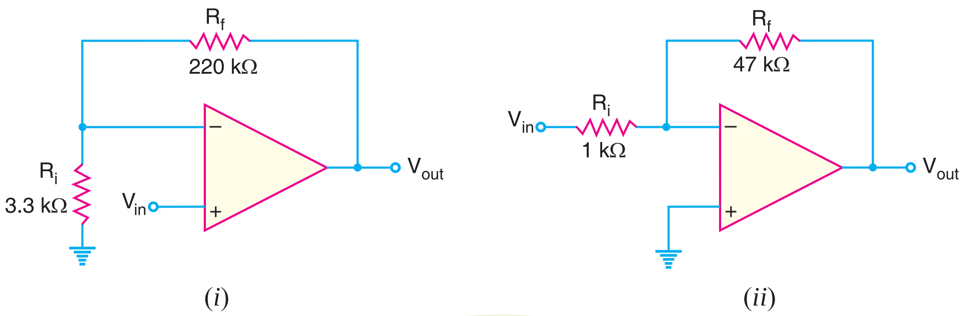


Fig. 25.61

Solution.

(*i*) For the noninverting amplifier shown in Fig. 25.61 (*i*), the closed-loop voltage gain (A_{CL}) is

$$A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{220\text{ k}\Omega}{3.3\text{ k}\Omega} = 1 + 66.7 = 67.7$$

$$\therefore \quad \text{Bandwidth, } BW = \frac{\text{Unity-gain } BW}{A_{CL}} = \frac{3\text{ MHz}}{67.7} = \mathbf{44.3\text{ kHz}}$$

(*ii*) For the inverting amplifier shown in Fig. 25.61 (*ii*),

$$A_{CL} = -\frac{R_f}{R_i} = -\frac{47\text{ k}\Omega}{1\text{ k}\Omega} = -47$$

$$\therefore \quad \text{Bandwidth, } BW = \frac{3\text{ MHz}}{47} = \mathbf{63.8\text{ kHz}}$$

Example 25.37. *Fig. 25.62 shows the circuit of voltage follower. Find* (*i*) *the closed-loop voltage gain and* (*ii*) *maximum operating frequency. The slew rate is 0.5 V/μs.*

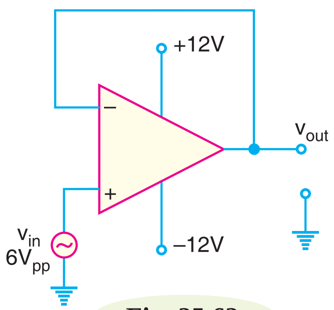


Fig. 25.62

Solution.

(*i*) For the voltage follower, $A_{CL} = \mathbf{1}$

(ii) Since A_{CL} = 1 for the circuit, $v_{out} = v_{in}$. Therefore, peak output voltage (V_{pk}) is one-half of $6V_{pp}$ *i.e.*, V_{pk} = 6/2 = 3 V. The maximum operating frequency (f_{max}) is given by ;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\ \text{V}/\mu\text{s}}{2\pi \times 3}$$

$$= \frac{500\ \text{kHz}}{2\pi \times 3} = \mathbf{26.53\ kHz} \qquad (\because\ 0.5\ \text{V}/\mu\text{s} = 500\ \text{kHz})$$

25.28 Multi-stage OP-Amp Circuits

When a number of OP-amp stages are connected in series, the overall voltage gain is equal to the product of individual stage gains. Fig. 25.63 shows connection of three stages. The first stage is connected to provide noninverting gain. The next two stages provide inverting gains.

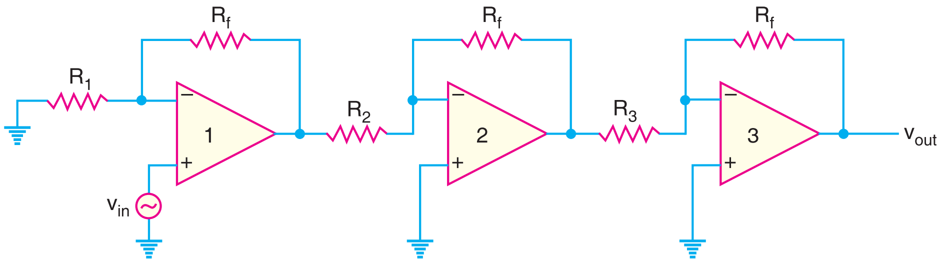


Fig. 25.63

The overall voltage gain *A* of this circuit is given by;

$$A = A_1 A_2 A_3$$

where A_1 = Voltage gain of first stage = $1 + (R_f/R_1)$

A_2 = Voltage gain of second stage = $-R_f/R_2$

A_3 = Voltage gain of third stage = $-R_f/R_3$

Since the overall voltage gain is positive, the circuit behaves as a noninverting amplifier.

Example 25.38. *Fig. 25.63 shows the multi-stage OP-amp circuit. The resistor values are : R_f = 470 kΩ ; R_1 = 4.3 kΩ ; R_2 = 33 kΩ and R_3 = 33 kΩ. Find the output voltage for an input of 80 μV.*

Solution. Voltage gain of first stage, $A_1 = 1 + (R_f/R_1) = 1 + (470\ \text{k}\Omega/4.3\ \text{k}\Omega) = 110.3$

Voltage gain of second stage, $A_2 = -R_f/R_2 = -470\ \text{k}\Omega/33\ \text{k}\Omega = -14.2$

Voltage gain of third stage, $A_3 = -R_f/R_3 = -470\ \text{k}\Omega/33\ \text{k}\Omega = -14.2$

∴ Overall voltage gain, $A = A_1A_2A_3 = (110.3) \times (-14.2) \times (-14.2) = 22.2 \times 10^3$

Output voltage, $v_{out} = A \times v_{in} = 22.2 \times 10^3 \times (80\ \mu\text{V})$ = **1.78V**

Example 25.39. *A three-stage OP-amp circuit is required to provide voltage gains of +10, –18 and –27. Design the OP-amp circuit. Use a 270 kΩ feedback resistor for all three circuits. What output voltage will result for an input of 150 μV?*

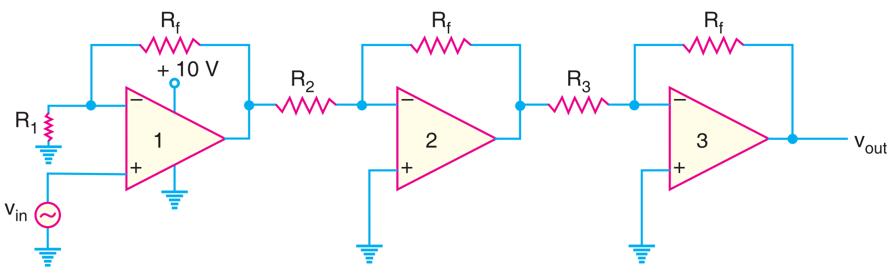


Fig. 25.64

Solution. Designing the above OP-amp circuit means to find the values of R_1, R_2 and R_3. The first stage gain is +10 so that this stage operates as noninverting amplifier.

Now $$+10 = 1 + \frac{R_f}{R_1} \quad \therefore \quad R_1 = \frac{R_f}{10-1} = \frac{270\text{ k}\Omega}{9} = \mathbf{30\text{ k}\Omega}$$

The second stage gain is –18 so that this stage operates as an inverting amplifier.

$$\therefore \quad -18 = -\frac{R_f}{R_2} \quad \text{or} \quad R_2 = \frac{R_f}{18} = \frac{270\text{ k}\Omega}{18} = \mathbf{15\text{ k}\Omega}$$

The third stage gain is –27 so that this stage operates as an inverting amplifier.

$$\therefore \quad -27 = -\frac{R_f}{R_3} \quad \text{or} \quad R_3 = \frac{R_f}{27} = \frac{270\text{ k}\Omega}{27} = \mathbf{10\text{ k}\Omega}$$

$$\text{Overall voltage gain, } A = A_1A_2A_3 = (10) \times (-18) \times (-27) = 4860$$

$$\text{Output voltage, } v_{out} = A \times v_{in} = (4860) \times (150\ \mu\text{V}) = \mathbf{0.729\text{ V}}$$

Example 25.40. *Show the connection of three OP-amp stages using an LM 348 IC to provide outputs that are 10, 20, and 50 times larger than the input and 180° out of phase w.r.t. input. Use a feedback resistor of R_f = 500 kΩ in all stages.*

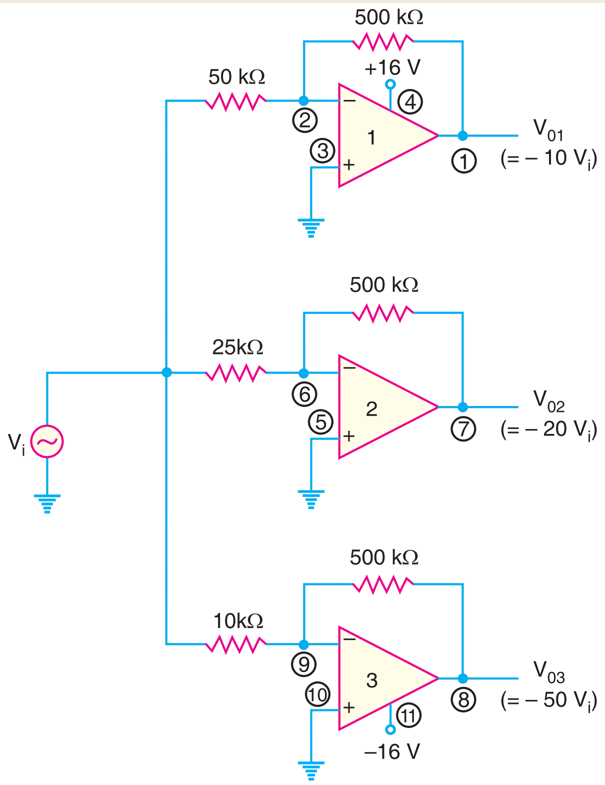


Fig. 25.65

Solution. The resistor component for each stage will be :

$$R_1 = -\frac{R_f}{A_1} = -\frac{500\text{ k}\Omega}{-10} = \mathbf{50\text{ k}\Omega}$$

$$R_2 = -\frac{R_f}{A_2} = -\frac{500\text{ k}\Omega}{-20} = \mathbf{25\text{ k}\Omega}$$

$$R_3 = -\frac{R_f}{A_3} = -\frac{500 \text{ k}\Omega}{-50} = \mathbf{10\ k\Omega}$$

The resulting circuit is shown in Fig. 25.65.

25.29 Effect of Negative Feedback on OP-Amp Impedances

In a negative feedback amplifier, a part of the output is fed in phase opposition to the input. The negative feedback produces remarkable changes in the circuit performance. The advantages of negative feedback are : stable gain, less distortion, increased bandwidth and affecting the input impedance and output impedance of the circuit. We now discuss the effect of negative feedback on the impedances of both noninverting and inverting amplifiers.

