Introduction to Operational Amplifiers

Syllabus: Ideal OPAMP, Inverting and Non-inverting OP-AMP circuits, OP-AMP applications: Voltage follower, addition, subtraction, integration, differentiation, Numerical examples as applicable.

* Operational amplifier or OP-amp:

An OP-amp is a very high gain differential amplifier with high input impedance and low output impedance.

or

An OP-amp is a direct-coupled high-gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output stage.

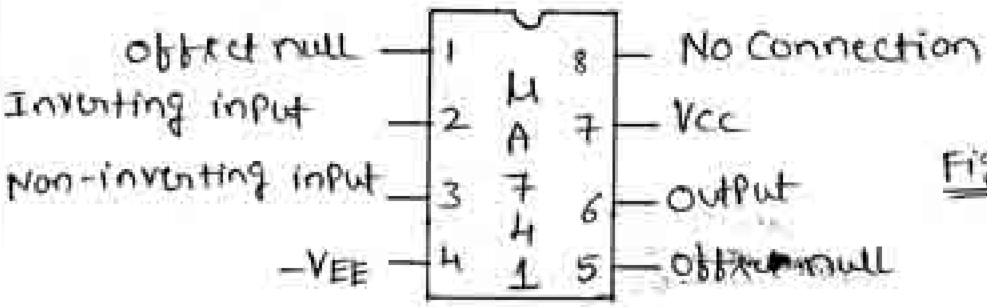
Note:

1. An OP-amp is a linear integrated circuit (IC)
2. The OP-amp is a versatile device (used to amplify both AC and dc input signals)
3. OP-amp is used to perform mathematical operations such as addition, subtraction, differentiation and integration.
4. Robert J. Widlar invented MA 741 IC (An internally compensated op-amp) in 1968

   MA → Fairchild (Manufacturer)
5. Advantages of OP-Amp over transistor amplifier
   - Less Power consumption
   - Low cost
   - More compact
   - More reliable
   - Easy design
   - Versatile device
   - Higher gain can be obtained etc
6. Applications of OP-amp.

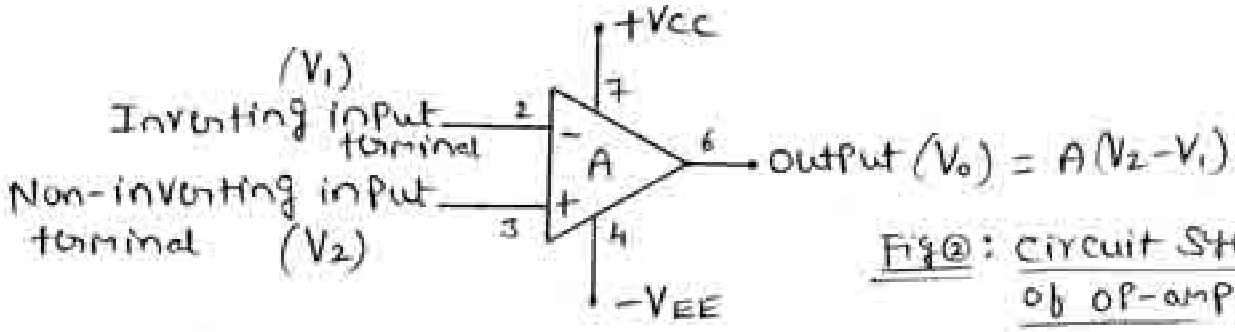
- Ac and dc signal amplification
- Active filters.
- Oscillators
- Comparators
- Regulators
- Biomedical instrumentation. etc

⑦ Pin diagram of OP-amp (μA 741 IC)



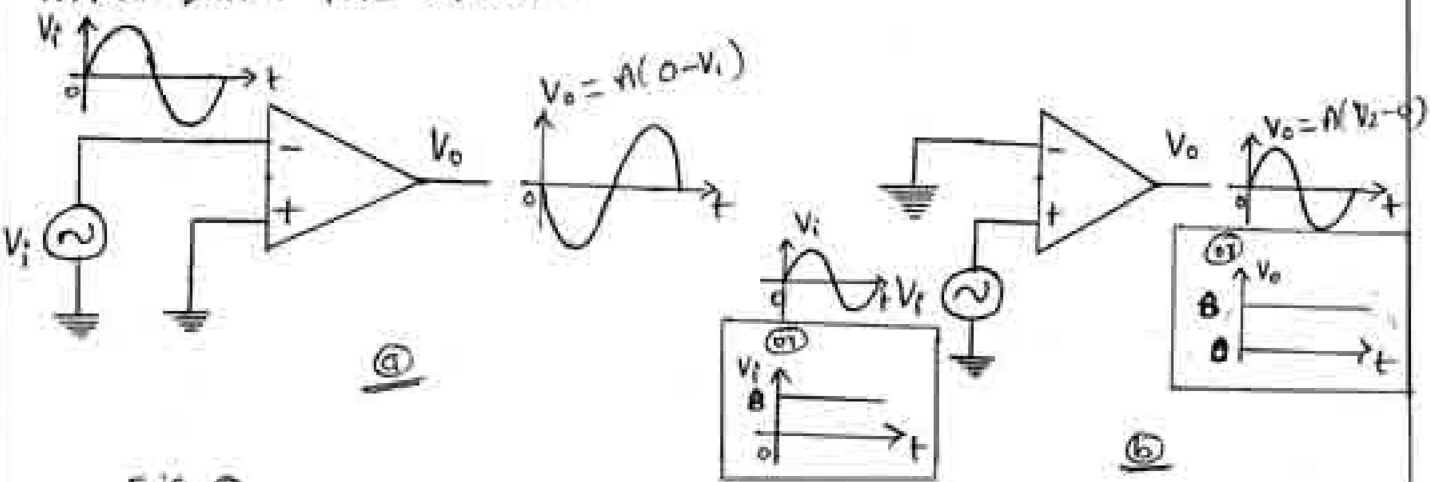
Fig①: Pin diagram of op-amp

⑧ Circuit Symbol of OP-amp ⓐ Schematic Symbol



Fig②: Circuit Symbol of OP-amp

⑨ ⓐ Single-Ended input: Input signal is connected to one input with the other input connected to ground.



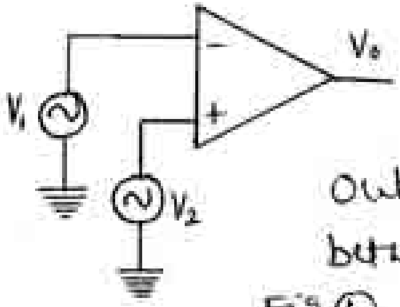
ⓐ

ⓑ

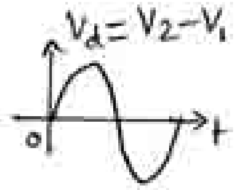
Fig③

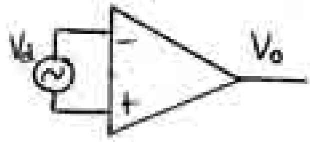
(b) Double-Ended (Differential) Input :

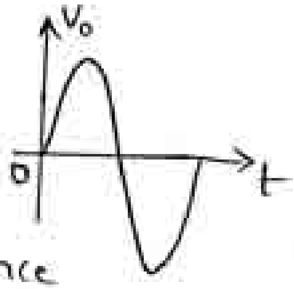
Input signals are applied to each input



$\Rightarrow$







Output is proportional to difference between the two inputs

Fig (4)

(10) Equivalent circuit (or) Circuit model of op-amp : (AC equivalent ckt)

Fig (5) shows the simplified circuit model of practical op-amp.

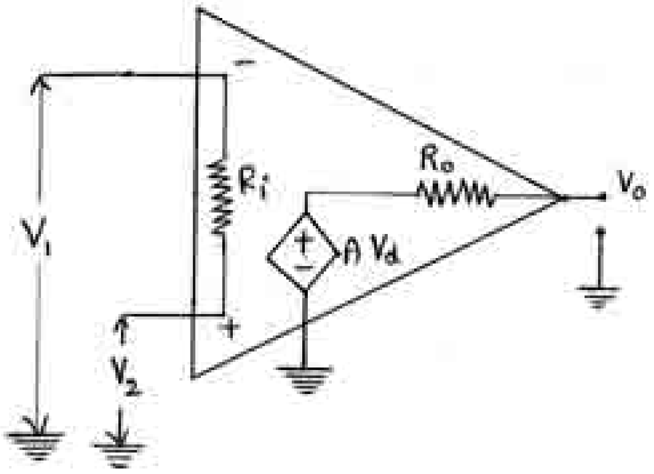


Fig (5) : circuit model of practical op-amp

→ AV_d $[A(V_2 - V_1)]$ is the Thevenin equivalent voltage source, & R_o is the Thevenin equivalent resistance

→ A is the gain (or) Large signal voltage gain

→ R_i is the input resistance

→ V_d $(V_2 - V_1)$ is the difference input voltage.

Fig (6) shows the Equivalent circuit of ideal op-amp.

→ An ideal op-amp has $A = \infty$, $R_i = \infty$ & $R_o = 0$

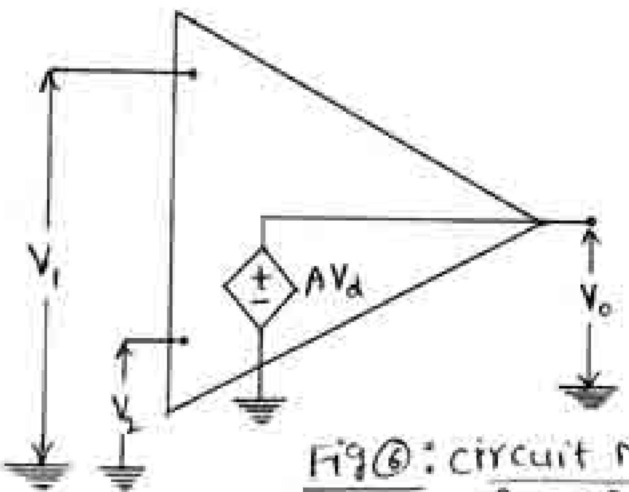


Fig (6) : circuit model of ideal op-amp

(11) Package types

There are three basic types of Linear IC Packages:
(a) The flat pack (b) The metal can or transistor pack
(c) The dual-in-line Package (DIP)

(12) Features of 741

- No external frequency compensation required
- Short-circuit Protection.
- offset null capability
- Large common-mode and differential voltage ranges.
- Low power consumption.
- No Latch-up Problem.

