Tejashree. S
Assistant
Professor.

MODULE-3

OPERATIONAL AMPLIFIERS.

SYLLABUS:

Operational Amplifiers - Introduction, the operational amplifier, Block diagram representation of Typical Op-amp, Schematic Symbol, Op-Amp parameters - gain, input resistance, output resistance, CMRR, slew-rate, Bandwidth, input offset voltage, Input bias current and offset current, the ideal Op-Amp, Equivalent circuit of Op-Amp, Open loop Op-Amp configurations, differential amplifier, Inverting & Non-inverting.

Operational Amplifier:

* An operational amplifier is a direct coupled high-gain amplifier consisting of one or more differential amplifier used to amplify ac and dc signals.
* It is designed to perform mathematical operations such as addition, subtraction, multiplication, differentiation and integration etc.

Block diagram representation of a Typical Op-Amp:

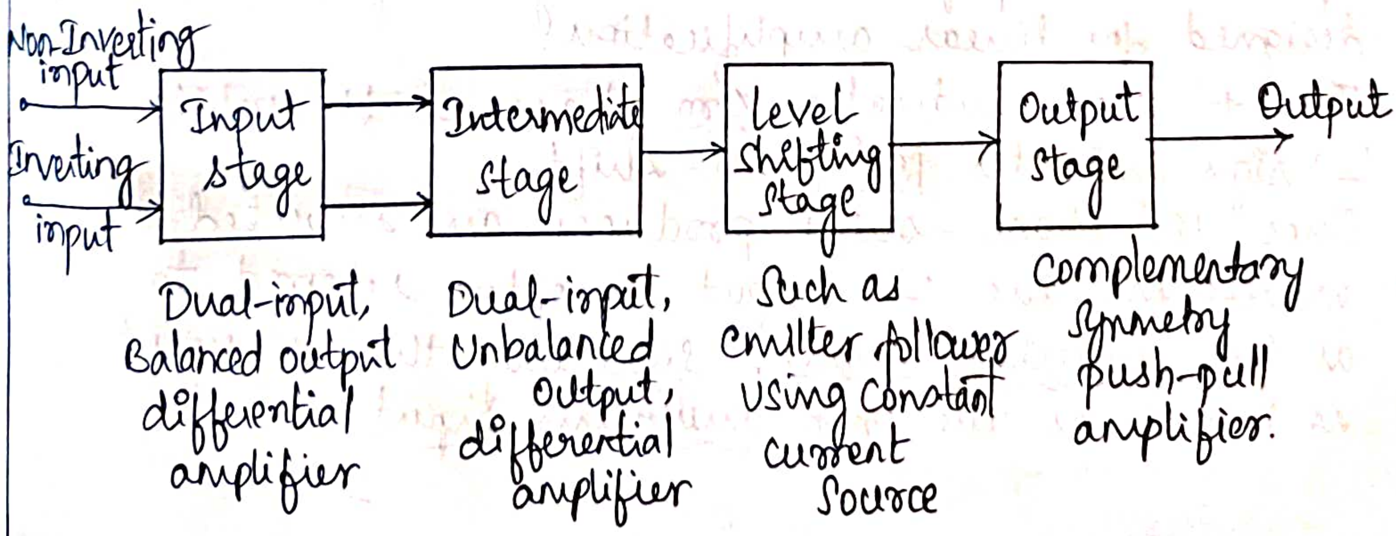

fig: Block diagram of a Typical Op-amp.

→ Input stage:
- provides most of the voltage gain and establishes input resistance.

→ Intermediate stage:
- driven by the output of first stage.
- output level of intermediate stage is above ground as direct coupling is used.

→ Level stage:
- level shifting stage is used to shift the output of intermediate stage downward.

→ Output stage:
- increases the output voltage swing.
- raises the current supplying capability.
- provides low output resistance.

Schematic Symbol:

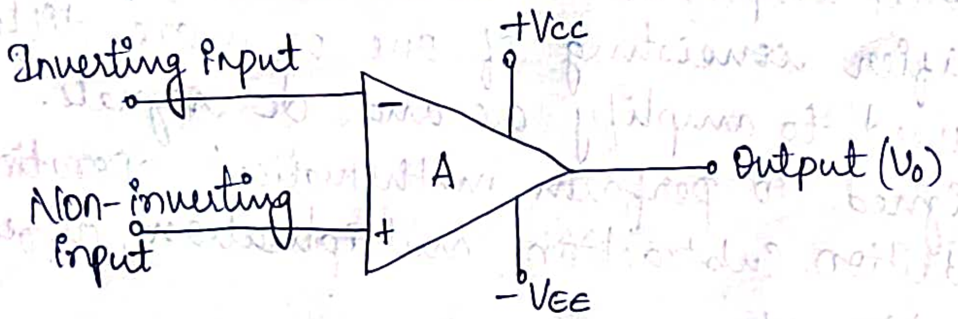

fig: schematic symbol for Op-amp.

- operational amplifiers are analog integrated circuits designed for linear amplification.
- The '+' sign indicates zero phase-shift, while '−' sign indicates 180° phase-shift.
- Since 180° phase-shift produces an inverted waveform, the '−' input is often referred to as the 'inverting input'. Similarly the '+' input is known as the 'non-inverting input'.

Tejashree S
ECE, SVIT

Operational Amplifier Parameters:

(1) Open-loop voltage gain:

The open-loop voltage gain of an operational amplifier is defined as the ratio of output voltage to input voltage measured with no feedback applied.

$$\boxed{A_{V(OL)} = \frac{V_{out}}{V_{in}}}$$

where $A_{V(OL)}$ = open-loop voltage gain.

V_{out} & V_{in} = output and input voltages.

- The open-loop voltage gain is often expressed in decibels (dB) rather than as a ratio.

$$\boxed{A_{V(OL)_{dB}} = 20 \log_{10}\left(\frac{V_{out}}{V_{in}}\right)}$$

- Most operational amplifiers have open-loop voltage gain of 90 dB.

(2) Closed-loop voltage gain:

The closed-loop voltage gain of an operational amplifier is defined as the ratio of output voltage to input voltage measured with a small proportion of the output fedback to the input. (negative feedback applied).

$$\boxed{A_{V(CL)} = \frac{V_{out}}{V_{in}}}$$

$$\boxed{A_{V(CL)_{dB}} = 20 \log\left(\frac{V_{out}}{V_{in}}\right)}$$

where $A_{V(CL)}$ = closed loop voltage gain

V_{out} & V_{in} = output and input voltages.

Tejashree. S
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Problem:

* An operational amplifier operating with negative feedback produces an output voltage of 2V when supplied with an input of 400μV. Determine the value of closed-loop voltage gain.

Soln:

$$A_{v(CL)} = \frac{V_{out}}{V_{in}}$$

Given: $V_{in} = 400 \times 10^{-6}$ V

$V_o = 2V$.

$$A_{v(CL)} = \frac{2}{400 \times 10^{-6}}$$

$$\boxed{A_{v(CL)} = 5000}.$$

$$A_{v(CL)dB} = 20 \log_{10}(5000)$$

$$= 20 \times 3.7$$

$$\boxed{A_{v(CL)} = 74\,dB}.$$

③ Input Resistance:

The input resistance of an operational amplifier is defined as the ratio of input voltage to input current expressed in ohms.

$$\boxed{R_{in} = \frac{V_{in}}{I_{in}}}$$

Where, R_{in} - input resistance in ohms.

V_{in} & I_{in} = input voltage and currents.

* An operational amplifier has an input resistance of 2MΩ. Determine the input current when an input voltage of 5mV is present.

Soln: Given: $V_{in} = 5mV$, $R_{in} = 2M\Omega$, $I_{in} = ?$

$$R_{in} = \frac{V_{in}}{I_{in}}$$

$$I_{in} = \frac{V_{in}}{R_{in}} = \frac{5mV}{2M} = \frac{5 \times 10^{-3}}{2 \times 10^{6}}$$

$$\boxed{I_{in} = 2.5 \times 10^{-9} A}$$

Tejashree.S
ECE, SVIT

④ **Output resistance:**

Output resistance, R_o is the equivalent resistance that can be measured between the output terminal of the op-amp and the ground.

It is 75Ω for the 741C op-amp.

⑤ **CMRR:** Common mode Rejection Ratio.

It can be defined as the ratio of the differential voltage gain Ad to the common mode voltage gain Acm,

$$\boxed{CMRR = \frac{A_d}{A_{cm}}}$$

where A_d = differential voltage gain.

- The measure of an amplifiers ability to reject common mode signals is called as common mode rejection ratio.

CMRR in decibels (dB),

$$\boxed{CMRR = 20 \log \left(\frac{A_d}{A_{cm}}\right)}$$

where A_{cm} = common mode voltage gain

* Determine the CMRR and express it in dB for an op-amp with an open-loop differential voltage gain of 85000 & a common mode gain of 0.25.

Soln: $A_{OL} = 85000$, $A_c = 0.25$

$$CMRR = \frac{A_{OL}}{A_{cm}} = \frac{85000}{0.25}$$

$$CMRR = 20 \log(340000)$$

$$\boxed{CMRR = 110.629 \text{ dB}}$$

⑥ **Slew rate:**

Slew rate is defined as the maximum rate of change of output voltage per unit of time and is expressed in volts per microseconds.

$$\boxed{SR = \left.\frac{dV_o}{dt}\right|_{max} \quad V/\mu s}$$

- Slew rate changes with change in voltage gain and is normally specified at unity (+1) gain.