(*i*) Noninverting Amplifier. (Fig. 25.66). The expressions for the input and output impedances on account of negative voltage feedback in noninverting amplifier are the same as for discrete amplifier (Art. 13.4).

$$Z_{in}\ (^*NI) = Z_{in}(1 + m_v\, A_{OL})$$

$$Z_{out}\ (NI) = \frac{Z_{out}}{1 + m_v\, A_{OL}}$$

where Z_{in}, Z_{out} = impedance values without feedback

$Z_{in}(NI), Z_{out}(NI)$ = impedance values with negative feedback

m_v = feedback factor

A_{OL} = voltage gain without feedback = open-loop gain

Note that negative feedback in noninverting amplifier has greatly increased the input impedance and at the same time decreased the output impedance. The increased impedance is an advantage because the amplifier will now present less of a load to its source circuit.

The decreased output impedance is also a benefit because the amplifier will be better suited to drive low impedance loads.

Voltage-follower (*VF*) impedances. Since voltage follower is a special case of noninverting amplifier with feedback fraction $m_v = 1$,

$$\therefore \quad Z_{in(VF)} = Z_{in}\ (1 + A_{OL})$$

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{OL}}$$

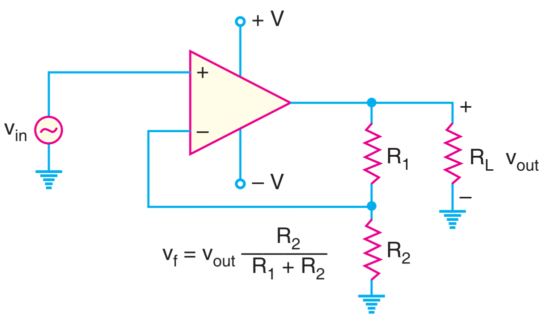


Fig. 25.66

Noninverting feedback amplifier.

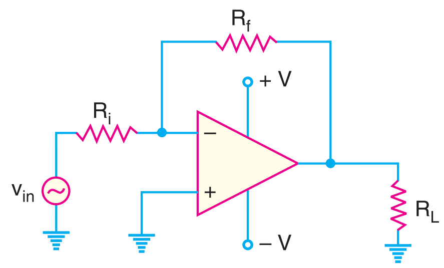


Fig. 25.67

Inverting feedback amplifier.

* Note that '*NI*' means noninverting amplifier.

Note that the voltage-follower input impedance is greater for given Z_{in} and A_{OL} than for the non-inverting configuration with the voltage-divider feedback circuit. Also, its output impedance is much smaller.

(ii) Inverting Amplifier. Fig. 25.67 shows the inverting amplifier. It can be shown that :

Input impedance, $Z_{in(*I)} \simeq R_i$

Output impedance, $Z_{out(I)} \simeq Z_{out}$ of *OP*-amp

Note that *the addition of negative voltage feedback to the inverting OP-amp reduces the input impedance of the circuit.* The reduction of Z_{in} is the primary difference betwen the inverting and the noninverting negative feedback circuits. Otherwise, the effects of negative voltage feedback are nearly identical for the two circuits.

Example 25.41. (*i*) *Determine the input and output impedances of the amplifier in Fig. 25.68. The OP-amp date sheet gives Z_{in} = 2 MΩ, Z_{out} = 75 Ω and open loop gain of 200,000.*

(*ii*) *Find the closed-loop voltage gain.*

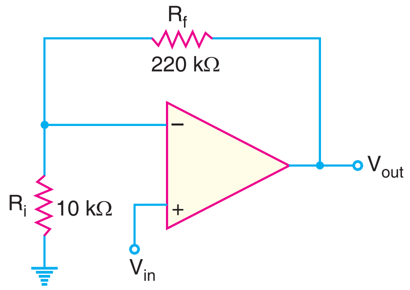


Fig. 25.68

Solution.

(i) Feedback fraction, $m_v = \dfrac{R_i}{R_i + R_f} = \dfrac{10 \text{ k}\Omega}{10 \text{ k}\Omega + 220 \text{ k}\Omega} = \dfrac{10 \text{ k}\Omega}{230 \text{ k}\Omega} = 0.043$

Input impedance, $Z_{in(NI)} = Z_{in}\,(1 + A_{OL} m_v)$

$= (2\text{M}\Omega)\ [(1 + 200,\ 000 \times 0.043)]$

$= (2\text{M}\Omega)\ [\ 1 + 8600] = \mathbf{17{,}202\ M\Omega}$

Output impedance, $Z_{out(NI)} = \dfrac{Z_{out}}{1 + A_{OL} m_v} = \dfrac{75\ \Omega}{1 + 8600} = \mathbf{8.7 \times 10^{-3}\ \Omega}$

(ii) Closed-loop voltage gain, $A_{CL} = 1 + \dfrac{R_f}{R_i} = 1 + \dfrac{220 \text{ k}\Omega}{10 \text{ k}\Omega} = \mathbf{23}$

Comments. Note the effect of negative voltage feedback on noninverting amplifier.

(a) Input and output signals are in phase.

(b) A virtually infinite input impedance.

(c) Virtually zero output impedance.

Example 25.42. *The same OP-amp in example 25.41 is used in a voltage-follower arrangement. Determine the input and output impedances.*

Solution. For voltage follower, feedback factor $m_v = 1$.

$\therefore \quad Z_{in(VF)} = Z_{in}(1 + A_{OL}) = 2\text{M}\Omega\ (1 + 200{,}000) = \mathbf{400{,}002\ M\Omega}$

$Z_{out(VF)} = \dfrac{Z_{out}}{1 + A_{OL}} = \dfrac{75\ \Omega}{1 + 200{,}000} = \mathbf{0.38 \times 10^{-3}\ \Omega}$

* Note that "*I*" means inverting amplifier.

Note that $Z_{in(VF)}$ is much greater than $Z_{in(NI)}$ and $Z_{out(VF)}$ is much less than $Z_{out(NI)}$ from example 25.41.

Example 25.43. *Find the values of the input and output impedances in Fig. 25.69. Also determine the closed-loop voltage gain. The OP-amp has the following parameters: Z_{in} = 4 MΩ; Z_{out} = 50 Ω and open-loop voltage gain = 50,000.*

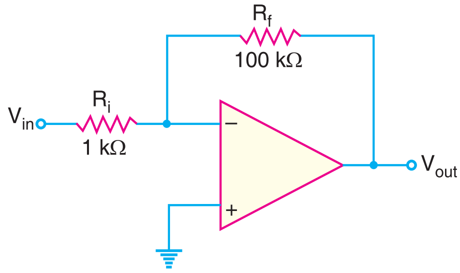


Fig. 25.69

Solution.

$$Z_{in}(I) \simeq R_i = \mathbf{1\ k\Omega}$$

$$Z_{out}(I) \simeq Z_{out} = \mathbf{50\ \Omega}$$

$$A_{CL} = -\frac{R_f}{R_i} = -\frac{100\ k\Omega}{1\ k\Omega} = \mathbf{-100}$$

25.30 Faults in Feedback Circuit

A failure of the feedback circuit in an *OP*-amp is one of the easiest problems in the world to locate. The most noticeable effect is that *voltage gain of the amplifier will change drastically*. Sometimes the gain will increase; sometimes it will decrease. It all depends on which component goes bad. For example, consider the circuit shown in Fig. 25.70.

(*i*) Under normal conditions: Under normal conditions, the output from the amplifier is $v_{out} = A_{CL}\, v_{in}$. The waveform would be correct. This is shown in Fig. 25.70 (*i*)

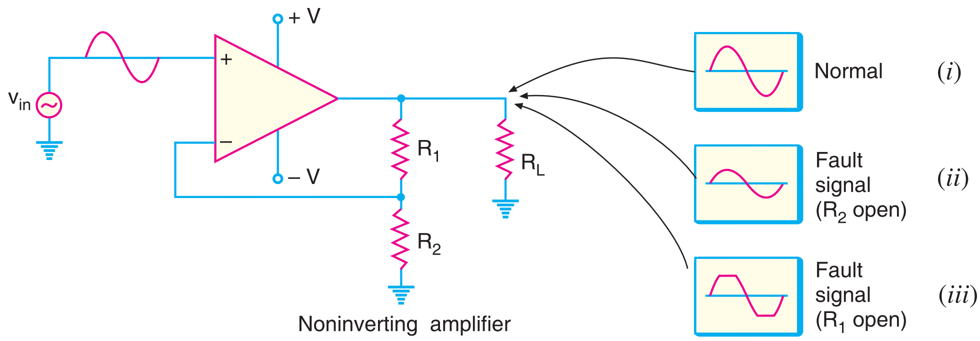


Fig. 25.70

(*ii*) When R_2 is open: If R_2 opens, the feedback circuit would consist solely of R_1. In this case, the gain would *drop*. It is because the circuit would now act as a *voltage follower. In other words, the circuit would now be a buffer with an output voltage that is equal to the input voltage. Thus we would have the output signal as shown in Fig. 25.70 (*ii*). The waveform would be correct but we would have unity gain.

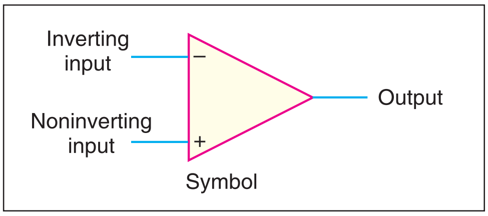
(*iii*) When R_1 is open: When R_1 opens, the entire feedback circuit would be effectively removed. This would cause the gain of the amplifier to increase to the value of open-loop gain A_{OL}. Clearly, the output voltage will clip at or near the values of +*V* and – *V*. This results in the distorted output signal as shown in Fig. 25.70 (*iii*).

* $A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{R_1}{R_2} = 1 + \frac{R_1}{\infty} = 1 + 0 = 1$

Under these conditions, the closed-loop voltage gain would be unity.

