Operational Amplifiers and Applications

Syllabus: *Introduction to Op-Amp, Op-Amp Input Modes, Op-Amp Parameters - CMRR, Input Offset Voltage and Current, Input Bias Current, Input and Output Impedance, Slew Rate. Applications of Op-Amp - Inverting amplifier, Non-Inverting amplifier, Summer, Voltage follower, Integrator, Differentiator, Comparator.* ***(8 Hours)***

Introduction

An operational amplifier, or op-amp, is the most important and versatile analog IC. ***It is a direct coupled multistage voltage amplifier with an extremely high gain.*** With the help of op-amp, the circuit design becomes very simple. The variety of useful circuits can be built without the necessity of knowing about the complex internal circuitry.

Fig. 1 shows circuit symbol and circuit model of an op-amp.

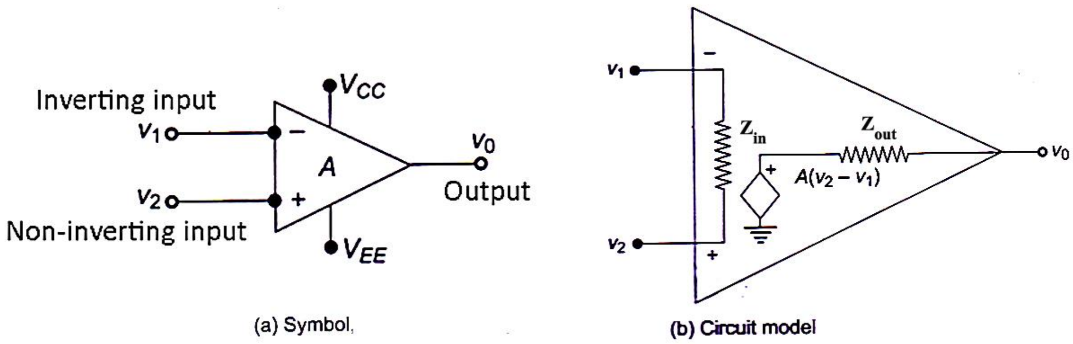


Fig. 1 Circuit symbol and model of an op-amp

An op-amp has two input terminals – an inverting input V_1 and a non-inverting input V_2, and an output V_o. It requires two power supplies: $+V_{CC}$ and $-V_{EE}$. It has a very high input impedance Z_{in}, a very low output impedance Z_{out} and a very high gain A.

Advantages of Op-Amps

- Low cost
- Small size
- Versatility
- Flexibility
- Dependability

Applications of Op-Amps

- Op-amps have become an integral part of almost every electronic circuit which uses linear integrated circuits.
- Op-amps are used in analog signal processing and analog filtering.
- They are used to perform mathematical operations such as addition, subtraction, multiplication, integration, differentiation, etc.

- They are used in the fields of process control, communications, computers, power and signal sources, displays and measuring systems.
- They are used in linear applications like voltage follower, differential amplifier, inverting amplifier, non-inverting amplifier, etc. and non-linear applications like precision rectifiers, comparators, clampers, Schmitt trigger circuit, etc.

Ideal Op-Amp

Fig. 2 gives the representation of ideal and practical op-amps.

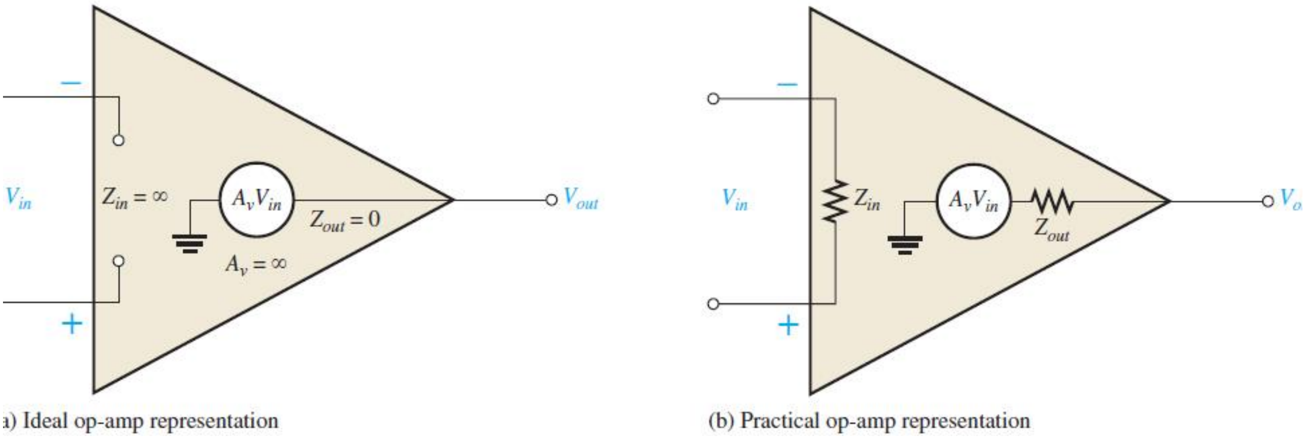


Fig. 2 Representation of ideal and practical op-amps

An ideal op-amp has the following characteristics:

1. **Infinite voltage gain ($A_{ol} = \infty$):** The voltage gain, also known as differential open loop gain is infinite in an ideal op-amp.
2. **Infinite input impedance ($Z_{in} = \infty$):** The input impedance is infinite in an ideal op-amp. This means that no current can flow into an ideal op-amp.
3. **Zero output impedance ($Z_{out} = 0$):** The output impedance is zero in an ideal op-amp. This means that the output voltage remains the same, irrespective of the value of the load connected.
4. **Zero offset voltage ($V_{OS} = 0$):** The presence of the small output voltage even when $V_1 = V_2 = 0$ is called offset voltage. In an ideal op-amp, offset voltage is zero. This means the output is zero if the input is zero.
5. **Infinite bandwidth ($BW = \infty$):** The range of frequencies over which the amplifier performance is satisfactory is called its bandwidth. The bandwidth of an ideal op-amp is infinite.
6. **Infinite CMRR ($CMRR = \infty$):** The ratio of differential gain to common mode gain is called common mode rejection ratio (CMRR). In an ideal op-amp, CMRR is infinite. This means that the common mode gain is zero in an ideal op-amp.
7. **Infinite slew rate ($S = \infty$):** Slew rate is the maximum rate of change of output voltage with time. In an ideal op-amp, slew rate is infinite. This means that the changes in the output voltage occur simultaneously with the changes in the input voltage.

8. **No effect of temperature:** The characteristics of an ideal op-amp do not change with the changes in temperature.
9. **Zero PSRR ($PSRR = 0$):** Power supply rejection ratio (PSRR) is defined as the ratio of the change in input offset voltage due to the change in supply voltage producing it, keeping other power supply voltage constant. In an ideal op-amp, PSRR is zero.

Practical Op-Amp

Characteristics of a practical op-amp are *very high voltage gain*, *very high input impedance*, and *very low output impedance*.

Internal Block Diagram of an Op-Amp

A typical op-amp is made up of three types of amplifier circuits: a differential amplifier, a voltage amplifier, and a push-pull amplifier, as shown in Fig. 3.

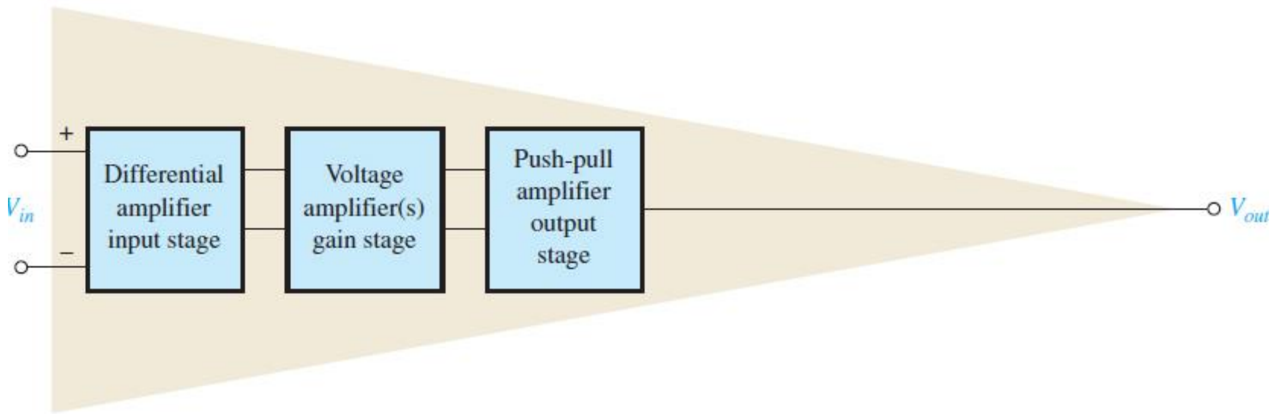


Fig. 3 Basic internal arrangement of an op-amp

- The differential amplifier is the input stage for the op-amp. It provides amplification of the difference voltage between the two inputs.
- The second stage is usually a class A amplifier that provides additional gain. Some op-amps may have more than one voltage amplifier stage.
- A push-pull class B amplifier is typically used for the output stage.

Op-Amp IC 741

IC 741is the most popular IC version of op-amp. It is an 8-pin IC as shown in Fig. 4.

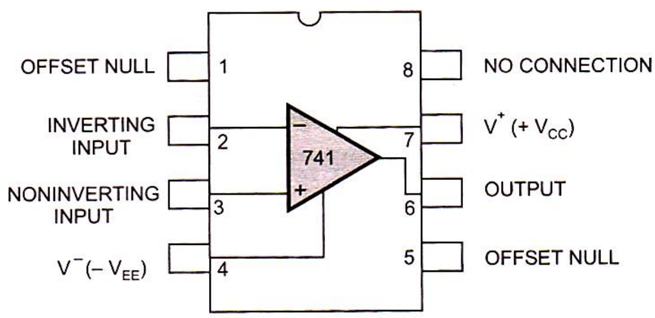


Fig. 4 Pin diagram of IC 741

- Pin 2 is the inverting input terminal and Pin 3 is the non-inverting input terminal

- Pin 6 is the output terminal
- Pin 4 is for $-V_{EE}$ (V^-) supply and pin 7 is for $+V_{CC}$ (V^+) supply
- Pins 1 and 5 are offset null pins. These are used to nullify offset voltage
- Pin 8 is a dummy pin and no connection is made to this pin

Op-Amp Input Modes

The input signal modes are determined by the differential amplifier input stage of the op-amp.

Differential Mode

In the differential mode, either one signal is applied to an input with the other input grounded or two opposite-polarity signals are applied to the inputs.

Single-Ended Differential Mode

When an op-amp is operated in the single-ended differential mode, one input is grounded and a signal voltage is applied to the other input, as shown in Fig. 5.

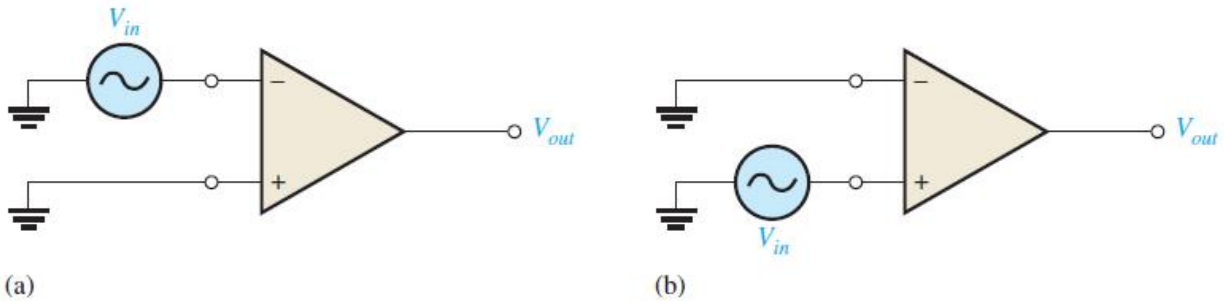


Fig. 5 Single-ended differential mode

In the case where the signal voltage is applied to the inverting input as in Fig. 5 (a), an inverted, amplified signal voltage appears at the output. In the case where the signal is applied to the noninverting input with the inverting input grounded, as in Fig. 5(b), a noninverted, amplified signal voltage appears at the output.

