Operational Amplifiers

Syllabus: *Introduction to Operational Amplifiers: Ideal OPAMP, Inverting and Non Inverting OPAMP circuits, OPAMP applications: voltage follower, addition, subtraction, integration, differentiation; Numerical examples as applicable.* ***(6 Hours)***

Introduction to Operational Amplifiers

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.

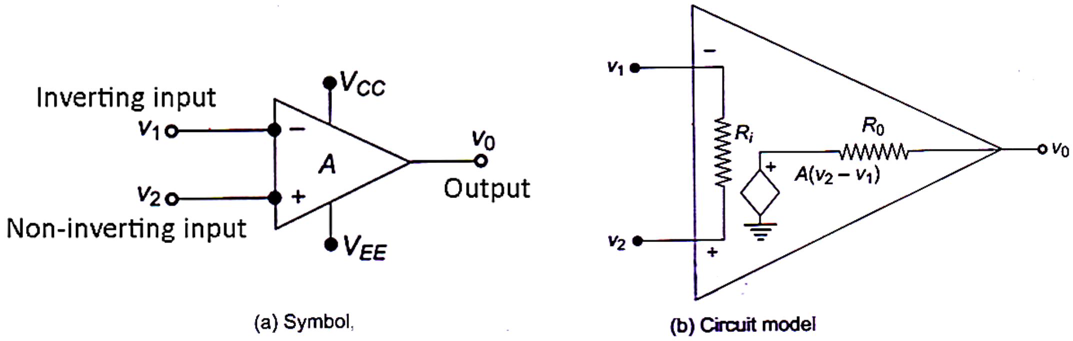


Fig. 1 Circuit symbol and model of an Op-Amp

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 R_{in}, a very low output impedance R_o and a very high gain A.

Block Diagram of an Op-Amp

The block diagram of an op-amp is as shown in Fig. 2.

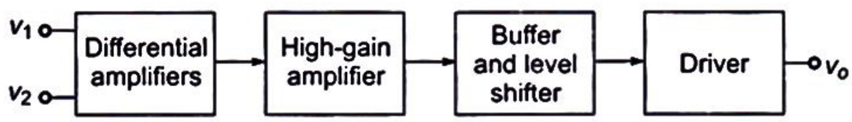


Fig. 2 Block diagram of an op-amp

- The differential amplifier is two BJT or MOSFET amplifiers connected in opposition so as to amplify the difference of two input signals. It has a very high input impedance.
- The high-gain amplifier is another differential amplifier which provides additional voltage gain. Practically, it is not a single amplifier, but a chain of cascaded amplifiers called multistage amplifiers.
- The buffer is an emitter follower used for matching the load. If the output is nonzero for zero input, the level shifter makes it zero.

- Driver is a power amplifier which increases the output voltage swing and keeps the voltage swing symmetrical with respect to ground.

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.

Op-Amp IC 741

IC 741is the most popular IC version of op-amp. It is an 8-pin IC as shown in Fig. 3.

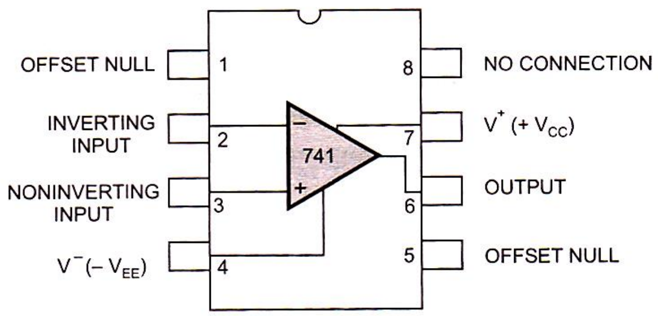


Fig. 3 Pin diagram of IC 741

- 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

Differential Amplifier

An op-amp is basically a differential amplifier or difference amplifier which amplifies the difference between the two input signals. The output voltage is proportional to the difference between two input voltages. We can write this as

$$V_o \propto (V_2 - V_1)$$

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

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

where A_d is the **differential gain** given by $\boldsymbol{A_d = \frac{V_o}{V_d}}$

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

The differential gain is also called ***open loop voltage gain***.

