MODULE 3

Module - 3

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 (12.1, 12.2 of Text 2).

Applications of Op-Amp – Inverting amplifier, Non-Inverting amplifier, Summer, Voltage follower, Integrator, Differentiator, Comparator (6.2 of Text 1).

Textbooks:

1. *"Basic Electronics", D.P. Kothari, I. J. Nagrath, McGraw Hill Education (India) Private Limited, 2014.*
2. *"Electronic Devices", Thomas L Floyd, Pearson Education, 9th edition 2012*

Introduction

Op-Amp (operational amplifier) is basically an amplifier available in the IC form. The word "operational" is used because the amplifier can be used to perform a variety of mathematical operations such as addition, subtraction, integration, differentiation etc.Fig.3.1 shows the symbol of an op-amp.

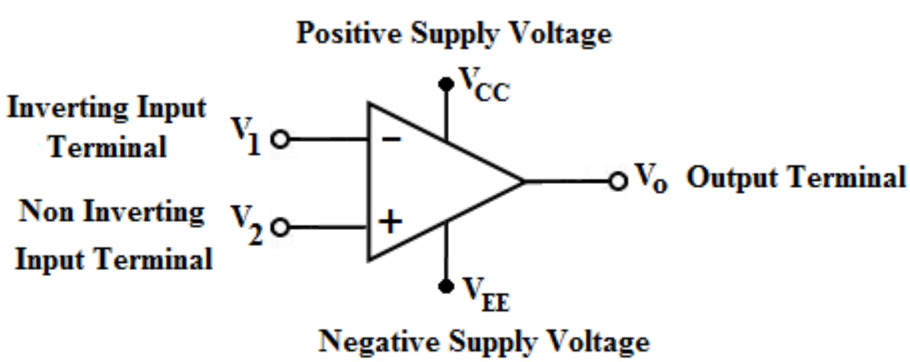


Fig.3.1: Symbol of Op-Amp

- It has two inputs and one output. The input marked "-" is known as Inverting input and the input marked "+" is known as Non-inverting input.
- If two different voltages V_1 and V_2 are applied to an ideal Op-Amp then output voltage V_o is equal to the voltage difference between the input terminals.

$$V_0 = A(V_2 - V_1)$$

where A is the voltage gain, Hence an Op-Amp is a differential amplifier.

- If a voltage V_i is applied at the inverting input (keeping the non-inverting input at ground) as shown fig.3.2 than the output voltage $V_o = -AV_i$ is out of phase with respect to the input signal by 180^0.

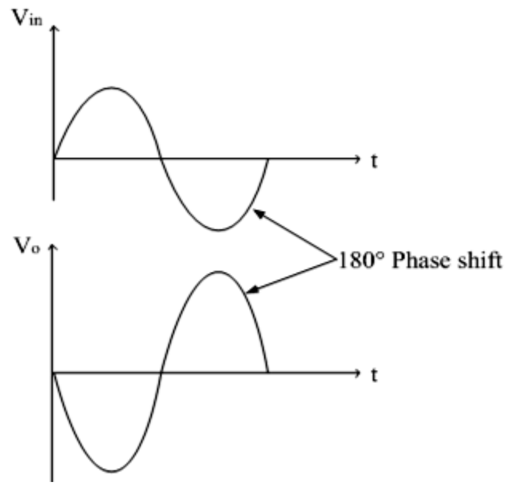


Fig.3.2: Op-amp in inverting mode

- If a voltage V_i is fed at the non-inverting input (keeping the inverting input at ground) as shown in fig.3.3 than the output voltage $V_o= AV_i$ is in phase with the input signal.

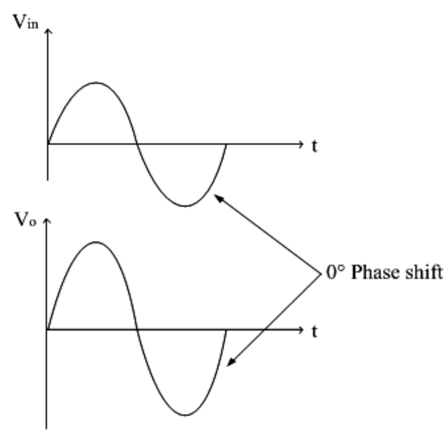


Fig.3.3: Op-Amp in Non-inverting mode

Characteristics of an Ideal Op-Amp

- Consider an ideal Op-Amp shown in the fig.3.4. It has two inputs V_1 and V_2 applied to the inverting and noninverting terminals. This Op-Amp is said to be ideal Op-Amp if it has following characteristics.

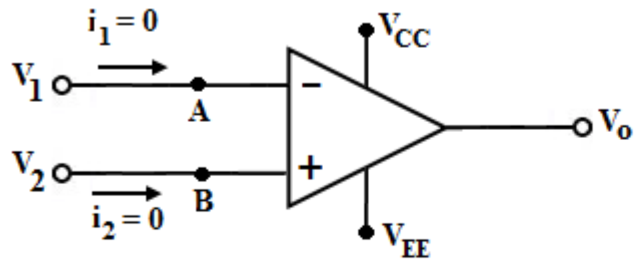


Fig.3.4: Ideal Op-Amp

1. Infinite voltage gain (ie $A_V = \infty$)
2. Infinite input impedance ($R_i = \infty$)
3. Zero output impedance($R_o = 0$)
4. Infinite Bandwidth (B.W. = ∞)
5. Infinite Common mode rejection ratio (ie CMRR = ∞)
6. Infinite slew rate (ie S = ∞)
7. Zero power supply rejection ratio (PSRR = 0) i.e output voltage is zero when power supply $V_{CC} = 0$
8. Zero offset voltage(i.e when the input voltages are zero, the output voltage will also be zero)
9. Perfect balance (i.e the output voltage is zero when the input voltages at the two input terminals are equal)
10. The characteristics are temperature independent.

Op-Amp Input Modes

Single ended mode:

- In the single ended mode the input signal is applied only to one of the input terminal and other input terminal is connected to ground.
- When the input signal is applied to inverting terminal as shown in the fig.3.5.(a) an inverted amplified signal appears at the output.
- When the input signal is applied to non inverting terminal as shown in the fig.3.5.(b) a non inverted amplified signal appears at the output.