Double-Ended Differential Mode

In the double-ended differential mode, two opposite-polarity (out-of-phase) signals are applied to the inputs, as shown in Fig. 6(a). The amplified difference between the two inputs appears on the output.

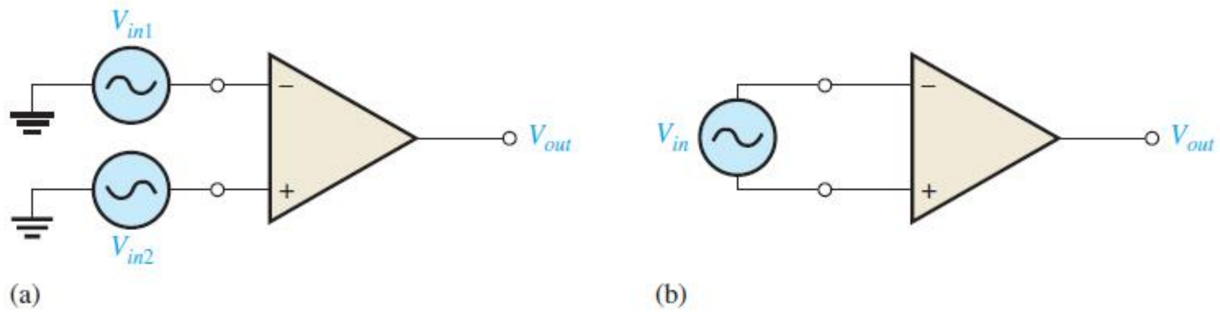


Fig. 6 Double-ended differential mode

Equivalently, the double-ended differential mode can be represented by a single source connected between the two inputs, as shown in Fig. 6(b).

Common Mode

In the common mode, two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in Fig. 7.

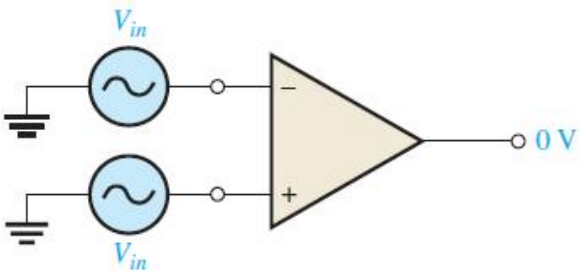


Fig. 7 Common mode operation

When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage. This action is called *common-mode rejection*. Its importance lies in the situation where an unwanted signal appears commonly on both op-amp inputs. Common-mode rejection means that this unwanted signal will not appear on the output and distort the desired signal.

Op-Amp Parameters

Open-Loop Voltage Gain (Differential Gain)

An op-amp amplifies the difference between the two input signals $\boldsymbol{V_d = V_2 - V_1}$. The output voltage is given by

$$\boldsymbol{V_o = A_{ol}V_d = A_{ol}(V_2 - V_1)}$$

where A_{ol} is the ***open-loop voltage gain***, also called ***differential gain*** given by $\boldsymbol{A_{ol} = \frac{V_o}{V_d}}$

The open-loop voltage gain of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components.

Generally A_{ol} is expressed in decibel (dB) as $\boldsymbol{A_{ol} = 20\, log_{10}\left(\frac{V_o}{V_d}\right)\, dB}$.

Common Mode Gain

If we apply two input voltages which are equal i.e. if $V_1 = V_2$, then ideally the output must be zero. But practically, the output voltage not only depends on the difference voltage but also depends on the average common level of the two inputs. Such a common level is called common mode signal $\boldsymbol{V_c = \frac{V_1+V_2}{2}}$.

The differential amplifier produces the output voltage proportional to common mode signal and the output voltage is given as

$$\boldsymbol{V_o = A_{cm}V_c}$$

where A_{cm} is the ***common mode gain*** given by $\boldsymbol{A_{cm} = \frac{V_o}{V_c}}$

Common Mode Rejection Ratio

Common mode rejection ratio (CMRR) is the ability of an op-amp to reject a common mode signal. ***It is defined as the ratio of open-loop voltage gain A_{ol} to common mode gain A_{cm}.***

$$CMRR = \frac{A_{ol}}{A_{cm}}$$

The higher the CMRR, the better. A very high value of CMRR means that the open-loop gain, A_{ol}, is high and the common-mode gain, A_{cm}, is low.

CMRR is a large value and is often expressed in decibel as

$$CMRR = 20\, log_{10}\left(\frac{A_{ol}}{A_{cm}}\right)\, dB$$

Maximum Output Voltage Swing $V_{O(p-p)}$

With no input signal, the output of an op-amp is ideally 0 V. This is called the quiescent output voltage. When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{CC}$. In practice, however, this ideal can be approached but never reached. $V_{O(p-p)}$ varies with the load connected to the op-amp and increases directly with load resistance.

Input Offset Voltage

The ideal op-amp produces zero volts out for zero volts in. In a practical op-amp, a small dc voltage appears at the output when no differential input voltage is applied.

The ***input offset voltage***, V_{OS}, is the differential dc voltage required between the inputs to force the output to zero volts.

Typical values of input offset voltage are in the range of 2 mV or less. In the ideal case, it is 0 V.

Input Offset Current

Ideally, the two input bias currents are equal, and thus their difference is zero. In a practical op-amp, however, the bias currents are not exactly equal.

The ***input offset current***, I_{OS}, is the difference of the input bias currents, expressed as an absolute value.

$$I_{OS} = |I_1 - I_2|$$

Input Bias Current

The ***input bias current*** is the average of the two input currents of the op-amp. It is calculated as follows:

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

It is the dc current required by the inputs of the amplifier to properly operate the first stage. The concept of input bias current is illustrated in Fig. 8.

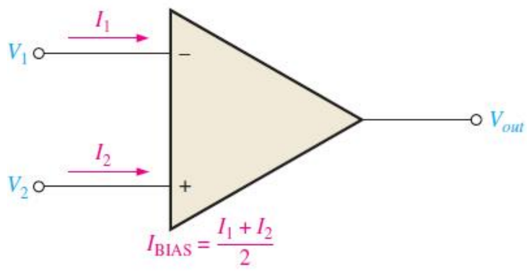


Fig. 8 Input bias current

Input Impedance

Two basic ways of specifying the input impedance of an op-amp are the differential and the common mode.

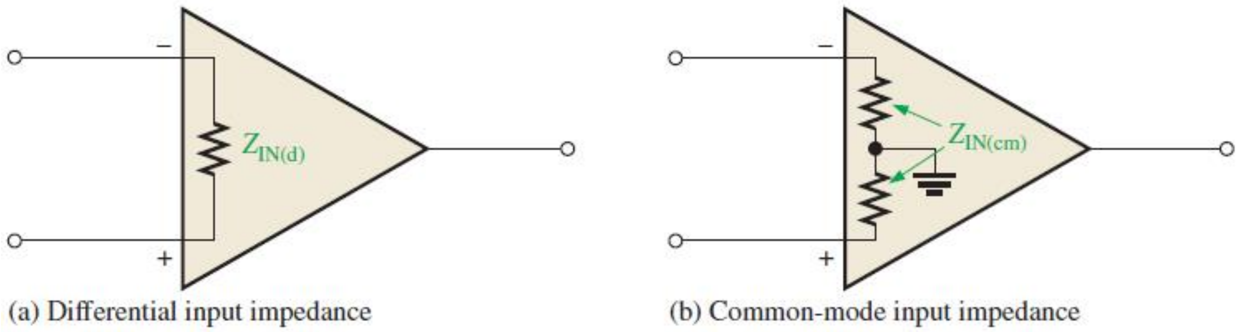


Fig. 9 Op-amp input impedance

The ***differential input impedance*** is the total resistance between the inverting and the noninverting inputs, as illustrated in Fig. 9(a). It is measured by determining the change in bias current for a given change in differential input voltage.

The ***common-mode input impedance*** is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage. It is depicted in Fig. 9(b).

Output Impedance

The output impedance is the resistance viewed from the output terminal of the op-amp, as indicated in Fig. 10.

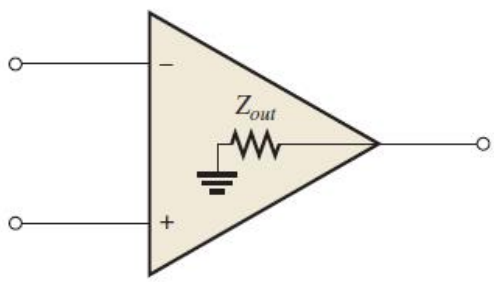
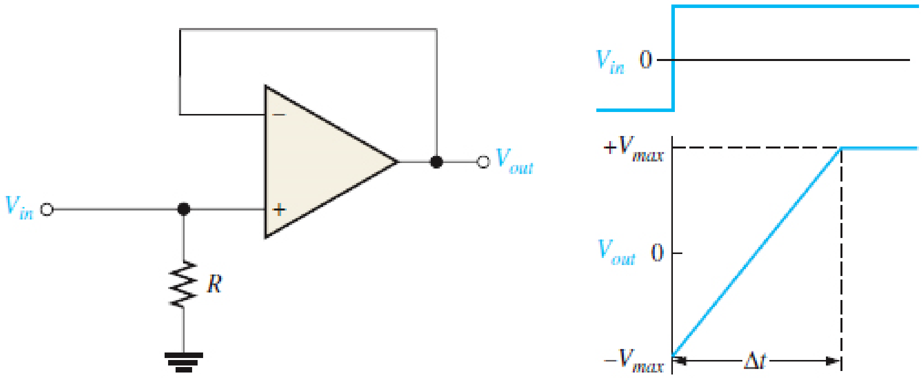


Fig. 10 Op-amp output impedance

Slew Rate

Slew rate is defined as the maximum rate of change of output voltage in response to a step input voltage.



(a) Test circuit (b) Step input voltage and the resulting output voltage

Fig. 11 Slew rate measurement

Slew rate is measured with an op-amp connected as shown in Fig. 11 (a). A pulse is applied to the input and the resulting ideal output voltage is indicated in Fig. 11 (b). The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit. A certain time interval Δt is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$ once the input step is applied.

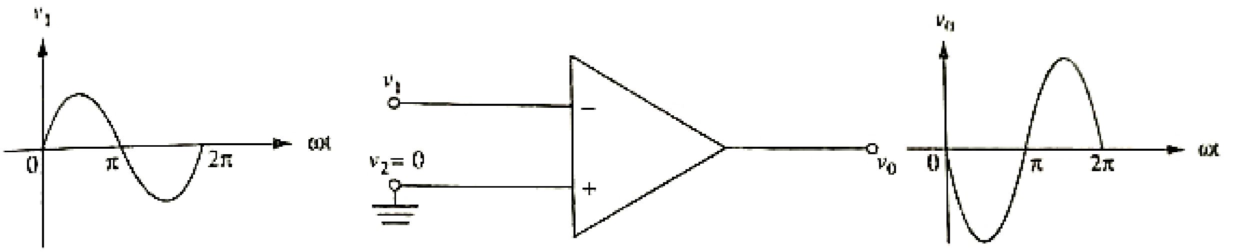
$$\boldsymbol{Slew\ rate = S = \frac{\Delta V_{out}}{\Delta t}}$$

where $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond ($V/\mu s$).

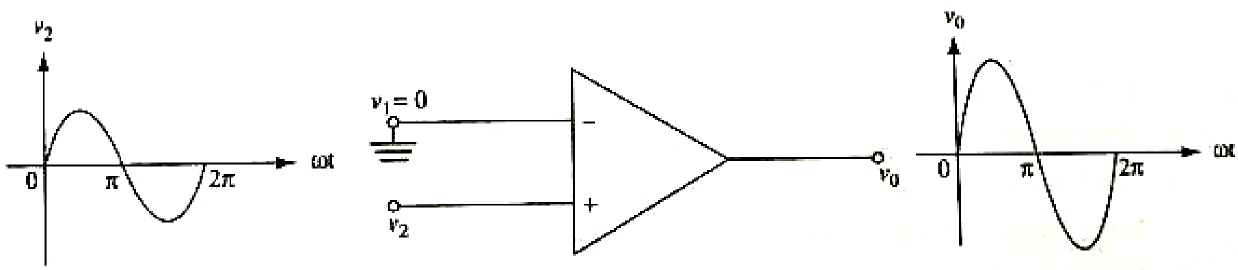
Operation of an Op-Amp

An op-amp is basically differential amplifier which amplifies the difference between the two input signals.