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

$$\boldsymbol{V_o = A_c V_c}$$

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

The total output of a differential amplifier is then given by

$$\boxed{\boldsymbol{V_o = A_d V_d + A_c V_c = A_d (V_2 - V_1) + A_c \left(\frac{V_1 + V_2}{2}\right)}}$$

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 differential gain $\boldsymbol{A_d}$ to common mode gain $\boldsymbol{A_c}$.**

$$\boxed{\boldsymbol{CMRR = \frac{A_d}{A_c}}}$$

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

$$\boxed{\boldsymbol{CMRR = 20 \log_{10}\left(\frac{A_d}{A_c}\right)} \textbf{ dB}}$$

Slew Rate

Slew rate is defined as the maximum rate of change of output voltage with time.

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

Ideal Op-Amp

An ideal op-amp has the following characteristics:

1. **Infinite voltage gain ($\boldsymbol{A_{OL}} = \infty$):** The voltage gain, also known as differential open loop gain is infinite in an ideal op-amp.
2. **Infinite input impedance ($\boldsymbol{R_{in}} = \infty$):** 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 ($\boldsymbol{R_o = 0}$):** 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 ($\boldsymbol{V_{ios} = 0}$):** 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 ($\boldsymbol{BW} = \infty$):** 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 ($\boldsymbol{CMRR} = \infty$):** 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 ($\boldsymbol{S} = \infty$):** 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 ($\boldsymbol{PSRR = 0}$):** 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.

Operation of an Op-Amp

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

Fig. 4 shows the basic operation of an op-amp as inverting and non-inverting amplifiers.

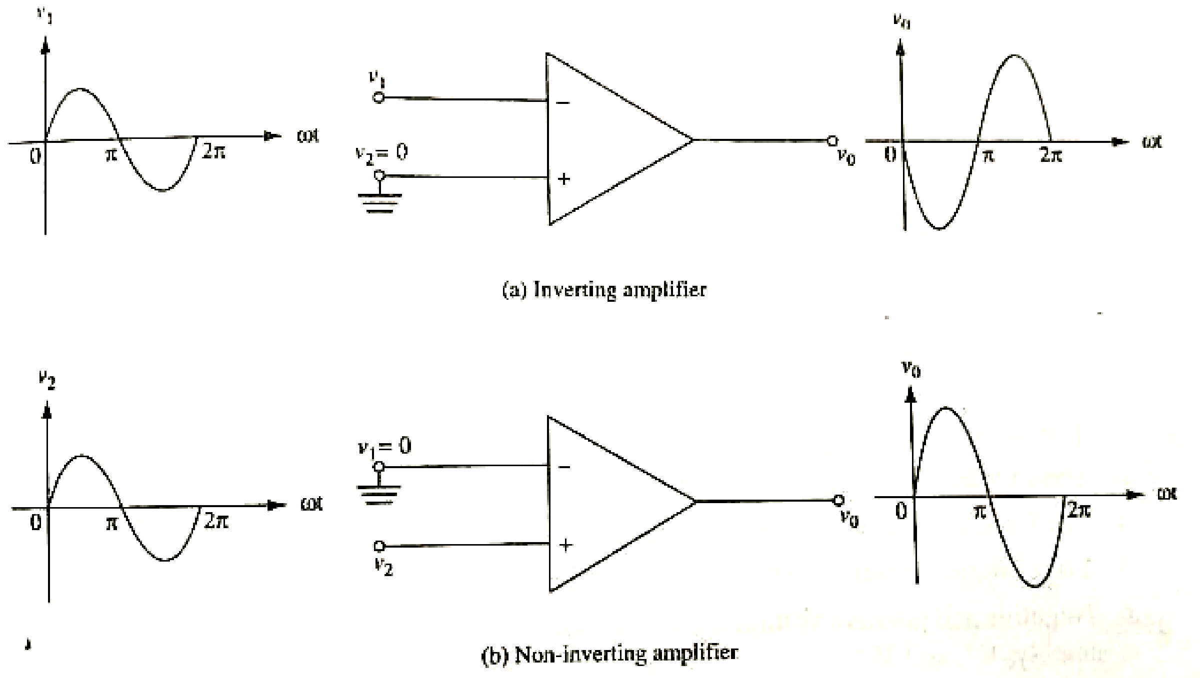


Fig. 4 Basic operation of an op-amp

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. 4 (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. 4 (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. 5 shows an inverting amplifier using op-amp.