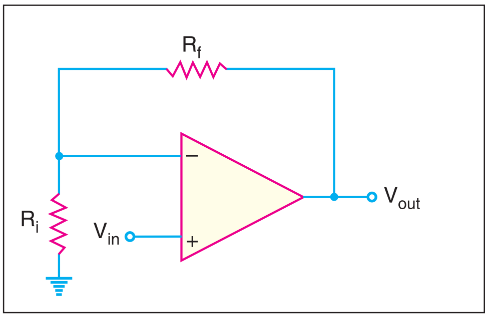
25.31 Summary of OP-AMP Configurations

Basic OP-AMP



- Very high open-loop voltage gain
- Very high input impedance
- Very low output impedance

Noninverting Amplifier



- Voltage gain:

$$A_{CL}(NI) = 1 + \frac{R_f}{R_i}$$

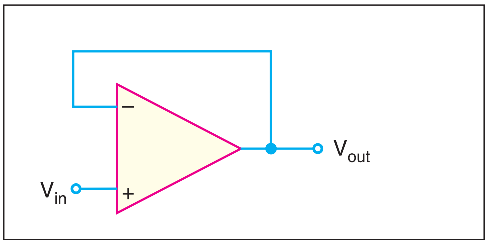
- Input impedance:

$$Z_{in(NI)} = (1 + A_{OL} m_v)\, Z_{in}$$

- Output impedance:

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{OL} m_v}$$

Voltage Follower



- Voltage gain:

$$A_{CL(VF)} = 1$$

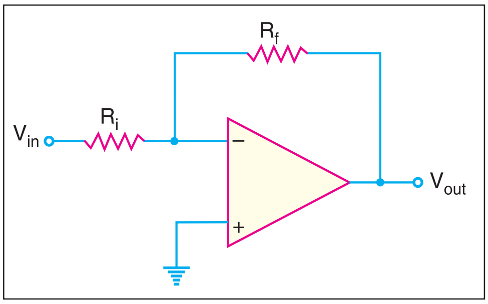
- Input impedance:

$$Z_{in(VF)} = (1 + A_{OL})\, Z_{in}$$

- Output impedance:

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{OL}}$$

Inverting Amplifier



- Voltage gain:

$$A_{CL} = -\frac{R_f}{R_i}$$

- Input impedance:

$$Z_{in(I)} \simeq R_i$$

- Output impedance:

$$Z_{out(I)} \simeq Z_{out}$$

25.32 Summing Amplifiers

A summing amplifier is an inverted *OP*-amp that can accept two or more inputs. *The output voltage of a summing amplifier* is *proportional to the negative of the algebraic sum of its input voltages*. Hence the name **summing amplifier**. Fig. 25.71 shows a three-input summing amplifier but any number of inputs can be used. Three voltages V_1, V_2 and V_3 are applied to the inputs and produce currents I_1, I_2 and I_3. Using the concepts of infinite impedance and virtual ground, you can see that inverting input of the *OP*-amp is at virtual ground (0*V*) and there is no current to the input. This means that the three input currents I_1, I_2 and I_3 combine at the summing point *A* and form the total current (I_f) which goes through R_f as shown in Fig. 25.71.

$$\therefore \quad I_f = I_1 + I_2 + I_3$$

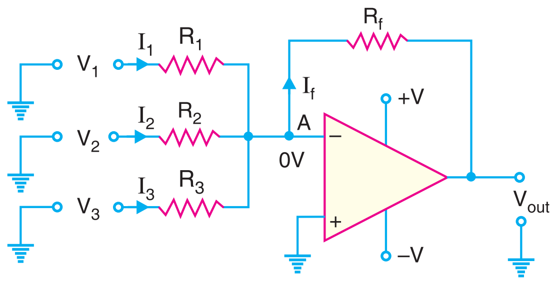


Fig. 25.71

When all the three inputs are applied, the output voltage is

$$\text{Output voltage, } V_{out} = -I_f R_f = -R_f (I_1 + I_2 + I_3)$$

$$= -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

$$\therefore \quad V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

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

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3)$$

Thus the output voltage is proportional to the algebraic sum of the input voltages (of course neglecting negative sign). An interesting case results when the **gain of the amplifier is unity.** In that case, $R_f = R_1 = R_2 = R_3$ and output voltage is

$$V_{out} = -(V_1 + V_2 + V_3)$$

Thus, when the gain of summing amplifier is unity, the output voltage is the algebraic sum of the input voltages.

Summing Amplifier

Summing amplifier with gain greater than unity. When R_f is larger than the input resistors, the amplifer has a gain of R_f/R where R is the value of each input resistor. The general expression for the output voltage is

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3 + \ldots)$$

As you can see, the output voltage is the sum of input voltages multiplied by a constant determined by the ratio R_f/R.

Example 25.44. *Determine the output voltage for the summing amplifier in Fig. 25.72.*

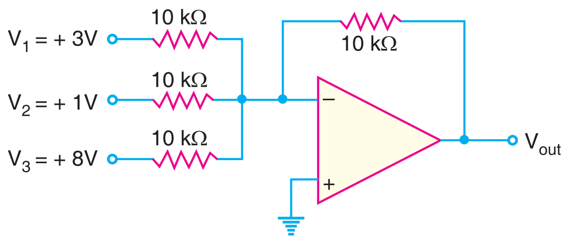


Fig. 25.72

Solution. Referring to Fig. 25.72, all the three input resistor values are equal and each is equal to the value of feedback resistor. Therefore, the gain of the summing amplifier is 1. As a result, the output voltage is the algebraic sum of three input voltages.

$$\therefore \quad V_{out} = -(V_1 + V_2 + V_3) = -(3 + 1 + 8) = \mathbf{-12\ V}$$

Example 25.45. *Determine the output voltage for the summing amplifier shown in Fig. 25.73.*

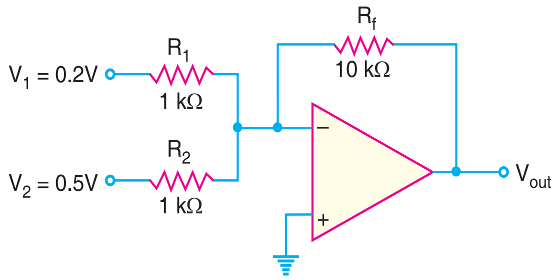


Fig. 25.73

Solution. $R_f = 10$ kΩ and $R_1 = R_2 = R = 1$ kΩ. Therefore, gain of the amplifier $= -R_f/R = -10$ kΩ/1kΩ $= -10$.

Now $$V_{out} = -\frac{R_f}{R}(V_1 + V_2) = -\frac{10\text{ k}\Omega}{1\text{ k}\Omega}(0.2 + 0.5) = \mathbf{-7V}$$

Note that the output voltage is not equal to the sum of input voltages. Rather it is equal to the sum of input voltages multiplied by the amplifier gain. In other words, the output voltage is proportional to the sum of the input voltages.

Example 25.46. *Determine the output voltage for the summing amplifier shown in Fig. 25.74.*

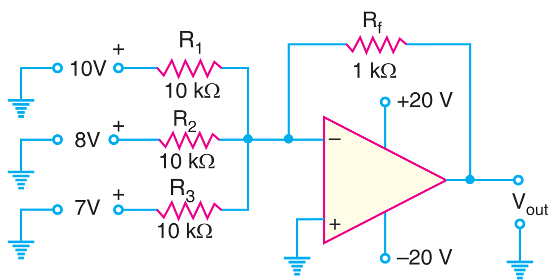


Fig. 25.74

Solution. $R_f = 1$ kΩ and $R_1 = R_2 = R_3 = R = 10$ kΩ. Therefore, gain of the amplifier $= -R_f/R = -1$ kΩ/10 kΩ $= -1/10$.

Now
$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3) = -\frac{1\text{ k}\Omega}{10\text{ k}\Omega}(10 + 8 + 7) = \mathbf{-2.5\ V}$$

Note that output voltage of the amplifier is not equal to the sum of input voltages, but rather is proportional to the sum of input voltages. In this case, it is equal to one-tenth of the input sum. Picking random values of V_1, V_2 and V_3 will show that this circuit always provides an output voltage that is one-tenth of the sum of input voltages.

Example 25.47. *Two voltages of + 0.6V and – 1.4 V are applied to the two input resistors of a summing amplifier. The respective input resistors are 400 kΩ and 100 kΩ and feedback resistor is 200 kΩ. Determine the output voltage.*

Solution. The output voltage of the summing amplifier is given by:
$$V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

Here $R_f = 200$ kΩ; $R_1 = 400$ kΩ; $R_2 = 100$ kΩ; $V_1 = +0.6$V; $V_2 = -1.4$ V

$$\therefore \quad V_{out} = -200\text{ k}\Omega\left(\frac{0.6}{400\text{ k}\Omega} + \frac{-1.4}{100\text{ k}\Omega}\right) = \mathbf{2.5\ V}$$

Note that a summing amplifier produces an output voltage that is proportional to the *algebraic sum of* the input voltages.

Example 25.48. *Determine the output voltage from the circuit shown in Fig. 25.75 for each of the following input combinations*:

V_1(V)	V_2(V)	V_3(V)
+ 10	0	+10
0	+10	+10
+10	+10	+10

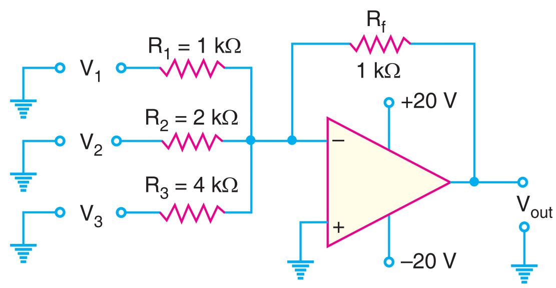


Fig. 25.75

Solution. The output voltage from the circuit is given by:
$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$
$$= -\left(\frac{1\text{ k}\Omega}{1\text{ k}\Omega}V_1 + \frac{1\text{ k}\Omega}{2\text{ k}\Omega}V_2 + \frac{1\text{ k}\Omega}{4\text{ k}\Omega}V_3\right)$$
$$\therefore \quad V_{out} = -(V_1 + 0.5\,V_2 + 0.25\,V_3)$$

The output voltage for the first set of inputs is

$$V_{out} = -(10 + 0.5 \times 0 + 0.25 \times 10) = \mathbf{-\ 12.5\ V}$$

The output voltage for the second set of inputs is

$$V_{out} = -(0 + 0.5 \times 10 + 0.25 \times 10) = \mathbf{-\ 7.5\ V}$$

The output voltage for the third set of inputs is

$$V_{out} = -(10 + 0.5 \times 10 + 0.25 \times 10) = \mathbf{-\ 17.5\ V}$$

Example 25.49. *Calculate the output voltage for the circuit of Fig. 25.76. The inputs are V_1 = 50 sin (1000 t)mV and V_2 = 10 sin (3000t) mV.*

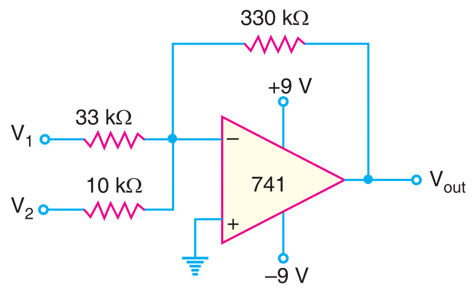


Fig. 25.76

Solution. The output voltage for the circuit is

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2\right) = -\left(\frac{330\,k\Omega}{33\,k\Omega}V_1 + \frac{330\,k\Omega}{10\,k\Omega}V_2\right)$$

$$= -(10\,V_1 + 33\,V_2) = -[10 \times 50 \sin(1000t) + 33 \times 10 \sin(3000t)]\ \text{mV}$$

$$= \mathbf{-\ [0.5\ sin\ (1000\ \mathit{t}) + 0.33\ sin\ (3000\mathit{t})]\ V}$$

25.33 Applications of Summing Amplifiers

By proper modifications, a summing amplifier can be made to perform many useful functions. There are a number of applications of summing amplifiers. However, we shall discuss the following two applications by way of illustration:

1. As averaging amplifier

2. As subtractor

1. As averaging amplifier. By using the proper input and feedback resistor values, a summing amplifier can be designed to provide an output voltage that is equal to the *average* of input voltages. A summing amplifier will act as an averaging amplifier when *both* of the following conditions are met:

(i) All input resistors (R_1, R_2 and so on) are *equal in value.*

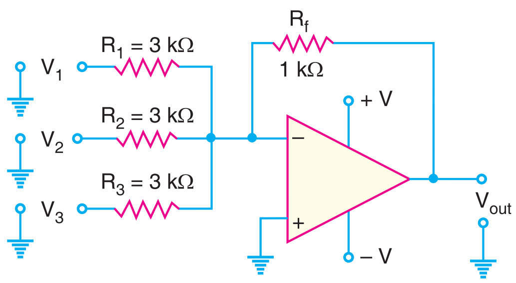


Fig. 25.77

(ii) The ratio of any input resistor to the feedback resistor is equal to the number of input circuits.