- The slew rate of an op-amp is fixed.
- Thus slew rate is one of the important factors in selecting the op-amp for ac applications.
- The slew rate for 741 IC is 0.5V/μs.

⑦. Bandwidth:

The gain-bandwidth product (GB) is the bandwidth of the op-amp when the voltage gain is 1.

- This is the maximum frequency at which op-amp can operate with expected behavior.
- 741 op-amp has GB of 1MHz.

⑧ Input-offset voltage: V_{os}

- Input offset voltage is the voltage that must be applied between the two input terminals of an op-amp to null the output.
- V_{os} → ideal value '0' volts
  V_{os} → practical value 2mV or less.
- Input offset voltage, V_{os} is the differential dc voltages required between the inputs to force the output to zero volts.
- The smaller the value of V_{os}, the better the input terminals are matched.
- For 741C precision op-amp has $V_{os} = 150\mu V$ maximum.

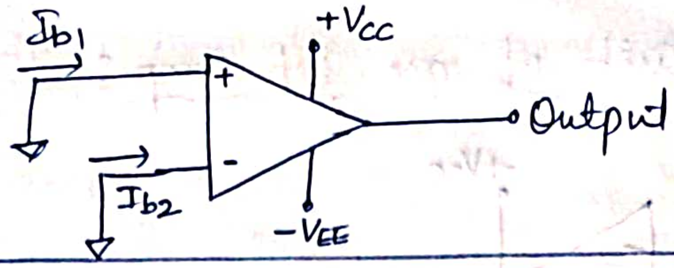
⑨ Input offset current:

The algebraic difference between the currents into the inverting and non-inverting terminals is referred to as input offset current I_{io}.

$$\boxed{I_{io} = |I_{B1} - I_{B2}|}$$

where I_{B1} is the current into the non inverting input and I_{B2} - current into the inverting input.

- The input offset current for 741C is 200nA maximum.



(10) **Input-Bias current:**

It is the average of the currents that flow into the inverting and non-inverting input terminals of the op-amp.

$$\boxed{I_B = \frac{I_{B1} + I_{B2}}{2}}$$

where I_{B1} & I_{B2} are the two input currents.

- For the 741C $I_B = 500nA$.
- whereas I_B for the precision 741C is $\pm 7nA$.

The Ideal Op-Amp characteristics:

→ The Ideal op-Amp would exhibit the following electrical characteristics:

1. Infinite voltage gain A.
2. Infinite input resistance R_i, so that almost any signal source can drive it.
3. Zero output impedance/resistance R_o, so that output can drive an infinite number of other devices.
4. Zero output voltage when input voltage is zero.
5. Infinite bandwidth so that any frequency signal from 0 to ∞ Hz can be amplified without attenuation.
6. Infinite common-mode rejection ratio so that the output common-mode noise voltage is zero.
7. Infinite slew rate so that output voltage changes occur simultaneously with input voltage changes.

Tejashree S
Assistant professor
ECE, SVIT.

Equivalent circuit of an Op-Amp:

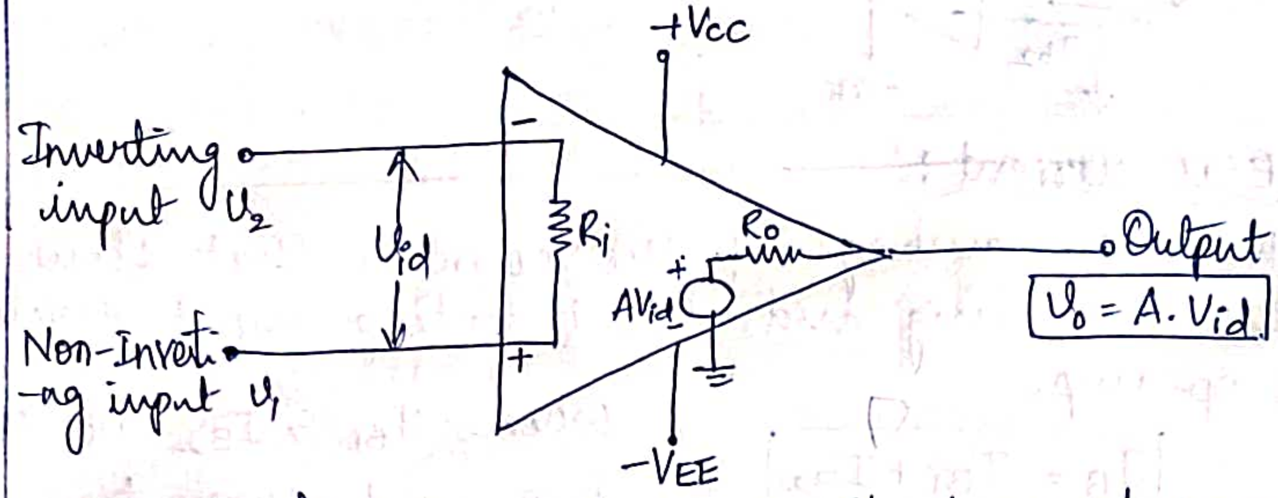


fig: Equivalent circuit of an op-amp.

- The equivalent circuit is useful in analysing the basic operating principles of op-amps and in observing the effects of feedback arrangements.
- The output voltage for the above circuit is

$$V_0 = A . V_{id}$$

$$\boxed{V_0 = A (V_1 - V_2)} \longrightarrow (1)$$

where, A - large - signal voltage gain.

V_{id} = difference input voltage

V_1 = voltage at the non-inverting input terminal with respect to ground.

V_2 = voltage at the inverting terminal with respect to ground.

- Eqn (1) indicates the output voltage V_o is directly proportional to the algebraic difference between the two input voltages,

Open-Loop Op-Amp Configurations:

- Open-loop indicates the output signal is not fedback in any form as part of the input signal.
- When connected in open-loop configurations, the op-amp simply functions as high-gain amplifier.

- There are three open-loop op-amp configurations,
1. Differential amplifier
2. Inverting amplifier.
3. Non-inverting amplifier.

1. Differential Amplifier:

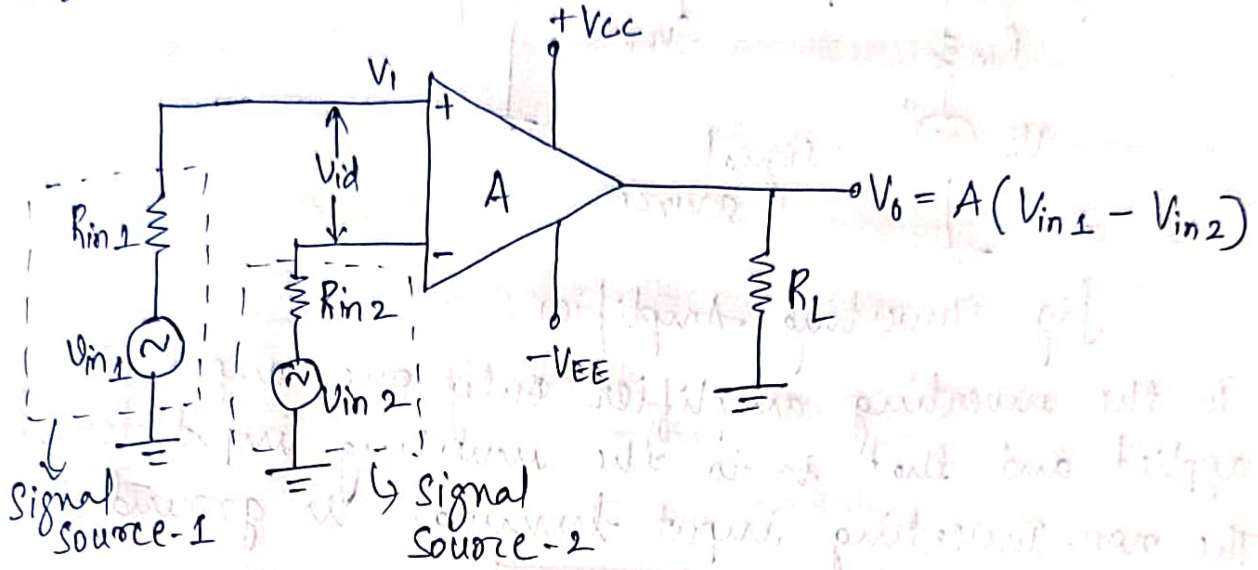


fig: open-loop Differential Amplifier.

- Figure shows the open-loop differential amplifier in which input signals V_{in1} and V_{in2} are applied to the positive and negative input terminals.
- Since the op-amp amplifies the difference between the two input signals, this configuration is called the differential amplifier.
- The source resistances R_{in1} and R_{in2} are normally negligible compared to input resistance R_i.
- Therefore, the voltage drop across these resistors can be assumed to be zero. i.e, $\boxed{V_1 = V_{in1} \text{ and } V_2 = V_{in2}}$.