Fig. 12 shows the basic operation of an op-amp as inverting and non-inverting amplifiers.



(a) Inverting amplifier



(b) Non-inverting amplifier

Fig. 12 Basic operation of an op-amp

When a voltage V_1 is applied to the inverting input with the non-inverting input grounded ($V_2 = 0$), the output voltage is

$$V_o = A(V_2 - V_1) = A(0 - V_1) = -AV_1$$

This indicates that the output voltage is amplified with a gain A and inverted (phase or polarity reversed) with respect to the input voltage as shown in Fig. 12 (a).

On the other hand, when a voltage V_2 is applied to the non-inverting input with the inverting input grounded ($V_1 = 0$), the output voltage is

$$V_o = A(V_2 - V_1) = A(V_2 - 0) = AV_2$$

This indicates that the output voltage is amplified with a gain A and is in the same phase or polarity as the input voltage as shown in Fig. 12 (b).

Assumptions

While analyzing the operation of op-amp circuits, two assumptions are made:

1. **Zero Input Current:** Since the input resistance of an ideal op-amp is infinite, no current flows into an op-amp. This makes the input current zero.
2. **Virtual Ground:** An ideal op-amp has an infinite gain. We know that output voltage $V_o = A(V_2 - V_1)$. That makes $(V_2 - V_1) = \frac{V_o}{A}$. If gain A is infinite, that means the difference $V_2 - V_1 = 0$, or $V_1 = V_2$.

   This means that the input terminals of an op-amp are always at the same potential. Thus, if one terminal is grounded, the other one can be treated to be virtually grounded.

Basic Op-Amp Circuits

Inverting Amplifier

An amplifier which produces a phase shift of 180° between input and output is called ***inverting amplifier.*** Fig. 13 shows an inverting amplifier using op-amp.

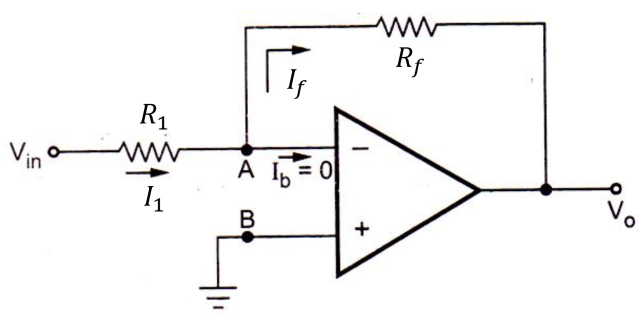


Fig. 13 Inverting amplifier

From the circuit, the potential at node B, $V_B = 0$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = 0$.

From the circuit,

$$I_1 = \frac{V_{in} - V_A}{R_1} = \frac{V_{in} - 0}{R_1} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = \frac{V_{in}}{R_1}}$$

and

$$I_f = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f}$$

$$\boldsymbol{I_f = -\frac{V_o}{R_f}}$$

Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

$$\frac{V_{in}}{R_1} = -\frac{V_o}{R_f}$$

$$\boxed{\boldsymbol{V_o = -\left(\frac{R_f}{R_1}\right) V_{in}}}$$

Here $\frac{R_f}{R_1}$ is called the gain of the amplifier and negative sign indicates that the output is inverted.

Fig. 14 shows the input and output waveforms of an inverting amplifier.

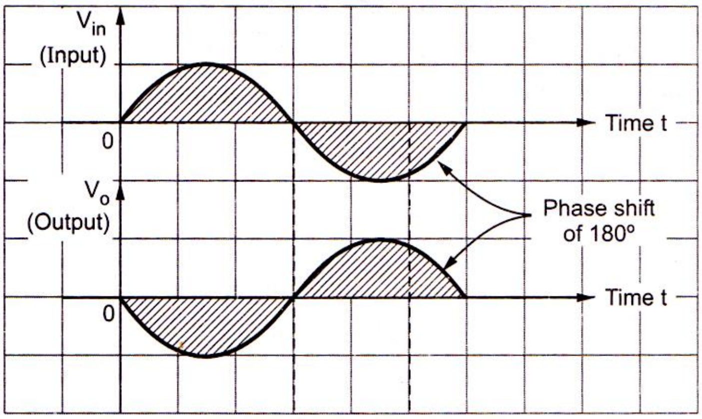


Fig. 14 Waveforms of inverting amplifier

Non-Inverting Amplifier

An amplifier which amplifies the input without producing any phase shift between input and output is called ***non-inverting amplifier***. Fig. 15 shows a non-inverting amplifier using op-amp.

From the circuit, the potential at node B, $V_B = V_{in}$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = V_{in}$.

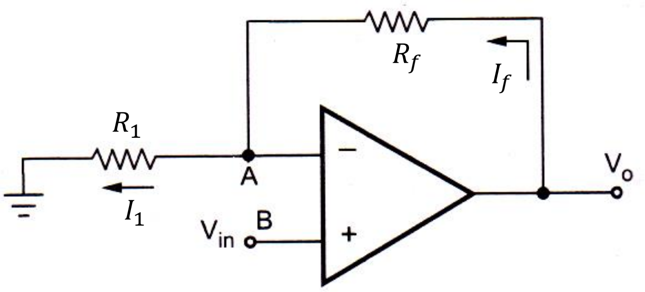


Fig. 15 Non-inverting amplifier

From the circuit,

$$I_1 = \frac{V_A - 0}{R_1} = \frac{V_{in} - 0}{R_1} \qquad (\because V_A = V_{in})$$

$$\boldsymbol{I_1 = \frac{V_{in}}{R_1}}$$

and

$$I_f = \frac{V_o - V_A}{R_f} = \frac{V_o - V_{in}}{R_f}$$

$$\boldsymbol{I_f = \frac{V_o - V_{in}}{R_f}}$$

Since op-amp input current is zero, I_f passes through R_1 as I_1. That is,

$$I_1 = I_f$$

$$\frac{V_{in}}{R_1} = \frac{V_o - V_{in}}{R_f}$$

$$\frac{V_{in}}{R_1} = \frac{V_o}{R_f} - \frac{V_{in}}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_{in}}{R_1} + \frac{V_{in}}{R_f}$$

$$\frac{V_o}{R_f} = \left(\frac{1}{R_1} + \frac{1}{R_f}\right) V_{in}$$

$$V_o = R_f \left(\frac{R_1 + R_f}{R_1 R_f}\right) V_{in}$$

$$V_o = \left(\frac{R_1 + R_f}{R_1}\right) V_{in}$$

$$\boxed{\boldsymbol{V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}}}$$

Here $\left(1 + \frac{R_f}{R_1}\right)$ is called the gain of the amplifier. Fig. 16 shows the input and output waveforms of an inverting amplifier.

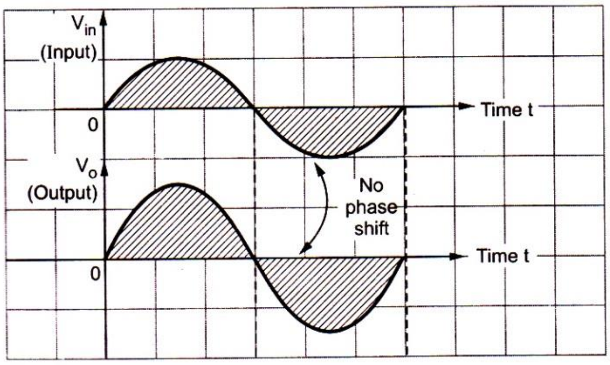


Fig. 16 Waveforms of non-inverting amplifier

Op-Amp Applications

Voltage Follower

A circuit in which the output voltage follows the input voltage is called ***voltage follower.*** Fig. 17 shows a voltage follower circuit using an op-amp.

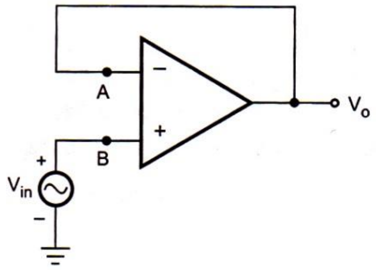


Fig. 17 Voltage follower

From the circuit, the potential at node B, $V_B = V_{in}$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = V_{in}$.

The node A is directly connected to the output. Hence

$$V_o = V_A$$

Now since $V_A = V_{in}$,

$$\boxed{\boldsymbol{V_o = V_{in}}}$$

In a voltage follower gain is unity $(A = 1)$. A voltage follower is also called ***source follower***, ***unity gain amplifier***, ***buffer amplifier*** or ***isolation amplifier***. Fig. 18 shows the input and output waveforms of a voltage follower.

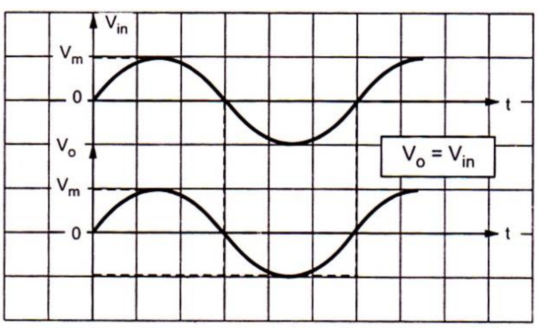


Fig. 18 Waveforms of voltage follower

Advantages of Voltage Follower

1. Very large input resistance
2. Very low output resistance
3. Large bandwidth
4. The output follows the input exactly without any phase shift

Summing Amplifier (Summer or Adder)

Inverting Summing Amplifier

In this circuit, the input signals to be added are applied to the inverting input terminal. An adder with two inputs is shown in Fig. 19.

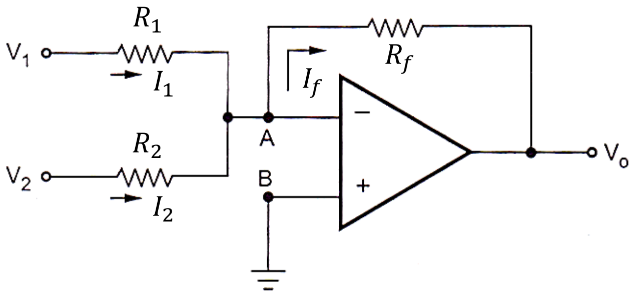


Fig. 19 Inverting summing amplifier (adder) with two inputs

From the circuit, the potential at node B, $V_B = 0$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = 0$.

From the circuit,

$$I_1 = \frac{V_1 - V_A}{R_1} = \frac{V_1 - 0}{R_1} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = \frac{V_1}{R_1}}$$

Similarly,

$$I_2 = \frac{V_2 - V_A}{R_2} = \frac{V_2 - 0}{R_2}$$

$$\boldsymbol{I_2 = \frac{V_2}{R_2}}$$

and

$$I_f = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f}$$

$$\boldsymbol{I_f = -\frac{V_o}{R_f}}$$

Now since op-amp input current is zero, I_1 and I_2 together pass through R_f as I_f. That is,

$$I_f = I_1 + I_2$$

$$-\frac{V_o}{R_f} = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$

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

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

If $R_1 = R_2 = R$,

$$V_o = -\frac{R_f}{R}(V_1 + V_2)$$

If $R_1 = R_2 = R_f$,

$$\boxed{V_o = -(V_1 + V_2)}$$

This shows that the output is the sum of the input signals. The negative sign indicates that the phase is inverted.

Three-Input Adder (Inverting Summing Amplifier)

An adder with three inputs is shown in Fig. 20.

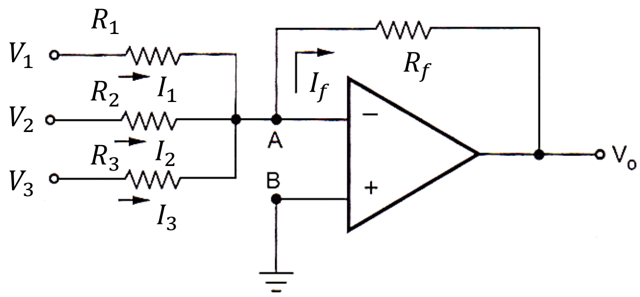


Fig. 20 Inverting summing amplifier (adder) with three inputs

From the circuit, the potential at node B, $V_B = 0$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = 0$.