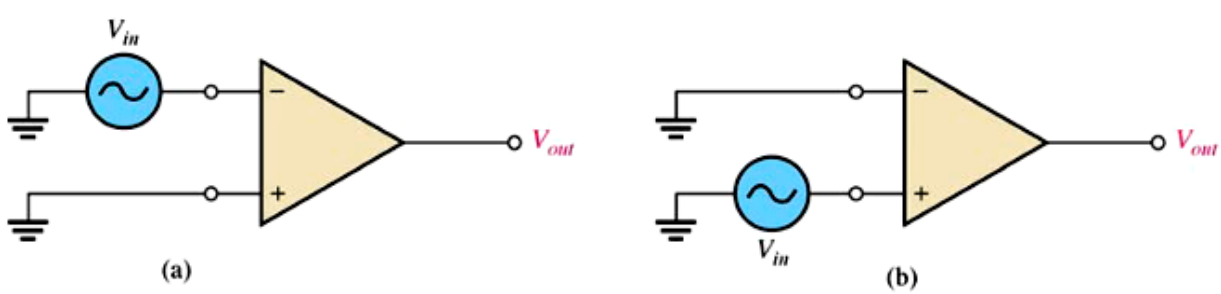


Fig.3.5: Single ended mode

Differential Mode:

- In the differential mode two opposite polarity (out of phase) signals are applied to the inputs as shown in the fig.3.6.
- The amplified difference between the two inputs appears at the output.

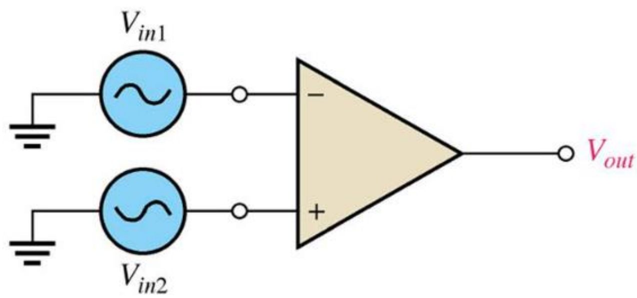


Fig.3.6: Differential mode

Common Mode:

➢ Two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in the fig.3.7.

➢ When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage.

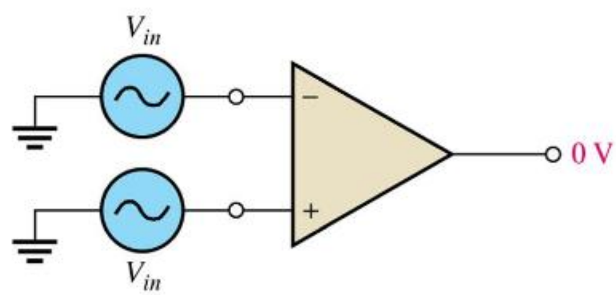


Fig.3.7: Common mode

Op--amp Parameters

Input Bias Current:

- The input bias current (I_B) is the average of the current that enter into the two input terminals with the output at zero volts.
- Typically the input bias current is around 80nA.
- This input bias current makes a voltage drop across the equivalent source impedance seen from the input side of opamp.

Input Offset Current:

- The input offset current is the difference between the two input currents of the opamp with the output at zero volts.
- Typically the input offset current for a 741 op-amp is 20 nA.

Input Offset Voltage

- In the ideal op amp when both inputs are at zero volts the output should be zero volts.
- Due to imbalances within the device a small amount of voltage will appear at the output.
- This extra voltage can be eliminated by giving a small voltage called Input offset voltage (V_{OS}) to the amplifier.
- Typically the input offset voltage for a 741 op-amp is around 1mV.

Common-Mode Rejection Ratio:

- In OPAMP, the output voltage is proportional to the difference between the voltages applied to its two input terminals.
- When the two input voltages are equal ideally the output voltages should be zero.
- A signal applied to both input terminals of the opamp is called as common-mode signal. Usually it is an unwanted noise voltage.
- The ability of an op-amp to suppress common-mode signals is expressed in terms of its common-mode rejection ratio (CMRR).
- CMRR = 20 $\log_{10}$[Differential Voltage Gain/Common Mode Gain] dB

$$\mathrm{CMRR} = \frac{A_d}{A_{CM}}$$

Slew Rate

- The slew rate is the maximum rate of change of output voltage for a step input voltage.
- The slew rate makes the output voltage to change at a slower rate than the applied input.
- Eventually the output waveform is a distortion of the input waveform.
- The typical value for the slew rate is 0.5V/µs.

Input Impedance (Z_i)

It is defined as the impedance seen by the input (source) applied to one input terminal when the other input terminal is connected to ground.

Output Impedance (Z_O)

It is defined as the impedance given by the output (load) for a particular applied input.

Problem:

1. **A certain op-amp has an open-loop voltage gain of 100,000 and a common-mode gain of 0.25. Determine the CMRR and express it in decibels.**

$$\mathrm{CMRR} = \frac{A_d}{A_{CM}} = \frac{100000}{0.25} = 400000$$

$$\mathrm{CMRR} = 20\log\left(\frac{A_d}{A_{CM}}\right) = 20\log(400000) = 112\mathrm{dB}$$

Block Diagram of an Op-Amp

- An Op-Amp consists of four blocks cascaded as shown in the fig.3.8.

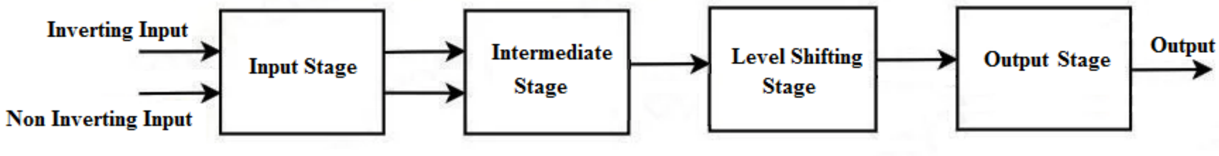


Fig.3.8: Block diagram of an Op-Amp

Input stage

- It consists of a dual input, balanced output differential amplifier.
- Its function is to amplify the difference between the two input signals.
- It provides high differential gain, high input impedance and low output impedance.