Thus, $\boxed{V_0 = A(V_{in1} - V_{in2})}$

- Hence, the output voltage is equal to the voltage gain A times the difference between two input voltages.

Tejashree.S
Assistant professor
ECE, SVIT

(2) Inverting-Amplifier:

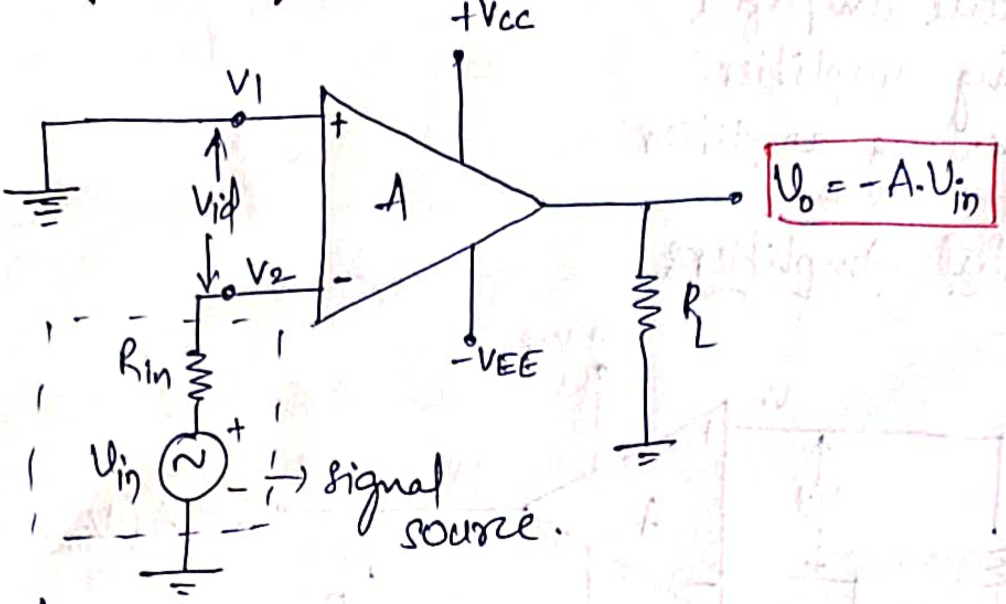


fig: Inverting Amplifier.

- In the inverting amplifier only one input is applied and that is to the inverting input terminal.
- The non-Inverting input terminal is grounded.

Since $\boxed{V_1 = 0V}$ and $\boxed{V_2 = V_{in}}$

WKT, $V_0 = A \cdot (V_1 - V_2) \longrightarrow (1)$

$= A(0 - V_{in})$

$\boxed{V_0 = -A \cdot V_{in}} \longrightarrow (2)$

- The negative sign indicates that the output voltage is out of phase with respect to input by 180°.
- Thus in the inverting amplifier the input signal is amplified by gain A and is also inverted at the output.

(3) Non-Inverting Amplifier:

- The figure below shows non-inverting amplifier.
- The input is applied to the non-inverting input terminal, and the inverting terminal is connected to ground.

Hence, $\boxed{V_1 = V_{in}}$ and $\boxed{V_2 = 0V}$

$$V_0 = (V_1 - V_2)\cdot A$$
$$= (V_{in} - 0)\cdot A$$
$$\boxed{V_0 = A\cdot V_{in}} \longrightarrow (3).$$

This means that the output voltage is larger than the input voltage by gain A and is in-phase with the input signal.

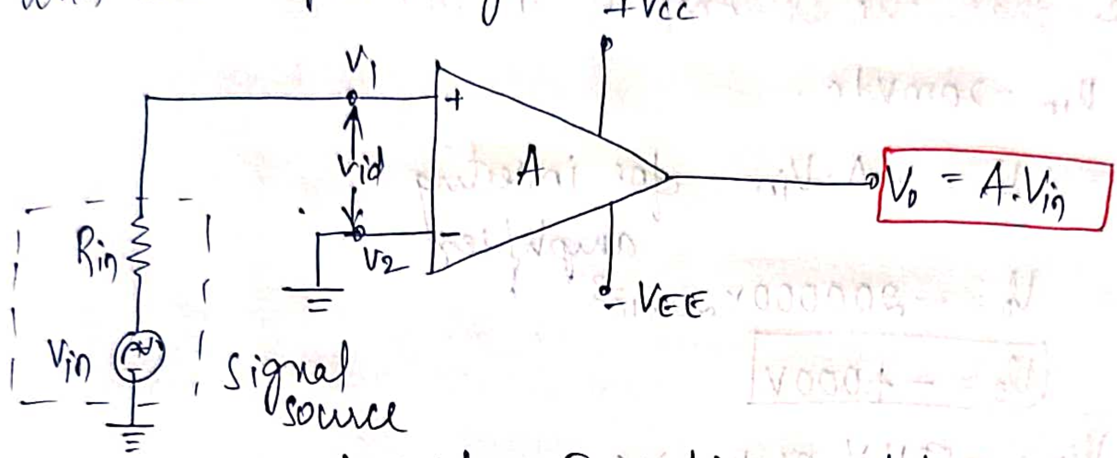


fig: Non-Inverting Amplifier.

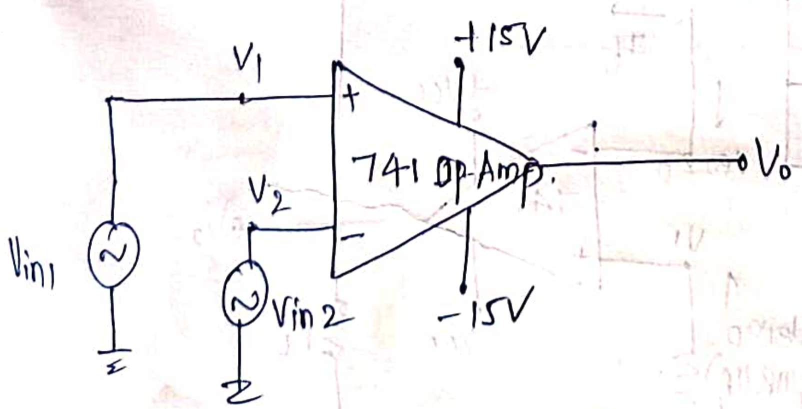
Problems:

① Determine the output voltage in each of the following cases for the open-loop differential amplifier.

a) $V_{in1} = 5\mu V$ dc, $V_{in2} = -7\mu V dc$.

b) $V_{in1} = 10mV rms$, $V_{in2} = 20mV rms$.

Soln:



Note:
For 741 op-Amp.
$A = 200{,}000$
$R_i = 2M\Omega$
$R_o = 7.5\Omega$
$+V_{cc} = 15V$
$V_{EE} = -15V$
O/p vtg swing $= \pm 14V$

a) WKT, $V_0 = A(V_{in1} - V_{in2})$
$$= 200000(5\mu - (-7\mu))$$
$$\boxed{V_0 = 2.4Vdc}$$

Tejashree S
Assistant professor
ECE, SVIT

b) $V_0 = A(V_{in1} - V_{in2})$ $\quad V_{in1} = 10mV_{rms}$

$= 200000(10m - 20m)$ $\quad V_{in2} = 20mV_{rms}$

$\quad A = 200000$

$\boxed{V_0 = -2000 V_{rms}}$

2. Determine the output voltage for the inverting amplifier

a) $V_{in} = 20mVdc$

b) $V_{in} = -50\mu V$ peak sine wave.

Assume that the Op-Amp is a 741.

Soln. a) $V_{in} = 20mVdc.$

$V_0 = -A \cdot V_{in}$ for inverting amplifier.

$V_0 = -200000 \times 20 \times 10^{-3}$

$\boxed{V_0 = -4000V}$

b) $V_{in} = -50\mu V$ peak sine wave

$V_0 = -A \cdot V_{in}$

$= -200000 \times -50 \times 10^{-6}$

$\boxed{V_0 = 10V \text{ peak}}$ sine wave

Op-Amp Applications:

1. Inverting Configurations:

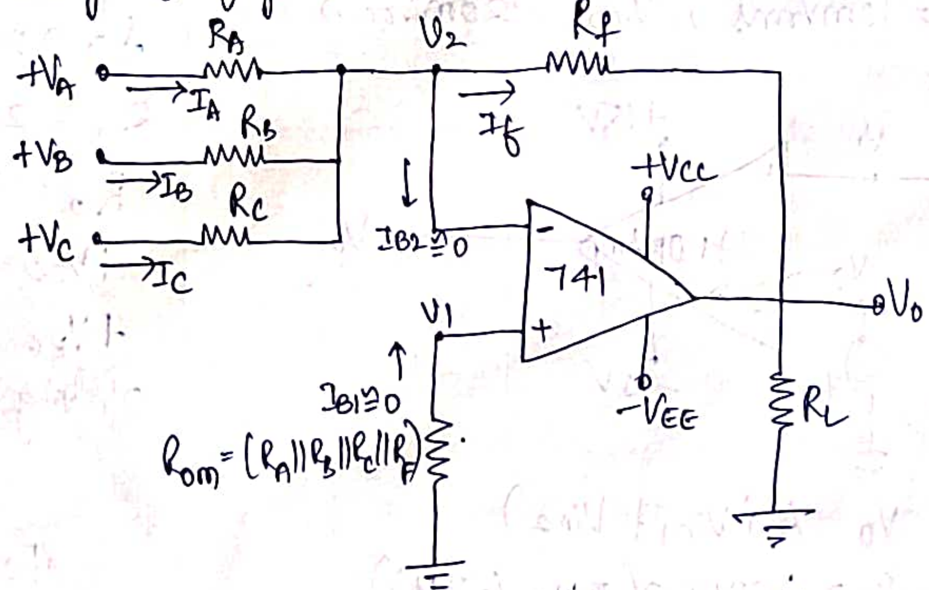


fig: Inverting configuration with three inputs can be used as a summing, scaling and averaging amplifier