From the circuit,

$$I_1 = \frac{V_1 - V_A}{R_1} = \frac{V_1 - 0}{R_1} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = \frac{V_1}{R_1}}$$

Similarly,

$$I_2 = \frac{V_2 - V_A}{R_2} = \frac{V_2 - 0}{R_2}$$

$$\boldsymbol{I_2 = \frac{V_2}{R_2}}$$

Also

$$I_3 = \frac{V_3 - V_A}{R_3} = \frac{V_3 - 0}{R_3}$$

$$\boldsymbol{I_3 = \frac{V_3}{R_3}}$$

and

$$I_f = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f}$$

$$\boldsymbol{I_f = -\frac{V_o}{R_f}}$$

Now since op-amp input current is zero, I_1, I_2 and I_3 together pass through R_f as I_f. That is,

$$I_f = I_1 + I_2 + I_3$$

$$-\frac{V_o}{R_f} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

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

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

If $R_1 = R_2 = R_3 = R$,

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

If $R_1 = R_2 = R_3 = R_f$,

$$\boxed{V_o = -(V_1 + V_2 + V_3)}$$

This shows that the output is the sum of the input signals. The negative sign indicates that the phase is inverted.

Non-Inverting Summing Amplifier

In this circuit, the input signals to be added are applied to the non-inverting input terminal. Fig. 21 shows a non-inverting summing amplifier with two inputs.

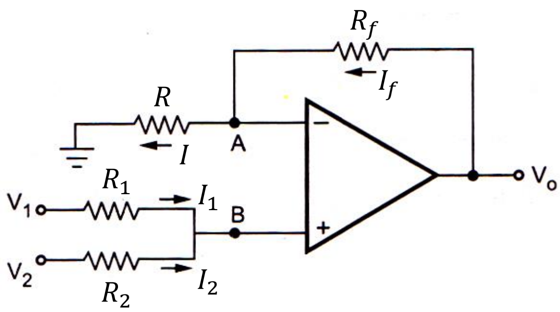


Fig. 21 Non-inverting summing amplifier

Let the potential at node B be V_B.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B$.

From the circuit,

$$I_1 = \frac{V_1 - V_B}{R_1}$$

and

$$I_2 = \frac{V_2 - V_B}{R_2}$$

Now since op-amp input current is zero,

$$I_1 + I_2 = 0$$

$$\therefore \frac{V_1 - V_B}{R_1} + \frac{V_2 - V_B}{R_2} = 0$$

$$\frac{V_1}{R_1} - \frac{V_B}{R_1} + \frac{V_2}{R_2} - \frac{V_B}{R_2} = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = \frac{V_B}{R_1} + \frac{V_B}{R_2}$$

$$\frac{R_2V_1 + R_1V_2}{R_1R_2} = V_B\left(\frac{R_1 + R_2}{R_1R_2}\right)$$

$$V_B = \frac{R_2V_1 + R_1V_2}{R_1 + R_2} \qquad (1)$$

At node A,

$$I = \frac{V_A}{R} = \frac{V_B}{R} \qquad (\because V_A = V_B)$$

and

$$I_f = \frac{V_o - V_A}{R_f} = \frac{V_o - V_B}{R_f}$$

Now since op-amp input current is zero,

$$I = I_f$$

$$\frac{V_B}{R} = \frac{V_o - V_B}{R_f}$$

$$\frac{V_B}{R} = \frac{V_o}{R_f} - \frac{V_B}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_B}{R} + \frac{V_B}{R_f}$$

$$\frac{V_o}{R_f} = V_B\left(\frac{R + R_f}{RR_f}\right)$$

$$V_o = V_B\left(\frac{R + R_f}{R}\right) \qquad (2)$$

Substituting Eqn. (1) in (2),

$$V_o = \left(\frac{R_2V_1 + R_1V_2}{R_1 + R_2}\right)\left(\frac{R + R_f}{R}\right)$$

$$\boxed{V_o = \frac{R_2(R + R_f)}{R(R_1 + R_2)}V_1 + \frac{R_1(R + R_f)}{R(R_1 + R_2)}V_2}$$

If $R_1 = R_2 = R$,

$$V_o = \frac{R + R_f}{2R}(V_1 + V_2)$$

If $R_1 = R_2 = R = R_f$,

$$\boxed{V_o = V_1 + V_2}$$

This shows that the output is the sum of the input signals.

Subtractor

In a subtractor circuit, the output is the difference between the two inputs. Fig. 22 shows a subtractor circuit using an op-amp.

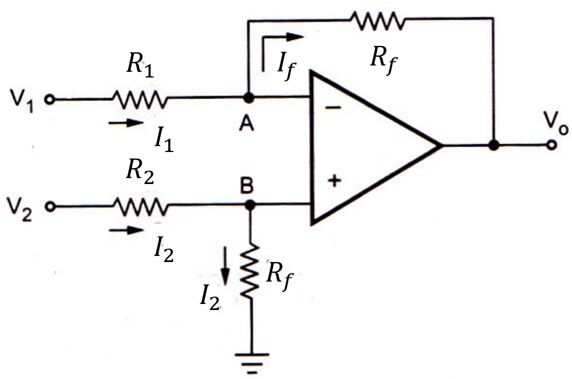


Fig. 22 Subtractor

From the circuit, the potential at node B,

$$V_B = \left(\frac{R_f}{R_2 + R_f}\right)V_2$$

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A,

$$V_A = V_B = \left(\frac{R_f}{R_2 + R_f}\right)V_2 \tag{3}$$

From the circuit,

$$I_1 = \frac{V_1 - V_A}{R_1}$$

and

$$I_f = \frac{V_A - V_o}{R_f}$$

Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

$$\frac{V_1 - V_A}{R_1} = \frac{V_A - V_o}{R_f}$$

$$\frac{V_1}{R_1} - \frac{V_A}{R_1} = \frac{V_A}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_A}{R_1} + \frac{V_A}{R_f} - \frac{V_1}{R_1}$$

$$\frac{V_o}{R_f} = V_A\left(\frac{1}{R_1} + \frac{1}{R_f}\right) - \frac{V_1}{R_1}$$

$$\frac{V_o}{R_f} = V_A\left(\frac{R_1 + R_f}{R_1 R_f}\right) - \frac{V_1}{R_1}$$

$$V_o = V_A R_f\left(\frac{R_1 + R_f}{R_1 R_f}\right) - \frac{R_f}{R_1}V_1$$

$$V_o = V_A\left(\frac{R_1 + R_f}{R_1}\right) - \frac{R_f}{R_1}V_1 \qquad (4)$$

Substituting Eqn. (3) in (4),

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

$$\boxed{V_o = \frac{R_f(R_1 + R_f)}{R_1(R_2 + R_f)}V_2 - \frac{R_f}{R_1}V_1}$$

If $R_1 = R_2$,

$$\boxed{V_o = \frac{R_f}{R_2}V_2 - \frac{R_f}{R_1}V_1}$$

If $R_1 = R_2 = R$,

$$V_o = \frac{R_f}{R}(V_2 - V_1)$$

If $R_1 = R_2 = R = R_f$,

$$\boxed{V_o = V_2 - V_1}$$

This shows that the output is the difference between the two input signals.

Integrator

In an integrator circuit, the output is the integration of the input voltage. Fig. 23 shows an integrator circuit using an op-amp.

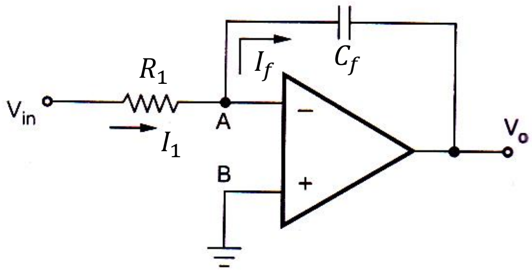


Fig. 23 Integrator

From the circuit, the potential at node B, $V_B = 0$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = 0$.

From the circuit,

$$I_1 = \frac{V_{in} - V_A}{R_1} = \frac{V_{in} - 0}{R_1} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = \frac{V_{in}}{R_1}}$$

and

$$I_f = C_f \frac{d(V_A - V_o)}{dt} = C_f \frac{d(0 - V_o)}{dt}$$

$$\boldsymbol{I_f = -C_f \frac{dV_o}{dt}}$$

Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

$$\frac{V_{in}}{R_1} = -C_f \frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = -\frac{V_{in}}{R_1 C_f}$$

Integrating both sides with respect to t,

$$\int \frac{dV_o}{dt} dt = -\frac{1}{R_1 C_f} \int V_{in}\, dt$$

$$\boxed{V_o = -\frac{1}{R_1 C_f} \int V_{in}\, dt}$$

This shows that the output is the integration of the input voltage. The term $\left(-\frac{1}{R_1 C_f}\right)$ indicates the gain of the amplifier.

Differentiator

In a differentiator circuit, the output is the differentiation of the input voltage. Fig. 24 shows a differentiator circuit using an op-amp.

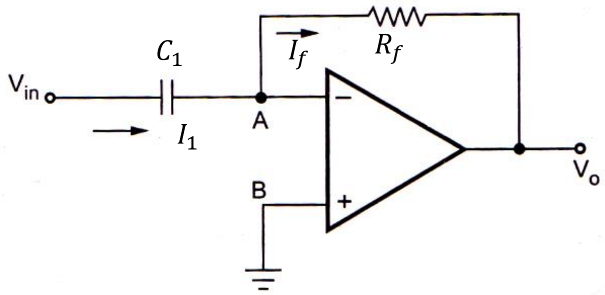


Fig. 24 Differentiator

From the circuit, the potential at node B, $V_B = 0$.

From the concept of virtual ground, the two input terminals are at same potential. Therefore, the potential at node A, $V_A = V_B = 0$.

From the circuit,

$$I_1 = C_1 \frac{d(V_{in} - V_A)}{dt} = C_1 \frac{d(V_{in} - 0)}{dt} \qquad (\because V_A = 0)$$

$$\boldsymbol{I_1 = C_1 \frac{dV_{in}}{dt}}$$

and

$$I_f = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f}$$

$$\boldsymbol{I_f = -\frac{V_o}{R_f}}$$

Since op-amp input current is zero, I_1 passes through R_f as I_f. That is,

$$I_1 = I_f$$

$$C_1 \frac{dV_{in}}{dt} = -\frac{V_o}{R_f}$$

$$\boxed{V_o = -R_f C_1 \frac{dV_{in}}{dt}}$$

This shows that the output is the differentiation of the input voltage. The term $(-R_f C_1)$ indicates the gain of the amplifier.

Comparator

In a comparator circuit, the amplitude of one voltage is compared with another. In this application, op-amp is used in the open-loop configuration with the input voltage on one input and reference voltage on the other. Fig. 25 shows a comparator circuit using an op-amp.

Here $V_2 = V_{in}$ and $V_1 = 0$.

When $V_{in} > V_1 = 0$, $\quad V_o = +V_{sat} \cong +V_{CC}$

When $V_{in} < V_1 = 0$, $\quad V_o = -V_{sat} \cong -V_{EE}$

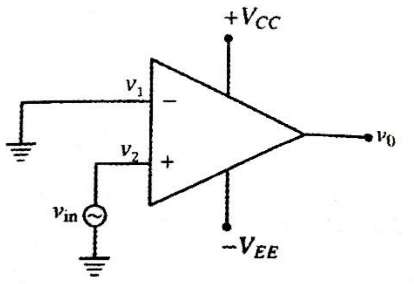


Fig. 25 Comparator

Fig. 26 shows the input and output voltages.

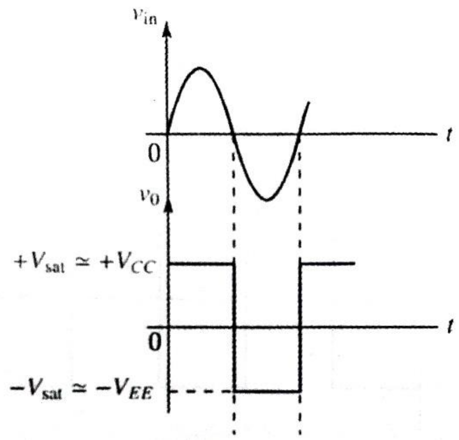


Fig. 26 Waveforms of comparator

The comparator circuit in Fig. 25 is also known as ***zero crossing detector***.

Numerical Examples

1. A certain op-amp has an open loop voltage gain of 1,00,000 and a common mode gain of 0.2. Determine the CMRR and express it in decibels.