Intermediate stage

- The overall gain requirement of an Op-Amp is very high. Since the input stage alone cannot provide such a high gain.
- Intermediate stage is used to provide the required additional voltage gain.
- It consists of another differential amplifier with dual input, and unbalanced (single ended) output

Level shifting stage

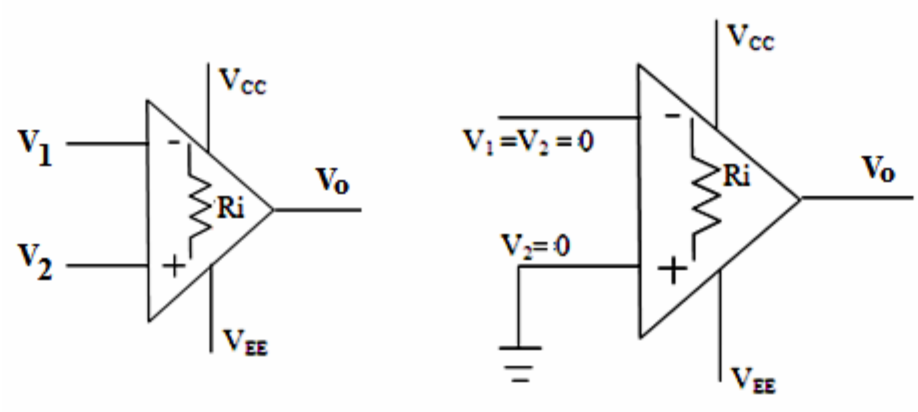
- As the Op-Amp amplifies D.C signals also, the small D.C. quiescent voltage level of previous stages may get amplified and get applied as the input to the next stage causing distortion the final output.
- Hence the level shifting stage is used to bring down the D.C. level to ground potential, when no signal is applied at the input terminals.

Output stage

- It consists of a push-pull complementary amplifier which provides large A.C. output voltage swing and high current sourcing and sinking along with low output impedance.

Virtual ground

- If two terminals are physically shorted then the voltages at both the terminals are same.
- For an Op-Amp when output voltage $V_o = 0$, we can say that both the input voltages are equal i.e. $V_1 = V_2$
- If both voltages are same then we can say that a virtual short exists between the inputs terminals of Op-Amp.



- Since the input impedances of an ideal Op-Amp is infinite ($R_i = \infty$). There is no current flow into the terminals.
- Hence when one terminal (say V_2) is connected to ground (i.e. $V_2 = 0$) then because of virtual short V_1 will also be zero. This virtual short is called as virtual ground.

Applications of Op-Amp

- An Op-Amp can be used as
    1. Inverting Amplifier
    2. Non-Inverting Amplifier
    3. Voltage follower
    4. Adder (Summer)
    5. Subtractor
    6. Integrator
    7. Differentiator

Inverting Amplifier

- An inverting amplifier shown in the fig.3.9 is one whose output is amplified and is out of phase by 180^0 with respect to the input.
- The input signal v_i is applied to the inverting terminal through a resistor R_1 and non inverting terminal is grounded.
- Feedback from the output terminal to the input terminal is provided through the resistor R_f.

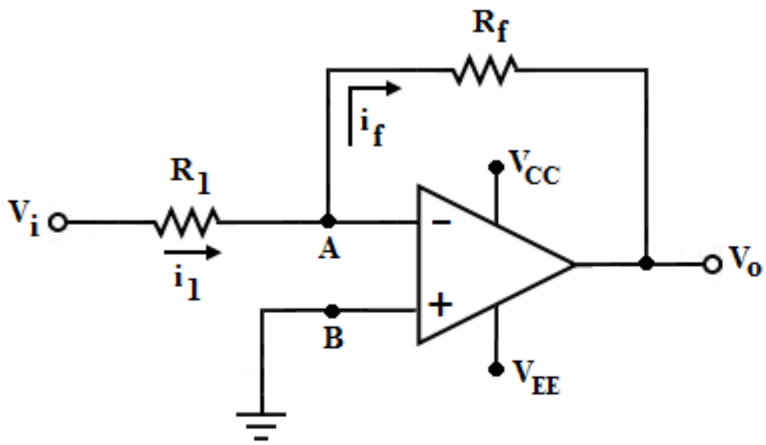


Fig.3.9: Inverting Amplifier

- Non inverting terminal of Op-amp is grounded, therefore $V_B = 0$. Due to virtual short, the inverting and non inverting terminals are at the same potential

$$V_A = V_B = 0$$

- Current i_1 is defined by

$$i_1 = \frac{V_i - V_A}{R_1} = \frac{V_i}{R_1}$$

- Current i_f is defined by

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

- Due to high input resistance, the current flowing into inverting input terminal is zero. Therefore

$$i_f = i$$

$$-\frac{V_o}{R_f} = \frac{V_i}{R_1}$$

$$\frac{V_o}{V_i} = A = -\frac{R_f}{R_1}$$

$$V_o = -\left(\frac{R_f}{R_1}\right)V_i$$

Where $A = -\frac{R_f}{R_1}$ is the gain of the amplifier and negative sign indicates that the output is inverted with respect to the input.

Non- Inverting Amplifier

- A non-inverting amplifier shown in the fig.3.10 is one whose output is amplified and is in-phase with the input.

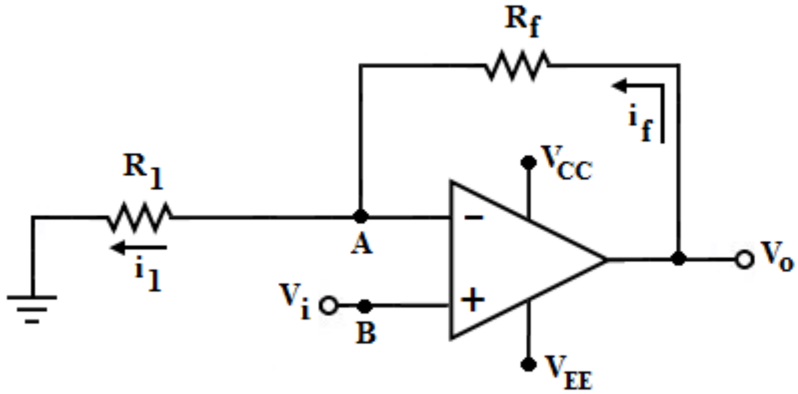


Fig.3.10: Non Inverting Amplifier

- Feedback from the output terminal to the input terminal is provided through the resistor R_f.
- Input signal is applied to non inverting terminal of Op-amp, therefore $V_B = V_i$. Due to virtual short, the inverting and non inverting terminals are at the same potential

$$V_A = V_B = V_i$$

- Due to zero output resistance, the output current flows through R_f and then to ground through R_1. Therefore

$$i_f = i$$

- Current i_1 is defined by

$$i_1 = \frac{V_A - 0}{R_1} = \frac{V_A}{R_1} = \frac{V_i}{R_1}$$

- Current i_f is defined by

$$i_f = \frac{V_o - V_A}{R_f} = \frac{V_o - V_i}{R_f}$$

- On equating both currents we get

$$\frac{V_o - V_i}{R_f} = \frac{V_i}{R_1}$$

$$\frac{V_o - V_i}{V_i} = \frac{R_f}{R_1}$$

$$\frac{V_o}{V_i} - 1 = \frac{R_f}{R_1}$$

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

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

Where $A = 1 + \frac{R_f}{R_1}$ is the gain of the amplifier and positive sign indicates that the output is in phase with respect to the input.