Fig. 25.77 shows the circuit of averaging amplifier. Note that it is a summing amplifier meeting the above two conditions. All input resistors are equal in value (3 kΩ). If we take the ratio of any input resistor to the feedback resistor, we get 3 kΩ/ 1 kΩ = 3. This is equal to the number of inputs to the circuit. Referring to the circuit in Fig. 25.77, the output voltage is given by;

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

Now $$\frac{R_f}{R_1} = \frac{R_f}{R_2} = \frac{R_f}{R_3} = \frac{1\text{ k}\Omega}{3\text{ k}\Omega} = \frac{1}{3}$$

$\therefore$ $$V_{out} = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

Note that V_{out} is equal to the average of the three inputs. The negative sign shows the phase reversal.

2. As subtractor. A summing amplifier can be used to provide an output voltage that is equal to the difference of two voltages. Such a circuit is called a **subtractor** and is shown in Fig. 25.78. As we shall see, this circuit will provide an output voltage that is equal to the difference between V_1 and V_2.

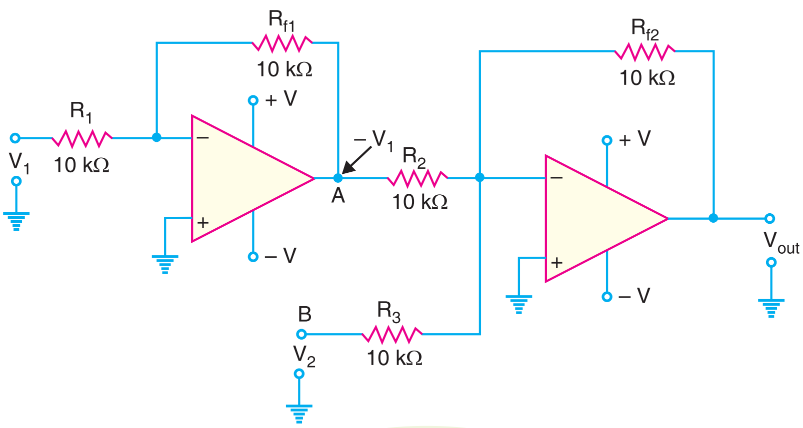


Fig. 25.78

The voltage V_1 is applied to a standard inverting amplifier that has *unity gain*. Because of this, the output from the inverting amplifier will be equal to $-V_1$. This output is then applied to the summing amplifier (also having unity gain) along with V_2. Thus output from second *OP*-amp is given by;

$$V_{out} = -(V_A + V_B) = -(-V_1 + V_2) = V_1 - V_2$$

It may be noted that the gain of the second stage in the subtractor can be varied to provide an output that is proportional to (rather than equal to) the difference between the input voltages. However, if the circuit is to act as a subtractor, the input inverting amplifier *must* have unity gain. Otherwise, the output will not be proportional to the true difference between V_1 and V_2.

25.34 OP-Amp Integrators and Differentiators

A circuit that performs the mathematical integration of input signal is called an *integrator.* The output of an integrator is proportional to the area of the input waveform over a period of time. A circuit that performs the mathematical differentiation of input signal is called a *differentiator.* The output of a differentiator is proportional to the rate of change of its input signal. Note that the two operations are opposite.

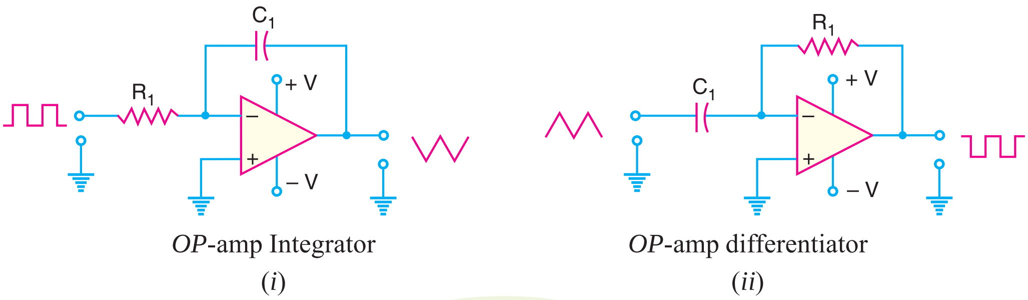


Fig. 25.79

Fig.25.79 shows *OP*-amp integrator and differentiator. As you can see, the two circuits are nearly identical in terms of their construction. Each contains a single *OP*-amp and an *RC* circuit. However, the difference in resistor/capacitor placement in the two circuits causes them to have input/output relationships that are exact opposites. For example, if the input to the integrator is a square wave, the output will be a triangular wave as shown in Fig. 25.79 (*i*). However, the differentiator will convert a triangular wave into square wave as shown in Fig. 25.79 (*ii*).

25.35 *OP*-Amp Integrator

As discussed above, an integrator is a circuit that performs integration of the input signal. The most popular application of an integrator is to produce a *ramp* output voltage (*i.e.* a linearly increasing or decreasing voltage). Fig. 25.80 shows the circuit of an *OP*-amp integrator. It consists of an *OP*-amp, input resistor *R* and feedback capacitor *C*. Note that the feedback component is a capacitor instead of a resistor.

As we shall see, when a signal is applied to the input of this circuit, the output-signal waveform will be the integration of input-signal waveform.

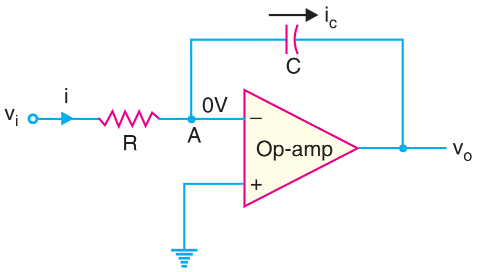


Fig. 25.80

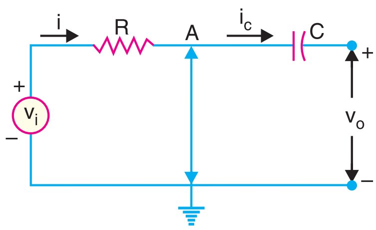


Fig. 25.81

Circuit Analysis. Since point *A* in Fig. 25.80 is at virtual ground, the *virtual-ground equivalent circuit of operational integrator will be as shown in Fig. 25.81. Because of virtual ground and infinite impedance of the *OP*-amp, all of the input current *i* flows through the capacitor *i.e.* $i = i_c$.

Now $$i = \frac{v_i - 0}{R} = \frac{v_i}{R} \quad ...(i)$$

Also voltage across capacitor is $v_c = 0 - v_o = -v_o$

$$\therefore \quad i_c = \frac{C\,dv_c}{dt} = -C\frac{dv_o}{dt} \quad ...(ii)$$

* Recall that virtual ground means that point *A* is 0V but it is not mechanically grounded. Therefore, no current flows from point *A* to ground.

From eqs. (*i*) and (*ii*), $$\frac{v_i}{R} = -C\frac{dv_o}{dt}$$

or $$\frac{dv_o}{dt} = -\frac{1}{RC}v_i \qquad ...(iii)$$

To find the output voltage, we integrate both sides of eq. (*iii*) to get,

$$v_o = -\frac{1}{RC}\int_0^t v_i\,dt \qquad ...(iv)$$

Eq. (*iv*) shows that the output is the integral of the input with an inversion and scale multiplier of 1/*RC*.

Output voltage. If a fixed voltage is applied to the input of an integrator, eq. (*iv*) shows that the output voltage grows over a period of time, providing a ramp voltage. Eq. (*iv*) also shows that the output voltage ramp (for a fixed input voltage) is opposite in polarity to the input voltage and is multiplied by the factor 1/*RC*. As an example, consider an input voltage v_1 = 1V to the integrator circuit of Fig. 25.82 (*i*). The scale factor of 1/*RC* is

$$-\frac{1}{RC} = -\frac{1}{(1\,\text{M}\Omega)\,(1\mu\text{F})} = -1$$

so that the output is a negative ramp voltage as shown in Fig. 25.82 (*ii*).

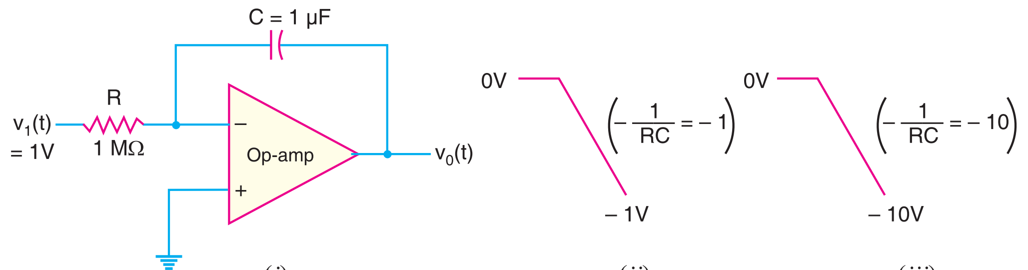


Fig. 25.82

If the scale factor is changed by making *R* = 100 kΩ, then,

$$-\frac{1}{RC} = -\frac{1}{(100\,\text{k}\Omega)\,(1\,\mu\text{F})} = -10$$

and output is then a steeper ramp voltage as shown in Fig. 25.82 (*iii*).

25.36 Critical Frequency of Integrators

The integrator shown in Fig. 25.80 (Refer back) has no feedback at 0 Hz. This is a serious disadvantage in low-frequency applications. By connecting a feedback resistor R_f in parallel with the capacitor, precise closed-loop voltage gain is possible. The circuit shown in Fig. 25.83 is an integrator with a feedback resistor R_f to provide increased stability.