(13) Differential amplifier :

It amplifies the difference of the two inputs V_d (V_2-V_1)

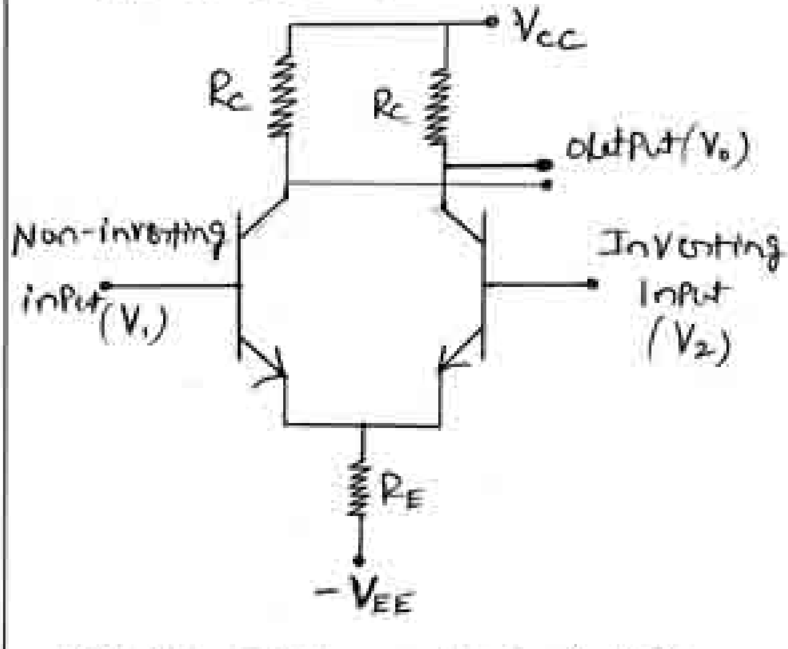


Fig (7): Differential amplifier

Output is,

$$V_0 \propto (V_1 - V_2)$$

$$\Rightarrow \boxed{V_0 = A(V_1 - V_2)} \text{ (or)}$$

$$\boxed{V_0 = A V_d}$$

where,

$A \rightarrow$ Large signal voltage gain
$V_1 \rightarrow$ voltage applied to the non-inverting input
$V_2 \rightarrow$ voltage applied to inverting input
$V_d \rightarrow$ difference voltage

(14)
- OP-amps which use BJT are called bipolar type opamp
- OP-amps having FET input circuit with the remainder of the circuit using BJT are called FET type OP-amps

* Block diagram of OP-amp (or) Internal Block diagram (or) Architecture of op-amp:

The block diagram of an OP-amp is shown in fig (8)

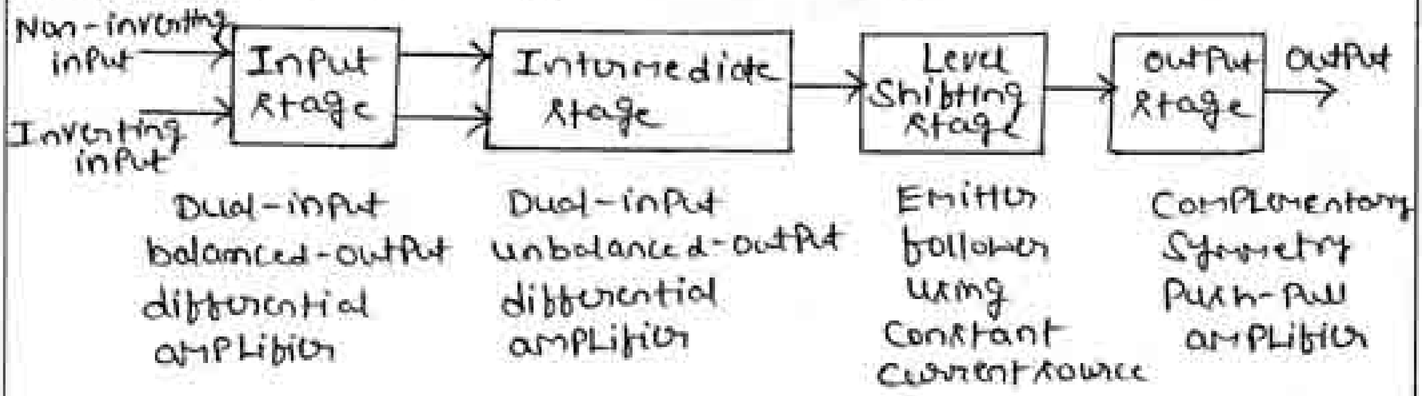


Fig (8): Block diagram of a typical OP-amp

There are four stages:

(1) Input stage (or) Differential amplifier stage

- It can amplify difference between the two input signals.
- Input resistance is very high, draws zero current from the input sources.

(2) Intermediate stage (stages) (or) High gain amplifier stage

- It uses direct coupling.
- It provides very high gain.

(3) Level translator stage (or) Level shifter stage (Buffer)

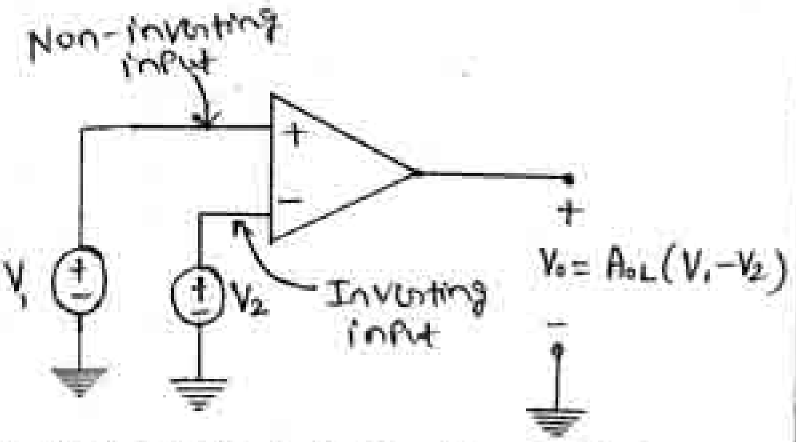
- It shifts the dc level of the output voltage of the intermediate stage to zero.

(4) output stage (or) Power amplifier stage (or) driver stage

- It has very small output resistance.
- output voltage is the same irrespective of the value of the load resistance connected to the output terminal.

Note: (I) Configurations (or) Voltage gain of OP-amp:

① Open-loop Configuration or Open-loop Voltage gain (A_{OL})



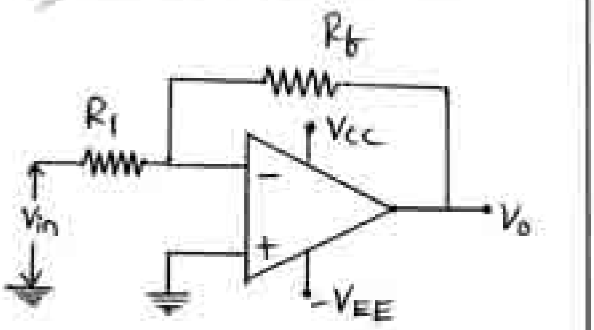
Fig①: Open loop Configuration

- A_{OL} is the open-loop voltage gain of op-amp (Typically $A_{OL} = 2\times10^5$)
- A_{OL} is the maximum possible voltage gain.
- There is no feedback from the output to input

- If input is in micro volts, output will be in volts.
- Output voltage cannot cross the value of power supply (or saturation value) V_{CC} (or V_{EE})
- So, if input is in milli volts, output reaches saturation value $V_{sat} = V_{CC}$ (or V_{EE}). This property of op-amp is called Saturation property.

② Closed-loop Configuration or Closed-loop Voltage gain (A_{CL})

- Open-loop voltage gain of op-amp is very high. Such high gain is not required in most applications.
- In order to reduce gain, Negative feedback is used (a part of the output signal is fed back in phase opposition to the input)



Fig②: Negative feedback op-amp circuit (Closed loop Configuration)

- Many other op-amp characteristics are improved with this.

(II) Total output of a differential amplifier (Practically) or (OP-amp)

The output of op-amp (DA) is. (DA → Differential Amplifier)

$V_o = A_d V_d$ — ①

where $A_d \rightarrow$ Differential gain (Gain with which the DA amplifies the difference between two input signals)

$\boxed{A_d = \frac{V_o}{V_d}}$

$V_d \rightarrow$ Difference between two inputs $(V_1 - V_2)$

If $V_1 = V_2$, then ideally output is zero $(V_o = 0)$

But in practical op-amp, output is,

$\boxed{A_{cm} = \frac{V_o}{V_{cm}}}$

$V_o = A_{cm} V_{cm}$ — ②

where $A_{cm} \rightarrow$ common mode gain (Gain with which DA amplifies the common mode signal)

$V_{cm} \rightarrow$ common mode signal $\left(\frac{V_1 + V_2}{2}\right)$

∴ Total output is,

$V_o = A_d V_d + A_{cm} V_{cm}$

$$\boxed{V_o = A_d V_d \left(1 + \frac{1}{CMRR} \frac{V_{cm}}{V_d}\right)}$$ // $\left[\because CMRR = \frac{A_d}{A_{cm}}\right]$

(iii) $A_d(dB) = 20\log_{10}(A_d)$

k OP-amp parameters (or) characteristics

① Differential gain (or) Differential mode gain (A_d) (or) Large signal voltage gain (A)

It is the factor by which the difference between the two input signals is amplified by the op-amp.

(or)

It is the ratio of the output voltage to the difference voltage. It is denoted by A_d

i.e $A_d = \frac{V_o}{V_d} = \frac{V_o}{V_1 - V_2}$

$\boxed{\text{Ideally: } A_d = \infty \quad \text{Practically: } A_d = A = 2\times10^5 \ (\mu A741)}$

② Common mode gain (A_{cm})

It is the factor by which the common mode input voltage is amplified by the op-amp.

(or)

It is the ratio of the output voltage to the common mode signal. It is denoted by 'A_{cm}'

i.e $A_{cm} = \frac{V_o}{V_{cm}} = \frac{V_o}{(V_1+V_2)/2}$

$\boxed{\text{Ideally: } A_{cm} = 0 \quad \text{Practically: } A_{cm} = 6-7 \ (\mu A741)}$

③ Common mode rejection ratio (CMRR)

It is the factor which explains the ability of an op-amp to reject the common mode signal.

(or)

It is the ratio of differential gain to common mode gain. It is denoted by 'CMRR'.

i.e $CMRR = \frac{A_d}{A_{cm}}$ (or) $CMRR(dB) = 20\log_{10}\left(\frac{A_d}{A_{cm}}\right)(dB)$

$\boxed{\text{Ideally: } CMRR = \infty \quad \text{Practically: } CMRR = 90dB \ (\mu A741)}$

(A_d is known as large-signal voltage gain A)

④ Differential input resistance (or) Input resistance (or) Input impedance (R_i)

It is the equivalent resistance measured at either the inverting (or) non-inverting input terminal with the other terminal connected to ground. It is denoted by 'R_i'.

$\boxed{\text{Ideally: } R_i = \infty \quad \text{Practically: } R_i = 2M\Omega \ (\text{For } \mu A741)}$

⑤ Output resistance (or) Output impedance (R_o)

It is the equivalent resistance measured between the output terminal of the op-amp and the ground. It is denoted by R_o.

$$\boxed{\begin{array}{l} \text{Ideally: } R_o = 0 \\ \text{practically: } R_o = 75\Omega\ (\mu A\ 741) \end{array}}$$

⑥ Bandwidth (BW)

It is the range of frequency over which the gain of op-amp is almost constant.