Voltage follower

- Voltage follower shown in the fig.3.11 is a circuit in which output voltage V_o follows input voltage V_i. i.e. output voltage V_o is equal to input voltage V_i

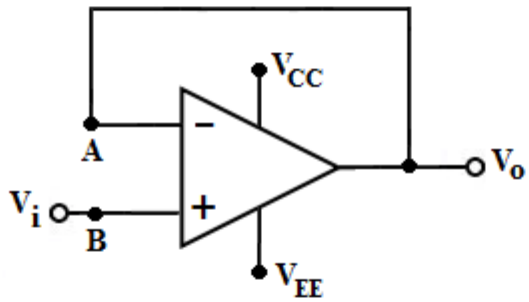


Fig.3.11: Voltage follower

- The voltage follower configuration is obtained from non-inverting amplifier by short circuiting R_f and open circuiting R_1.
- For non-inverting op-amp output voltage is given by

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

When $R_f = 0$ (short circuiting)

$R_1 = \infty$ (open circuiting) we get

$$V_o = \left(1 + \frac{0}{\infty}\right) V_i$$

$$V_o = V_i$$

- The closed loop gain is given by

$$A = \frac{V_o}{V_i} = 1$$

- Therefore the output voltage will be equal and in-phase with the input voltage. Thus voltage follower is nothing but a non-inverting amplifier with a voltage gain of unity.

Summing circuit

- Summing circuit is shown in the fig.3.12 is a circuit in which the output voltage is equal to the negative of the sum of the input voltages.

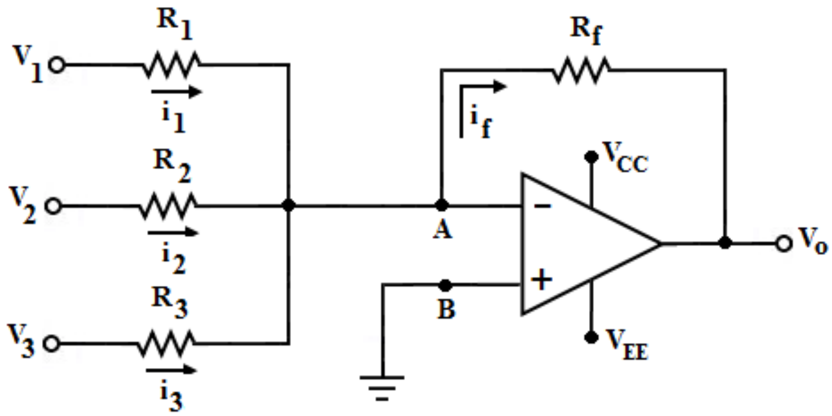


Fig.3.12: Op Amp Summer

- Non inverting terminal of Op-amp is grounded, therefore $v_B = 0$. Due to virtual short, the inverting and non inverting terminals are at the same potential

$$v_A = v_B = 0$$

- Current i is defined by

$$i = i_1 + i_2 + i_3$$

- Current i_1 is defined by

$$i_1 = \frac{v_1 - v_A}{R_1} = \frac{v_1}{R_1}$$

- Current i_2 is defined by

$$i_2 = \frac{v_2 - v_A}{R_2} = \frac{v_2}{R_2}$$

- Current i_3 is defined by

$$i_3 = \frac{v_3 - v_A}{R_3} = \frac{v_3}{R_3}$$

- Current i_f is defined by

$$i_f = \frac{v_A - v_o}{R_f} = -\frac{v_o}{R_f}$$

- Due to high input resistance, the current flowing into inverting input terminal is zero. Therefore

$$i_f = i$$

$$-\frac{v_o}{R_f} = \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}$$

$$v_o = -\left[\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right]$$

- If $R_f = R_1 = R_2 = R_3$ then

$$v_o = -[v_1 + v_2 + v_3]$$

- Therefore the output voltage is equal to the negative of the sum of the input voltages and hence summing circuit is also called as inverting summer

Subtractor

- Subtractor circuit is shown in the fig.3.13 is a circuit in which the output voltage is equal to the difference of the input voltages.

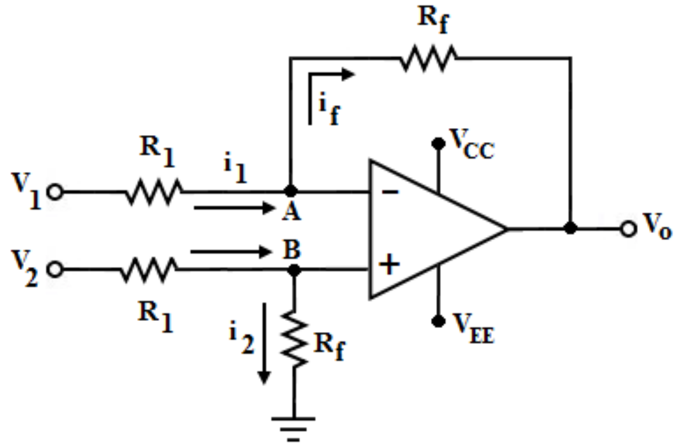


Fig.3.13: Subtractor

- The input voltages are applied to inverting and non inverting terminals of the op-amp circuit.
- The output voltage is determined by using superposition principle,
  i. Reduce v_2 to zero and find the output voltage v_{01} due to v_1
  ii. Reduce v_1 to zero and find the output voltage v_{02} due to v_2
  iii. Add both output voltages to get final output voltage.
- When v_2 is reduced to zero the resulting circuit is an inverting amplifier as shown in the fig.3.14 and the output voltage is given by