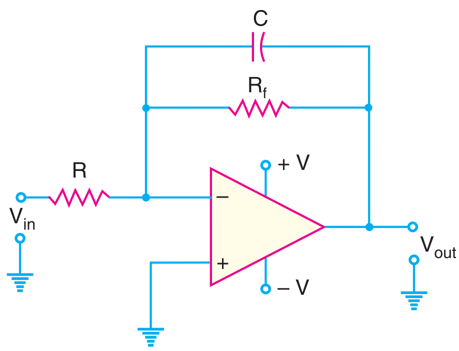
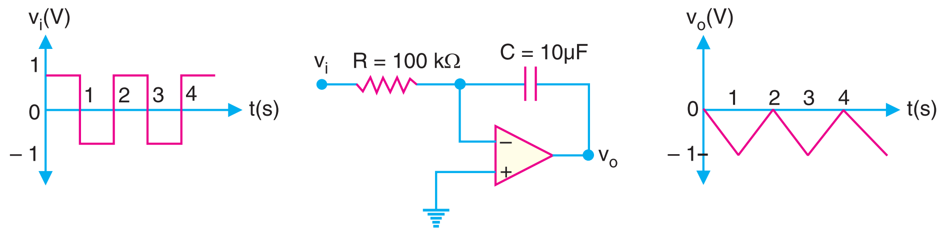


Fig. 25.83

All integrators have a critical frequency f_c below which they do not perform proper integration. If the input frequency is less than f_c, the circuit behaves like a simple inverting amplifier and no integration occurs. The following equation is used to calculate the critical frequency of an integrator:

$$f_c = \frac{1}{2\pi R_f C}$$

Example 25.50. *Fig. 25.84 (i) shows the OP-amp integrator and the square wave input. Find the output voltage.*



(*i*) (*ii*)

Fig. 25.84

Solution. The output voltage of this circuit is given by;

$$v_o = -\frac{1}{RC}\int_0^t v_i \, dt$$

Now $\quad RC = (100 \text{ k}\Omega)\ (10\ \mu\text{F}) = (100 \times 10^3 \Omega)\ (10 \times 10^{-6} \text{ F}) = 1\text{s}$

$$\therefore \quad v_o = -\int_0^t v_i \, dt$$

When we integrate a constant, we get a straight line. In other words, when input voltage to an integrator is constant, the output is a linear ramp. Therefore, the integration of the square wave results in the triangular wave as shown in Fig. 25.84 (*ii*). Since the input to the integrator is applied to the inverting input, the output of the circuit will be 180º out of phase with the input. Thus, when the input goes positive, the output will be a negative ramp. When the input is negative, the output will be a positive ramp. Fig. 25.84 (*ii*) shows this relationship.

Example 25.51. *Determine the lower frequency limit (critical frequency) for the integrator circuit shown in Fig. 25.85.*

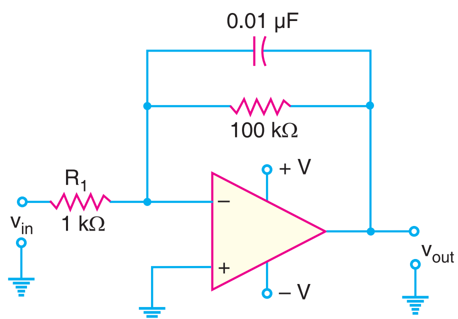


Fig. 25.85

Solution. The critical frequency for the integrator circuit shown in Fig. 25.85 is given by;

$$f_c = \frac{1}{2\pi R_f C}$$

Here $R_f = 100 \text{ k}\Omega = 10^5 \Omega$; $C = 0.01\ \mu\text{F} = 0.01 \times 10^{-6}$ F

$$\therefore \qquad f_c = \frac{1}{2\pi \times (10^5) \times (0.01 \times 10^{-6})} = \mathbf{159\ Hz}$$

Example 25.52. (*i*) *Determine the rate of change of the output voltage in response to a single pulse input to the integrator circuit shown in Fig. 25.86* (*i*).

(*ii*) *Draw the output waveform.*

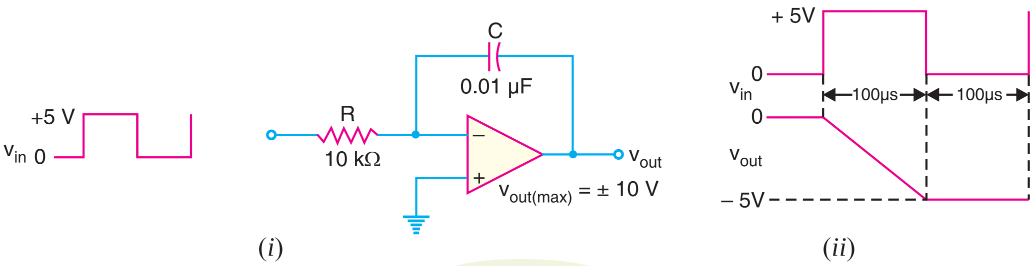


Fig. 25.86

Solution.

(*i*) Output voltage, $v_{out} = -\frac{1}{RC}\int_0^t v_{in}\, dt$

Therefore, the rate of change of output voltage is

$$\frac{\Delta v_{out}}{dt} = -\frac{v_{in}}{RC} = -\frac{5\text{ V}}{(10\text{ k}\Omega)\ (0.01\ \mu\text{F})} = -50\text{ kV/s} = \mathbf{-\ 50\ mV/\mu s}$$

(*ii*) The rate of change of output voltage is – 50 mV/μs. When the input is at + 5 V, the output is a negative-going ramp. When the input is at 0 V, the output is a constant level. In 100 μs, the output voltage decreases.

$$\therefore \qquad \Delta v_{out} = \frac{\Delta v_{out}}{dt} \times dt = -\frac{50\text{ mV}}{\mu\text{s}} \times 100\ \mu\text{s} = -5\text{V}$$

Therefore, the negative-going ramp reaches – 5 V at the end of the pulse (*i.e.* after 100 μs from the initial condition). The output voltage then remains constant at – 5 V for the time the input is zero. Fig. 25.86 (*ii*) shows the output waveform.

Example 25.53. *For the integrator circuit shown in Fig. 25.87 (i), how long does it take for the output to reach saturation ?*

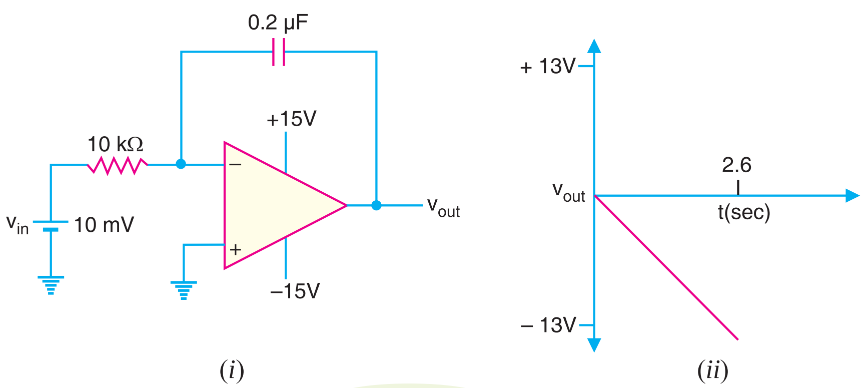


Fig. 25.87

Solution.

$$\text{Output voltage, } v_{out} = -\frac{1}{RC}\int_0^t v_{in}\, dt$$

Since the input voltage v_{in} (= 10 mV) is constant,

$$\therefore \quad v_{out} = -\frac{1}{RC} v_{in} t = -\frac{1}{(10\ k\Omega)\,(0.2\ \mu F)} \times (10\ mV) \times t$$

or $\quad v_{out} = -5t$ volts

Now $\quad$ Saturation voltage, $V_s = -V_{supply} + 2 = -15 + 2 = -13$ V

$$\therefore \quad \text{Time required, } t = \frac{V_s}{-5} = \frac{-13}{-5} = \textbf{2.6 seconds}$$

Fig. 25.87 (*ii*) shows the output waveform.

25.37 OP-Amp Differentiator

A differentiator is a circuit that performs differentiation of the input signal. In other words, a differentiator produces an output voltage that is proportional to the rate of change of the input voltage. Its important application is to produce a rectangular output from a ramp input. Fig. 25.88 shows the circuit of OP-amp differentiator. It consists of an OP-amp, an input capacitor C and feedback resistor R. Note how the placement of the capacitor and resistor differs from the integrator. The capacitor is now the input element.

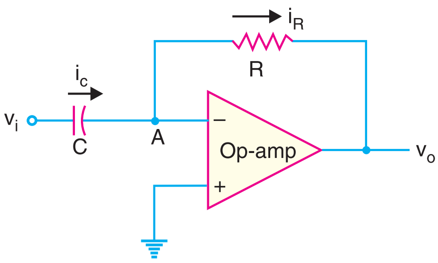


Fig. 25.88

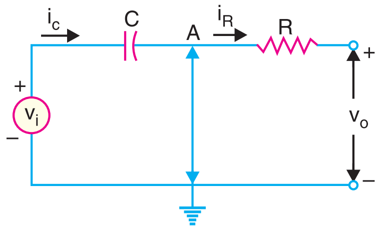


Fig. 25.89

Circuit analysis. Since point A in Fig. 25.88 is at virtual ground, the virtual-ground equivalent circuit of the operational differentiator will be as shown in Fig. 25.89. Because of virtual ground and infinite impedance of OP-amp, all the input current i_c flows through the feedback resistor R *i.e.* $i_c = i_R$.

$$\therefore \quad i_R = \frac{0 - v_o}{R} = -\frac{v_o}{R} \quad \text{and} \quad v_c = v_i - 0 = v_i$$

$$\text{Also} \quad i_c = C\frac{dv_c}{dt} = C\frac{dv_i}{dt}$$

$$\therefore \quad -\frac{v_o}{R} = C\frac{dv_i}{dt} \qquad (\because\ i_R = i_c)$$

$$\text{or} \quad v_o = -RC\frac{dv_i}{dt} \qquad ...(i)$$

Eq. (*i*) shows that output is the differentiation of the input with an inversion and scale multiplier of RC. If we examine eq. (*i*), we see that if the input voltage is constant, dv_i/dt is zero and the output voltage is zero. The faster the input voltage changes, the larger the magnitude of the output voltage.