(or)

It is the range of frequency over which the performance of the op-amp is satisfactory. It is denoted by BW.

$$\boxed{\begin{array}{l} \text{Ideally: } BW = \infty \\ \text{practically: } BW = 1MHz\ (741C) \end{array}}$$

$\mu A 741 IC$ is same as $741C$

⑦ Input offset voltage (V_{io})

It is the voltage that must be applied between the two input terminals of an op-amp to make output voltage zero (to null the output). It is denoted by V_{io}.

$$\boxed{\begin{array}{l} \text{Ideally: } V_{io} = 0 \\ \text{practically: } V_{io} = 6mV\ (741C) \end{array}}$$

$V_{io} = |V_1 - V_2|$ for $V_o = 0$

⑧ Output offset voltage (V_{oo})

It is the output voltage when both input voltages are zero. It is denoted by V_{oo}.

$$\boxed{\begin{array}{l} \text{Ideally: } V_{oo} = 0 \\ \text{practically: } V_{oo} = 1mV\ (741C) \end{array}}$$

⑨ Input offset current (I_{io})

It is the difference between the currents in the input terminals. It is denoted by 'I_{io}'.

i.e $I_{io} = |I_1 - I_2|$

Where, $I_1 \rightarrow$ current into the noninverting input

$I_2 \rightarrow$ current into the inverting input.

Ideally: $I_{io} = 0$
Practically: $I_{io} = 20nA$ (For μA 741)

200nA max

⑩ Input bias current (I_{ib})

It is the average of the currents in the input terminals. It is denoted by 'I_{ib}'

i.e $I_{ib} = \dfrac{I_1 + I_2}{2}$

Where, $I_1, I_2 \rightarrow$ current into non-inverting & inverting input respectively.

Ideally: $I_{ib} = 0$
Practically: $I_{ib} = 80nA$ (For μA 741)

500 nA [illegible]

⑪ Slew rate (SR)

It is the maximum rate of change of output voltage with respect to time. It is denoted by SR.

i.e $SR = \left.\dfrac{dV_o}{dt}\right|_{max}$ ($V/\mu s$)

Ideally: $SR = \infty$
Practically: $SR = 0.5V/\mu s$

⑫ Supply voltage rejection ratio (or) Power supply sensitivity (or) Power supply rejection ratio: (SVRR) (or) (PSRR)

It is the change in input offset voltage (V_{io}), caused by variations in supply voltage. It is denoted by SVRR (or) PSRR.

ie $SVRR = \frac{\Delta V_{io}}{\Delta V} \ (\mu V/V)$

Ideally : SVRR = 0

Practically : SVRR = 150 μV/V (741 C)

Note:

① Input Capacitance (C_i):

It is the equivalent capacitance measured at either the inverting (or) noninverting terminal with the other terminal connected to ground. It is defined by 'C_i'.

Practically : $C_i = 1.4\,PF$ for 741C

② Gain-Bandwidth product (GB)

It is the bandwidth of the OP-amp when the voltage gain is 1

Practically : GB = 1 MHz for 741C

③ Maximum signal frequency interms of slew rate (for an undistorted output)

Let the output voltage (sinusoidal signal) be.

$$V_o = V_m \sin(\omega t) \quad \text{—} ①$$

Diff w.r.t 't' on b.s

$$\frac{dv_o}{dt} = V_m \cos(\omega t).\omega$$

$$\Rightarrow \quad \left.\frac{dv_o}{dt}\right|_{max} = \omega V_m \quad \text{—} ② \qquad \left(\because \cos(\omega t)\big|_{max} = 1\right)$$

To prevent distortion at the output, the rate of change of output w.r.t must be less than the SR.

i.e $\left.\frac{dV_o}{dt}\right|_{max} \leq SR$ — ③

using ② in ③, we get,

$$\omega V_M \leq SR$$

$\Rightarrow$ $\omega \leq \frac{SR}{V_M} \Rightarrow \boxed{\omega_{max} = \frac{SR}{V_M}}$ (rad/s)

$\Rightarrow$ $f \leq \frac{SR}{2\pi V_M}$ ($\because \omega = 2\pi f$) $\Rightarrow \boxed{f_{max} = \frac{SR}{2\pi V_M}}$ (Hz)

④ OP-amp characteristics:

SL No	Parameter	Symbol	Ideal value	Typical value for μA741
1	Differential gain or Large signal Voltage gain or open-loop voltage gain.	A_d or A	∞	2×10^5
2	Common mode gain	A_{cm}	0	6
3	Common mode rejection ratio	CMRR	∞	90dB
4	Input resistance	R_i	∞	2MΩ
5	output resistance	R_o	0	75Ω
6	Bandwidth	BW	∞	1MHz
7	Input offset voltage	V_{io}	0	6mV
8	output offset voltage	V_{oo}	0	1mV
9	Input offset current	I_{io}	0	20nA
10	Input bias current	I_{ib}	0	80nA
11	Slew rate	SR	∞	0.5V/μs
12	Supply voltage rejection ratio	SVRR	0	150μV/V

⑤ Virtual ground or Virtual Short :

The op-amp inverting amplifier is shown in fig ⑪

The output voltage is,

$$V_o = A(V_2 - V_1) \quad \text{— ①}$$

Where, A → Large signal voltage gain

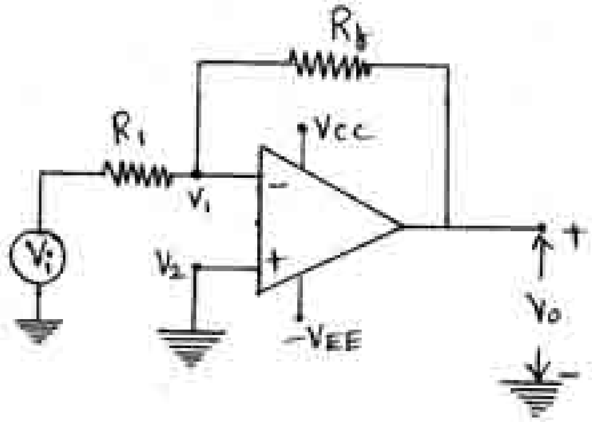


Fig ⑪ : Basic op-amp circuit

For an output voltage of 12V, the input voltage would be,

$$V_2 - V_1 = \frac{V_o}{A} \quad (\because \text{From } 1)$$

$$\Rightarrow V_2 - V_1 = \frac{12}{2\times10^5} \quad (\because \text{Practically, } A = 2\times10^5 \text{ for } \mu A\ 741)$$

$$\Rightarrow V_2 - V_1 = 0.06\,mV$$

Differential input voltage is very small. ($V_d = V_2 - V_1$)

Ideally, $V_2 - V_1 = 0$

$$\Rightarrow \boxed{V_1 = V_2} \quad \text{— ②}$$

From ②, we can conclude,

- Voltage at inverting terminal = Voltage at non-inverting terminal
- There exists a virtual short-circuit or virtual ground
- No current flows through the short circuit
- Current through R_1 = Current through R_f.

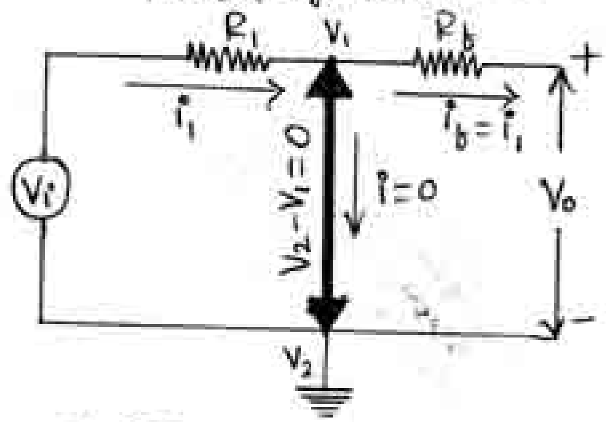


Fig ⑫ : virtual ground

⑥ The virtual short is indicated by a thick line between input terminals.

⑦ For an op-amp, output voltage cannot cross V_{cc} (V_{EE}) ($\simeq$ 12 to 15V) ($\because$ From saturation property)

⑧ No current flows into op-amp input terminals (∵ Input impedance is very high)

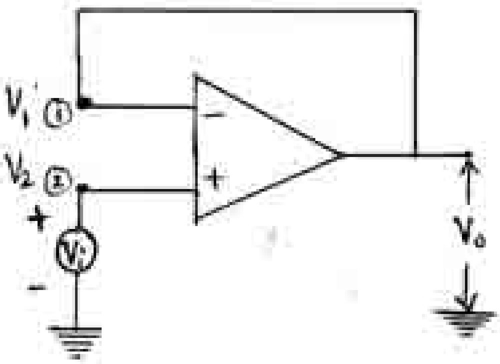
* Op-amp applications

① Voltage follower
② Inverting amplifier
③ Non-inverting amplifier
④ Summer (Adder)
⑤ Subtractor (difference amplifier)
⑥ Differentiator
⑦ Integrator.

* ① Voltage follower (or) Isolation amplifier (or) source follower (or) unity gain amplifier (or) buffer:

Definition: An op-amp circuit in which the output voltage follows the input voltage is called voltage follower (output voltage is equal to input voltage)

Circuit diagram:



Analysis:

From virtual ground concept,

$$V_1 = V_2 = V_i \quad — ①$$

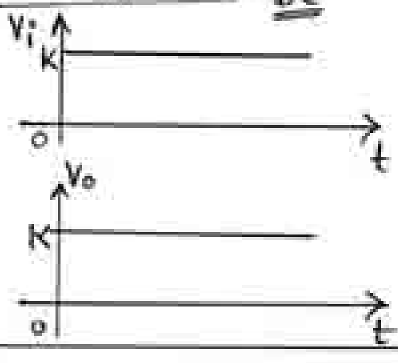
Since output is connected to input,

$$V_o = V_1 \quad — ②$$

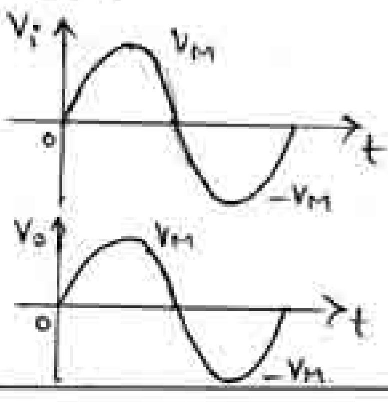
From ① & ②,

$$\boxed{V_o = V_i} \quad — ③$$

Wave forms: DC



AC



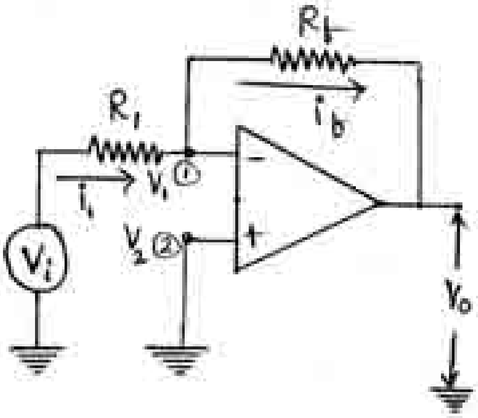
Conclusion:

- From eqn ③, the output voltage follows the input voltage

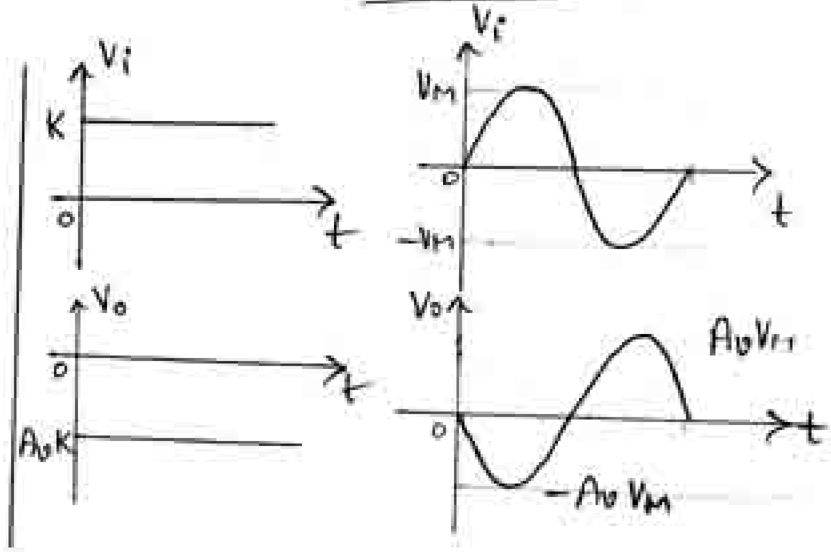
② Inverting amplifier:

Definition: An OP-amp circuit in which the output voltage is out of phase (180°) with respect to the input voltage is called inverting amplifier.