$$v_{o1} = -\left(\frac{R_f}{R_1}\right) v_1$$

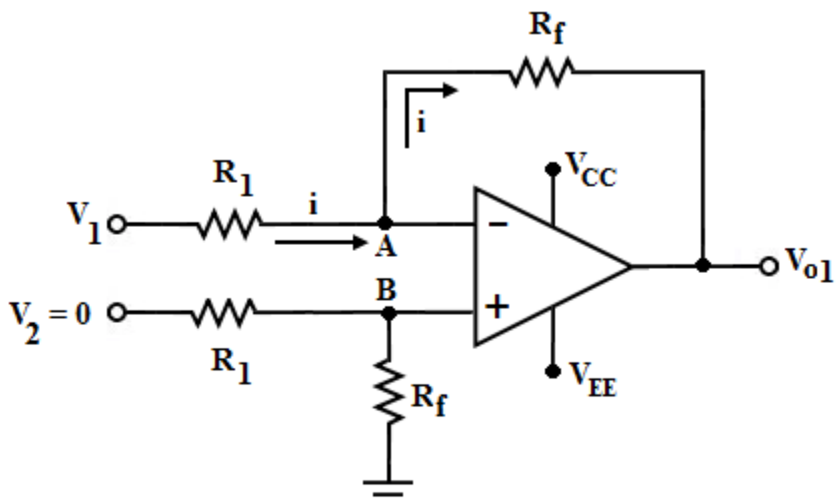


Fig.3.14: Subtractor when v_2 is reduced to zero

- When v_1 is reduced to zero the resulting circuit is a non inverting amplifier as shown in the fig.3.15 and the output voltage is given by

$$v_{o2} = \left(1 + \frac{R_f}{R_1}\right) v_B$$

$$v_{o2} = \left(\frac{R_1 + R_f}{R_1}\right) v_B$$

where v_B is the voltage at the non inverting terminal and is given by

$$v_B = \left(\frac{R_f}{R_1 + R_f}\right) v_2$$

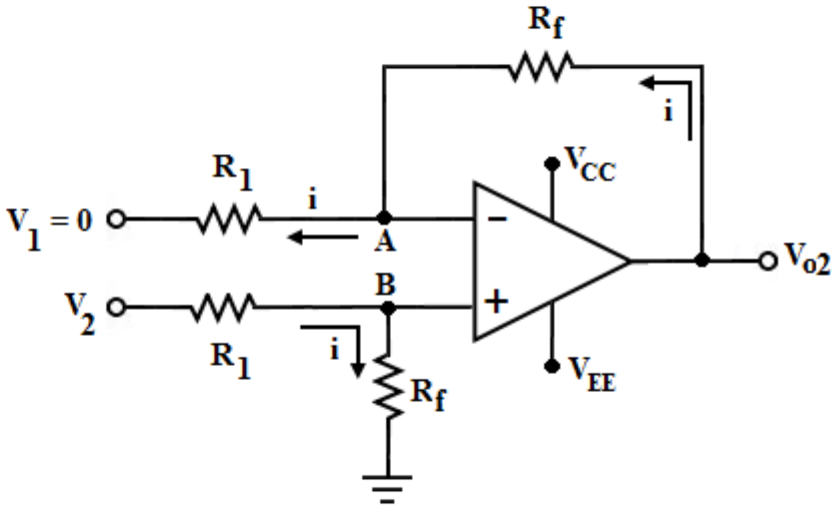


Fig.3.15: Subtractor when v_1 is reduced to zero

- On substituting we get

$$v_{o2} = \left(\frac{R_1 + R_f}{R_1}\right)\left(\frac{R_f}{R_1 + R_f}\right) v_2$$

$$v_{o2} = \left(\frac{R_f}{R_1}\right) v_2$$

- The output voltage is given by

$$v_o = v_{o1} + v_{o2}$$

$$v_o = -\left(\frac{R_f}{R_1}\right) v_1 + \left(\frac{R_f}{R_1}\right) v_2$$

$$v_o = \frac{R_f}{R_1}(v_2 - v_1)$$

- If $R_f = R_1$ then

$$v_o = v_2 - v_1$$

- Hence the output voltage is the difference of the input voltages.

Integrator

- Op-Amp integrator has a capacitor in the feedback path as shown in the fig.3.16 and its output voltage is the integration of the input voltage.

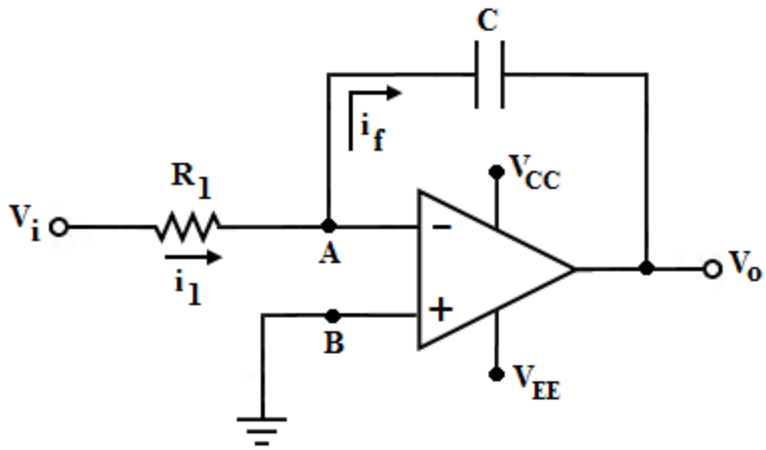


Fig.3.16: Op-amp Integrator

- Non inverting terminal of Op-amp is grounded, therefore $v_2 = 0$. Due to virtual short, the inverting and non inverting terminals are at the same potential

$$v_1 = v_2 = 0$$

- Due to high input resistance, the current flowing into inverting input terminal is zero. Therefore the same current flows through R and C

$$i_1 = i_f$$

- Current i_1 is defined by

$$i_1 = \frac{v_i - v_1}{R} = \frac{v_i}{R}$$

- Charge across the capacitor is given by

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

- Voltage across capacitor is also defined by

$$V = v_1 - v_o$$

- Therefore

$$\frac{dq}{dt} = C\frac{d(v_1 - v_o)}{dt}$$

- But $v_1 = 0$ and $\frac{dq}{dt} = i_f$

$$i_f = -C\frac{dv_o}{dt}$$

- On equating i_1 and i_f we get

$$\frac{v_i}{R} = -C\frac{dv_o}{dt}$$

$$\frac{dv_o}{dt} = -\frac{v_i}{RC}$$

- Integrate on both sides we get

$$\int \frac{dv_o}{dt} = -\frac{1}{RC}\int v_i\,dt$$

$$v_o = -\frac{1}{RC}\int v_i\,dt$$

- Hence the output voltage is the integration of the input voltage.