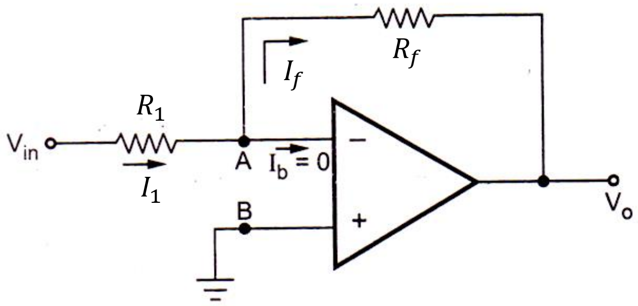


Fig. 5 Inverting amplifier

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

From the concept of virtual ground, the two input terminals are the 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. 6 shows the input and output waveforms of an inverting amplifier.

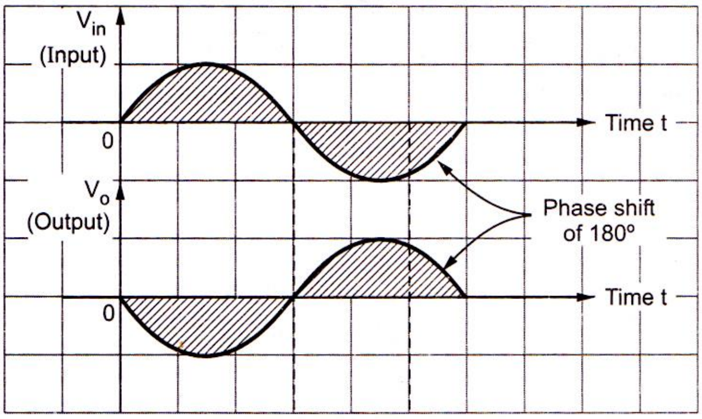


Fig. 6 Waveforms of inverting amplifier

Non-Inverting Amplifier

An amplifier which amplifies the input without producing any phase shift between input and output is called ***non-inverting amplifier***. Fig. 7 shows a non-inverting amplifier using op-amp.

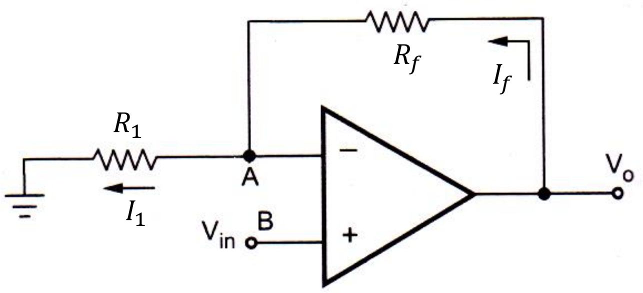


Fig. 7 Non-inverting amplifier

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

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

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. 8 shows the input and output waveforms of an inverting amplifier.

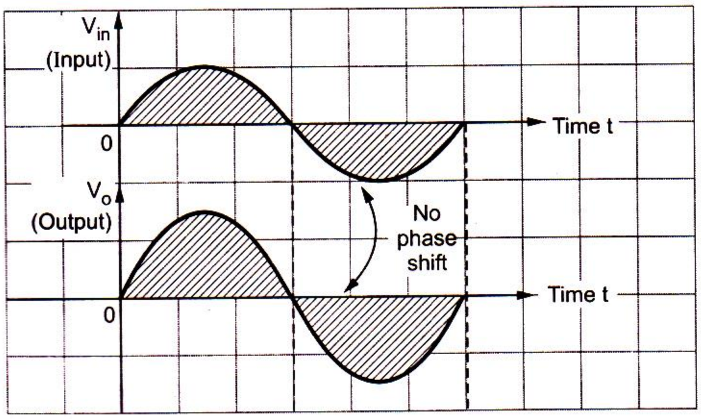


Fig. 8 Waveforms of non-inverting amplifier

Op-Amp Applications

Voltage Follower

A circuit in which the output voltage follows the input voltage is called ***voltage follower.*** Fig. 9 shows a voltage follower circuit using an op-amp.