   Solution:

Given

$A_{ol} = 1,00,000$

$A_{cm} = 0.2$

We know that

$$CMRR = \frac{A_{ol}}{A_{cm}}$$

$$= \frac{1,00,000}{0.2}$$

$$= 5,00,000$$

In decibels,

$$CMRR = 20\log_{10}\left(\frac{A_{ol}}{A_{cm}}\right)\ dB$$

$$= 20\log_{10} 5{,}00{,}000\ dB$$

$$= 20 \times 5.6989\ dB$$

$$= 113.98\ dB$$

2. A certain op-amp has an open loop differential voltage gain of 1,00,000 and CMRR = 4,00,000. Determine common mode gain and express CMRR in decibels.

   Solution:

Given

$A_{ol} = 1{,}00{,}000$

$CMRR = 4{,}00{,}000$

We know that

$$CMRR = \frac{A_{ol}}{A_{cm}}$$

$$\therefore A_{cm} = \frac{A_{ol}}{CMRR}$$

$$= \frac{1{,}00{,}000}{4{,}00{,}000}$$

$$= 0.25$$

Given $CMRR = 4{,}00{,}000$

In decibels,

$$CMRR = 20\log_{10} 4{,}00{,}000\ dB$$

$$= 20 \times 5.602\ dB$$

$$= 112.04\ dB$$

3. Determine the input bias current and input offset current of an op-amp if the current into non-inverting and inverting terminals are 8.3 μA and 7.9 μA respectively.

Solution:

Given $I_1 = 7.9\,\mu A$, $I_2 = 8.3\,\mu A$

We know that

Input bias current

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

$$= \frac{7.9 + 8.3}{2}\,\mu A$$

$$= \underline{\underline{8.1\,\mu A}}$$

Input Offset Current

$$I_{OS} = |I_1 - I_2|$$

$$= |7.9 - 8.3|$$

$$= \underline{\underline{0.4\,\mu A}}$$

4. For a particular op-amp, the input offset current is 20 nA while input bias current is 60 nA. Calculate the values of two input currents.

Solution:

Given $I_{OS} = 20\,nA$, $I_{BIAS} = 60\,nA$

We know that

$$I_{OS} = I_1 - I_2 \quad \text{and} \quad I_{BIAS} = \frac{I_1 + I_2}{2}$$

Then, $I_1 - I_2 = 20\,nA \longrightarrow (1)$

and $\frac{I_1 + I_2}{2} = 60\,nA$

i.e., $I_1 + I_2 = 120\,nA \rightarrow (2)$

Solving (1) and (2), we get

$2I_1 = 140\,nA$

$I_1 = \underline{70\,nA}$

Using this value of I_1 in (1),

we get $I_2 = I_1 - 20\,nA$

$= 70\,nA - 20\,nA$

$I_2 = \underline{50\,nA}$

5. When a pulse is applied to an op-amp, the output voltage changes from $-8\,V$ to $+7\,V$ in $0.75\,\mu s$. What is the slew rate?

   Solution:

   We know that,

   $$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

   $$= \frac{7\,V - (-8\,V)}{0.75\,\mu s} = \frac{15\,V}{0.75\,\mu s}$$

   $$= \underline{20\,V/\mu s}$$

6. How long does it take for the output voltage of an op-amp to go from $-10\,V$ to $+10\,V$, if the slew rate is $0.5\,V/\mu s$.

   Solution:

   We know that

   $$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

$$\Delta t = \frac{\Delta V_{out}}{\text{Slew rate}}$$

$$\Delta t = \frac{10V-(-10V)}{0.5\ V/\mu s}$$

$$\Delta t = 40\mu s$$

7. An op-amp has a slew rate of 0.8 V/μsec. What is the maximum amplitude of undistorted sine wave that the op-amp can produce at a frequency of 40 kHz? What is the maximum frequency of the sine wave that op-amp can reproduce if the amplitude is 3 V?

Solution:

We know that

$$\text{Slew rate} = \left.\frac{dV_o}{dt}\right|_{max}$$

Consider

$$V_o = V_m \sin \omega t$$

then $\frac{dV_o}{dt} = \omega V_m \cos \omega t$

The maximum value

$$\left.\frac{dV_o}{dt}\right|_{max} = \omega V_m$$

For undistorted output,

$$\left.\frac{dV_o}{dt}\right|_{max} \le \text{Slew rate}$$

$$\omega V_m \le \text{Slew rate}$$

$$2\pi f V_m \le \text{Slew rate}$$

$$f \le \frac{\text{Slew rate}}{2\pi V_m}$$

Hence

$$\boxed{f_{max} = \frac{\text{Slew rate}}{2\pi V_m}}$$

and $$V_m = \frac{\text{Slew rate}}{2\pi f_{max}}$$

Given

Slew rate = 0.8V/ μsec = 0.8×10^6 V/sec

If $f_{max} = 40$ kHz,

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

$$= \frac{0.8 \times 10^6}{2\pi \times 40 \times 10^3}$$

$$= 3.183 \text{ V}$$

If $V_m = 3$V,

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

$$= \frac{0.8 \times 10^6}{2\pi \times 3}$$

$$= 42.44 \text{ kHz}$$

8. Find the gain of a non-inverting amplifier if $R_f = 10$ kΩ and $R_1 = 1$ kΩ.

Solution:

Given $R_f = 10$ kΩ and $R_1 = 1$ kΩ

We know that the output of a non-inverting amplifier is

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

Here Gain $A = 1 + \frac{R_f}{R_1}$

$= 1 + \frac{10 k\Omega}{1 k\Omega}$

$= 1 + 10$

$A = 11$

9. A non-inverting amplifier has closed loop gain of 25. If input voltage $V_i = 10$ mV, $R_f = 10$ kΩ, determine the value of R_1 and output voltage V_o.

Solution:

Given, the closed loop gain $A = 25$

$V_i = 10 mV$, $R_f = 10 k\Omega$

We know that, for a non-inverting amplifier,

Gain $A = 1 + \frac{R_f}{R_1}$

Given, $A = 25$

Hence $1 + \frac{R_f}{R_1} = 25$

$\frac{R_f}{R_1} = 25 - 1 = 24$

Hence $R_1 = \frac{R_f}{24} = \frac{10 k\Omega}{24}$

$= 416.67\ \Omega$

The output voltage

$V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$

$= 25 \times 10 mV$

$= 250 mV$

10. Design an inverting and non-inverting operational amplifier to have a gain of 15.

Solution:

Given, gain $A = 15$

For an inverting amplifier,

$$V_o = -\frac{R_f}{R_1} V_{in}$$

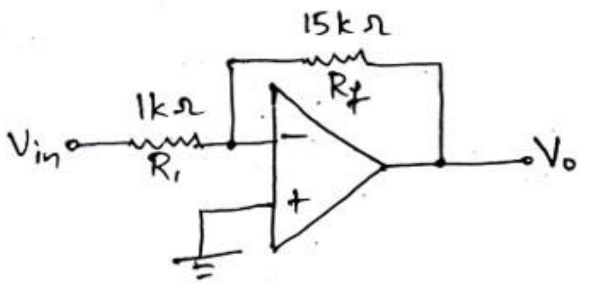
Given, gain $\frac{R_f}{R_1} = 15$

Hence $R_f = 15 R_1$

Take $\boxed{R_1 = 1\,k\Omega}$

Then $\boxed{R_f = 15\,k\Omega}$

The designed circuit can be drawn as below



For a non-inverting amplifier,

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

Given, gain $\left(1 + \frac{R_f}{R_1}\right) = 15$

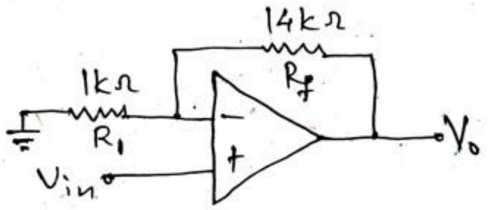
$$\frac{R_f}{R_1} = 15 - 1 = 14$$

$$R_f = 14 R_1$$

Take $\boxed{R_1 = 1\,k\Omega}$

Then $\boxed{R_f = 14\,k\Omega}$

The designed circuit can be drawn as below:

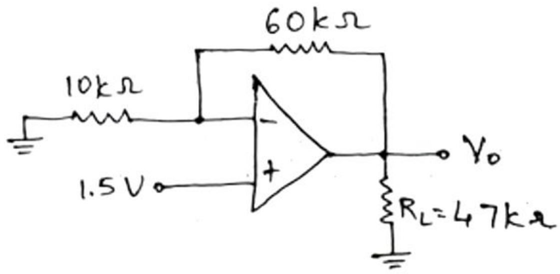


11. A non-inverting amplifier circuit has an input resistance of 10 kΩ and feedback resistance 60 kΩ with load resistance of 47 kΩ. Draw the circuit. Calculate the output voltage, voltage gain, load current when the input voltage is 1.5 V.

Solution:

The circuit can be drawn as below:

$R_1 = 10\,k\Omega$
$R_f = 60\,k\Omega$
$R_L = 47\,k\Omega$
$V_{in} = 1.5\,V$



We know that, the output of a non-inverting summing amplifier is

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

$$= \left(1 + \frac{60k}{10k}\right)(1.5)\,V$$

$$= (1 + 6)(1.5)\,V$$

$$= 7 \times 1.5\,V$$

$$= \underline{\underline{10.5\,V}}$$

The voltage gain

$$A = 1 + \frac{R_f}{R_1}$$

$$= 1 + \frac{60k}{10k}$$

$$= 1 + 6$$

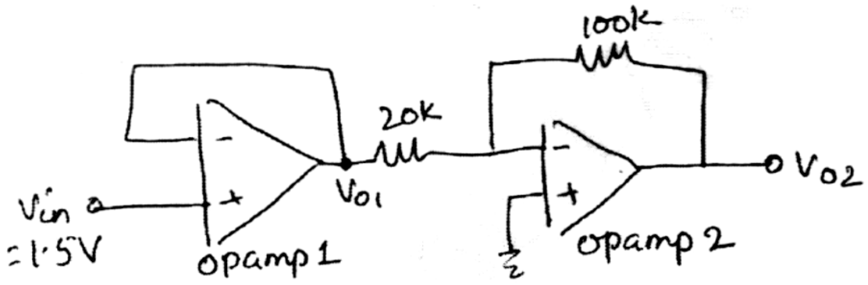
$$A = 7$$

The load current

$$I_L = \frac{V_o}{R_L}$$

$$= \frac{10.5\,V}{47\,k\Omega} = 0.223\,mA$$

12. For an op-amp circuit shown in the figure, find the output V_{o1} and V_{o2}. Also write the function of each op-amp used.



Solution:

The first stage is a voltage follower

Hence, the output

$$V_{o1} = V_{in}$$

$$V_{o1} = 1.5\,V$$

The second stage is an inverting amplifier

Here $R_1 = 20\,k\Omega$, $R_f = 100\,k\Omega$

Hence, the output

$$V_{o_2} = -\frac{R_f}{R_1} V_{o_1}$$

$$= -\frac{100k}{20k} \times 1.5\ V$$

$$= -5 \times 1.5\ V$$

$$V_{o_2} = -7.5V$$

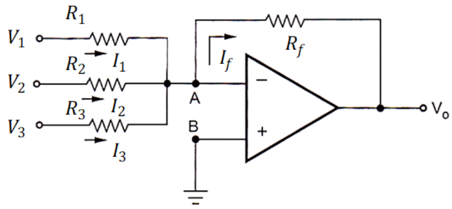
13. Calculate the output voltage of a three input inverting summing amplifier, given $R_1 = 200\ k\Omega$, $R_2 = 250\ k\Omega$, $R_3 = 500\ k\Omega$, $R_f = 1\ M\Omega$, $V_1 = -2V$, $V_2 = -1V$ and $V_3 = +3V$.