Example 25.54. *Fig. 25.90 (i) shows the square wave input to a differentiator circuit. Find the output voltage if input goes from 0V to 5V in 0.1 ms.*

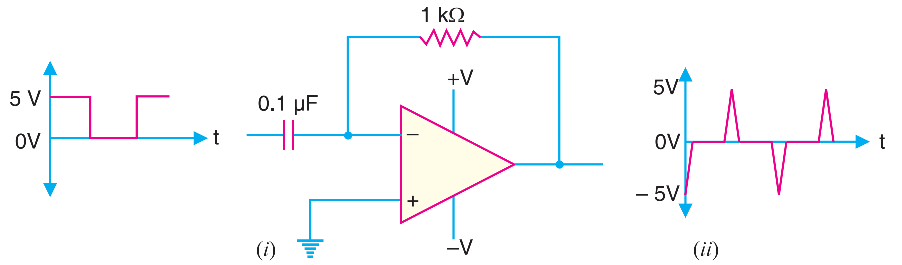


Fig. 25.90

Solution. Output voltage, $v_o = -RC\dfrac{dv_i}{dt}$

Now, $RC = (1\text{ k}\Omega)\times(0.1\ \mu\text{F}) = (10^3\ \Omega)\,(0.1\times10^{-6}\text{ F}) = 0.1\times10^{-3}\ s$

Also, $\dfrac{dv_i}{dt} = \dfrac{5\text{V}}{0.1\text{ ms}} = \dfrac{5\times10^4\text{ V}}{s} = 5\times10^4\text{ V/s}$

$\therefore\quad v_o = -(0.1\times10^{-3})\,(5\times10^4) = \mathbf{-5V}$

The signal quickly returns to zero as the input signal becomes constant. The output will be as shown in Fig. 25.90 (*ii*).

Example 25.55. *For the differentiator circuit shown in Fig. 25.91, determine the output voltage if the input goes from 0V to 10V in 0.4s. Assume the input voltage changes at constant rate.*

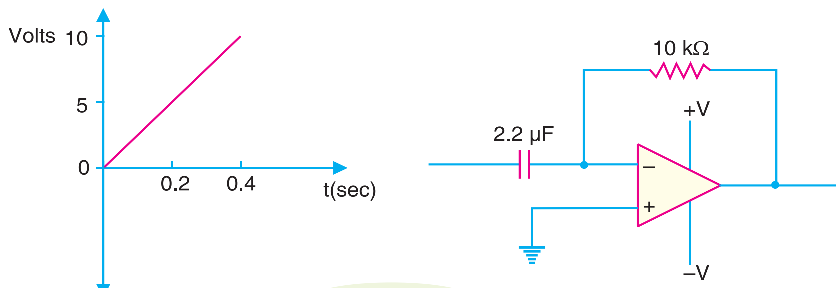


Fig. 25.91

Solution. Output voltage, $v_o = -RC\dfrac{dv_i}{dt}$

Now, $RC = (10\text{ k}\Omega)\times(2.2\ \mu\text{F}) = (10^4\ \Omega)\,(2.2\times10^{-6}\text{ F}) = 2.2\times10^{-2}\ s$

Also, $\dfrac{dv_i}{dt} = \dfrac{(10-0)\,V}{0.4s} = \dfrac{10V}{0.4s} = 25\text{ V/s}$

$\therefore\quad v_o = -(2.2\times10^{-2})\times25 = \mathbf{-0.55\ V}$

The output voltage stays constant at – 0.55 V.

Example 25.56. *For the differentiator circuit shown in Fig. 25.92(i), determine (i) the expression for the output voltage (ii) the output voltage for the given input.*

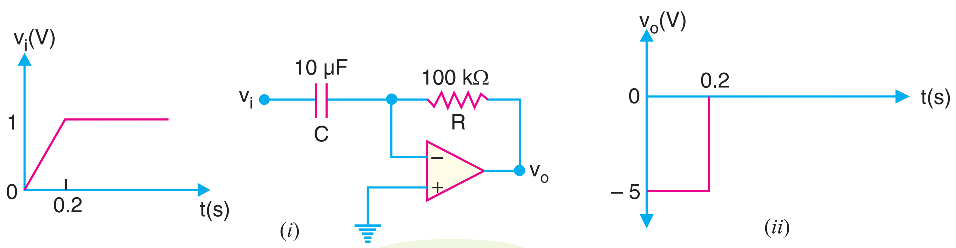


Fig. 25.92

Solution.

(*i*) For the differentiator shown in Fig. 25.92 (*i*), the output voltage is given by;

$$v_o = -RC\frac{dv_i}{dt} = -(100\,\text{k}\Omega)\times(10\,\mu\text{F})\frac{dv_i}{dt}$$

$$= -(100\times10^3\,\Omega)\times(10\times10^{-6}\,\text{F})\frac{dv_i}{dt} = -\frac{dv_i}{dt}$$

(*ii*) Since the input voltage is a straight line between 0 and 0.2*s*, the output voltage is

$$v_o = -\frac{dv_i}{dt} = -\frac{(1-0)}{0.2} = -5\text{V}$$

Therefore, between 0 to 0.2*s*, the output voltage is constant at – 5 V. For $t > 0.2s$, the input is constant so that output voltage is zero. Fig. 25.92 (*ii*) shows the output waveform.

25.38. Comparators

Often we want to compare one voltage to another to see which is larger. In this situation, a *comparator* may be used. *A comparator is an OP-amp circuit without negative feedback* and takes advantage of very high open-loop voltage gain of OP-amp. A comparator has two input voltages (noninverting and inverting) and one output voltage. Because of the high open-loop voltage gain of an *OP*-amp, a very small difference voltage between the two inputs drives the amplifier to saturation. For example, consider an *OP*-amp having A_{OL} = 100,000. A voltage difference of only 0.25 mV between the inputs will produce an output voltage of (0.25 mV) (100,000) = 25V. However, most of OP-amps have output voltages of less than ± 15V because of their d.c. supply voltages. Therefore, a very small differential input voltage will drive the OP-amp to saturation. This is the key point in the working of comparator.

Fig. 25.93 illustrates the action of a comparator. The input voltages are v_1 (signal) and v_2 (*reference voltage). If the differential input is positive, the circuit is driven to saturation and output goes to maximum positive value (**$+V_{sat}$ = + 13V). Reverse happens when the differential input goes negative *i.e.* now output is maximum negative ($-V_{sat}$ = – 13V). This circuit is called comparator because it compares v_1 to v_2 to produce a saturated positive or negative output voltage. Note that output voltage rapidly changes from – 13V to + 13V and *vice-versa*.

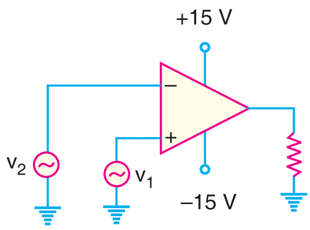


Fig. 25.93

25.39 Comparator Circuits

A comparator circuit has the following two characteristics :

(*i*) It uses no feedback so that the voltage gain is equal to the open-loop voltage gain (A_{OL}) of *OP*-amp.

(*ii*) It is operated in a non-linear mode.

These properties of a comparator permit it to perform many useful functions.

Two comparator integrated circuits.

* If this terminal is grounded, v_2 = 0V.

** Since in our case supply voltages are ± 15V,

$$+V_{sat} = +V_{supply} - 2 = 15 - 2 = +13\text{V}$$
$$-V_{sat} = -V_{supply} + 2 = -15 + 2 = -13\text{V}$$

1. As a square wave generator. A comparator can be used to produce a square wave output from a sine wave input. Fig. 25.94 shows the circuit of a comparator to produce square wave output. Note that inverting terminal (–) is grounded and signal (v_{in}) is applied to the noninverting terminal (+). Since the gain of a comparator is equal to A_{OL}, virtually any difference voltage at the inputs will cause the output to go to one of the voltage extremes ($+ V_{sat}$ or $- V_{sat}$) and stay there until the voltage difference is removed. The polarity of the input difference voltage will determine to which extreme ($+V_{sat}$ or $- V_{sat}$) the output of the comparator goes.

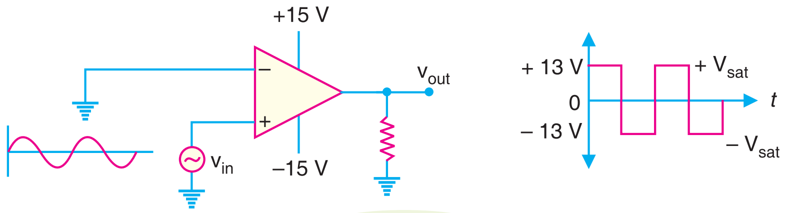


Fig. 25.94

When the input signal goes positive, the output jumps to about + 13 V. When the input goes negative, the output jumps to about – 13 V. The output changes rapidly from – 13 V to + 13 V and *vice-versa*. This change is so rapid that we get a square wave output for a sine wave input.

2. As a zero-crossing detector. When one input of a comparator is connected to ground, it is known as zero-crossing detector because the output changes when the input crosses 0 V. The zero-crossing circuit is shown in Fig. 25.95. The input and output waveforms are also shown. When the input signal is positive-going, the output is driven to positive maximum value (*i.e.* $+ V_{sat} = + 13$ V). When the input crosses the zero axis and begins to go negative, the output is driven to negative maximum value (*i.e.* $- V_{sat} = - 13$ V).

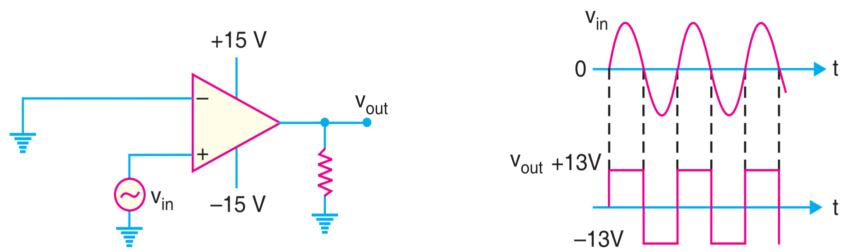


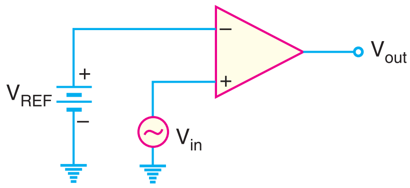
Fig. 25.95

From the input/output waveforms, you can see that every time the input crosses 0 V going positive, the output jumps to + 13 V. Similarly, every time the input crosses 0 V going negative, the output jumps to – 13 V. Since the change (+ 13 V or – 13 V) occurs every time the input crosses 0 V, we can tell when the input signal has crossed 0 V. Hence the name zero-crossing detector.

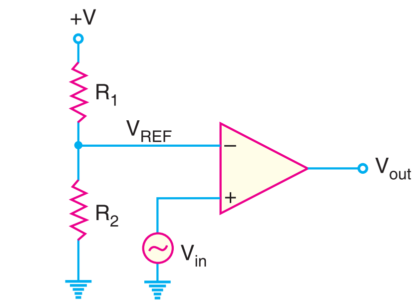
3. As a level detector. When a comparator is used to compare a signal amplitude to a fixed d.c. level (reference voltage), the circuit is referred to as a level detector. We can modify zero-crossing detector circuit to construct level detector. This can be done by connecting a fixed reference voltage V_{REF} to the inverting input as shown in Fig. 25.96 (*i*). A more practical arrangement is shown in Fig. 25.96 (*ii*) using a voltage divider to set the reference voltage as follows :

$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V)$$

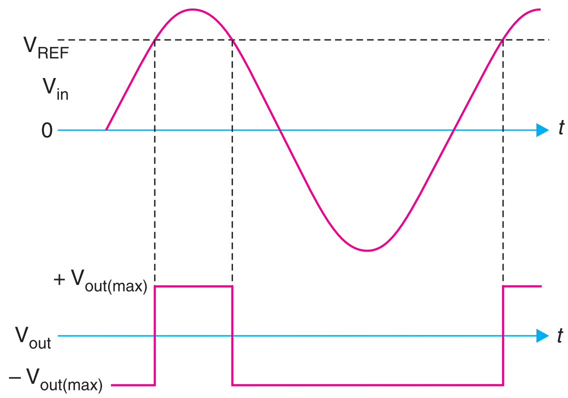
where + V is the positive *OP*-amp d.c. supply voltage.