- Figure shows, inverting configurations with three inputs V_A, V_B and V_C.
- Depending on the relationship between feedback resistor R_F and the input resistors R_A, R_B and R_C, the circuit can be used as a summing amplifier, scaling amplifier or an averaging amplifier.
- Apply KCL at node V_2.

$$I_A + I_B + I_C = I_B + I_F \longrightarrow (1)$$

- Since R_i and A of the op-amp are ideally infinite

$$I_B = 0A$$

$$V_1 = V_2 = 0,$$

$$(1) \Rightarrow \frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C} = 0 - \frac{V_o}{R_F}$$

$$\boxed{V_0 = -\left[\frac{R_F}{R_A}\cdot V_A + \frac{R_F}{R_B}\cdot V_B + \frac{R_F}{R_C}\cdot V_C\right]} \longrightarrow (2)$$

↳ general Equation

a) Summing amplifier:

If $R_A = R_B = R_C = R$,

then eqn (2) $\Rightarrow \boxed{V_0 = -\frac{R_F}{R}(V_A + V_B + V_C)} \longrightarrow (3)$

- This means that the output voltage is equal to the negative sum of all the inputs times the gain of the circuit R_F/R. Hence the circuit is called as a summing amplifier.
- When gain of the circuit is 1,

Then $\boxed{V_0 = -(V_A + V_B + V_C)} \longrightarrow (4)$

b) Scaling Amplifier:

If each input voltage is amplified by a different factor, then they are called scaling amplifier.

Tejashree S
Assistant professor
ECE, SVIT

- This condition can be accomplished if R_A, R_B and R_C are different in value.
- Thus output voltage of scaling amplifier is

$$\boxed{V_O = -\left(\frac{R_f}{R_A} V_A + \frac{R_F}{R_B} V_B + \frac{R_F}{R_C} \cdot V_C\right)}$$

where, $\frac{R_f}{R_A} \neq \frac{R_F}{R_B} \neq \frac{R_F}{R_C}$.

c) Averaging circuits:
- The Output voltage is equal to the average of all the input voltages.
- This is accomplished by using all input resistors of equal value $R_A = R_B = R_C = R$.
- The gain by which each input is amplified must be equal. to 1 over the number of inputs.

$$\boxed{\frac{R_f}{R} = \frac{1}{n}}$$

where n is the number of inputs

- Thus, if there are three inputs, we want $R_f/R = 1/3$

thus $\boxed{V_O = -\left(\frac{V_A + V_B + V_C}{3}\right)}$

② Non-Inverting Configuration:

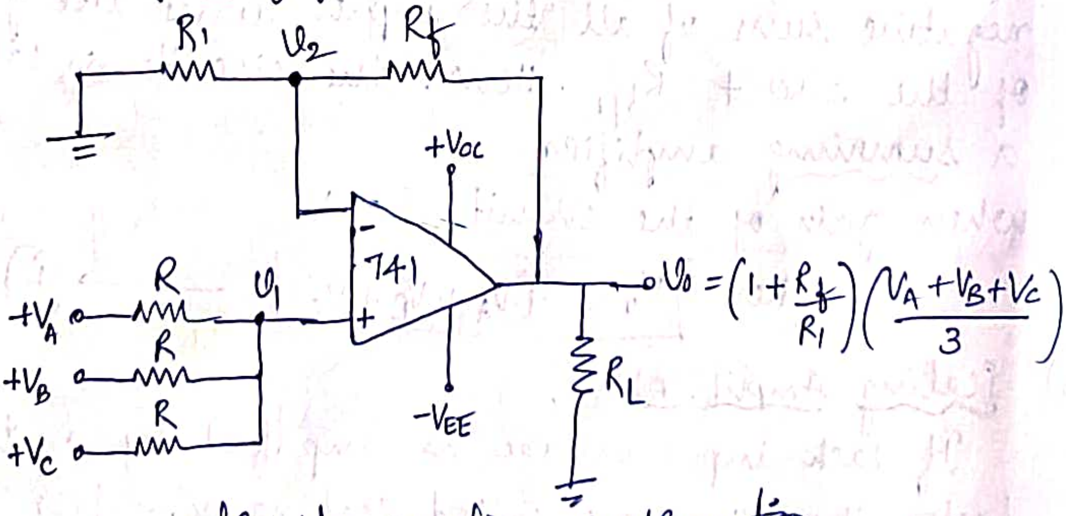


fig: Non-inverting configuration

- If input voltage sources and resistors are connected to the non-inverting terminal, the circuit can be used either as a summing or averaging amplifier.
- The voltage V_1 at the non-inverting terminal is

$$V_1 = \frac{V_A}{3} + \frac{V_B}{3} + \frac{V_C}{3} = \frac{V_A + V_B + V_C}{3}$$

$$\boxed{V_1 = \frac{V_A + V_B + V_C}{3}} \longrightarrow (1).$$

The gain of Non-Inverting Amplifier is.

$$\boxed{A_V = 1 + \frac{R_f}{R_1}} \longrightarrow (2).$$

Hence the output voltage V_0 is.

$$V_0 = A \cdot V_{in} = A \cdot V_1 \qquad V_{in} = V_1$$

$$\boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right)\left(\frac{V_A + V_B + V_C}{3}\right)} \longrightarrow (3).$$

a) Averaging amplifier:

- Equation (3) shows that output voltage is equal to the average of all input voltages times the gain of the circuit $(1 + R_f/R_1)$, Hence the name averaging amplifier.

b) Summing amplifier:

- Equation (3) reveals that if the gain $\left(1 + \frac{R_f}{R_1}\right)$ is equal to the number of inputs, the output voltage becomes equal to the sum of all the input voltages.

That is, if $\left(1 + \frac{R_f}{R_1}\right) = 3$. in Eq^n (3).

Then, $$\boxed{V_0 = V_A + V_B + V_C} \longrightarrow (4)$$

Tejashree S
Assistant Professor
ECE, SVIT

(3) Differential Configuration:

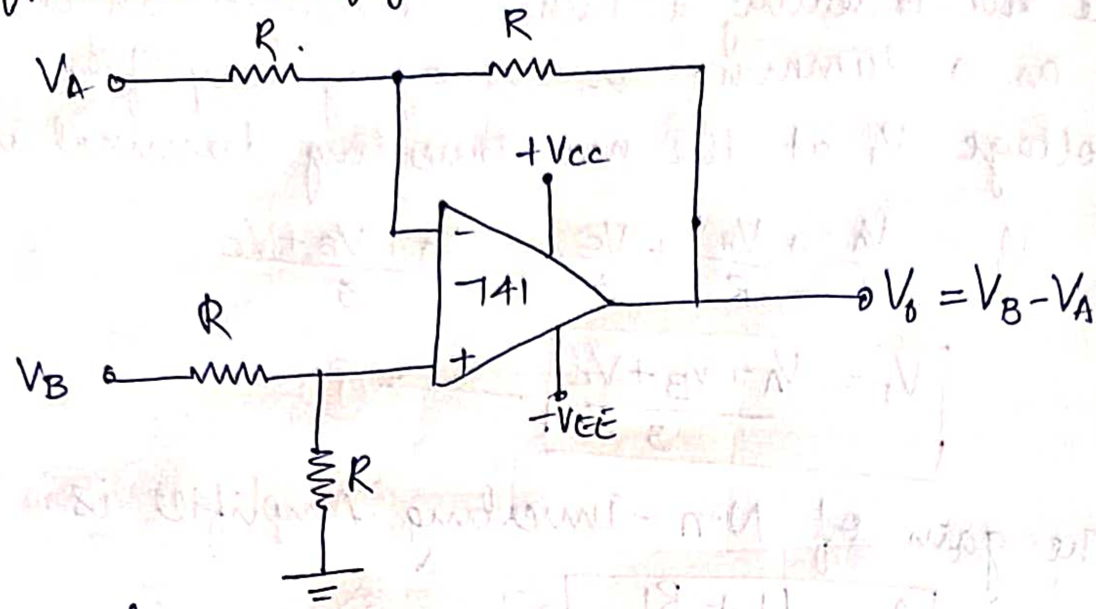


fig: Basic Differential amplifier used as a Subtractor.

a) Subtractor:

- In the above figure, input signals can be scaled to the desired values by selecting appropriate values for the external resistors. This is called as scaling amplifier.