Differentiator

- Op-Amp differentiator can be obtained from Op-Amp integrator by interchanging the R and C as shown in the fig.3.17 and its output voltage is the differentiation of the input voltage.

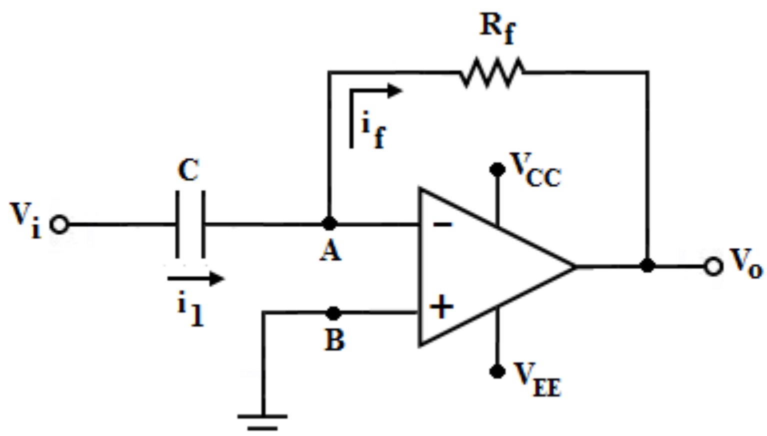


Fig.3.17: Op-amp differentiator

- Non inverting terminal of Op-amp is grounded, therefore $v_2 = 0$. Due to virtual short, the inverting and non inverting terminals are at the same potential

$$v_1 = v_2 = 0$$

- Due to high input resistance, the current flowing into inverting input terminal is zero. Therefore the same current flows through R and C

$$i_1 = i_f$$

- Current i_f is defined by

$$i_f = \frac{v_1 - v_o}{R} = -\frac{v_o}{R}$$

- Charge across the capacitor is given by

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

- Voltage across capacitor is also defined by

$$V = v_i - v_1$$

- Therefore

$$\frac{dq}{dt} = C\frac{d(v_i - v_1)}{dt}$$

- But $v_1 = 0$ and $\frac{dq}{dt} = i_i$

$$i_i = C\frac{dv_i}{dt}$$

- On equating i_1 and i_f we get

$$-\frac{v_o}{R} = C\frac{dv_i}{dt}$$

$$v_o = -RC\frac{dv_i}{dt}$$

- Hence the output voltage is the derivative of the input voltage.

Comparator

- **Op-amp comparator** compares one analogue voltage level with another analogue voltage level, or some preset reference voltage, V_{REF} and produces an output signal based on this voltage comparison. The output signal is either 0 (low) or 1 (high).

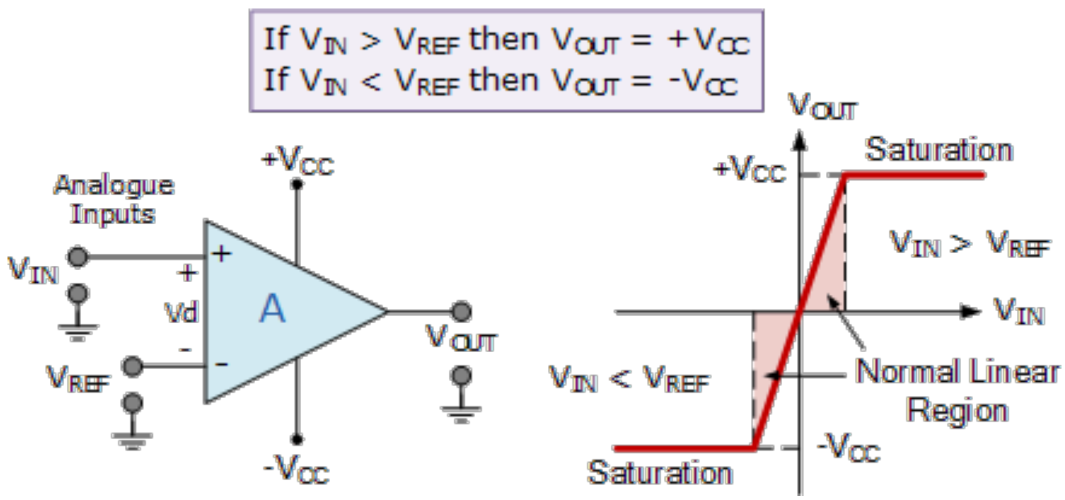


Fig.3.18: Op-amp comparator

- With reference to the op-amp comparator circuit shown in the fig.3.18, lets first assume that V_{IN} is less than the DC voltage level at V_{REF}, ($V_{IN} < V_{REF}$). As the non-inverting (positive) input of the comparator is less than the inverting (negative) input, the output will be LOW and at the negative supply voltage, $-V_{CC}$ resulting in a negative saturation of the output.
- If the input voltage, V_{IN} is increased so that its value is greater than the reference voltage V_{REF} on the inverting input, the output voltage rapidly switches HIGH towards the positive supply voltage, $+V_{CC}$ resulting in a positive saturation of the output. If the input voltage V_{IN} is reduced again so that it is slightly less than the reference voltage, the op-amp's output switches back to its negative saturation voltage acting as a threshold detector.