(*i*) Battery reference



(*ii*) Voltage-divider reference



(*iii*) Waveforms

Fig. 25.96

The circuit action is as follows. Suppose the input signal v_{in} is a sine wave. When the input voltage is less than the reference voltage (*i.e.* $V_{in} < V_{REF}$), the output goes to maximum negative level. It remains here until V_{in} increases above V_{REF}. When the input voltage exceeds the reference voltage (*i.e.* $V_{in} > V_{REF}$), the output goes to its maximum positive state. It remains here until V_{in} decreases below V_{REF}. Fig. 25.96 (*iii*) shows the input/output waveforms. Note that this circuit is used for non zero-level detection.

MULTIPLE-CHOICE QUESTIONS

1. A differential amplifier ....
   (*i*) is a part of an OP-amp
   (*ii*) has one input and one output
   (*iii*) has two outputs
   (*iv*) answers (*i*) and (*iii*)
2. When a differential amplifier is operated single-ended, ...
   (*i*) the output is grounded
   (*ii*) one input is grounded and signal is applied to the other
   (*iii*) both inputs are connected together
   (*iv*) the output is not inverted
3. In differential-mode, ...
   (*i*) opposite polarity signals are applied to the inputs
   (*ii*) the gain is one
   (*iii*) the outputs are of different amplitudes
   (*iv*) only one supply voltage is used
4. In the common-mode, ...
   (*i*) both inputs are grounded
   (*ii*) the outputs are connected together
   (*iii*) an identical signal appears on both inputs
   (*iv*) the output signals are in-phase

5. The common-mode gain is ....
(*i*) very high (*ii*) very low
(*iii*) always unity (*iv*) unpredictable
6. The differential gain is ....
(*i*) very high (*ii*) very low
(*iii*) dependent on input voltage
(*iv*) about 100
7. If A_{DM} = 3500 and A_{CM} = 0.35, the *CMRR* is ....
(*i*) 1225
(*ii*) 10,000
(*iii*) 80 *dB*
(*iv*) answers (*ii*) and (*iii*)
8. With zero volts on both inputs, an OP-amp ideally should have an output ....
(*i*) equal to the positive supply voltage
(*ii*) equal to the negative supply voltage
(*iii*) equal to zero
(*iv*) equal to the *CMRR*
9. Of the values listed, the most realistic value for open-loop voltage gain of an OP-amp is ....
(*i*) 1 (*ii*) 2000
(*iii*) 80 *dB* (*iv*) 100,000
10. A certain OP-amp has bias currents of 50 μA and 49.3 μA. The input offset current is ....
(*i*) 700 n*A* (*ii*) 99.3 μ*A*
(*iii*) 49.7 μ*A* (*iv*) none of these
11. The output of a particular OP-amp increases 8 V in 12 μs. The slew rate is ....
(*i*) 90 V/μs (*ii*) 0.67 V/μs
(*iii*) 1.5 V/μs (*iv*) none of these
12. For an OP-amp with negative feedback, the output is ....
(*i*) equal to the input
(*ii*) increased
(*iii*) fed back to the inverting input
(*iv*) fed back to the noninverting input
13. The use of negative feedback ....
(*i*) reduces the voltage gain of an OP-amp
(*ii*) makes the OP-amp oscillate
(*iii*) makes linear operation possible
(*iv*) answers (*i*) and (*iii*)
14. Negative feedback ....
(*i*) increases the input and output impedances
(*ii*) increases the input impedance and bandwidth
(*iii*) decreases the output impedance and bandwidth
(*iv*) does not affect impedance or bandwidth
15. A certain noninverting amplifier has R_i of 1 kΩ and R_f of 100 kΩ. The closed-loop voltage gain is ....
(*i*) 100,000 (*ii*) 1000
(*iii*) 101 (*iv*) 100
16. If feedback resistor in *Q*.15 is open, the voltage gain ....
(*i*) increases (*ii*) decreases
(*iii*) is not affected (*iv*) depends on R_i
17. A certain inverting amplifier has a closed-loop voltage gain of 25. The OP-amp has an open-loop voltage gain of 100,000. If an OP-amp with an open-loop voltage gain of 200,000 is substituted in the arrangement, the closed-loop gain ....
(*i*) doubles (*ii*) drops to 12.5
(*iii*) remains at 25 (*iv*) increases slightly
18. A voltage follower ....
(*i*) has a voltage gain of 1
(*ii*) in noninverting
(*iii*) has no feedback resistor
(*iv*) has all of these
19. The OP-amp can amplify ....
(*i*) a.c. signals only
(*ii*) d.c. signals only
(*iii*) both a.c. and d.c. signals
(*iv*) neither d.c. nor a.c. signals
20. The input offset current equals the ....
(*i*) difference between two base currents
(*ii*) average of two base currents
(*iii*) collector current divided by current gain
(*iv*) none of these
21. The tail current of a differential amplifier is ....
(*i*) half of either collector current

(ii) equal to either collector current
(iii) two times either collector current
(iv) equal to the difference in base currents

22. The node voltage at the top of the tail resistor is closest to ....
(i) collector supply voltage
(ii) zero
(iii) emitter supply voltage
(iv) tail current times base resistance

23. The tail current in a differential amplifier equals ....
(i) difference between two emitter currents
(ii) sum of two emitter currents
(iii) collector current divided by current gain
(iv) collector voltage divided by collector resistance

24. The differential voltage gain of a differential amplifier is equal to R_C divided by ....
(i) r'_e (ii) $r'_e/2$
(iii) $2\,r'_e$ (iv) R_E

25. The input impedance of a differential amplifier equals r'_e times ....
(i) β (ii) R_E
(iii) R_C (iv) 2β

26. A common-mode signal is applied to ....
(i) the noninverting input
(ii) the inverting input
(iii) both inputs
(iv) top of the tail resistor

27. The common-mode voltage gain is ....
(i) smaller than differential voltage gain
(ii) equal to differential voltage gain
(iii) greater than differential voltage gain
(iv) none of the above

28. The input stage of an OP-amp is usually a ....
(i) differential amplifier
(ii) class *B* push-pull amplifier
(iii) *CE* amplifier
(iv) swamped amplifier

29. The common-mode voltage gain of a differential amplifier is equal to R_C divided by ....
(i) r'_e (ii) $2\,r'_e$
(iii) $r'_e/2$ (iv) $2\,R_E$

30. Current cannot flow to ground through ....
(i) a mechanical ground
(ii) an a.c. ground
(iii) a virtual ground
(iv) an ordinary ground

Answers to Multiple-Choice Questions

1. (iv)	**2.** (ii)	**3.** (i)	**4.** (iii)	**5.** (ii)
6. (i)	**7.** (iv)	**8.** (iii)	**9.** (iv)	**10.** (i)
11. (ii)	**12.** (iii)	**13.** (iv)	**14.** (ii)	**15.** (iii)
16. (i)	**17.** (iii)	**18.** (iv)	**19.** (iii)	**20.** (i)
21. (iii)	**22.** (ii)	**23.** (ii)	**24.** (iii)	**25.** (iv)
26. (iii)	**27.** (i)	**28.** (i)	**29.** (iv)	**30.** (iii)

Chapter Review Topics

1. What is an operational amplifier (OP-amp)?
2. Give the block diagram of an operational amplifier.
3. What is a differential amplifier?
4. Draw the basic circuit of a differential amplifier.
5. Discuss the operation of a differential amplifier.
6. What do you mean by noninverting and inverting input of a differential amplifier?
7. What are common-mode and differential-mode signals?
8. What do you mean by *CMRR*?

9. What is the importance of *CMRR*?
10. Explain the d.c. analysis of a differential amplifier.
11. What do you mean by (*i*) output offset voltage (*ii*) input offset current?
12. Derive an expression for differential-mode voltage gain of a differential amplifier.
13. Derive an expression for the common-mode voltage gian of a differential amplifier.
14. Draw the schematic symbol of an operational amplifier indicating the various terminals.
15. What do you-mean by (*i*) open-loop voltage gain (*ii*) closed-loop voltage gain of an OP-amp?
16. Discuss OP-amp input/output polarity relationship.
17. What do you mean by bandwidth of an OP-amp?
18. What do you mean by slew rate of an OP-amp?
19. Discuss the frequency response of an OP-amp.
20. What is the need of negative feedback in an OP-amp?
21. Derive an expression for the voltage gain of an inverting amplifier.
22. Derive an expression for the voltage gain of a noninverting amplifier.
23. What is a voltage follower?
24. Draw the circuit of multistage OP-amp.
25. What is the effect of negative feedback on (*i*) noninverting amplifier (*ii*) inverting amplifier ?
26. Discuss the operation of a summing amplifier.
27. Discuss two applications of summing amplifiers.
28. Discuss the operation of an OP-amp integrator.
29. What is the most important application of an OP-amp integrator?
30. Discuss the operation of OP-amp differentiator.

Problems

1. In Fig 25.97, the transistors are identical with $\beta_{dc} = 200$. What is the output voltage? **[7.5 V]**

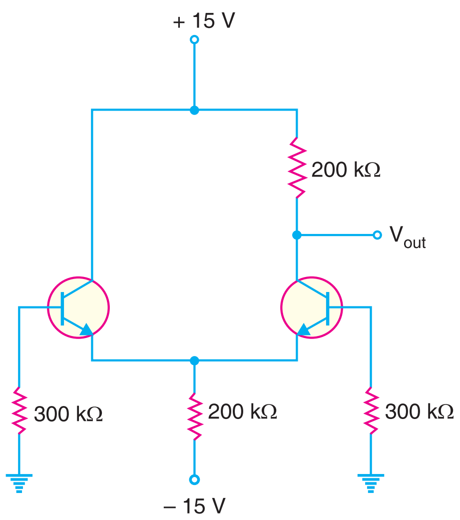


Fig. 25.97

2. In Fig. 25.97, the left transistor has $\beta_{dc} = 225$ and the right transistor has $\beta_{dc} = 275$. What are the base voltages? **[– 0.05 V ; – 0.0409 V]**
3. A data sheet gives an input bias current of 20 *nA* and an input offset current of 3 nA. What are the base currents? **[18.5 nA ; 21.5 nA]**
4. Find bias voltages and currents for the differential amplifier circuit in Fig. 25.98.