The output voltage of the differential amplifier with a gain of 1 is:

$$V_o = -\frac{R}{R}(V_A - V_B)$$

Note: Gain of differential Ampr is same as Inverting Ampr.

$$\therefore \boxed{V_o = V_B - V_A} \rightarrow (1)$$

from eqn (1), we can say that it acts as a Subtractor

b) Summing Amplifier:

- A four input summing amplifier may be constructed using the basic differential amplifier.
- Two additional input sources are connected, one each to the inverting and non-inverting input terminals through resistor R.

Tejashree. S
Assistant professor
ECE, SVIT

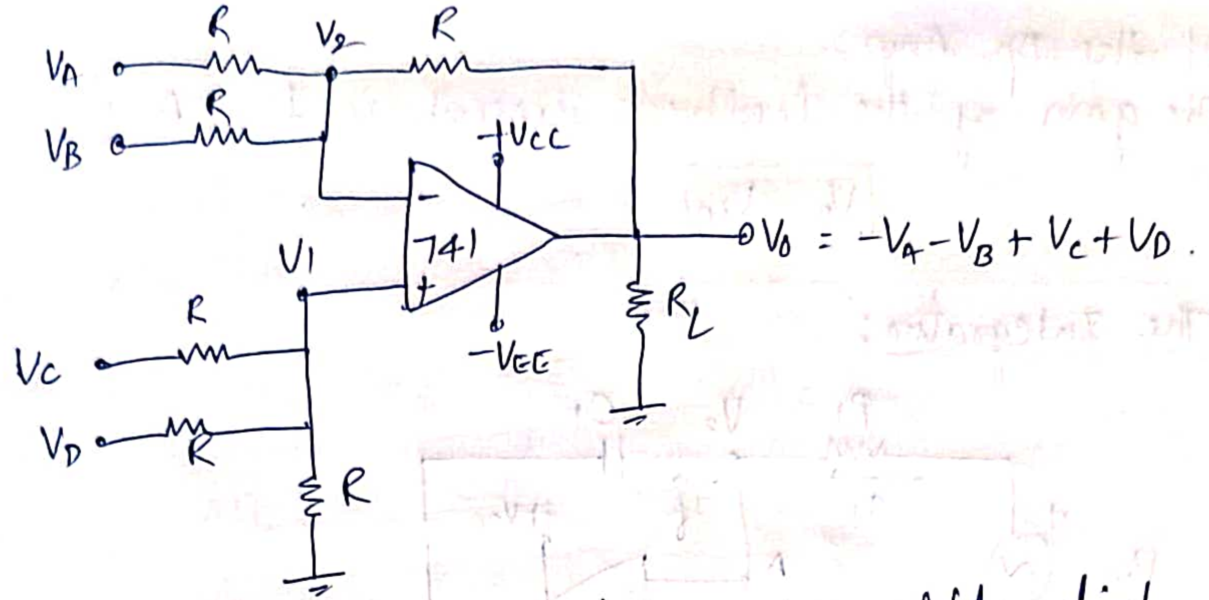


fig: Summing amplifier using differential configuration.

- Thus the output voltage due to all four input voltages is given by,

$$\boxed{V_o = -V_A \quad V_B + V_C + V_D}$$

(4) Voltage Follower:

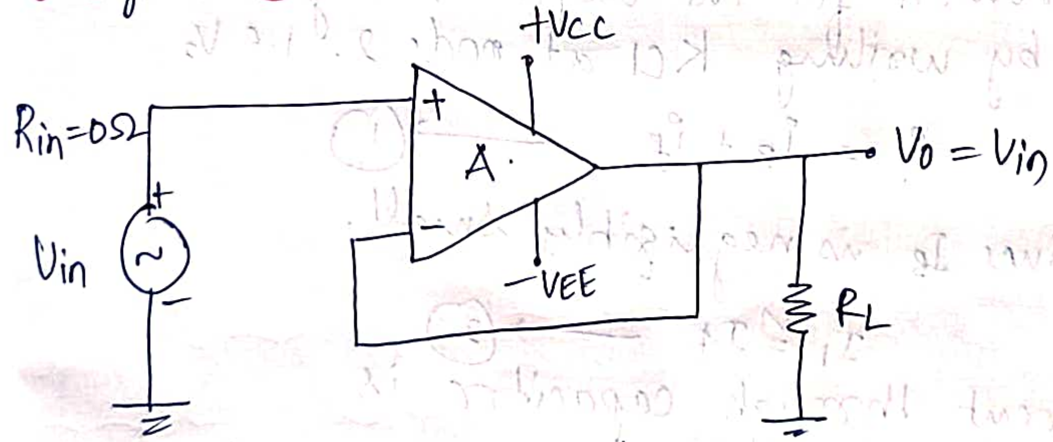


fig: Voltage Follower.

- when the non-inverting amplifier is configured for unity gain, it is called a voltage follower.
- In voltage follower, the output voltage is equal to and in phase with the input.
- In other words, the Voltage follower Output follows the input.
- The output voltage is fedback into the inverting terminal

of the Op-Amp.

- The gain of the feedback circuit is 1. $\boxed{A=1}$

$\therefore \boxed{V_0 = V_{in}}$

(5) The Integrator:

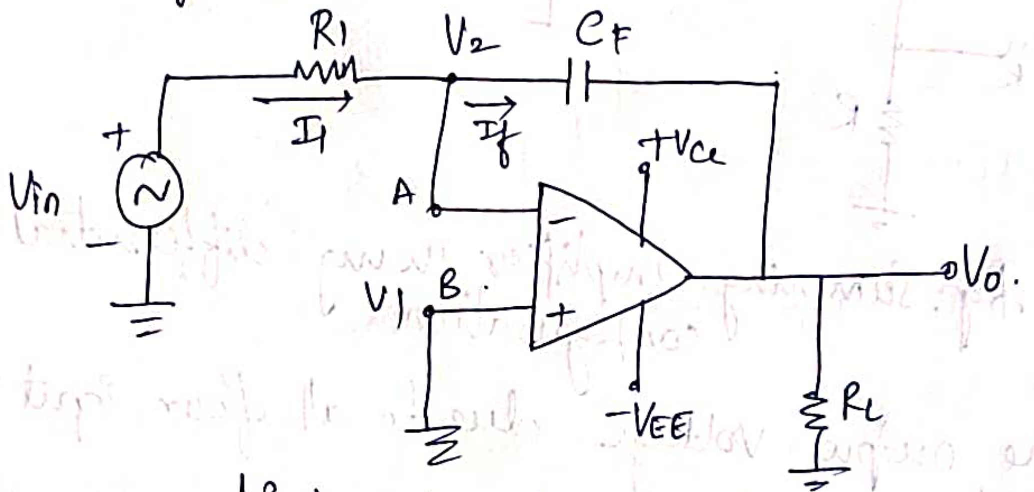


fig: Integrator circuit.

- A circuit in which the output voltage waveform is the integral of the input voltage waveform is called Integrator or integration amplifier.
- The expression for the output voltage V_0 can be obtained by writing KCL at node 2. i.e V_2.

$$i_1 = i_B + i_f \longrightarrow (1)$$

Since I_B is negligibly small,

$$I_1 \simeq I_f \longrightarrow (2)$$

- The current through capacitor is

$$i_c = C_f \cdot \frac{dV_c}{dt} \longrightarrow (3)$$

$$\therefore \frac{V_{in} - V_2}{R_1} = C_f \frac{d}{dt}(V_2 - V_0)$$

WKT $V_1 = V_2 \simeq 0$ because A is very large.

$$\therefore \frac{V_{in}}{R_1} = C_f \frac{d}{dt}(-V_0)$$

The output voltage can be obtained by integrating both sides with respect to time.

$$\int_0^t \frac{V_{in}}{R_1} dt = \int_0^t C_f \frac{d}{dt}(-V_0) dt$$

$$\frac{1}{R_1}\int_0^t V_{in} \cdot dt = -C_f \int_0^t \frac{d}{dt}(V_0) dt$$

$$\therefore \boxed{V_0 = \frac{-1}{R_1 C_f}\int_0^t V_{in}\, dt + C}$$

$$\left(-\frac{1}{R C_f}\right) = \text{gain}$$

where C is the integration constant.