Problems

1. **For an inverting amplifier R_1 = 100KΩ and R_f = 600KΩ. What is the output voltage for an input of -3V?**

Output voltage is given by,

$$v_o = -\left(\frac{R_f}{R_1}\right) v_i$$

$$v_o = -\left(\frac{600k}{100k}\right) * (-3)$$

$$v_o = 18V$$

2. **Design an inverting amplifier for output voltage of -10V and an input voltage of 1V.**

Output voltage of the inverting amplifier is given by,

$$v_o = -\left(\frac{R_f}{R_1}\right) v_i$$

$$\frac{R_f}{R_1} = -\frac{v_o}{v_i} = -\frac{-10}{1} = 10$$

$$R_f = 10R_1$$

Assume $R_1 = 1k\Omega$ therefore,

$$R_f = 10k\Omega$$

3. **For an inverting amplifier R_1 = 20KΩ, R_f = 200KΩ Calculate the output voltage for the following input voltages**

(i). V_i = 0.2V **(ii). V_i = 0.5sin314tV** **(iii). V_i = -0.4V**

Gain of the inverting Op-Amp is given by,

$$A = -\left(\frac{R_f}{R_1}\right)$$

$$A = -\left(\frac{200k}{20k}\right)$$

$$A = -10$$

Output voltage of the inverting amplifier is given by,

$$v_o = -A * v_i$$

When input voltage is V_i = 0.2V

$$v_o = -10 * 0.2$$

$$v_o = -2V$$

When input voltage is V_i = 0.5sin314tV

$$v_o = -10 * 0.5\sin 314t$$

$$v_o = -5\sin 314tV$$

When input voltage is V_i = -0.4V

$$v_o = -10 * -0.4$$

$$v_o = 4V$$

4. For an inverting amplifier R_1 = 10KΩ, R_f = 100KΩ and V_i = 1V. Calculate i_1 and V_O.

$$i_1 = \frac{v_i - 0}{R_1} = \frac{1}{10k} = 0.1mA$$

$$v_o = -\left(\frac{R_f}{R_1}\right) v_i = -\left(\frac{100k}{10k}\right) * 1 = -10V$$

5. Design an amplifier with a gain of +9 and R_f = 12 KΩ using an op-Amp

Since the gain is positive, it is a non-inverting amplifier. Voltage gain is expressed as

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

$$9 = 1 + \frac{R_f}{R_1}$$

$$\frac{R_f}{R_1} = 8$$

$$R_1 = \frac{R_f}{8} = \frac{12k}{8} = 1.5k\Omega$$

6. For a summing circuit if V_1 = +1V, V_2 = +3V and V_3 = +2V with R_f = 3KΩ, R_1 = R_2 = R_3 = 2KΩ. Determine the output voltage.

Output voltage of the summing circuit is given by

$$v_o = -\left[\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3\right]$$

Since $R_1 = R_2 = R_3$

$$v_o = -\frac{R_f}{R_1}[v_1 + v_2 + v_3]$$

$$v_o = -\frac{3k}{2k}[1 + 3 + 2]$$

$$v_o = -9V$$

7. Design an Adder using Op-Amp to give the output voltage V_o = - ($2V_1 + 3V_2 + 5V_3$)

Output voltage of the summing circuit is given by

$$v_o = -\left[\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3\right]$$

On comparing with given expression we get,

$$\frac{R_f}{R_1} = 2$$

$$\frac{R_f}{R_2} = 3$$

$$\frac{R_f}{R_3} = 5$$

Let $R_f = 1k\Omega$, therefore

$$R_1 = \frac{R_f}{2} = \frac{1k}{2} = 0.5k\Omega$$

$$R_2 = \frac{R_f}{3} = \frac{1k}{3} = 0.33k\Omega$$

$$R_3 = \frac{R_f}{5} = \frac{1k}{5} = 0.2k\Omega$$

8. **Design an Adder using Op-Amp to give the output voltage $V_O = 2(0.1V_1 + 0.5V_2 + 2V_3)$**

$V_O = 0.2V_1 + V_2 + 4V_3$

$V_O = -(0.2(-V_1) + 1(-V_2) + 4(-V_3))$

Output voltage of the summing circuit is given by

$$v_o = -\left[\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right]$$

On comparing with given expression we get,

$$\frac{R_f}{R_1} = 0.2$$

$$\frac{R_f}{R_2} = 1$$

$$\frac{R_f}{R_3} = 4$$

Let $R_f = 1k\Omega$, therefore

$$R_1 = \frac{R_f}{0.2} = \frac{1k}{0.2} = 5k\Omega$$

$$R_2 = \frac{R_f}{1} = \frac{1k}{1} = 1k\Omega$$

$$R_3 = \frac{R_f}{4} = \frac{1k}{4} = 0.25k\Omega$$

Note: In place of V_1, V_2 and V_3 we have to apply $-V_1$, $-V_2$ and $-V_3$ respectively.

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

Given: $R_f = 100k\Omega$

$C = 1\mu F$

$V_i = 10\sin(3000\pi t)$ mV [$V_i = V_m\sin\omega t = V_m\sin2\pi ft$]

Output voltage of the differentiator is given by

$$v_o = -RC\frac{dv_i}{dt}$$

$$v_o = -100 * 10^3 * 1 * 10^{-6} * \frac{d(10\sin(3000\pi t)mV)}{dt}$$

$$v_o = -0.1 * 10 * 3000\pi * \cos(3000\pi t)mV$$

$$v_o = -3000\pi * \cos(3000\pi t)mV$$

10. The input sinusoidal voltage of 2sin(2000πt)V is applied to a basic differentiator circuit . Find the output voltage if R_f = 1.5kΩ and C = 0.1μF.

Given: $R_f = 1.5k\Omega$

$C = 0.1\mu F$

$V_i = 2\sin(2000\pi t)V$ [$V_i = V_m\sin\omega t = V_m\sin2\pi ft$]

Output voltage of the differentiator is given by

$$v_o = -RC\frac{dv_i}{dt}$$

$$v_o = -1.5 * 10^3 * 0.1 * 10^{-6} * \frac{d(2\sin(2000\pi t))}{dt}$$

$$v_o = -0.15 * 10^{-3} * 2 * 2000\pi * \cos(2000\pi t)V$$

$$v_o = -1.885 * \cos(2000\pi t)V$$

11. The input sinusoidal voltage with peak value of 6mV and of 2kHz is applied to a ideal integrator circuit. Find the output voltage if R_1 = 100kΩ and C = 1μF.