Circuit diagram:



Waveforms:



Analysis:

Applying KCL at node ①.

$$i_1 = i_f$$ (Since input impedance of op-amp is very high, no current flows into op-amp input terminals)

$$\Rightarrow \frac{V_i - V_1}{R_1} = \frac{V_1 - V_o}{R_f}$$

$$\Rightarrow \frac{V_i}{R_1} = \frac{-V_o}{R_f}$$ [From virtual ground concept. $V_1 = V_2 = 0$]

$$\Rightarrow \boxed{V_o = -\left(\frac{R_f}{R_1}\right)V_i} \quad -④ \quad \text{(or)} \quad \boxed{\frac{V_o}{V_i} = -\frac{R_f}{R_1} = A_v} \quad -⑤$$

where

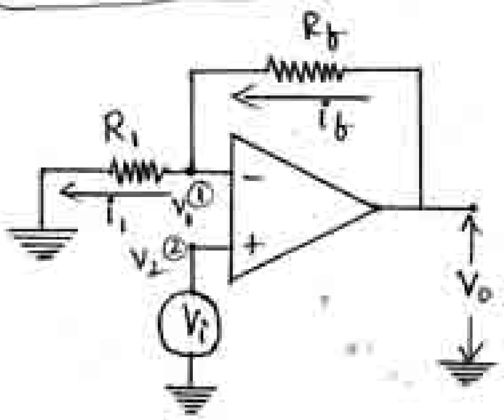
$A_v \rightarrow$ Closed loop voltage gain

Conclusion: From eqn ⑤, negative sign indicates that the output is inverted w.r.t the input.

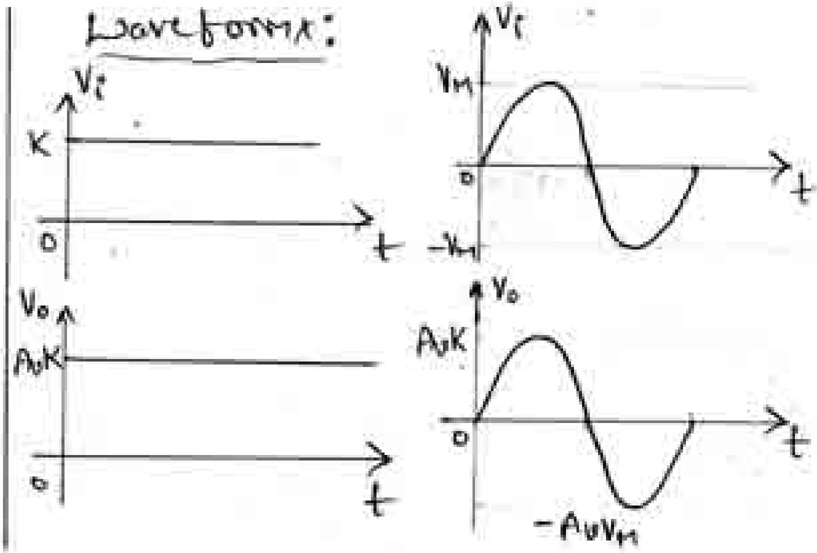
③ Non-inverting amplifier:

Definition: An op-amp circuit in which the output voltage is in phase with the input voltage is called Non-inverting amplifier.

Circuit diagram:



Waveforms:



Analysis:

Applying KCL at node ①.

$$i_f = i_1 \quad (\because \text{No current flows into op-amp input terminals})$$

$$\Rightarrow \frac{V_o - V_1}{R_f} = \frac{V_1 - 0}{R_1} \quad \left(\text{From virtual ground concept, } V_1 = V_2 = V_i\right)$$

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

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

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

$$\Rightarrow \boxed{\frac{V_o}{V_i} = 1 + \frac{R_f}{R_1} = A_v} \; — ⑥ \quad \text{or} \quad \boxed{V_o = \left(1 + \frac{R_f}{R_1}\right)V_i} \; — ⑦$$

Where, $A_v \rightarrow$ closed loop voltage gain.

Conclusion: From ⑥ or ⑦, • The output voltage is in-phase with the input voltage. • A_v depends on R_f & R_1

* (h) Summer (adder) or Summing amplifier:

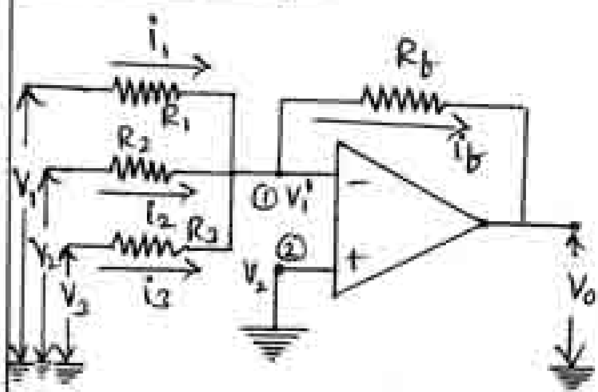
Definition: An op-amp circuit, in which the output voltage is the sum of the input signal voltages is called Summer.

There are types:

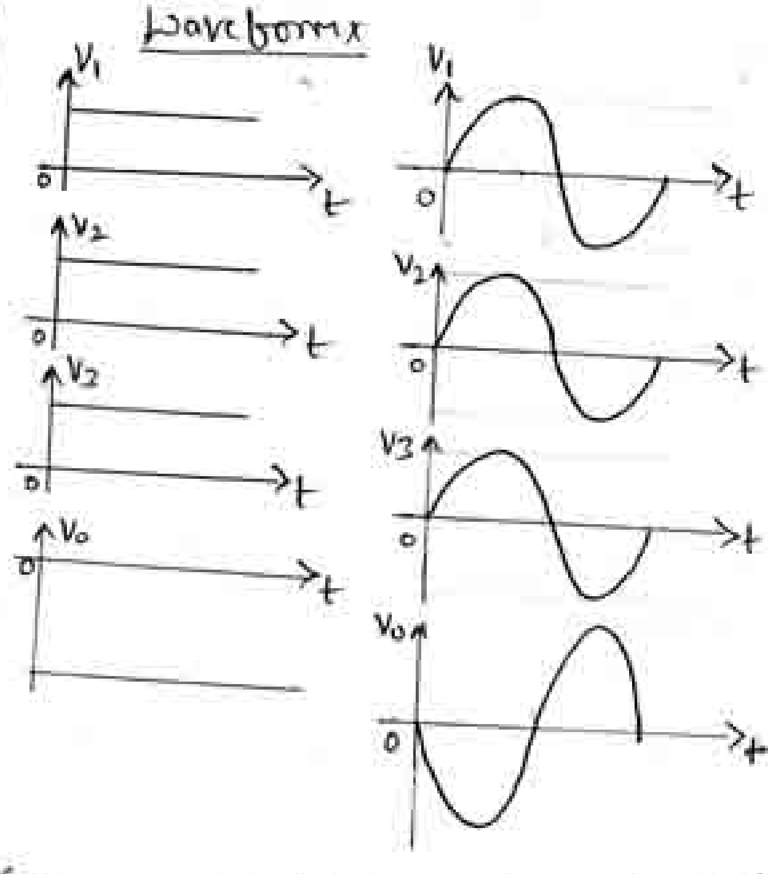
(a) Inverting summing amplifier:

Definition: An op-amp circuit, in which the output voltage is the inverted sum of the input voltages is called inverting summing amplifier.

Circuit diagram



Waveforms



Analysis:

Applying KCL at node ①.

$$i_1 + i_2 + i_3 = i_f$$ ($\because$ No current flows into op-amp input terminals)

$$\Rightarrow \frac{V_1 - V_1'}{R_1} + \frac{V_2 - V_1'}{R_2} + \frac{V_3 - V_1'}{R_3} = \frac{V_1' - V_0}{R_f}$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_0}{R_f}$$ (From virtual ground concept, $V_1' = V_2 = 0$)

$$\Rightarrow \boxed{V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)} \quad -⑧$$

Conclusion:

From ⑧, the output voltage is proportional to the inverted sum of the input voltages.

Note:

① From ④, • If $R_f = R_1$, $V_o = -V_i$ (or) $\frac{V_o}{V_i} = -1 = A_v$ amplifier is unity gain inverting amplifier.

② From ⑦, • Irrespective of the value of R_1 & R_f, $V_o \geq V_i$

• If $R_f = 0$ (or) $R_1 = \infty$, then $V_o = V_i$, amplifier is unity gain non-inverting amplifier.

③ From ⑧ • If $R_1 = R_2 = R_3 = R_f$, then, $V_o = -(V_1 + V_2 + V_3)$ output voltage is the negative of the sum of the input voltages [Gain of the summer is unity (1)]

• If $R_1 = R_2 = R_3 = 3R_f$, then, $V_o = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$

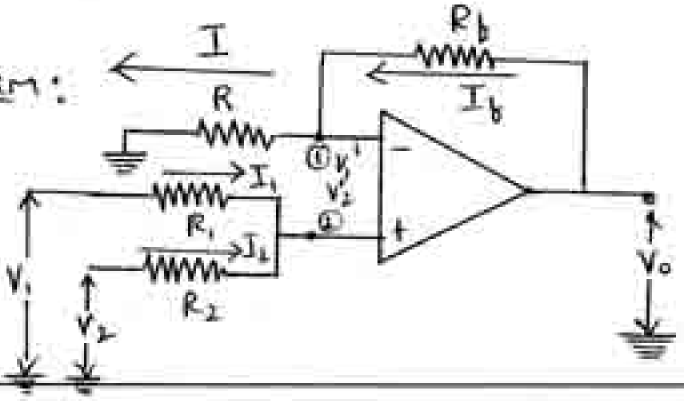
(or) $R_1 = R_2 = 2R_f$ & $V_3 = 0$, then $V_o = -\left(\frac{V_1 + V_2}{2}\right)$

then circuit is averager (or) averaging circuit

ⓑ Non-inverting Summer:

Definition: An op-amp circuit, in which the output voltage is the sum of the input voltages is called Non-inverting Summer.