The frequency response of the basic integrator is

$$\boxed{f = \frac{1}{2\pi R_1 C_f}}$$

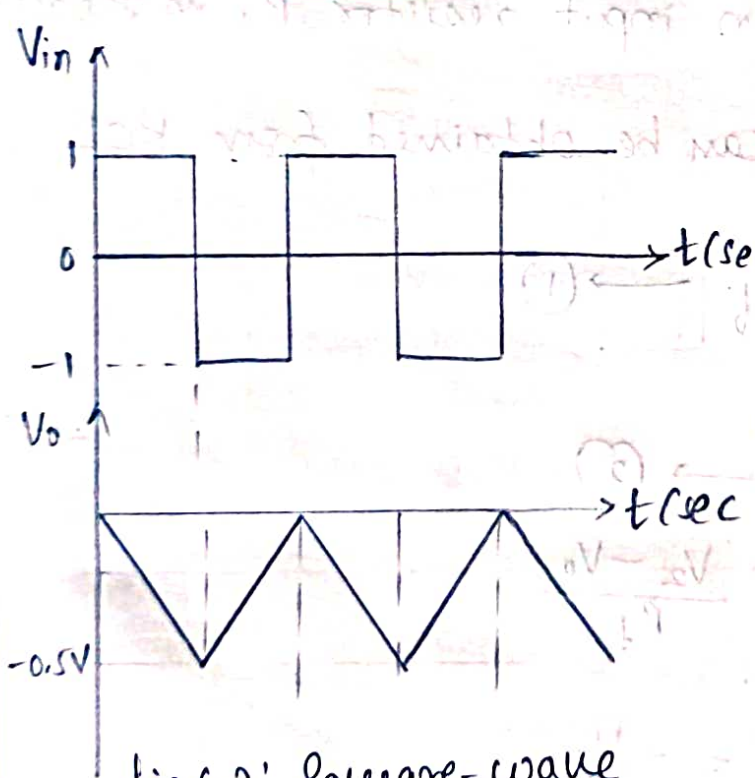


fig (a): Square-wave input

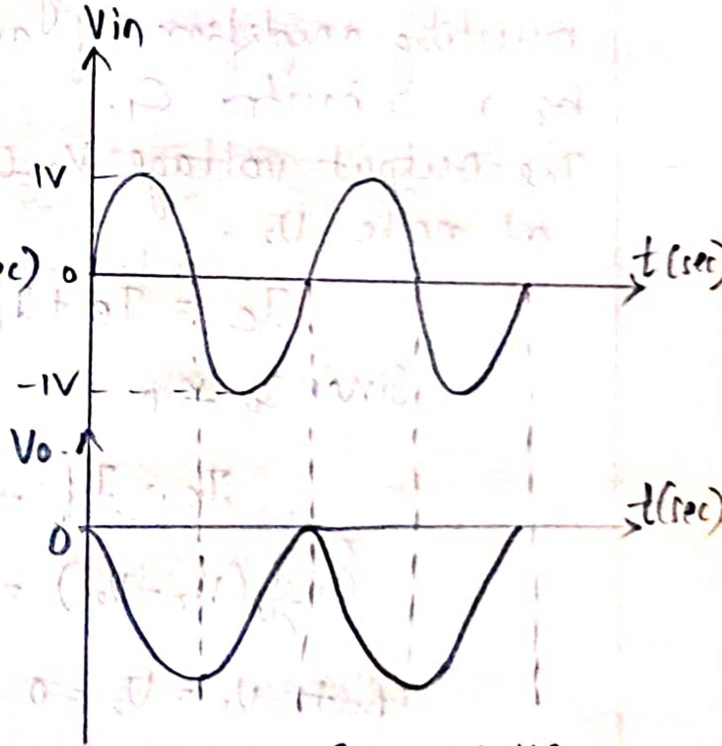


fig (b): Sine-wave input.

Tejashree.S
Assistant professor
ECE, SVIT.

(6) Differentiator:

- In differentiator circuit, the output is the differentiation of the input voltage.

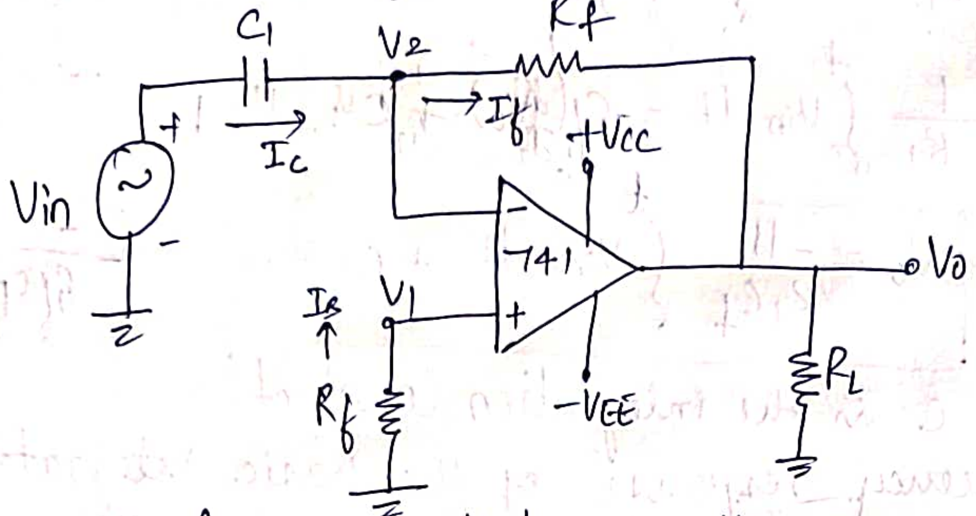


fig: Differentiator circuit.

- The differentiator may be constructed from a basic inverting amplifier if an input resistor R_1 is replaced by a capacitor. C_1.
- The output voltage V_o can be obtained from KCL at node V_2.

$$I_C = I_B + I_f \longrightarrow (1)$$

Since $I_B \simeq 0$.

$$I_C = I_f \longrightarrow (2).$$

$$C_1 \frac{d}{dt}(V_{in} - V_2) = \frac{V_2 - V_o}{R_f}$$

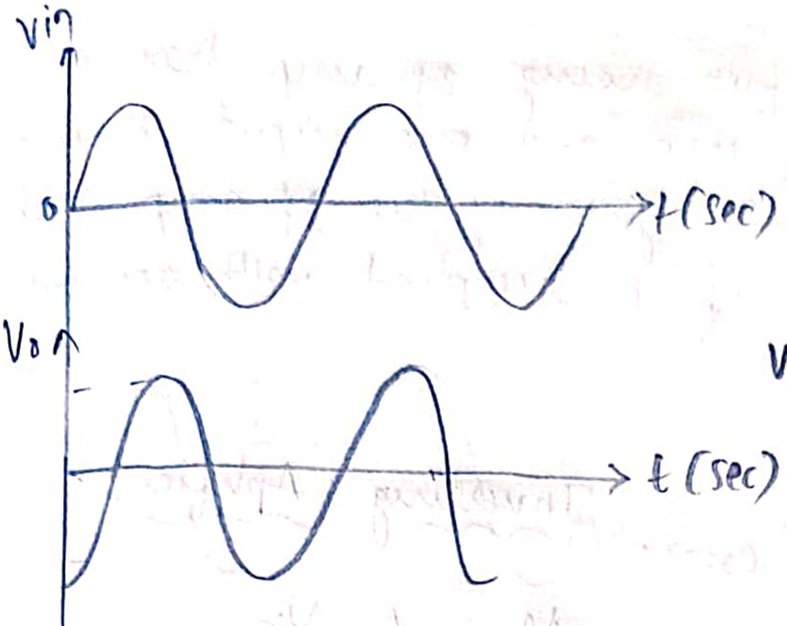
But $V_1 = V_2 = 0$.

$$\therefore C_1 \cdot \frac{dv_{in}}{dt} = -\frac{V_o}{R_f}$$

Thus, $$\boxed{V_o = -R_f C_1 \frac{dv_{in}}{dt}} \longrightarrow (3).$$

- The frequency response of differentiator circuit is

$$\boxed{f = \frac{1}{2\pi C_1 R_f}}$$



fig(a) sine-wave input.

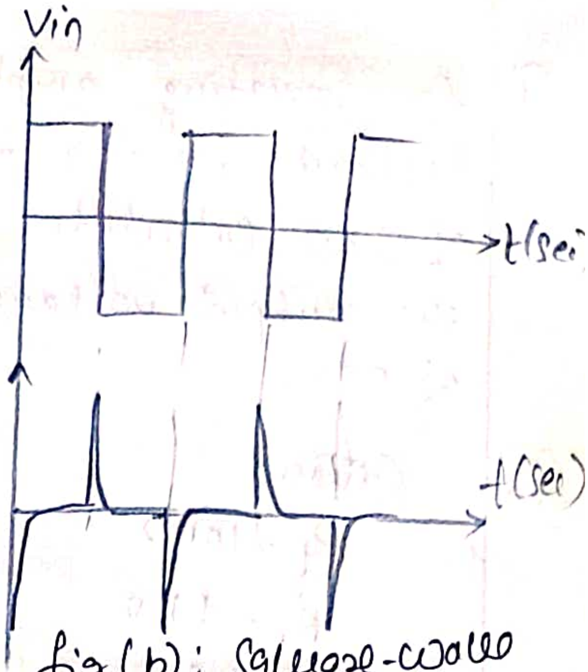


fig (b): square-wave input.

Formulae:

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

(2) $I_{bias} = \frac{I_{B1} + I_{B2}}{2}$

(3) $I_{OS} = |I_{b1} - I_{b2}|$

(4) Slew rate $= \frac{\Delta V_{out}}{\Delta t}$

(5) $V_{in} = V_m \sin \omega t \cdot V$

(6) For inverting Ampr,

$V_0 = -\frac{R_f}{R_1} V_{in}$

$A = R_f / R_1$

$V_0 = -A V_{in}$.

(7) For Non-inverting Ampr

$V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}$.