Solution:

Given $R_1 = 200\ k\Omega$, $R_2 = 250\ k\Omega$, $R_3 = 500\ k\Omega$

$R_f = 1\ M\Omega$

$V_1 = -2V$, $V_2 = -1V$, $V_3 = +3V$



We know that,
The output voltage of a three-input inverting summing amplifier is

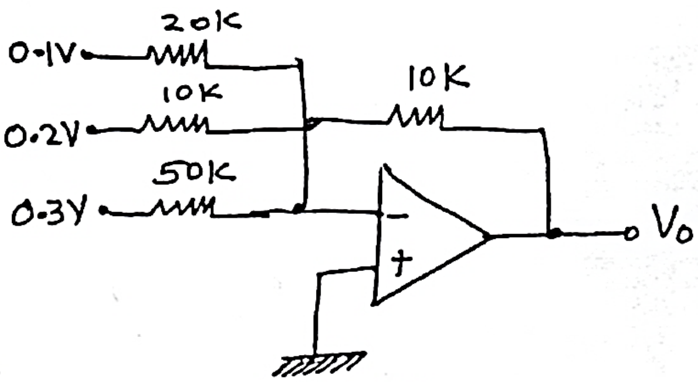
$$V_o = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$$

$$= -\left[\frac{1M}{200k}(-2) + \frac{1M}{250k}(-1) + \frac{1M}{500k}(+3)\right] V$$

$$= -\left[(5)(-2) + (4)(-1) + (2)(3)\right] V$$

$$= -\left[-10 - 4 + 6\right] V = -(-8) V = 8\ V$$

14. Determine V_o for the circuit shown below.



Solution:

The given circuit is a three-input inverting summing amplifier.

Here $R_1 = 20\,k\Omega$, $R_2 = 10\,k\Omega$, $R_3 = 50\,k\Omega$,

$R_f = 10\,k\Omega$

$V_1 = 0.1\,V$, $V_2 = 0.2\,V$, $V_3 = 0.3\,V$

We know that, the output of a three-input inverting summing amplifier is

$$V_o = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$$

$$= -\left[\frac{10k}{20k}(0.1) + \frac{10k}{10k}(0.2) + \frac{10k}{50k}(0.3)\right] V$$

$$= -\left[(0.5)(0.1) + (1)(0.2) + (0.2)(0.3)\right] V$$

$$= -\left[0.05 + 0.2 + 0.06\right] V$$

$$= -0.31\,V$$

15. Design an adder circuit using op-amp to obtain an output voltage, $V_o = -[2V_1 + 3V_2 + 5V_3]$. Assume $R_f = 10\,k\Omega$.

Solution:

Given $V_o = -[2V_1 + 3V_2 + 5V_3]$

The output of a 3-input inverting summing amplifier is given by

$$V_o = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$$

Comparing with given expression,

$$\frac{R_f}{R_1} = 2, \quad \frac{R_f}{R_2} = 3, \quad \frac{R_f}{R_3} = 5$$

Or $R_1 = \frac{R_f}{2}$, $R_2 = \frac{R_f}{3}$, $R_3 = \frac{R_f}{5}$

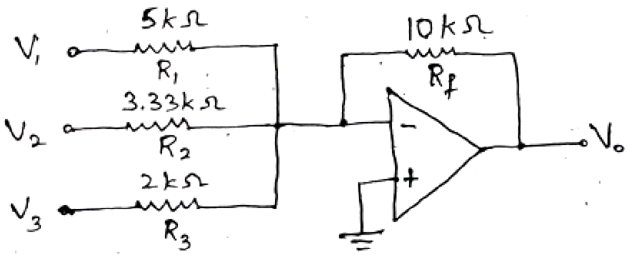
Using $R_f = 10\,k\Omega$,

$$R_1 = \frac{10\,k\Omega}{2} = 5\,k\Omega$$

$$R_2 = \frac{10\,k\Omega}{3} = 3.33\,k\Omega$$

$$R_3 = \frac{10\,k\Omega}{5} = 2\,k\Omega$$

The designed circuit can be drawn as below:



16. Design an op-amp circuit that will produce an output equal to $-[4V_1 + V_2 + 0.1V_3]$.

Solution:

Given $V_o = -\left[4V_1 + V_2 + 0.1V_3\right]$

The required circuit is a 3-input inverting summing amplifier whose

$$V_o = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$$

Comparing with given expression,

$$\frac{R_f}{R_1} = 4, \quad \frac{R_f}{R_2} = 1, \quad \frac{R_f}{R_3} = 0.1$$

or $R_1 = \frac{R_f}{4}$, $R_2 = \frac{R_f}{1}$, $R_3 = \frac{R_f}{0.1}$

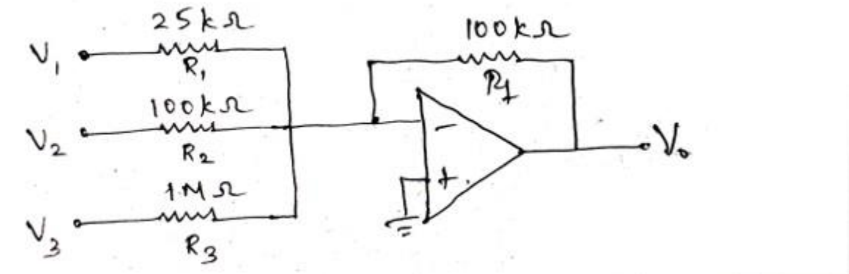
Take $R_f = 100\,k\Omega$

Then $R_1 = \dfrac{100\,k\Omega}{4} = \underline{25\,k\Omega}$

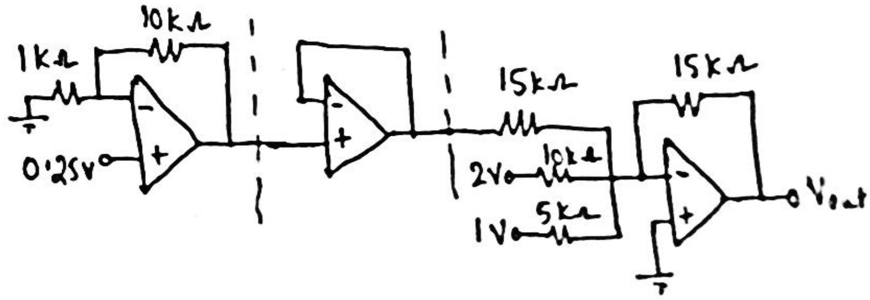
$R_2 = \dfrac{100\,k\Omega}{1} = \underline{100\,k\Omega}$

$R_3 = \dfrac{100\,k\Omega}{0.1} = \underline{1\,M\Omega}$

The designed circuit can then be drawn as below:



17. Find the output of the following op-amp circuit.



Solution:

The first stage is a non-inverting amplifier

Here $R_1 = 1\,k\Omega$, $R_f = 10\,k\Omega$, $V_{in} = 0.25\,V$

Hence, output

$$V_A = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

$$= \left(1 + \frac{10k}{1k}\right)(0.25)\ V$$

$$= (1 + 10)(0.25)\ V$$

$$= 11 \times 0.25\ V = \underline{2.75\,V}$$

The second stage is a voltage follower

Hence $V_B = V_A$

$V_B = 2.75V$

The third stage is a three-input inverting summing amplifier.

Here $R_1 = 15k\Omega$, $R_2 = 10k\Omega$, $R_3 = 5k\Omega$

$V_1 = V_B = 2.75V$, $V_2 = 2V$, $V_3 = 1V$

$R_f = 15k\Omega$

Hence, the output voltage

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

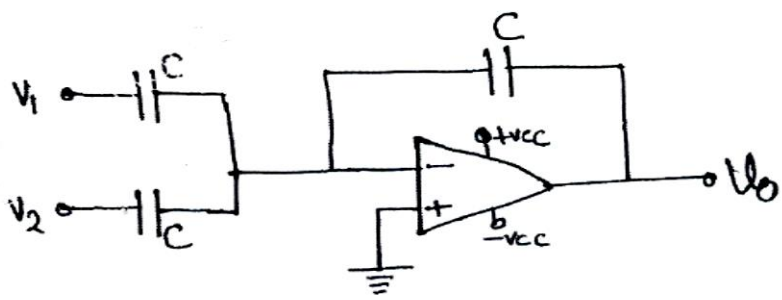
$$= -\left[\frac{15k}{15k}(2.75) + \frac{15k}{10k}(2) + \frac{15k}{5k}(1)\right]V$$

$$= -\left[(1)(2.75) + \left(\frac{3}{2}\right)(2) + (3)(1)\right]V$$

$$= -\left[2.75 + 3 + 3\right]V$$

$$= -8.75\,V$$

18. Find the output of the op-amp circuit shown in the figure below.



Solution:

The given circuit is an inverting summing amplifier (using capacitors)

Here, $I_1 = C\frac{dV_1}{dt}$

$I_2 = C\frac{dV_2}{dt}$

and $I_f = -C\frac{dV_o}{dt}$

From the circuit,

$$I_f = I_1 + I_2$$

$$-C\frac{dV_o}{dt} = C\frac{dV_1}{dt} + C\frac{dV_2}{dt}$$

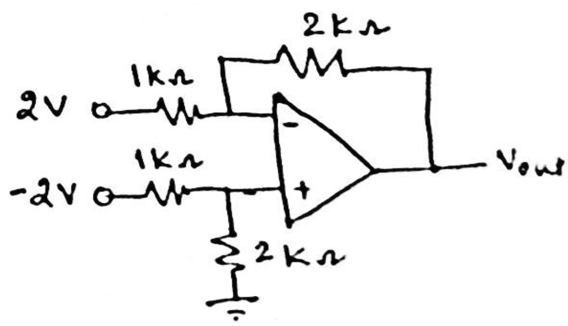
$$\frac{dV_o}{dt} = -\left(\frac{dV_1}{dt} + \frac{dV_2}{dt}\right)$$

Integrating both sides w.r.t. t

$$\int \frac{dV_o}{dt}\,dt = -\left[\int\frac{dV_1}{dt}\,dt + \int\frac{dV_2}{dt}\,dt\right]$$

$$\boxed{V_o = -(V_1 + V_2)}$$

19. Find the output of the following op-amp circuit.



Solution:

The given circuit is a subtractor.

Given $R_1 = R_2 = 1k\Omega$, $R_f = 2k\Omega$

$V_1 = 2V$; $V_2 = -2V$

We know that, the output voltage of a subtractor is

$$V_{out} = \frac{R_f}{R_2} V_2 - \frac{R_f}{R_1} V_1$$

$$= \frac{2k}{1k}(-2) - \frac{2k}{1k}(2) \text{ V}$$

$$= (2)(-2) - (2)(2) \text{ V}$$

$$= (-4-4) \text{ V}$$

$$= \underline{\underline{-8 \text{ V}}}$$

20. A sinusoidal signal with peak value 6 mV and 2 kHz frequency is applied to the input of an ideal op-amp integrator with $R_1 = 100 \text{ k}\Omega$ and $C_f = 1\mu\text{F}$. Find the output voltage.

Solution:

Given

$R_1 = 100 \text{ k}\Omega = 100 \times 10^3 \Omega$

$C_f = 1 \mu F = 1 \times 10^{-6} F$

$V_m = 6 mV = 6 \times 10^{-3} V$

$f = 2 \text{ kHz} = 2 \times 10^3 \text{ Hz}$

The input sinusoidal signal can be written as

$$V_{in} = V_m \sin \omega t \text{ V}$$

$$= 6 \times 10^{-3} \times \sin 2\pi f t \text{ V}$$

$$= 6 \sin(2\pi \times 2 \times 10^3 t) \times 10^{-3} \text{ V}$$

$$\boxed{V_{in} = 6 \sin(4\pi \times 10^3 t) \text{ mV}}$$

For an integrator,

$$V_o = -\frac{1}{R_1 C_f} \int_0^t V_{in} \, dt$$

$$= -\frac{1}{100\times10^{3}\times 1\times10^{-6}} \int_0^t 6\sin(4\pi\times10^{3}t)\,dt \text{ mV}$$

$$= -\frac{6}{100\times10^{-3}} \left[\frac{-\cos(4\pi\times10^{3}t)}{4\pi\times10^{3}}\right]_0^t \text{ mV}$$

$$= -\frac{0.015}{\pi}\left[-(\cos(4\pi\times10^{3}t)-1)\right] \text{ mV}$$

$$V_o = \frac{0.015}{\pi}\left[\cos(4\pi\times10^{3}t)-1\right] \text{ mV}$$

$$V_o = \frac{0.015}{\pi}\left[\cos(4000\pi t)-1\right] \text{ mV}$$

21. The input to the basic differentiator circuit is a sinusoidal voltage of peak value of 10 mV and frequency 1.5 kHz. Find the output if $R_f = 100\text{ k}\Omega$ and $C_1 = 1\mu F$.