Circuit diagram:



Analysis:

Applying KCL at node 2

$$I_1 + I_2 = 0$$ (No current flows into input)

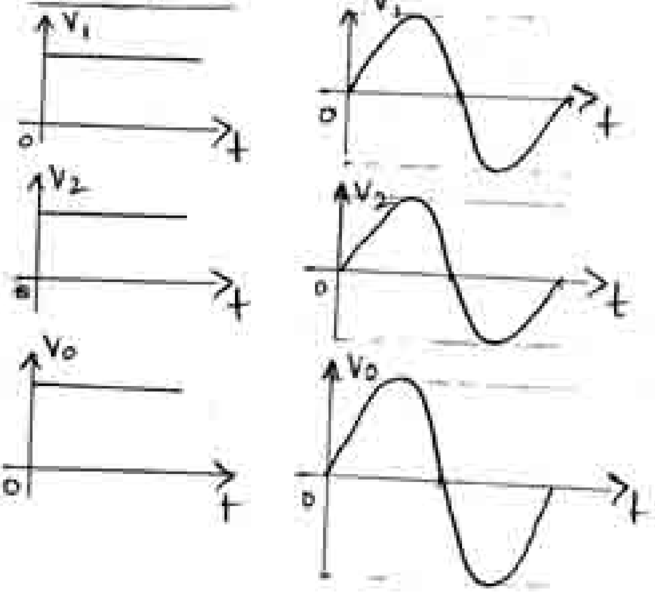
$$\Rightarrow \frac{V_1 - V_2'}{R_1} + \frac{V_2 - V_2'}{R_2} = 0$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} = V_2'\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

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

$$\Rightarrow V_2' = \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2} \quad \text{--- (9)}$$

Waveforms



Applying KCL at node 1.

$$I_f = I$$

$$\Rightarrow \frac{V_0 - V_1'}{R_f} = \frac{V_1' - 0}{R}$$

$$\Rightarrow \frac{V_0}{R_f} = V_1'\left(\frac{1}{R} + \frac{1}{R_f}\right)$$

$$\Rightarrow \frac{V_0}{\cancel{R_f}} = V_1'\left(\frac{R_f + R}{R \cancel{R_f}}\right)$$

$$V_0 = V_1'\left(\frac{R + R_f}{R}\right) \quad \text{--- (10)}$$

(From virtual ground, $V_1' = V_2' = \dfrac{R_2 V_1 + R_1 V_2}{R_1 + R_2}$)

$$\Rightarrow V_0 = \left(\frac{R_2 V_1 + R_1 V_2}{R_1 + R_2}\right)\left(\frac{R + R_f}{R}\right)$$

$$\Rightarrow V_0 = \frac{R_2(R + R_f)}{R(R_1 + R_2)} V_1 + \frac{R_1(R + R_f)}{R(R_1 + R_2)} V_2$$

$$\Rightarrow \boxed{V_0 = \frac{(1 + R_f/R)}{(1 + R_1/R_2)} V_1 + \frac{(1 + R_f/R)}{(1 + R_2/R_1)} V_2} \quad \text{--- (11)}$$

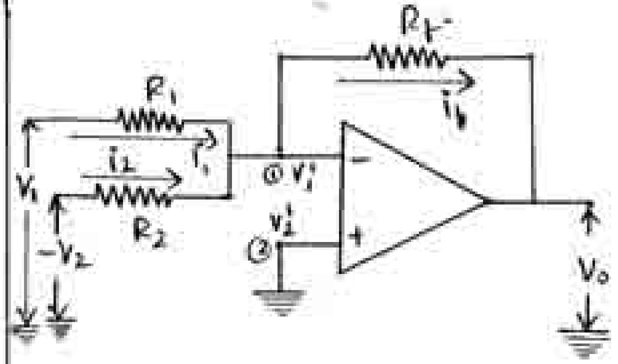
Conclusion:
From (11), the output voltage is proportional to the sum of the input voltages.

Note: (1) From (11), If $R = R_f = R_1 = R_2$, $V_o = V_1 + V_2$
∴ output voltage is equal to the non-inverted sum of the input voltages (2) From (8), if V_1, V_2 & V_3 are negative, $V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3$

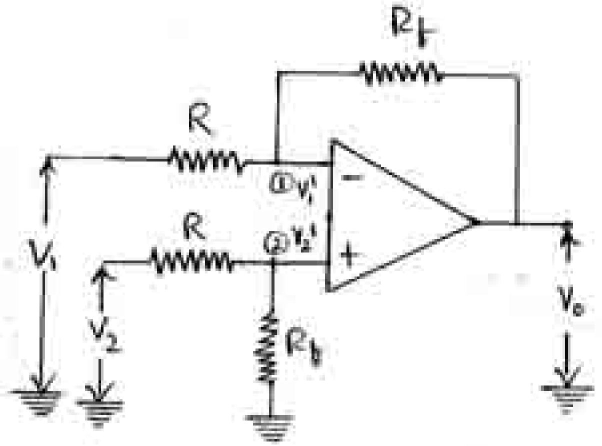
* (5) Subtractor (or) Difference amplifier

Definition: An op-amp circuit, in which the output voltage is the difference (subtraction) of two input voltages is called Subtractor.

Circuit diagram:



(or)



Applying KCL at node (1),

$$i_1 + i_2 = i_f$$

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

$$\Rightarrow \frac{V_1}{R_1} - \frac{V_2}{R_2} = \frac{-V_o}{R_f} \quad (\because V_1' = V_2' = 0)$$

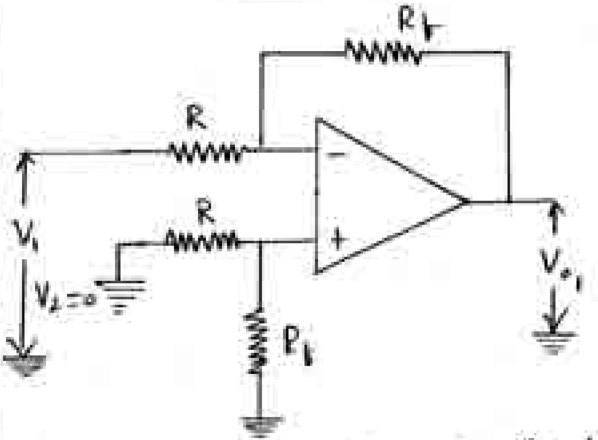
$$\Rightarrow \boxed{V_o = \frac{R_f}{R_2}V_2 - \frac{R_f}{R_1}V_1} \quad -(12)$$

If $R_1 = R_2 = R_f$, then

$$\boxed{V_o = V_2 - V_1} \quad -(13)$$

Let us use superposition theorem.

Case(i): Let $V_2 = 0$



The resulting circuit is inverting amplifier

$$\therefore V_{o_1} = -\frac{R_f}{R}V_1 \quad -(14)$$

Case (ii): Let $V_1 = 0$

The resulting circuit is shown in fig (*)

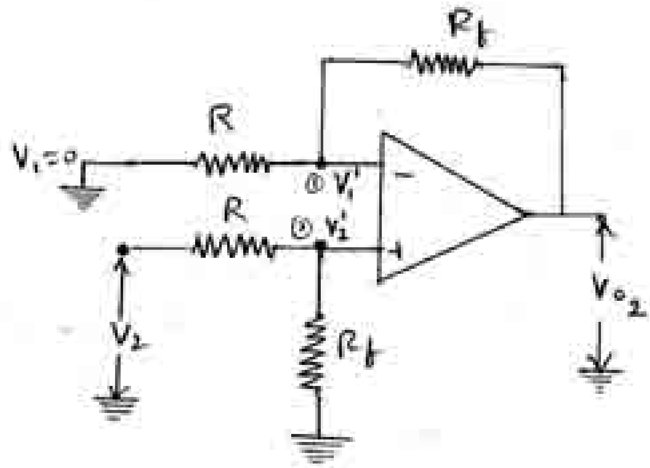


Fig (*):

The circuit is non-inverting amplifier.

$$\therefore V_{o_2} = \left(1 + \frac{R_f}{R}\right) V_2' \quad \text{— (15)}$$

From potential divider rule

$$V_2' = \frac{V_2 R_f}{R + R_f} \quad \text{— (16)}$$

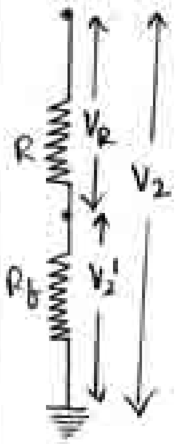
Using (16) in (15), we get

$$V_{o_2} = \left(1 + \frac{R_f}{R}\right) V_2 \left(\frac{R_f}{R + R_f}\right)$$

$$= \left(\frac{\cancel{R + R_f}}{R}\right) V_2 \left(\frac{R_f}{\cancel{R + R_f}}\right)$$

$$V_{o_2} = \frac{R_f}{R} V_2 \quad \text{— (17)}$$

Voltage @ Potential divider rule



Voltage across R_f.

$$V_2' = \frac{V_2 \times R_f}{R + R_f}$$

Voltage across R.

$$V_R = \frac{V_2 R}{R + R_f}$$

From superposition theorem, the output voltage is

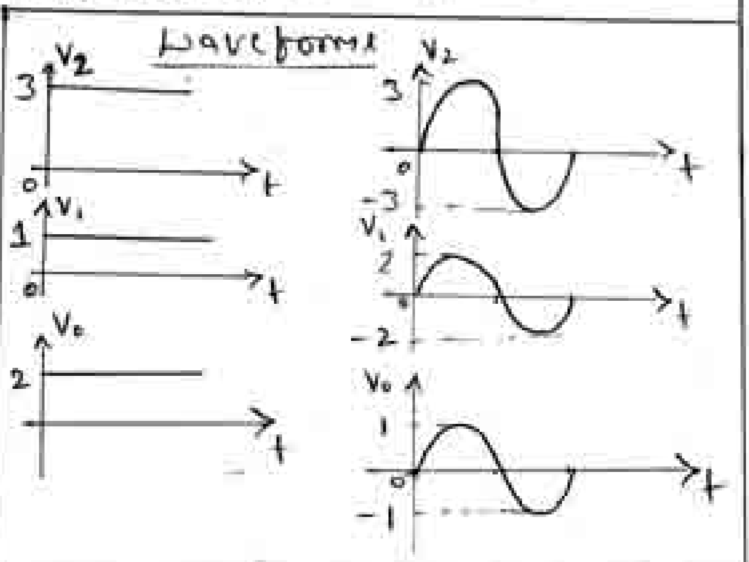
$$V_o = V_{o_1} + V_{o_2}$$

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

$$\boxed{V_o = \frac{R_f}{R}(V_2 - V_1)} \quad \text{— (18)}$$

If $R = R_f$, then

$$\boxed{V_o = V_2 - V_1} \quad \text{— (19)}$$

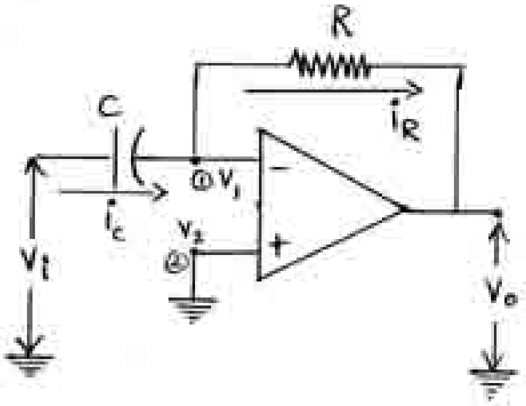


Conclusion: From (13) or (19), the output voltage is the difference of the two input voltages.