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

$V_0 = A \cdot V_{in}$

(8) $I_L = \frac{V_0}{R_L}$

(9) $I_1 = C \cdot \frac{dV_1}{dt}$, $I_2 = C \cdot \frac{dV_2}{dt}$

(10) For Inverting Summer

$V_0 = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)$

(11) For Non-inverting Summer

$V_0 = (V_1 + V_2 + V_3)\left(1 + \frac{R_f}{R_1}\right)$

(12) For Subtractor

$V_0 = \frac{R_f}{R_2} V_2 - \frac{R_f}{R_1} V_1$

(13) For Integrator

$V_0 = -\frac{1}{R_1 C_f} \int_0^t V_{in} \cdot dt$

(14) For Differentiator

$V_0 = -R_f \cdot C_1 \frac{dV_{in}}{dt}$

(15) $V_0 = V_2 - V_1$ for Subtractor

Tejashree.S
Assistant Professor
ECE, SVIT

① An inverting amplifier using op-amp has a feedback resistor of $10 k\Omega$ and one input resistor of $1 k\Omega$. Calculate the gain of the op-amp and the output voltage if it supplied with an input of 0.5V.

Soln: Given:

$R_f = 10 k\Omega$

$R_1 = 1 k\Omega$

$A_v = ?$

$V_0 = ?$

$V_{in} = 0.5V$

$A_v = \frac{-R_f}{R_1} = -\frac{10 \cancel{K}}{1 \cancel{K}}$

$\boxed{A_v = -10}$

Inverting Aplifier:

$V_0 = -A_v . V_{in}$

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

$V_0 = -\frac{R_f}{R_1} . V_{in}$

$V_0 = -\frac{10 \cancel{K}}{1K} . 0.5$

$\boxed{V_0 = -5V}$

② Find the gain of non-inverting amplifier if $R_f = 10 k\Omega$ and $R_1 = 1 k\Omega$. and output voltage for $V_{in} = 10V$.

Soln. Given

$R_f = 10 k\Omega$

$R_1 = 1 k\Omega$

$V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}$

$= 11 \times 10$

$\boxed{V_0 = 110V}$

For non-inverting amplifier:

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

$= 1 + \frac{10 \cancel{K}}{1 \cancel{K}}$

$\boxed{A = 11}$

③ A non-inverting amplifier has a closed loop gain of 25. If input voltage $V_i = 10mV$, $R_f = 10 k\Omega$. Determine the value of R_1 and output voltage V_0.

Tejashree. S
Assistant Professor
ECE, SUIT.

Soln: Given:

Closed loop gain $A = 25$

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

WKT, for non-inverting ampr.

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

$$25 = 1 + \frac{10K}{R_1}$$

$$25 - 1 = \frac{10K}{R_1}$$

$$24 = \frac{10K}{R_1}$$

$$R_1 = \frac{10K}{24}$$

$$\boxed{R_1 = 416.67\Omega}$$

Output Voltage V_o:

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

$$= 25 \times 10mV$$

$$\boxed{V_o = 250mV}$$

④ Design an inverting and non-inverting operational amplifier to have a gain of 15.

Soln: Given:

Gain $A = 15$.

For inverting Ampr:

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

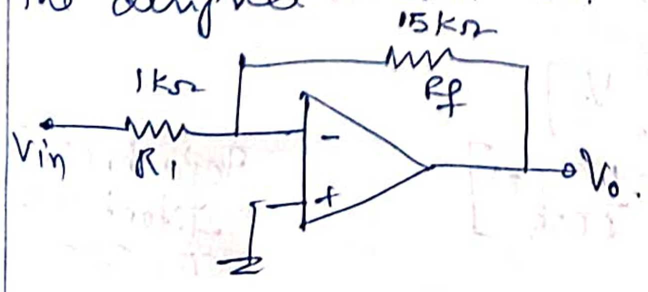
Given, gain $= \frac{R_f}{R_1} = 15$

$$R_f = 15 \cdot R_1$$

Take $\boxed{R_1 = 1K\Omega}$

$\therefore \boxed{R_f = 15K\Omega}$

The designed circuit is.



For Non-Inverting Ampr:

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

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

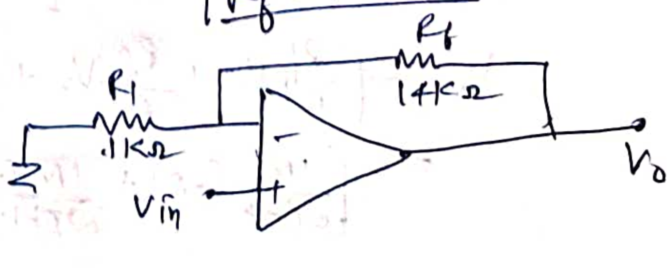
$$\frac{R_f}{R_1} = 15 - 1$$

$$\frac{R_f}{R_1} = 14$$

$$R_f = 14 \cdot R_1$$

Take $\boxed{R_1 = 1K\Omega}$

$\boxed{R_f = 14K\Omega}$



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

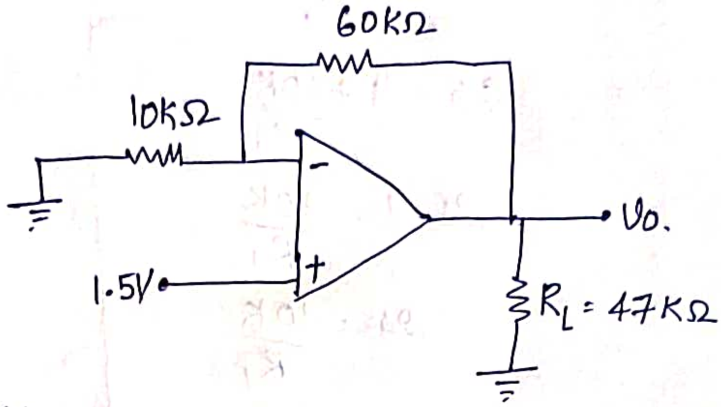
Soln: Given:

$R_1 = 10k\Omega$

$R_f = 60k\Omega$

$R_L = 47k\Omega$

$V_{in} = 1.5\Omega$



WKT, $V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}$

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

$= (1+6)(1.5)$

$\boxed{V_0 = 10.5V}$

The voltage gain,

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

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

$\boxed{A = 7}$

The load current,

$I_L = \frac{V_0}{R_L}$

$= \frac{10.5V}{47k\Omega}$

$\boxed{I_L = 0.223mA}$

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

Soln: Given:

$R_1 = 200k\Omega$, $R_2 = 250k\Omega$, $R_3 = 500k\Omega$, $R_f = 1M\Omega$

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

$V_0 = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$

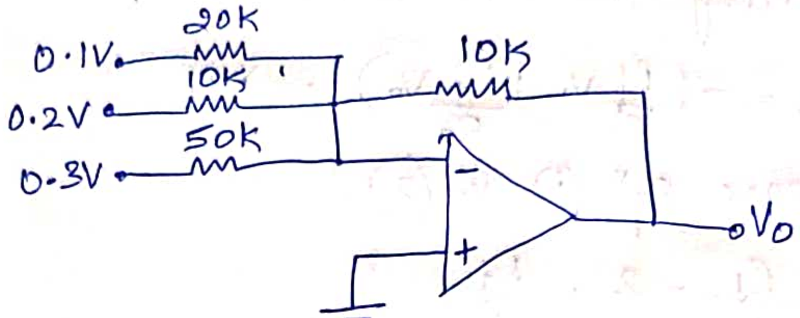
$= -\left[\frac{1M}{200k}(-2) + \frac{1M}{250k}(-1) + \frac{1M}{500k}(3)\right]$

Tejashree. S
Assistant Professor
ECE, SVIT

$$= -[5(-2) + 4(-1) + 2(3)]$$

$$\boxed{V_0 = 8V}$$

(7) Determine V_0 for the circuit below.



Soln: Given:

$R_1 = 20K\Omega$, $R_2 = 10K\Omega$, $R_3 = 50K\Omega$, $V_1 = 0.1V$, $V_2 = 0.2V$, $V_3 = 0.3V$

Three-input inverting summing ampr.

$$V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} \cdot V_2 + \frac{R_f}{R_3} \cdot V_3\right]$$

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

$$\boxed{V_0 = -0.31V}$$

(8) Design an adder circuit using op-amp to obtain an output voltage, $V_0 = -[2V_1 + 3V_2 + 5V_3]$. Assume $R_f = 10K\Omega$

Soln: Given: $V_0 = -[2V_1 + 3V_2 + 5V_3] \longrightarrow (1)$

$$V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right] \rightarrow (2)$$

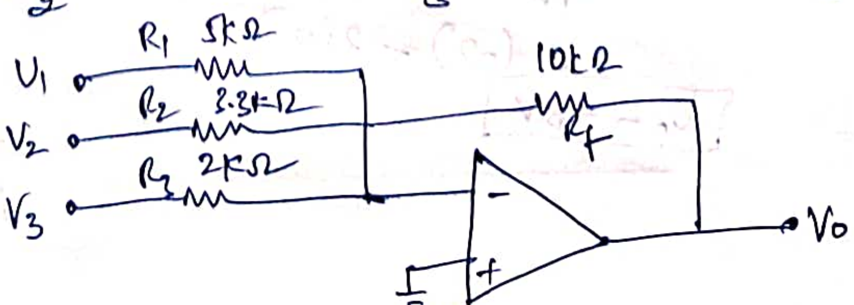
compare Eq^n (1) & (2)

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

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

given $R_f = 10K\Omega$

$\therefore R_1 = \frac{10K}{2} = 5K\Omega$, $R_2 = \frac{10K}{3} = 3.33K\Omega$, $R_3 = \frac{10K}{5} = 2K\Omega$.