Solution:

Given

$R_f = 100\text{ k}\Omega = 100\times10^{3}\,\Omega$

$C_1 = 1\,\mu F = 1\times10^{-6} F$

$V_m = 10\text{ mV} = 10\times10^{-3} V$

$f = 1.5\text{ kHz} = 1.5\times10^{3}\text{ Hz}$

The input sinusoidal voltage can be written as

$$V_{in} = V_m \sin \omega t \text{ V}$$

$$= 10\times10^{-3}\sin 2\pi f t \text{ V}$$

$$= 10\sin(2\pi\times1.5\times10^{3}t)\times10^{-3} \text{ V}$$

$$\boxed{V_{in} = 10\sin(3\pi\times10^{3}t) \text{ mV}}$$

For a differentiator,

$$V_o = -R_f C_1 \frac{dV_{in}}{dt}$$

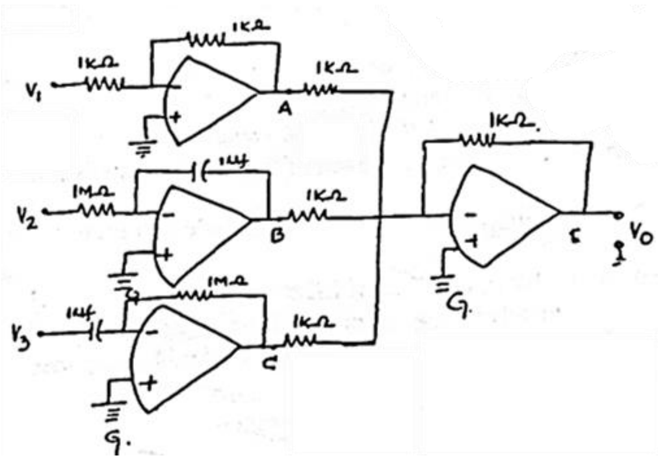
$$= -100\times10^{3}\times1\times10^{-6}\times\frac{d}{dt}\left[10\sin(3\pi\times10^{3}t)\right]\text{mV}$$

$$= -100\times10^{-3}\times10\cos(3\pi\times10^{3}t)\times3\pi\times10^{3}\ \text{mV}$$

$$V_o = -3000\pi\cos(3\pi\times10^{3}t)\,\text{mV}$$

$$V_o = -3000\pi\cos(3000\pi t)\ \text{mV}$$

22. Write expression for output voltage at points A, B, C, D and E as shown in figure.



Solution:

Stage A is an inverting amplifier

$R_1 = 1\,k\Omega,\quad R_f = 1\,k\Omega$

Hence $$V_A = -\frac{R_f}{R_1}V_1$$

$$= -\frac{1k}{1k}V_1$$

$$\boxed{V_A = -V_1}$$

Stage B is an integrator

$R_1 = 1\,M\Omega,\quad C_f = 1\,\mu F$

Hence $$V_B = -\frac{1}{R_1C_f}\int V_2\,dt$$

$$= -\frac{1}{1\times10^{6}\times1\times10^{-6}}\int V_2\,dt$$

$$\boxed{V_B = -\int V_2\,dt}$$

Stage C is a differentiator

$C_1 = 1\mu F$, $R_f = 1\,M\Omega$

Hence

$$V_C = -R_f C_1 \frac{dV_3}{dt}$$

$$= -1\times10^6 \times 1\times10^{-6} \times \frac{dV_3}{dt}$$

$$\boxed{V_C = -\frac{dV_3}{dt}}$$

Final stage is a 3-input inverting summing amplifier

Hence

$$V_o = -\left[\frac{R_f}{R_1}V_A + \frac{R_f}{R_2}V_B + \frac{R_f}{R_3}V_C\right]$$

Here $R_1 = R_2 = R_3 = R_f = 1\,k\Omega$

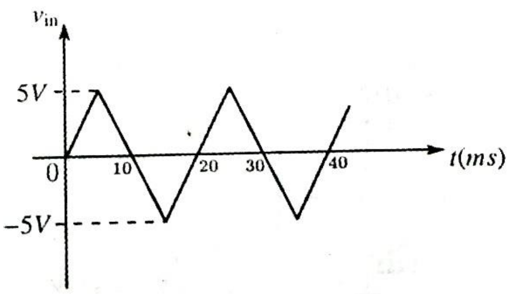
Hence

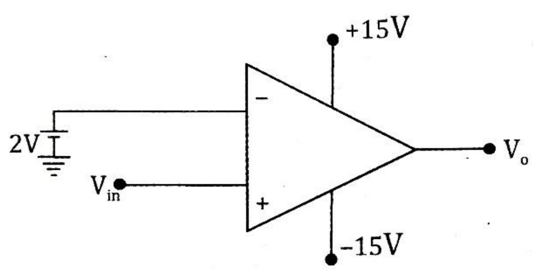
$$V_o = -\left[V_A + V_B + V_C\right]$$

$$= -\left[-V_1 - \int V_2\,dt - \frac{dV_3}{dt}\right]$$

$$\boxed{V_o = V_1 + \int V_2\,dt + \frac{dV_3}{dt}}$$

23. For the circuit given, draw the output waveform if the input voltage is as shown in the figure.





Solution:

The given circuit is a comparator.

The inverting input terminal is at +2V.

i.e., $V_1 = 2V$

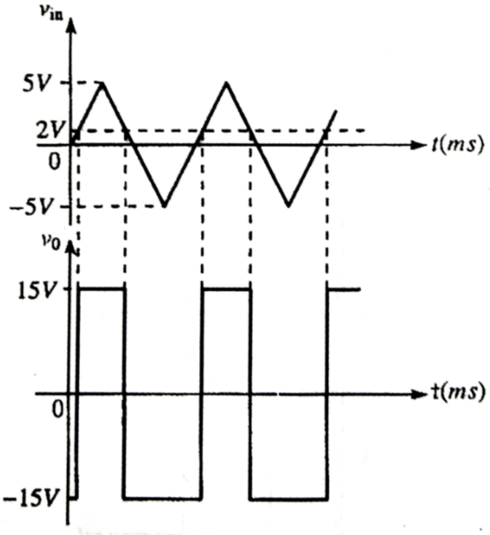
When $V_{in} > 2V$, $V_o = +V_{sat}$

$= +V_{cc} = +15 V$

When $V_{in} < 2V$, $V_o = -V_{sat}$

$= -V_{EE} = -15 V$

The output voltage v_o can be drawn as shown:



Questions

1. What is an op-amp? Mention the applications of op-amp.
   (Sep '20, Jan '20, Jul '19, Jul '18, Jan '18, Jan '17, Jan '16, MQP '15, MQP '14)
2. Describe the characteristics of basic op-amp. List out its ideal characteristics.
   (MQP '18 – 8M)
3. What is op-amp? List out the ideal and practical characteristics of op-amp.
   (Jan '19 – 7M)
4. List and explain the characteristics of an ideal op-amp.
   (Sep '20 – 6M, Jan '20 – 6M, Jul '19 – 6M, Jan '19 – 5M, MQP '18 – 8M, Jul '18 – 5M, Jan '18 – 6M, Jul '17 – 4M, Jan '17 – 6M, Jul '16 – 7M, Jan '16 – 4M, Jul '15 – 6M, Jan '15 – 5M, MQP '15, MQP '14 – 6M)
5. Explain the internal block diagram of an operational amplifier. ***(Jan '19 – 6M, Jul '16)***
6. With neat circuit diagrams, explain the different input modes of an op-amp.
   (Jan '20 – 6M, Jan '19 – 6M)
7. Explain the following terms related to op-amp: (i) Open loop voltage gain (ii) Common mode gain (iii) CMRR (iv) Maximum Output Voltage Swing (v) Input Offset Voltage (vi) Input Offset Current (vii) Input bias current (viii) Input impedance (ix) Output impedance

(x) Slew rate (xi) PSRR/Supply voltage rejection ratio (xii) Virtual ground.
(Sep '20 – 8M, Jan '20 – 8M, Jul '19 – 8M, Jan '19 – 8M, MQP '18 – 10M, Jul '18 – 6M, Jan '18 – 5M, Jul '16 – 5M, Jan '16 – 6M)

8. Write a short note on virtual ground concept of an op-amp. ***(Jan '18 – 6M)***
9. Explain the operation of an op-amp as an (i) Inverting amplifier (ii) Non inverting amplifier. Derive an expression for the output voltage and voltage gain.
(Jan '19 – 8M, Jan '18 – 4M, Jul '17 – 6M, Jan '17 – 6M, Jul '16 – 5M)
10. Explain the operation of an op-amp as an inverting amplifier with neat diagram and waveforms. Derive the expression for output voltage.
(Jan '20 – 6M, MQP '18 – 8M, Jul '18 – 7M, Jan '18 – 5M)
11. Explain the operation of an op-amp as a non-inverting amplifier with neat diagram and waveforms. Derive the expression for output voltage.
(Sep '20 – 8M, Jan '20 – 7M, Jan '19 – 6M, MQP '18 – 6M, Jul '18 – 4M)
12. With neat circuit and necessary equations, explain the voltage follower circuit using op-amp. Mention its important properties.
(Jan '20 – 4M, Jul '19 – 4M, MQP '18 – 4M, Jan '18, Jul '17 – 6M, Jan '17 – 6M, Jan '16 – 4M, Jul '15 – 5M, MQP '15 – 6M, MQP '14)
13. Explain how an op-amp can be used as (i) Inverting summer (ii) Non inverting summer.
(Jan '18, Jul '17, MQP '14)
14. Derive an expression for the output voltage of an inverting summer.
(Jan '20 – 6M, Jul '19, MQP '18 – 6M)
15. With neat circuit, explain the operation of three input adder circuit. Derive expression for V_0. ***(Sep '20 – 8M)***
16. Draw the three input inverting summer circuit and derive an expression for its output voltage. ***(Jan '19 – 5M, MQP '18 – 8M, Jan '18 – 5M, Jan '16 – 5M, MQP '15 – 5M)***
17. Show with a circuit diagram, how an op-amp can be used as a subtractor. Derive an expression for the output voltage.
(Sep '20 – 7M, Jul '19 – 4M, Jan '19 – 8M, Jan '17 – 8M)
18. Explain difference amplifier using op-amp. ***(Sep '20 – 6M)***
19. With a neat circuit diagram, show how an op-amp can be used as an integrator. Derive the expression for output voltage.
(Sep '20 – 6M, Jan '20 – 4M, Jul '19 – 5M, Jan '19 – 5M, MQP '18 – 6M, Jul '18 – 5M, Jan '18 – 4M, Jul '17 – 4M, Jan '17, Jul '16 – 6M, Jan '16 – 6M, MQP '14)
20. With a neat circuit diagram, show how an op-amp can be used as a differentiator. Derive the expression for output voltage.
(Jul '19 – 6M, MQP '18 – 6M, Jan '18, Jan '17, Jan '15 – 5M)
21. Define the following and derive the expression for its output voltage
i) Differentiator ii) Integrator ***(Jan '20 – 6M)***
22. With a neat circuit diagram, derive an equation for op-amp application as

i) Inverting amplifier ii) Non-inverting amplifier iii) Inverting 2-input summer
iv) Subtractor v) Integrator vi) Differentiator ***(Jul '19 – 12M)***

23. With a neat circuit diagram, show how an op-amp can be used as a comparator.

24. A certain op-amp has an open loop differential voltage gain of 1,00,000 and CMRR = 4,00,000. Determine common mode gain and express CMRR in decibels. ***(Sep '20 – 6M)***

25. A certain op-amp has an open loop voltage gain of 1,00,000 and a common mode gain of 0.2. Determine the CMRR and express it in decibels. ***(MQP '18 – 4M)***

26. An op-amp has an open loop voltage gain of 10^4 and a common mode voltage gain of 0.1. Express the CMRR in dB. ***(Jul '16 – 8M)***

27. An op-amp has a slew rate of 0.8 V/μsec. What is the maximum amplitude of undistorted sine wave that the op-amp can produce at a frequency of 40 kHz? What is the maximum frequency of the sine wave that op-amp can reproduce if the amplitude is 3 V? ***(Sep '20 – 4M)***

28. An inverting amplifier has $R_1 = 20\ k\Omega$, $R_f = 100\ k\Omega$. Find the output voltage, input resistance and input current for an input voltage of 1V. ***(Sep '20 – 4M)***