Given: $R_f = 100k\Omega$

$C = 1\mu F$

$V_i = 6\sin(4000\pi t)V$ [$V_i = V_m\sin\omega t = V_m\sin2\pi ft$]

Output voltage of the integrator is given by

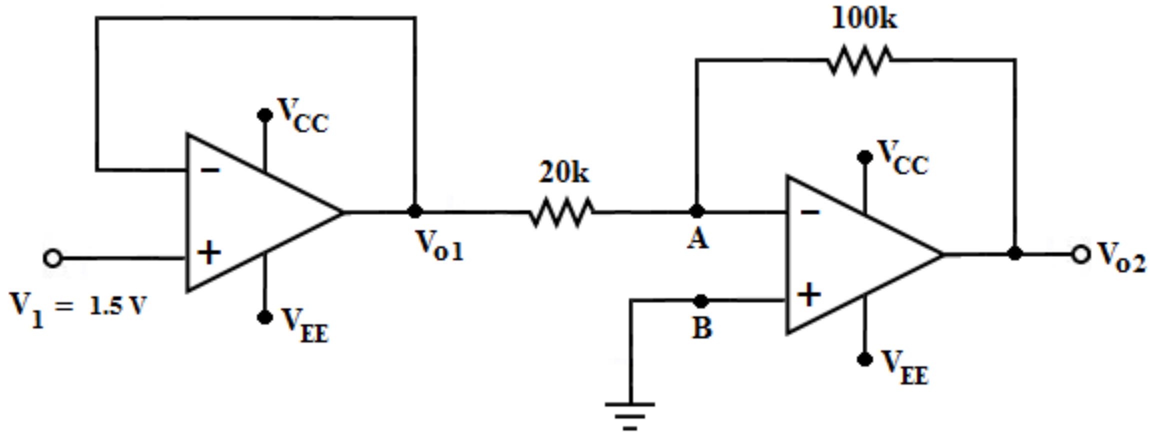
$$v_o = -\frac{1}{RC}\int v_i\, dt$$

$$v_o = -\frac{1}{100 * 10^3 * 1 * 10^{-6}}\int 6\sin(4000\pi t)\, dt$$

$$v_o = -60 * \left(-\frac{\cos(4000\pi t)}{4000\pi}\right)V$$

$$v_o = 4.77 * \cos(4000\pi t)mV$$

12. For an op-amp given the figure find the output voltage v_{o1} and v_{o2}.



V_{o1} is the voltage follower output hence it is given by

$$V_o = V_1$$

Therefore,

$$V_{o1} = 1.5V$$

V_{o2} is the inverting op-amp output hence it is given by

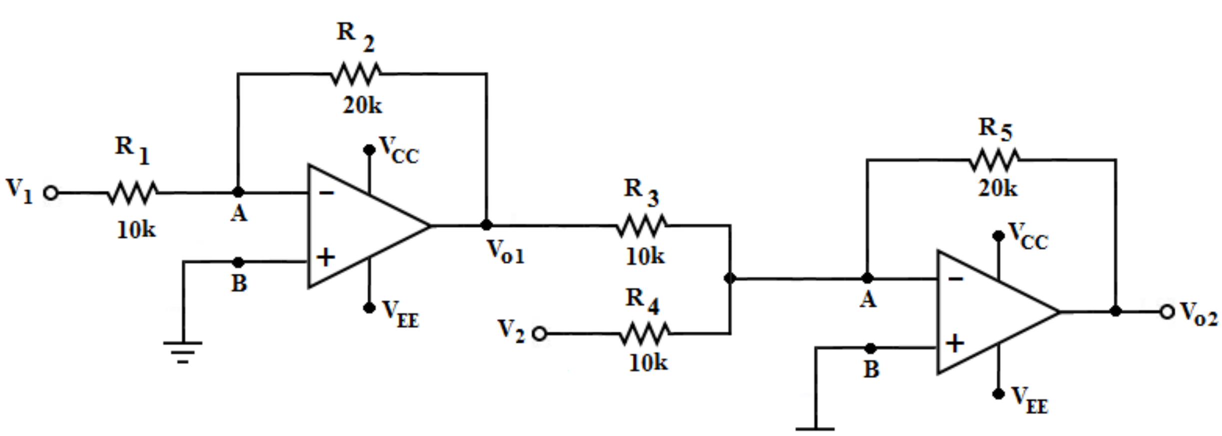
$$V_{o1} = -\left(\frac{R_f}{R_1}\right)V_i$$

Therefore,

$$V_o = -\left(\frac{100k}{20k}\right) * 1.5$$

$$V_o = -7.5V$$

13. Find an output voltage expression for the given circuit



V_{o1} is the inverting op-amp output hence it is given by

$$V_{o1} = -\left(\frac{R_f}{R_1}\right)V_i$$

Therefore,

$$V_{o1} = -\left(\frac{20k}{10k}\right) * V_1$$

$$V_{o1} = -2V_1$$

V_{o2} is the summing op-amp output hence it is given by

$$V_o = -\left[\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2\right]$$

Therefore,

$$V_{o2} = -\left[\frac{R_5}{R_3}V_{01} + \frac{R_5}{R_2}v_2\right]$$

$$V_{o2} = -\left[\frac{20k}{10k} * (-2V_1) + \frac{20k}{10k}v_2\right]$$

$$V_o = 2V_2 - 4V_{01}$$

Question Bank

1. What is op-amp? List the characteristics of an ideal Op-Amp
2. Derive the output voltage for the following
    a. Inverting amplifier
    b. Non-Inverting amplifier
    c. Integrator
    d. Differentiator
    e. Summing amplifier
    f. Subtractor
3. Explain voltage follower with neat circuit and necessary equations
4. Obtain the expression for voltage gain of an Inverting amplifier
5. Obtain the expression for voltage gain of an Non-Inverting amplifier
6. Calculate the output of the three input summing amplifier, given R_1 = 200kΩ, R_2 = 250kΩ, R_3 = 500kΩ, R_f = 1MΩ, V_1 = -2V, V_2 = -1V and V_3 = 3V
7. For a non inverting amplifier R_1 = 20KΩ, R_f = 200KΩ Calculate the output voltage for the following input voltages
    (i). V_i = 0.2V (ii). V_i = 0.5sin314tV (iii). V_i = -0.4V
8. A non-inverting amplifier circuit has an input resistance of 10KΩ and feedback resistance 60KΩ with load resistance of 47KΩ. Draw the circuit. Calculate the output voltage, voltage gain, load current when the input voltage is 1.5V.
9. The input to the basic differentiator circuit is a sinusoidal voltage of peak value of 10mV and frequency 1.5 KHz. Find the output if, R_f = 100KΩ and C1 = 1μF.
10. A certain op-amp has an open loop voltage gain of 100000 and a common mode gain of 0.2. Determine the CMRR and express it in decibels.