(9) Develop a summer circuit using op-amp to get the following output voltage $V_0 = -(2V_1 + 2V_2)$

Sol: Given: $V_0 = -(2V_1 + 2V_2) \longrightarrow (1)$

The inverting summer circuit output voltage is

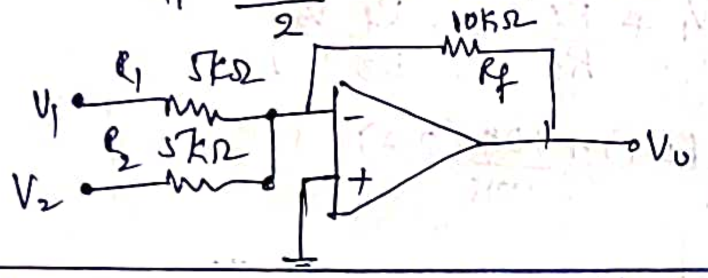
$$V_0 = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2\right) \longrightarrow (2)$$

compare Eq^n (1) & (2).

$$\frac{R_f}{R_1} = 2, \quad \frac{R_f}{R_2} = 2.$$

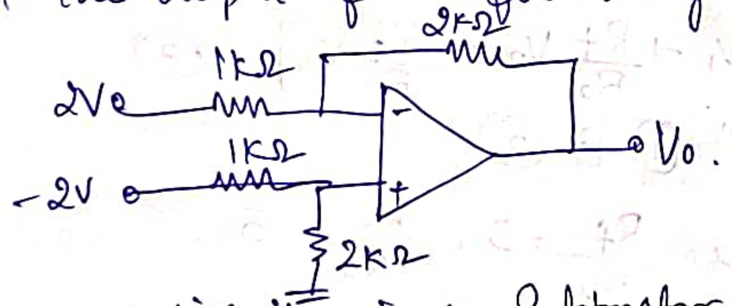
Take $R_f = 10K\Omega$.

$$R_1 = \frac{10K}{2} = 5K\Omega, \quad R_2 = \frac{10K}{2} = 5K\Omega.$$



(10) Design an op-amp circuit that will produce an output voltage of $V_0 = -(4V_1 + V_2 + 0.1V_3)$ (Assume $R_f = 100K\Omega$) Ans: $R_1 = 25K\Omega$, $R_2 = 100K\Omega$, $R_3 = 1M\Omega$.

(11) Find the output of the following op-amp circuit



Sol: The given circuit is a Subtractor.

Given: $R_1 = R_2 = 1K\Omega$, $R_f = 2K\Omega$, $V_1 = 2V$, $V_2 = -2V$

WKT. $V_0 = \frac{R_f}{R_1}V_2 - \frac{R_f}{R_2}V_1$

$= \frac{2K}{1K}(-2) - \frac{2K}{1K}(+2)$

$= 2(-2) - 2(2)$

$$\boxed{V_0 = -8V}$$

Tejashree. S
Assistant Professor
ECE, SVIT

Inverting Amplifier: Continued:

Voltage gain derivation: (Output voltage)

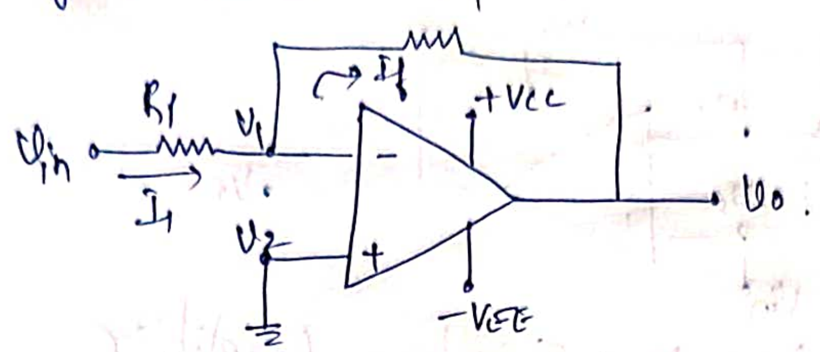


fig: Inverting Amplifier.

- An amplifier which produces a phase shift of 180° between input and output is called inverting ampr.
- From the circuit, the potential at node 2, $\boxed{V_2 = 0}$.

Hence from the concept of virtual ground, the two input terminals are at same potential.

$$\therefore \boxed{V_1 = V_2 = 0}$$

Apply KCL at node 1.

$$I_1 = I_f \longrightarrow (1)$$

WKT $$I_1 = \frac{V_{in} - 0}{R_1} \longrightarrow (2)$$

$$I_f = \frac{V_1 - V_o}{R_f} = \frac{0 - V_o}{R_f} \longrightarrow (3)$$

Sub (2) & (3) in (1).

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

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

where, $\frac{R_f}{R_1}$ is the gain of amplifier and negative sign indicates output is inverted.

Non-Inverting Amplifier:

Voltage gain derivation: (output voltage)

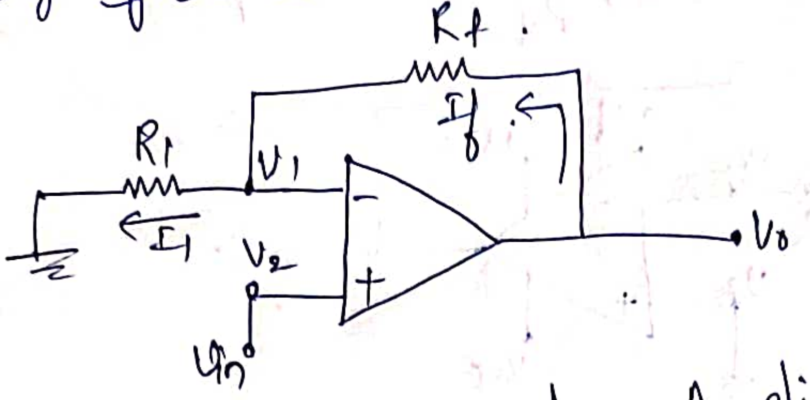


fig: Non-Inverting Amplifier

- An amplifier which amplifies the input without producing any phase shift between input and output is called non-inverting ampr.
- from the circuit, potential at node 2, $\boxed{V_2 = V_{in}}$

Hence from the concept of virtual ground, the two input terminals are at same potential.

$$\therefore \boxed{V_1 = V_2 = V_{in}}$$

Apply KCL at node 1.

$$I_1 = I_f \longrightarrow (1)$$

WKT
$$I_1 = \frac{V_1 - 0}{R_1} = \frac{V_{in} - 0}{R_1} \longrightarrow (2)$$

$$I_f = \frac{V_o - V_1}{R_f} = \frac{V_o - V_{in}}{R_f} \longrightarrow (3)$$

Sub (2) & (3) in (1)

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

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

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

$$\frac{V_0}{R_f} = V_{in}\left(\frac{1}{R_1} + \frac{1}{R_f}\right)$$

$$V_0 = R_f \cdot V_{in}\left(\frac{R_1 + R_f}{R_1 R_f}\right)$$

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

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

$$\boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}}$$

Here $\left(1 + \frac{R_f}{R_1}\right)$ is the gain of the amplifier.

---

(12) A sinusoidal signal with peak value 6mV and 2KHz frequency is applied to the input of an ideal op-amp integrator with $R_1 = 100K\Omega$ and $C_f = 1\mu F$. Find the output voltage.

Soln: Given: $R_1 = 100K\Omega$, $C_f = 1\mu F$, $V_m = 6mV$, $f = 2KHz$.

WKT, $V_{in} = V_m \cdot \sin \omega t \cdot V$.

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

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

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

For an integrator,

$$V_0 = -\frac{1}{R_1 C_f}\int_0^t V_{in} \cdot dt$$

$$V_0 = -\frac{1}{100 \times 10^3 \times 1 \times 10^{-6}}\int_0^t 6 \sin(4\pi \times 10^3 t)\,dt\ mV.$$

$$= \frac{-6}{100 \times 10^{-3}}\left[\frac{-\cos(4\pi \times 10^3)t}{4\pi \times 10^3}\right]_0^t mV$$

$$= \frac{-0.015}{\pi}\left[-\{\cos(4\pi \times 10^3 t) - 1\}\right] mV$$

$$= \frac{0.015}{\pi}\left[\cos(4\pi \times 10^3 t) - 1\right] mV$$

$$\boxed{V_0 = \frac{0.015}{\pi}\left(\cos(4000\pi t) - 1\right) mV}$$

(13) The input to the basic differentiator circuit is a sinusoidal voltage of peak value of 10mV and frequency 1.5KHz. Find the output if $R_f = 100K\Omega$ and $C_1 = 1\mu F$.

Soln: Given:

$R_f = 100K\Omega$, $C_1 = 1\mu F$, $V_m = 10mV$, $f = 1.5KHz$.

WKT, $V_{in} = V_m \sin\omega t \cdot V$

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

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

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

For a differentiator,

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

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

$V_o =$

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

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

Tejashree. S
Assistant professor
ECE, SVIT.