29. A non-inverting amplifier has closed loop gain of 25. If input voltage $V_i = 10\ mV$, $R_f = 10\ k\Omega$, determine the value of R_1 and output voltage V_o. ***(Sep '20 – 6M)***

30. Find the gain of a non-inverting amplifier if $R_f = 10\ k\Omega$ and $R_1 = 1\ k\Omega$. ***(Sep '20, Jan '16 – 6M)***

31. Find the gain and output voltage for a non-inverting amplifier using op-amp when input voltage is i) 0.5 V ii) −3V ***(Jan '20 – 2M)***

32. A non-inverting amplifier circuit has an input resistance of 10 kΩ and feedback resistance 60 kΩ with load resistance of 47 kΩ. Draw the circuit. Calculate the output voltage, voltage gain, load current when the input voltage is 1.5 V. ***(Jan '19 – 6M, MQP '18 – 8M)***

33. Design an inverting and non-inverting operational amplifier to have a gain of 15. ***(Jan '18 – 5M)***

34. Calculate the output voltage of a three input inverting summing amplifier, given $R_1 = 200\ k\Omega$, $R_2 = 250\ k\Omega$, $R_3 = 500\ k\Omega$, $R_f = 1\ M\Omega$, $V_1 = -2V$, $V_2 = -1V$ and $V_3 = +3V$. ***(Jan '19 – 5M, Jul '16 – 4M)***

35. Design an op-amp circuit to obtain output expression as $V_o = -[V_1 + 3V_2 + 5V_3]$. ***(Jul '19 – 6M)***

36. Design an adder circuit using op-amp to obtain an output expression $V_o = -[0.1V_1 + 0.5V_2 + 20V_3]$, where V_1, V_2 and V_3 are inputs. Select $R_f = 10\ k\Omega$. ***(Jul '19 – 7M, Jul '18 – 6M)***

37. Design an adder circuit using op-amp to obtain an output voltage, $V_o = -[2V_1 + 3V_2 + 5V_3]$. Assume $R_f = 10\ k\Omega$. ***(Jan '20 – 6M, MQP '18 – 6M, Jan '18 – 6M)***

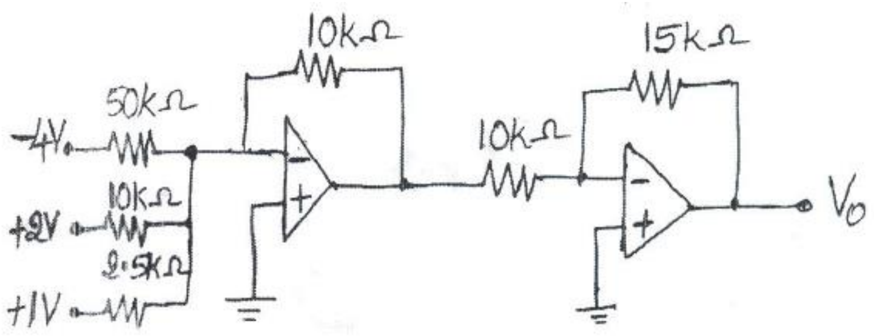
38. Design an op-amp circuit that will produce an output equal to $-[4V_1 + V_2 + 0.1V_3]$. ***(Jan '18 – 6M)***

39. Design an inverting summing circuit with feedback $R_f = 100\ k\Omega$ using an op-amp to generate the output $V_o = -[3V_1 + 4V_2 + 5V_3]$. ***(Jan '17 – 6M)***

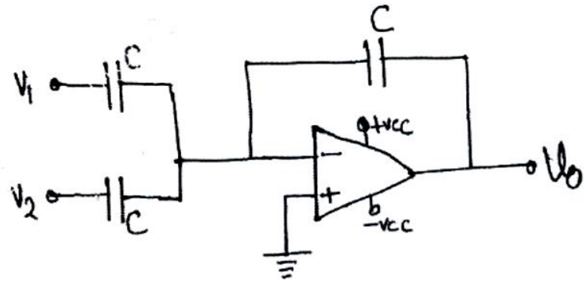
40. Design an adder circuit using op-amp to obtain an output voltage of $V_o = -[0.1V_1 + 0.5V_2 + 2V_3]$, where V_1, V_2 and V_3 are input voltages. Draw the circuit diagram. ***(Jul '15 – 8M)***

41. The input to the basic differentiator circuit is a sinusoidal voltage of peak value of 10 mV and frequency 1.5 kHz. Find the output if $R_f = 100\ k\Omega$ and $C_1 = 1\mu F$. ***(MQP '18 – 4M)***

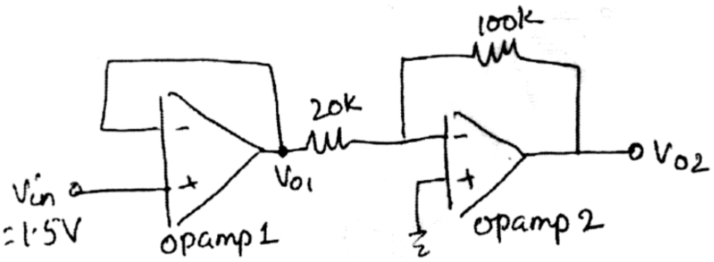
42. Calculate the output voltage for the circuit shown in the figure. ***(Jan '20 – 8M)***



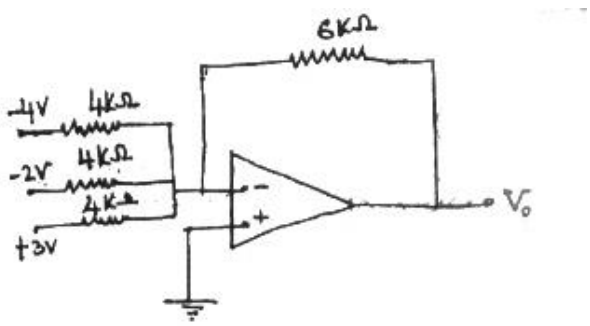
43. Find the output of the op-amp circuit shown in the figure below. ***(Jul '19 – 6M)***



44. For an op-amp circuit shown in the figure, find the output V_{o1} and V_{o2}. Also write the function of each op-amp used. ***(Jan '19 – 6M, MQP '18 – 6M)***

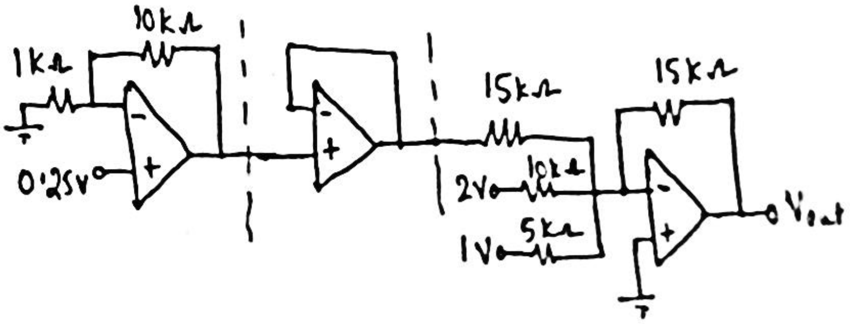


45. Find the output of the following op-amp circuit. ***(Jul '18 – 5M)***

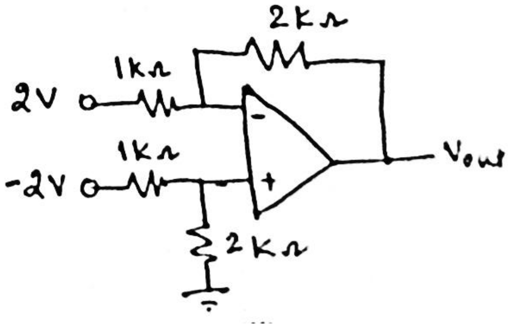


46. Find the output of the following op-amp circuit.

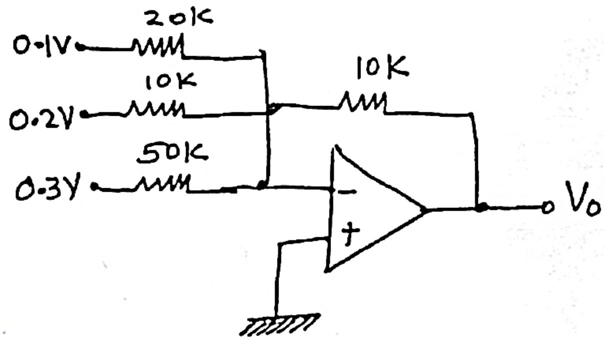
(Jul '17 – 5M, Jan '17 – 5M, MQP '14 – 5M)



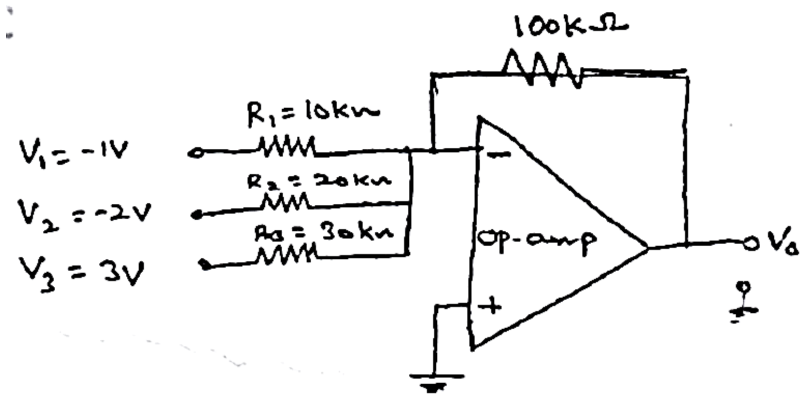
47. Find the output of the following op-amp circuit. ***(Jul '17 – 5M)***



48. Determine V_O for the circuit shown below. ***(Jul '16 – 5M)***

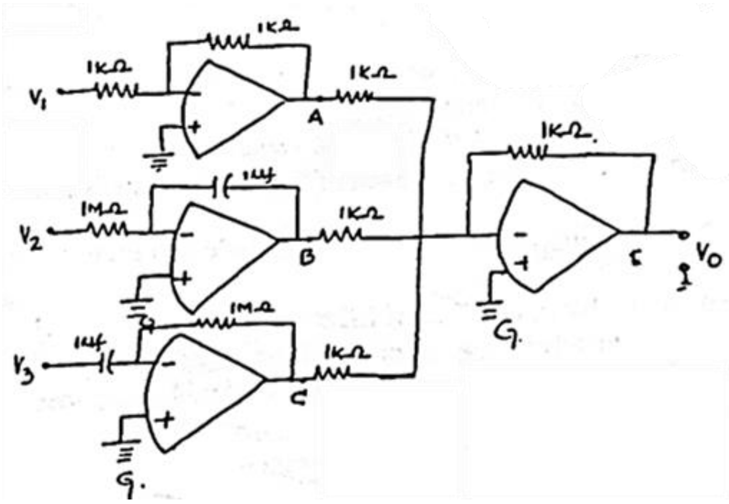


49. For the circuit shown in the figure, calculate the output voltage. ***(Jan '16 – 4M)***

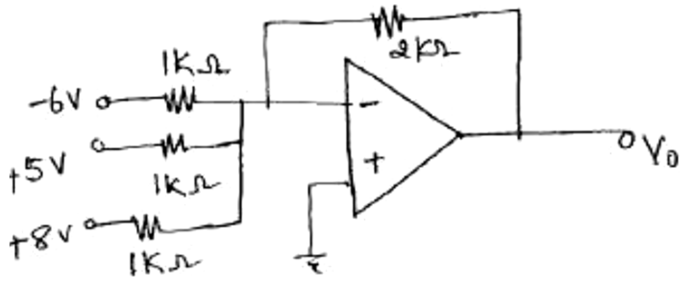


50. Write expression for output voltage at points A, B, C, D and E as shown in figure.

(Jan '15 – 10M)



51. Find the output of the following op-amp Circuit ***(MQP '14 – 5M)***



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2. D.P. Kothari, I. J. Nagrath, ***"Basic Electronics"***, McGraw Hill Education (India) Private Limited, 2014.
3. David A. Bell, ***"Operational Amplifiers and Linear IC's"***, 2nd edition, PHI/Pearson, 2004.