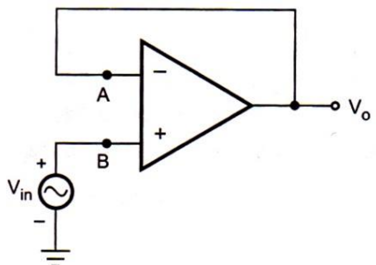


Fig. 9 Voltage follower

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

From the concept of virtual ground, the two input terminals are the 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. 10 shows the input and output waveforms of a voltage follower.

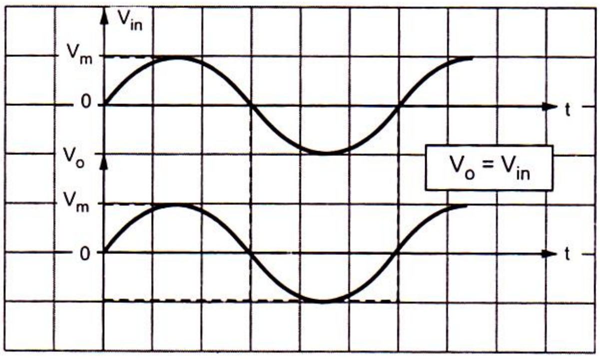


Fig. 10 Waveforms of voltage follower

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 (Adder)

Inverting Summing Amplifier

In this circuit, the input signals to be added are applied to the inverting input terminal.

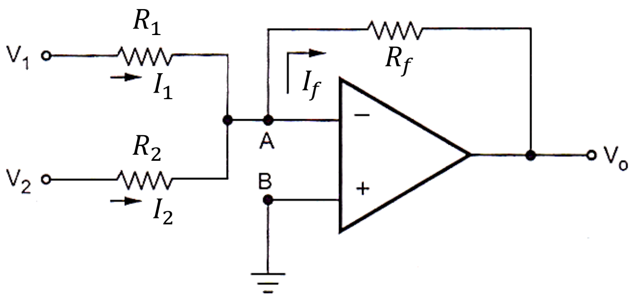


Fig. 11 Inverting summing amplifier (adder) with two inputs

An adder with two inputs is shown in Fig. 11.

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

From the concept of virtual ground, the two input terminals are the 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. 12.

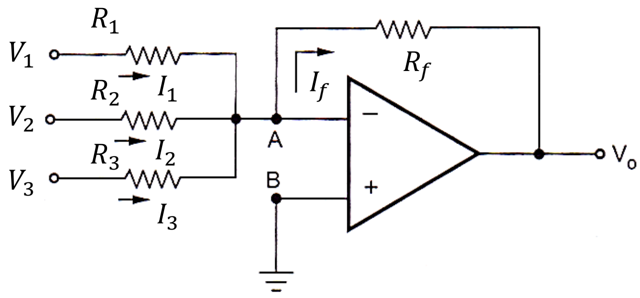


Fig. 12 Inverting summing amplifier (adder) with three inputs

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

From the concept of virtual ground, the two input terminals are the 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. 13 shows a non-inverting summing amplifier with two inputs.

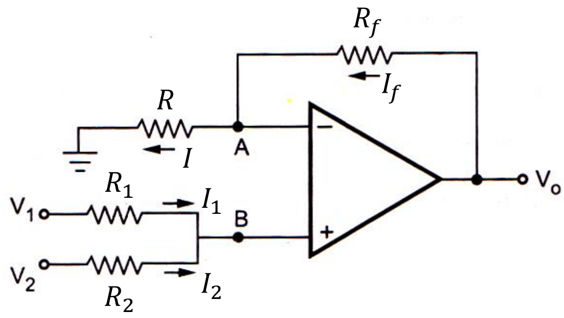


Fig. 13 Non-inverting summing amplifier

Let the potential at node B be V_B.