* ⑥ Differentiator:

Definition: An op-amp circuit, in which the output voltage is the differentiation (derivative) of the input voltage is called differentiator.

Circuit diagram



Analysis:

Applying KCL at node ①.

$$i_c = i_R$$

$$C\frac{d(V_i - V_1)}{dt} = \frac{V_1 - V_o}{R}$$

$$\Rightarrow C\frac{dV_i}{dt} = \frac{-V_o}{R} \quad \left(\because \text{From virtual ground concept, } V_1 = V_2 = 0\right)$$

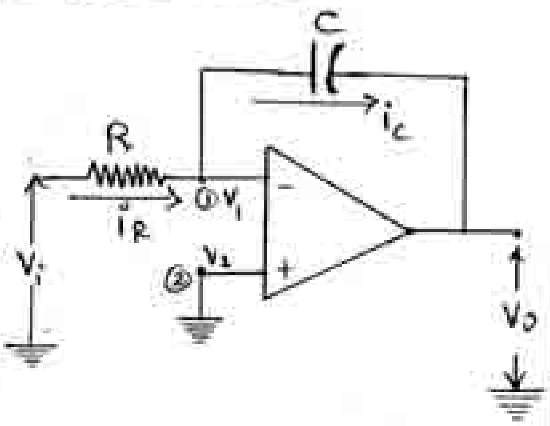
$$\Rightarrow \boxed{V_o = -RC\frac{dV_i}{dt}} \quad —⑳$$

Conclusion: From ⑳, the output voltage is proportional to the time derivative of the input voltage.

* ⑦ Integrator:

Definition: An op-amp circuit, in which the output voltage is the integration of the input voltage is called integrator

Circuit diagram:



Analysis:

Applying KCL at node ①.

$$i_R = i_c$$

$$\frac{V_i - V_1}{R} = C\frac{d(V_1 - V_o)}{dt}$$

$$\Rightarrow \frac{V_i}{R} = -C\frac{dV_o}{dt} \quad \left(\text{From virtual ground concept, } V_1 = V_2 = 0\right)$$

$$\Rightarrow dV_o = -\frac{1}{RC} V_i\, dt$$

Integrating on b.s.

$$\boxed{V_o = -\frac{1}{RC}\int_0^t V_i\,dt + V_o(0)} \quad \text{— (21)}$$

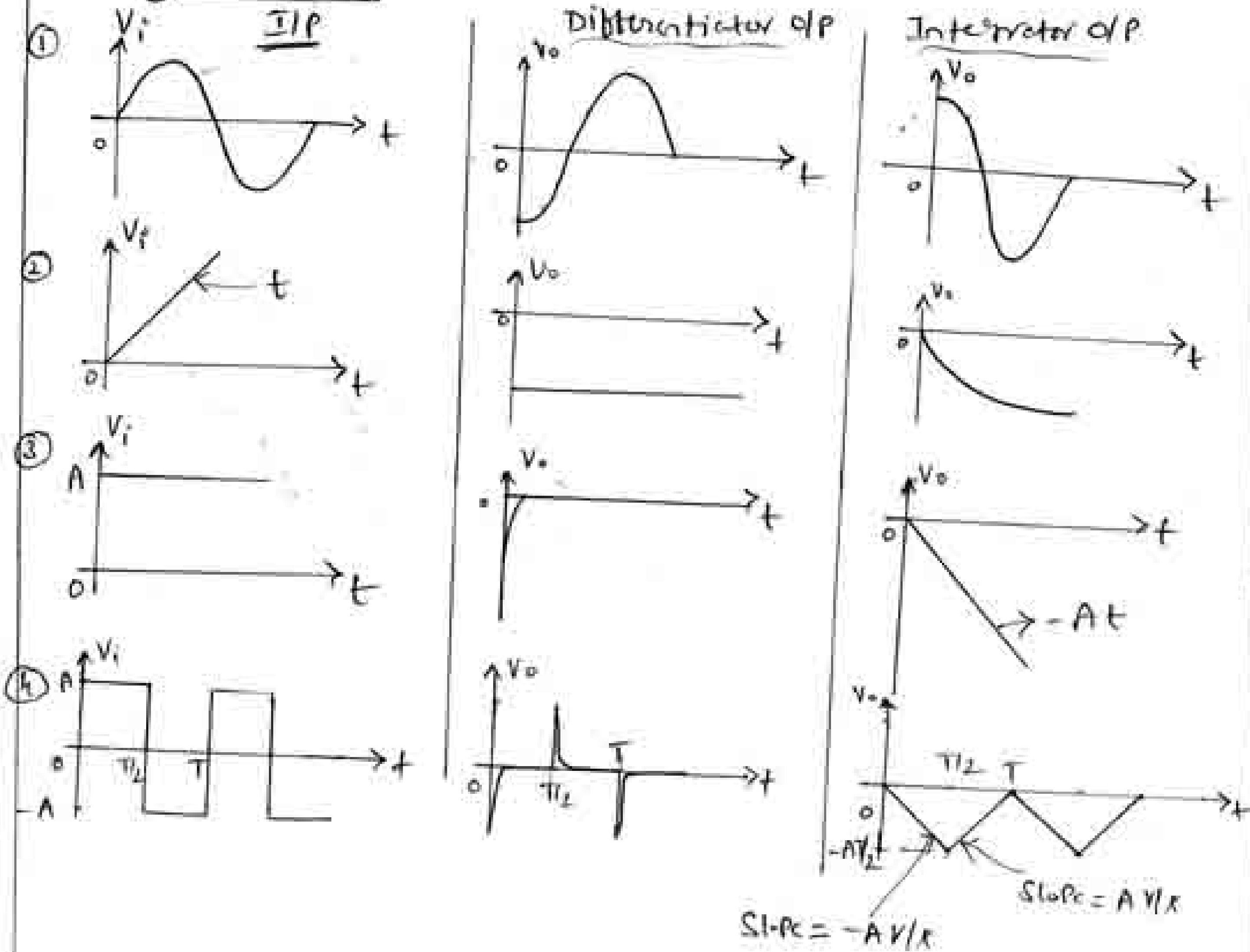
Where. $V_o(0) \rightarrow$ Initial Voltage on capacitor at $t=0$
(constant of integration)

If $V_o(0)=0$, then

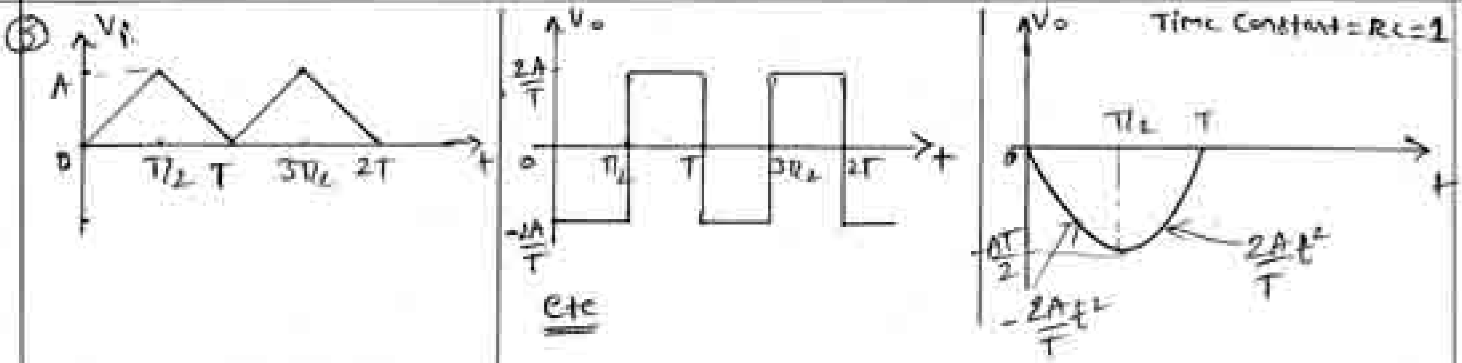
$$\boxed{V_o = -\frac{1}{RC}\int_0^t V_i\,dt} \quad \text{— (22)}$$

Conclusion: From (21) & (22), the output Voltage is Proportional to the integral of the input Voltage.

Note: (1) Waveforms



(5)



(II) Ideal Voltage transfer characteristic of an OP-amp

The output voltage,

$V_o = A V_d$

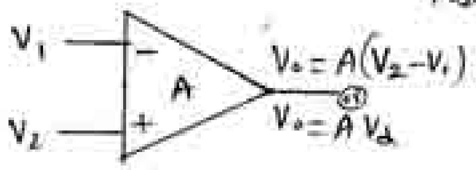


Fig (*):

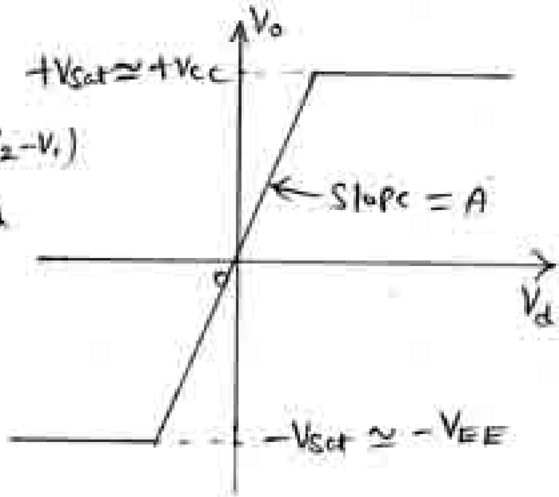


Fig (**): Ideal Voltage transfer characteristic of an OP-amp

From characteristics

- As V_d increases, V_o increases linearly until it attains the saturation voltages & thereafter it remains constant.
-

(III) Need for an OP-amp

Let two signals V_1 & V_2 to be summed as shown in fig (***)

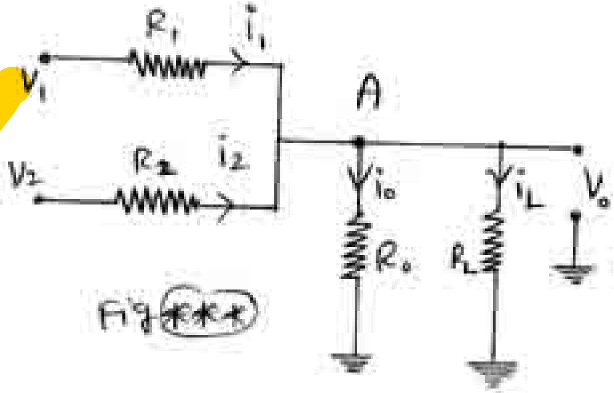


Fig (***)

Applying KCL at node A

$$i_1 + i_2 = i_o + i_L$$

$$\Rightarrow \frac{V_1 - V_o}{R_1} + \frac{V_2 - V_o}{R_2} = \frac{V_o}{R_o} + \frac{V_o}{R_L}$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} = V_o\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_o} + \frac{1}{R_L}\right]$$

$$\Rightarrow V_o\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_P}\right] = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$

$$\Rightarrow V_o\left[1+\frac{R_P}{R_1}+\frac{R_P}{R_2}\right]=V_1\left(\frac{R_P}{R_1}\right)+V_2\left(\frac{R_P}{R_1}\right)$$ $\boxed{\text{where } R_P=\frac{1}{R_o}+\frac{1}{R_L}}$

$$\Rightarrow \boxed{V_o=\frac{V_1\left(\frac{R_P}{R_1}\right)+V_2\left(\frac{R_P}{R_1}\right)}{\left[1+\frac{R_P}{R_1}+\frac{R_P}{R_2}\right]}} \quad — (*)$$

From eqn (*), it is clear that V_o depends on R_P which in turn depends on R_L.