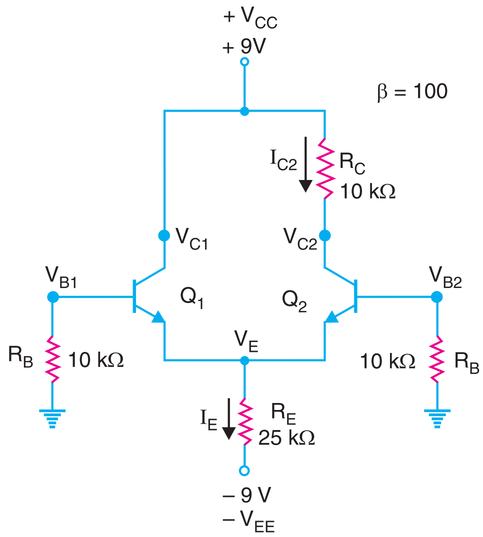


Fig. 25.98

[V_E = – 0.7 V ; I_E = 0.332 mA ; $I_{E1} = I_{E2}$ = 0.166 mA ; $I_{C1} = I_{C2}$ = 0.166 mA ; $I_{B1} = I_{B2}$ = 1.66 µA; V_{C1} = 9 V ; V_{C2} = 7.34 V]

5. Find the bias voltages and currents for the differential amplifier circuit shown in Fig. 25.99.

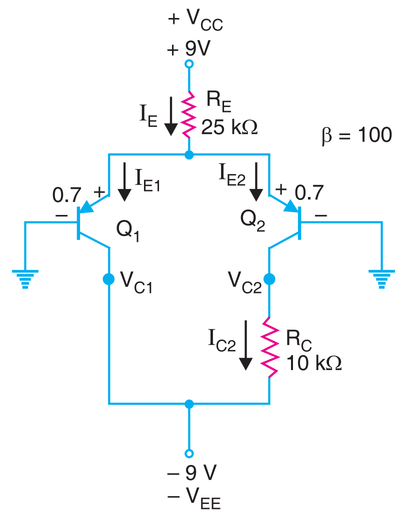


Fig. 25.99

[V_E = 0.7 V ; I_E = 0.332 mA ; $I_{E1} = I_{E2}$ = 0.166 mA ; $I_{C1} = I_{C2}$ = 0.166 mA ; $I_{B1} = I_{B2}$ = 1.66 µA; V_{C1} = – 9 V ; V_{C2} = – 7.34 V]

6. For the circuit shown in Fig. 25.100, determine (*i*) common-mode voltage gain (*ii*) differential-mode voltage gain (*iii*) *CMRR*. **[(*i*) 0.42 (*ii*) 90.6 (*iii*) 216]**

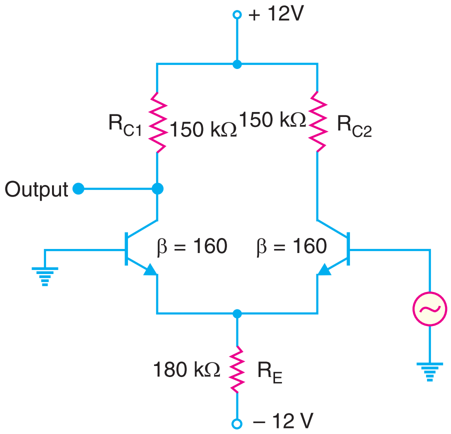


Fig. 25.100

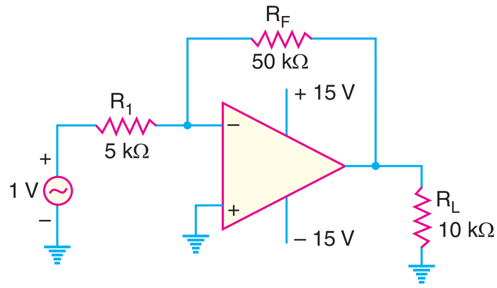


Fig. 25.101

7. For the circuit shown in Fig. 25.101, find (*i*) closed-loop voltage gain (*ii*) the instantaneous voltage across R_F when the signal voltage is + 1*V* (*iii*) the instantaneous voltage on the –terminal when the signal voltage is + 1*V*. **[(*i*) 10 (*ii*) 10 *V* (*iii*) 0 *V*]**

8. A noninverting amplifier has an R_i of 1 kΩ and an R_f of 100 kΩ. Determine (*i*) V_f (*ii*) feedback factor if V_{out} = 5 V. **[(*i*) 49.5 mV ; (*ii*) 9.9 × 10^{-3}]**

9. Determine the closed-loop voltage gain for the circuit shown in Fig. 25.102. **[11]**

10. Determine the closed-loop voltage gain for the circuit shown in Fig. 25.103. **[101]**

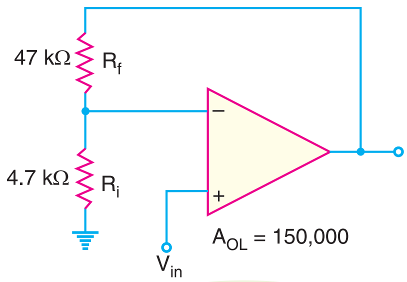


Fig. 25.102

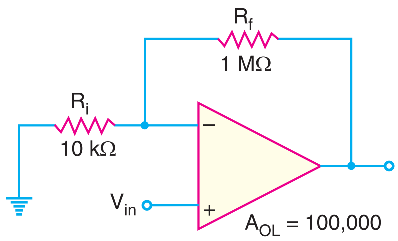


Fig. 25.103

11. Find the closed-loop voltage gain for each of the circuits shown in Fig. 25.104. **[1 ; – 1]**

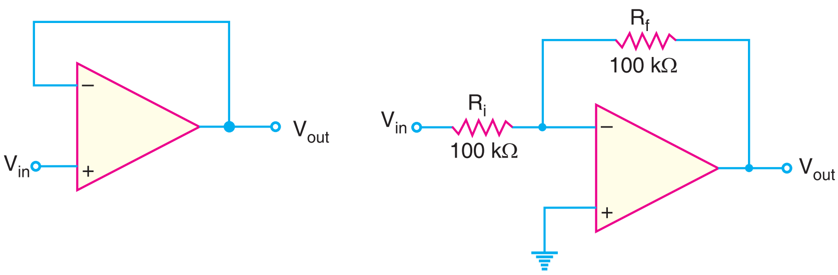


Fig. 25.104

12. Determine the approximate values of (*i*) I_{in} (*ii*) I_f (*iii*) V_{out} (*iv*) closed-loop voltage gain for the circuit in Fig. 25.105. **[(*i*) 455 μ*A* (*ii*) 455 μ*A* (*iii*) – 10*V* (*iv*) – 10]**

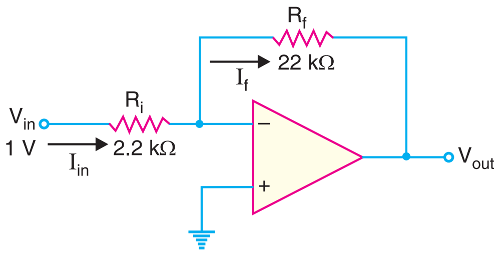


Fig. 25.105

13. Calculate the output voltage of the circuit in Fig. 25.106 for R_f = 68 kΩ. **[V_o = – 3.39 V]**

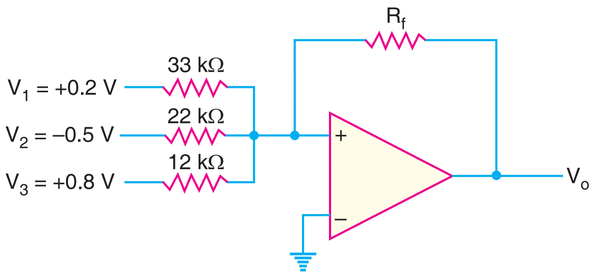


Fig. 25.106

14. What output voltage results in the circuit of Fig. 25.107 for V_1 = + 0.5 V? **[V_o = 0.5 V]**

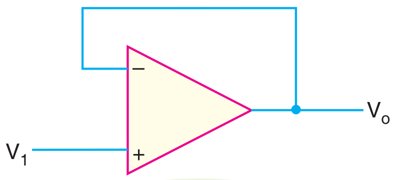


Fig. 25.107

15. Calculate the output voltages V_2 and V_3 in the circuit of Fig. 25.108. **[V_2 = – 2 V ; V_3 = 4.2 V]**

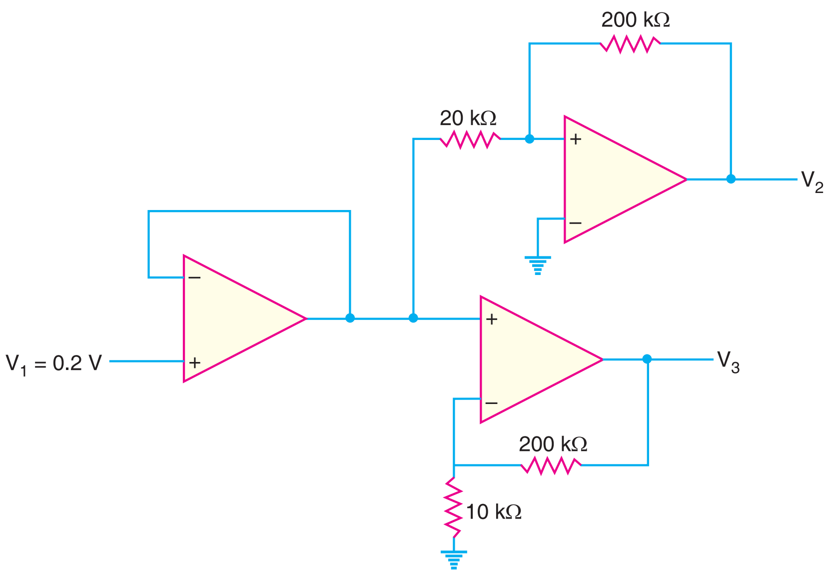


Fig. 25.108

Discussion Questions

1. What is the difference between a discrete circuit and an integrated circuit (IC)?
2. Why are OP-amps produced as IC?
3. What is the difference between differential amplifier and the conventional amplifier?
4. What do + and – signs on the symbol of an OP-amp indicate?
5. Why is OP-amp generally operated with negative feedback?
6. Why is common-mode gain of a DA very low?
7. What is the importance of CMRR?
8. When is OP-amp driven to saturation?
9. In which circuit we take the advantage of high open-loop voltage gain of an OP-amp?
10. What is a noninverting amplifier?
11. Why is the input impedance of an OP-amp very high?
12. Why is the open-loop voltage gain of an OP-amp high?
13. What do you mean by virtual ground?
14. Why is the output impedance of an OP-amp very low?
15. What are the advantages of negative feedback in OP-amps?

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