From the concept of virtual ground, the two input terminals are the 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,

$$I_1 + I_2 = 0$$

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

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

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

$$\frac{R_2 V_1 + R_1 V_2}{R_1 R_2} = V_B \left(\frac{R_1 + R_2}{R_1 R_2}\right)$$

$$V_B = \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2} \tag{1}$$

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,

$$I = I_f$$

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

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

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

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

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

Substituting Eqn. (1) in (2),

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

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

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. 14 shows a subtractor circuit using an op-amp.

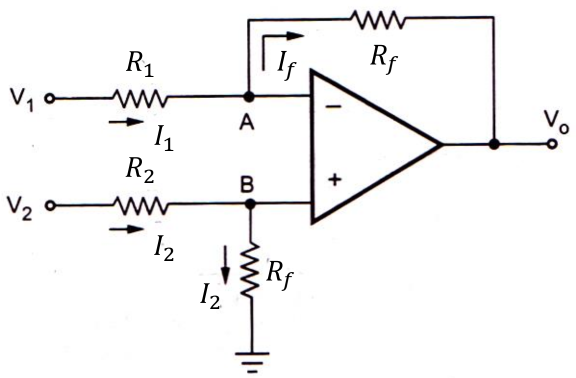


Fig. 14 Subtractor

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 the 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,

$$I_1 = I_f$$

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

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

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

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

$$\frac{V_o}{R_f} = V_A\left(\frac{R_1 + R_f}{R_1R_f}\right) - \frac{V_1}{R_1}$$

$$V_o = V_AR_f\left(\frac{R_1 + R_f}{R_1R_f}\right) - \frac{R_f}{R_1}V_1$$

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

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. 15 shows an integrator circuit using an op-amp.

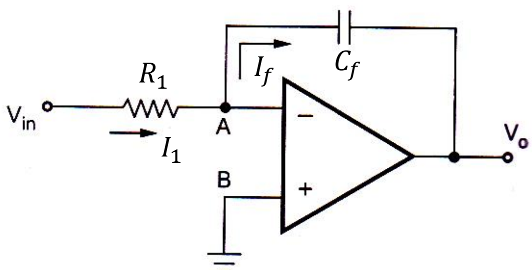


Fig. 15 Integrator

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

From the concept of virtual ground, the two input terminals are the 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. 16 shows a differentiator circuit using an op-amp.

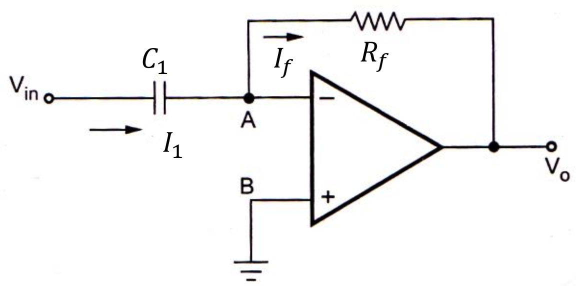


Fig. 16 Differentiator

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

From the concept of virtual ground, the two input terminals are the 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,

$$I_1 = I_f$$

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

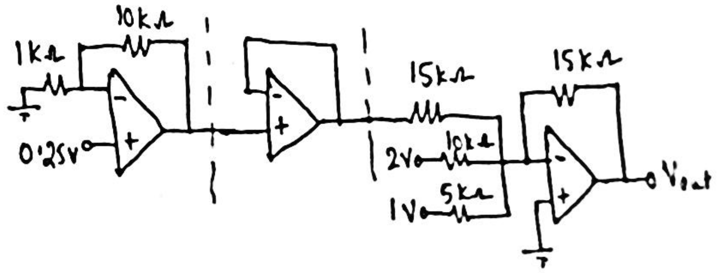
$$\boxed{V_o = -R_f C_1 \frac{dV_{in}}{dt}}$$