It is desirable to make V_o independent of R_L. This is possible if $R_o << R_L$ (or) $\frac{1}{R_o} >> \frac{1}{R_L}$ $\left(R_P \simeq \frac{1}{R_o}\right)$

But R_P will be small, results in small value of V_o which is undesirable. Therefore it is necessary to use amplifier whose gain (or output voltage) is independent of R_L.

Thus op-amp is preferred since close loop voltage gain (or output voltage) is independent of R_L (depends only on external resistors R_f & R_1).

1. For an inverting amplifier $R = 10k\Omega$ & $R_f = 60k\Omega$. What is the output voltage for $V_i = 2V$?

Sol: Given $R = 10k\Omega$, $R_f = 60k\Omega$, $V_i = 2V$, $V_o = ?$

For an inverting amplifier,

$$V_o = -\frac{R_f}{R} V_i = -\frac{60\times10^3}{10\times10^3}(2) = \underline{\underline{-12V}}$$

2. Design an inverting amplifier for output voltage of $-10V$ & an input voltage of $1V$.

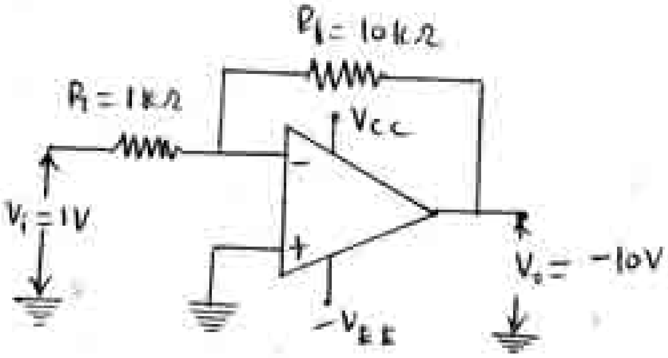
Sol: Given $V_o = -10V$, $V_i = 1V$, $R_1 = ?$, $R_f = ?$

For an inverting amplifier,

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

$$\Rightarrow -10 = -\frac{R_f(1)}{R_1}$$

$$\Rightarrow \frac{R_f}{R_1} = 10$$



Assume $R_1 = 1k\Omega$ //.

$\therefore R_f = 10k\Omega$ //.

3. The output signal of an op-amp with a slew-rate of $5V/\mu s$ has a maximum value of $15V$. Find the max freq for undistorted output voltage.

Sol: Given $SR = 5V/\mu s$, $V_m = 15V$, $f_{max}(\omega_{max}) = ?$

We have $f_{max} = \dfrac{SR}{2\pi V_m}$; $\omega_{max} = \dfrac{SR}{V_m}$

$$= \frac{5/10^{-6}}{2\pi(15)} \qquad \omega_{max} = \frac{5/10^{-6}}{15}$$

$f_{max} = \underline{53.05\ KHz}$ (or) $\omega_{max} = \underline{333.33\ rad/s}$

4) Determine the output voltage of an op-amp for the input voltages of 0.05mV & 0.04mV. The differential gain of the amplifier is 50000 & CMRR = 2×10^5.

Sol: Given $V_o = ?$, $V_1 = 0.05mV$, $V_2 = 0.04mV$, $A_d = 50000$, $CMRR = 2\times10^5$

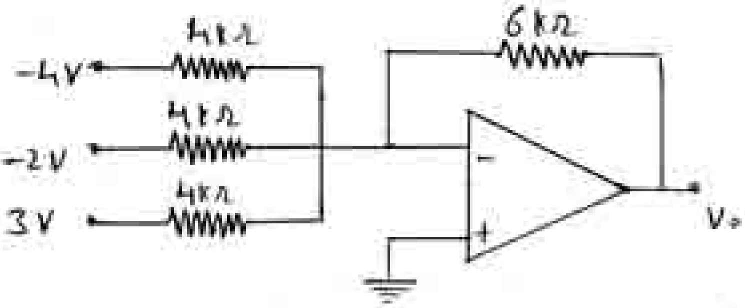
We have,

$$V_o = A_d V_d + A_c V_c$$
$$= 50000 \times 10\times10^{-6} + 0.25 \times 45\times10^{-6}$$
$$= 0.5 + 11.25\times10^{-6}$$
$$= \underline{500.011\ mV}$$

$\because V_d = V_1 - V_2$
$= 0.05\times10^{-3} - 0.04\times10^{-3}$
$= 0.01\times10^{-3} = 10\times10^{-6}$

$A_c = \frac{A_d}{CMRR} = \frac{50000}{2\times10^5} = 0.25$

5) Find the output voltage for the circuit shown in fig 5



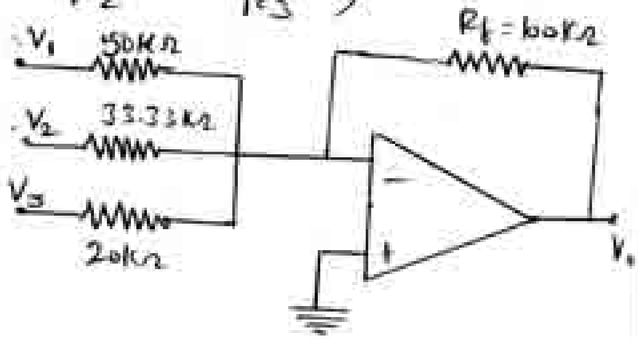
Sol. We have,

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$
$$= -\frac{R_f}{R_1}(V_1 + V_2 + V_3) \quad (\because R_1 = R_2 = R_3 = 4k\Omega)$$
$$= -\frac{6K}{4K}(-4 - 2 + 3)$$
$$= \underline{4.5V}$$

⑥ Design an adder circuit for $V_o = -[2V_1 + 3V_2 + 5V_3]$

Sol: Given $V_o = -(2V_1 + 3V_2 + 5V_3)$

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



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

Let $R_f = 100k\Omega$

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

$\Rightarrow R_1 = 50k\Omega$ $R_2 = 33.33k\Omega$ $R_3 = 20k\Omega$

7) Design an adder circuit for $V_o = 3V_1 + 2V_2 - 4V_3$

Sol: Given $V_o = 3V_1 + 2V_2 - 4V_3$

$\Rightarrow V_o = -[3(-V_1) + 2(-V_2) + 4V_3]$

Comparing with

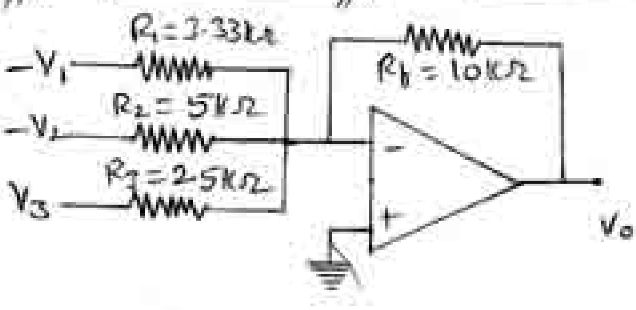
$$V_o = -\left[\frac{R_f}{R_1}(-V_1) + \frac{R_f}{R_2}(-V_2) + \frac{R_f}{R_3}V_3\right]$$

$\frac{R_f}{R_1} = 3$, $\frac{R_f}{R_2} = 2$, $\frac{R_f}{R_3} = 4$

Let $\boxed{R_f = 10k\Omega}$

$\therefore R_1 = \frac{10k}{3}$, $R_2 = \frac{10k}{2}$, $R_3 = \frac{10k}{4}$

$\boxed{R_1 = 3.33k\Omega}$ $\boxed{R_2 = 5k\Omega}$ $\boxed{R_3 = 2.5k\Omega}$



8) A differential amplifier has open circuit gain of 10^4, the input signals are 1.2 MV & 2.4 MV. Determine the output voltage.

Sol: Given $A_d = 10^4$, $V_2 = 2.4\times10^{-6}V$, $V_1 = 1.2\times10^{-6}V$, $V_o = ?$

Output Voltage,
$$V_o = A_d V_d$$
$$= A_d(V_2 - V_1) \quad (\because \text{since } A_c \text{ is not given})$$
$$= 10^4(2.4 - 1.2)\times10^{-6}$$
$$= \underline{0.012V}$$

9) For the circuit shown in fig ①. draw the output voltage for the input voltage shown in fig ①

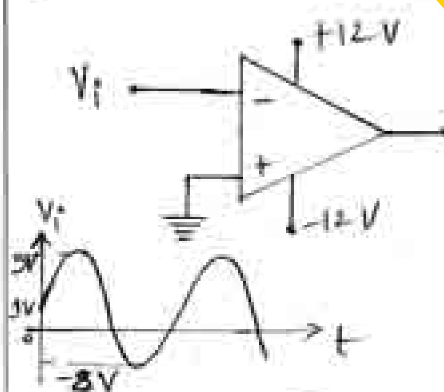


Fig 19(a)