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

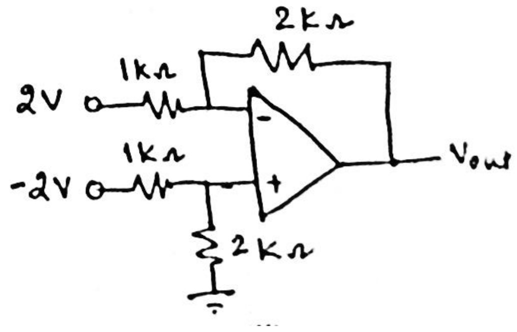
Questions

1. What is an Op-Amp? Mention the applications of Op-Amp.
   (Dec '17, Dec '16, Dec '15, MQP '15, MQP '14)
2. Explain the block diagram of an operational amplifier. ***(Jun '16)***
3. Define the following parameters of an Op-Amp: (i) Differential gain (ii) Common mode gain (iii) CMRR (iv) PSRR (v) Slew rate.
   (Dec '17 – 5M, Jun '16 – 5M, Dec '15 – 6M)
4. Explain the characteristics of an ideal Op-amp.
   (Dec '17 – 6M, Jun '17 – 4M, Dec '16 – 6M, Jun '16 – 7M, Dec '15 – 4M, Jun '15 – 6M, Dec '14 – 5M, MQP '15, MQP '14 – 6M)
5. Write a short note on virtual ground concept of an Op-Amp. ***(Dec '17 – 6M)***
6. Explain the operation of an Op-Amp as an (i) Inverting amplifier (ii) Non inverting amplifier. Derive an expression for the output voltage.
   (Dec '17 – 4M, Jun '17 – 6M, Dec '16 – 6M, Jun '16 – 5M)
7. Draw the circuit of inverting Op-Amp. Derive the expression for the voltage gain.
   (Dec '17 – 5M)
8. With neat circuit and necessary equations, explain the voltage follower circuit using operational amplifier. Mention its important properties.
   (Dec '17, Jun '17 – 6M, Dec '16 – 6M, Dec '15 – 4M, Jun '15 – 5M, MQP '15 – 6M, MQP '14)

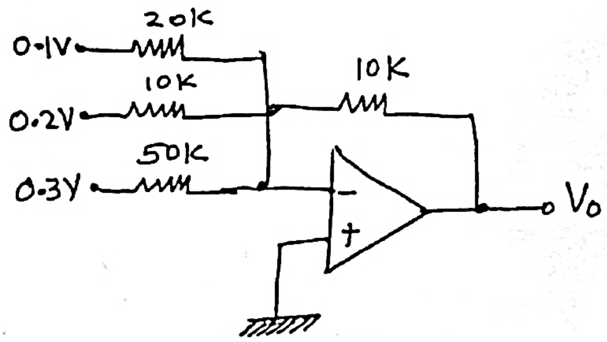
9. Explain how an Op-Amp can be used as (i) Inverting summer (ii) Non inverting summer. ***(Dec '17, Jun '17, MQP '14)***
10. Derive the expression for the output of a three input summing amplifier. ***(Dec '17 – 5M, Dec '15 – 5M, MQP '15 – 5M)***
11. Show with a circuit diagram, how an Op-Amp can be used as a subtractor. ***(Dec '16 – 8M)***
12. With a neat circuit diagram, show how an Op-Amp can be used as an integrator. Derive the expression for output voltage. ***(Dec '17 – 4M, Jun '17 – 4M, Dec '16, Jun '16 – 6M, Dec '15 – 6M, MQP '14)***
13. With a neat circuit diagram, show how an Op-Amp can be used as a differentiator. Derive the expression for output voltage. ***(Dec '17, Dec '16, Dec '14 – 5M)***
14. 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. ***(Jun '16 – 8M)***
15. Find the gain of a non-inverting amplifier if $R_f = 10\ k\Omega$ and $R_1 = 1\ k\Omega$. ***(Dec '15 – 6M)***
16. Design an inverting and non inverting operational amplifier to have a gain of 15. ***(Dec '17 – 5M)***
17. 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 $V_3 = +3V$. ***(Jun '16 – 4M)***
18. Design an adder using Op-Amp to give the output voltage $V_o = -[2V_1 + 3V_2 + 5V_3]$. ***(Dec '17 – 6M)***
19. Design an Op-Amp circuit that will produce an output equal to $-[4V_1 + V_2 + 0.1V_3]$. ***(Dec '17 – 6M)***
20. Design an inverting summing circuit with feedback $R_f = 100\ k\Omega$ using an Op-Amp to generate the output $V_o = -[3V_1 + 4V_2 + 5V_3]$. ***(Dec '16 – 6M)***
21. 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. ***(Jun '15 – 8M)***
22. Find the output of the following Op-Amp circuit. ***(Jun '17 – 5M, Dec '16 – 5M, MQP '14 – 5M)***



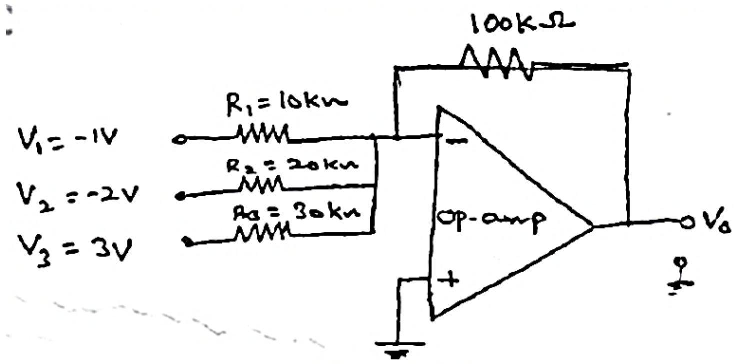
23. Find the output of the following Op-Amp circuit. ***(Jun '17 – 5M)***



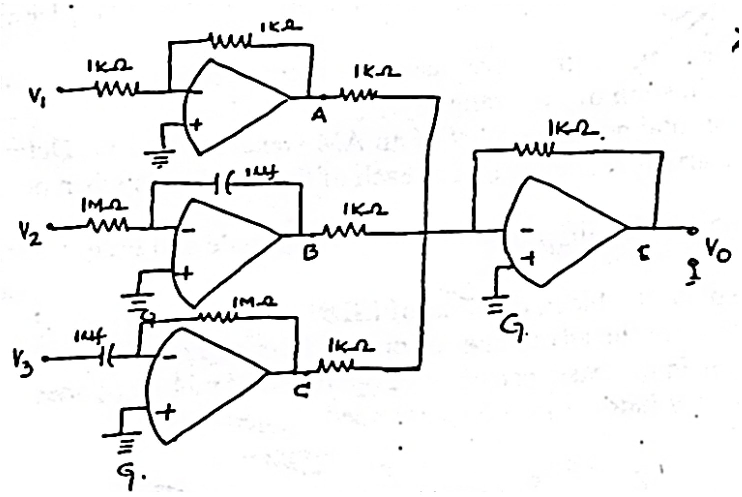
24. Determine V_0 for the circuit shown below. ***(Jun '16 – 5M)***



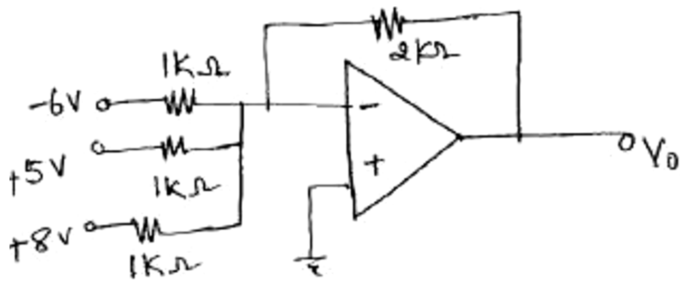
25. For the circuit shown in the figure, calculate the output voltage. ***(Dec '15 – 4M)***



26. Write expression for output voltage at points A, B, C, D and E as shown in figure.
(Dec '14 – 10M)



27. Find the output of the following Op-Amp Circuit ***(MQP '14 – 5M)***



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