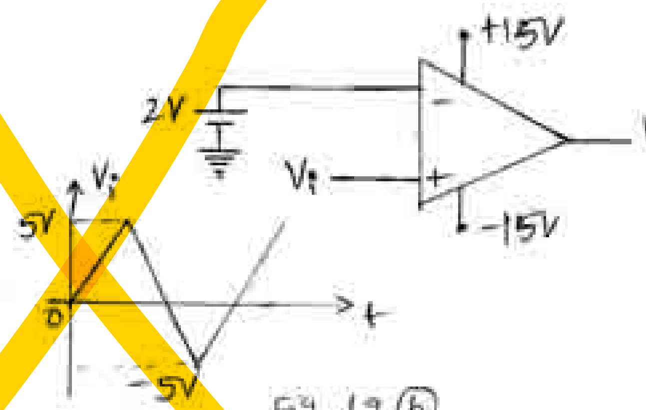
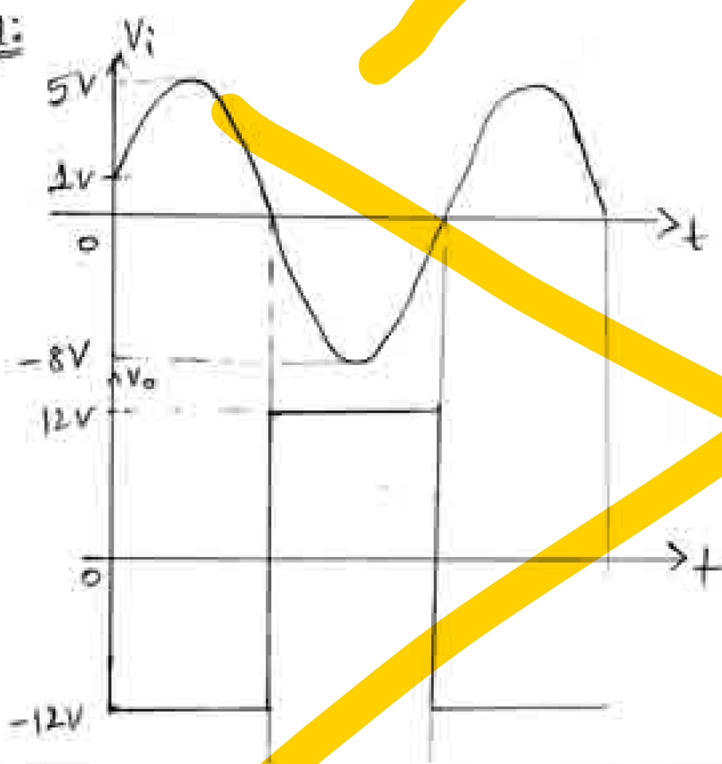
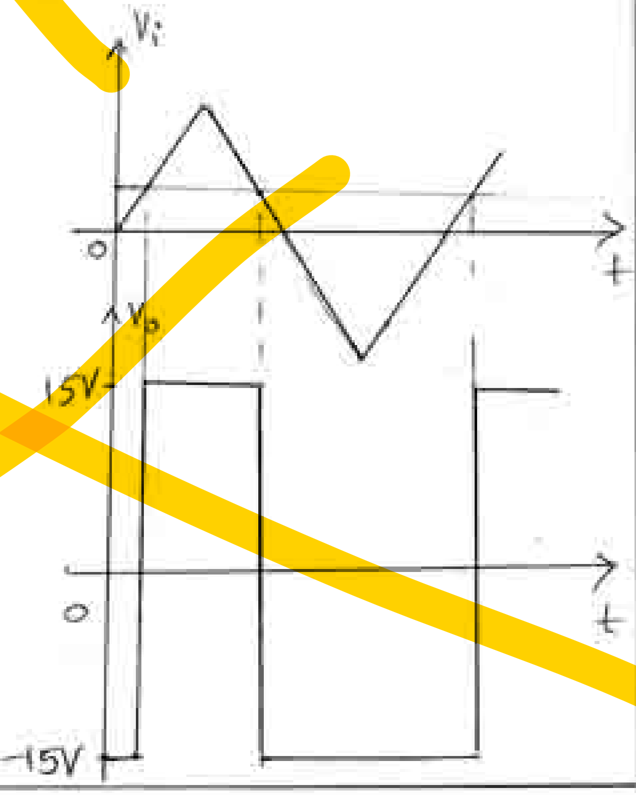


Fig 19(b)

Sol:





(10) Calculate the CMRR for the circuit measurements shown in fig (10).

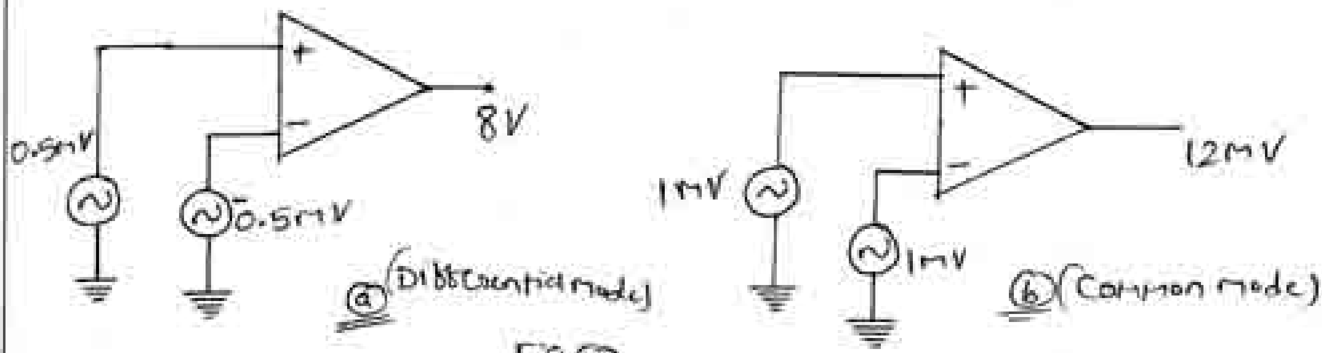


Fig (10)

Sol:
Fig 10(a) can be redrawn as shown in fig 11(a) & fig 10(b) can be redrawn as shown in fig 11(b).

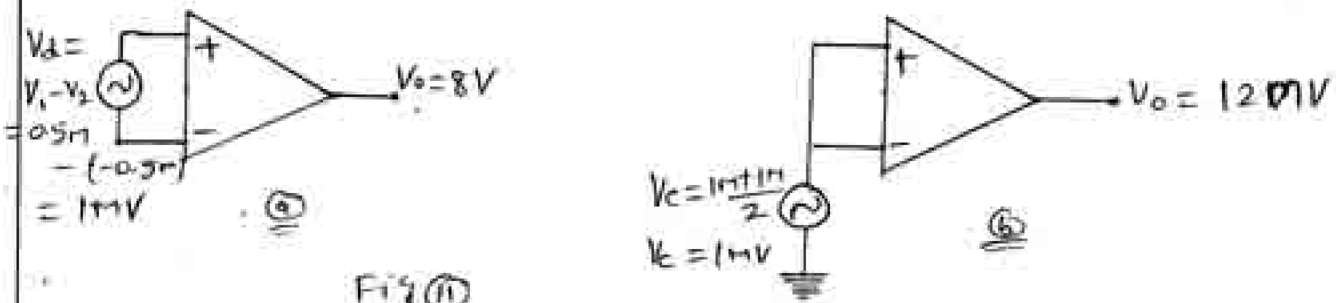


Fig (11)

From fig (11)(a),

$$A_d = \frac{V_o}{V_d} = \frac{8}{1\times10^{-3}} = 8000.$$

From fig (11)(b),

$$A_c = \frac{V_o}{V_c} = \frac{12\times10^{-3}}{1\times10^{-3}} = 12$$

$\therefore$ CMRR is,

$$CMRR = \frac{A_d}{A_c} = \frac{8000}{12} = 666.66$$

(or)

$$CMRR\,(dB) = 20\log_{10}\frac{A_d}{A_c} = 20\log_{10}(666.66) = 56.47\,dB$$

(11) Determine the output voltage of an op-amp for input voltages of $V_{i_1} = 150\,\mu V$, $V_{i_2} = 140\,\mu V$. The amplifier has a differential gain of $A_d = 4000$ & the value of CMRR is:
(a) 100 (b) 10^5.

Sol: Difference voltage, $V_d = V_{i_1} - V_{i_2} = 150\times10^{-6} - 140\times10^{-6} = 10\,\mu V$

Common mode voltage, $V_c = \frac{V_{i_1} + V_{i_2}}{2} = \frac{150\times10^{-6} + 140\times10^{-6}}{2} = 145\,\mu V$

(a) We have, $V_o = A_d V_d \left(1 + \frac{1}{CMRR} \frac{V_c}{V_d}\right)$

$$= (4000)(10\times10^{-6})\left(1 + \frac{1}{100}\frac{145\times10^{-6}}{10\times10^{-6}}\right)$$

$$= 40\times10^{-3}(1 + 0.145)$$

$$= 45.8mV$$

(b) $V_o = (4000)(10\times10^{-6})\left(1 + \frac{1}{10^5}\frac{145\times10^{-6}}{10\times10^{-6}}\right)$

$$= 40\times10^{-3}(1.000145)$$

$$= 40.0058mV$$

12) Calculate the output voltage of a non-inverting amplifier for $V_1 = 2V$, $R_f = 500k\Omega$ & $R_1 = 100k\Omega$

Sol: Given $V_1 = 2V$, $R_f = 500k\Omega$, $R_1 = 100k\Omega$, $V_o = ?$

For non-inverting amplifier,

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = \left(1 + \frac{500\times10^3}{100\times10^3}\right)2 = 6(2) = 12V$$

13) A 741C is an op-amp with $A = 100,000$ & a minimum $CMRR_{dB} = 70dB$. What is the common-mode voltage gain? If a desired & common-mode signal each has a value of 5MV, what is the output voltage?

Sol: Given $A = A_d = 100,000$, $CMRR(dB) = 70dB$, $A_c = ?$

$V_c = 5\times10^{-6}V$, $V_o = ?$

We have $CMRR(dB) = 20\log_{10}\frac{A}{A_c}$

$$\Rightarrow \quad 70 = 20\log_{10}\frac{A}{A_c}$$

$$\Rightarrow \quad \frac{A}{A_c} = 10^{70/20}$$

$$\Rightarrow \quad A_c = \frac{A}{10^{7/2}} = \frac{100,000}{10^{7/2}} = 31.622$$

We have
$$V_o(CM) = A_c V_c$$
$$= 31.622 \times 5 \times 10^{-6}$$
$$V_o(CM) = 158.11 \mu V$$

14) Assume that negative saturation occurs at 1V less than the supply voltage with an op-amp. How much inverting input voltage does it take to drive the op-amp of fig (14) into negative saturation?

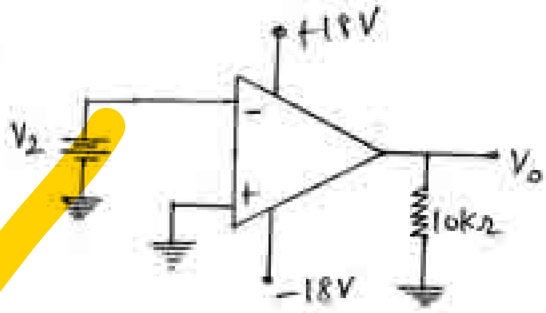


Fig (14)

Sol: Given $V_{cc} = \pm 18V$, Negative saturation voltage $= -17V$

$V_2 = ?$ $\quad A = 2 \times 10^5$ (Assume)

Given negative saturation voltage $= -17V$, output saturates negatively at $-17V$.

$$\therefore V_2 = \frac{17}{200{,}000} = 85 \mu V \qquad [\because V_o = A V_2]$$

15) The input voltage to an op-amp is a large voltage step. The output is an exponential waveform that changes 0.75V in 50ns. What is the slew rate of the op amp?

Sol: Given $dV = 0.75V$, $dt = 50ns$

We have, $SR = \frac{dV}{dt} = \frac{0.75}{50 \times 10^{-9}} = 15 V/\mu s$

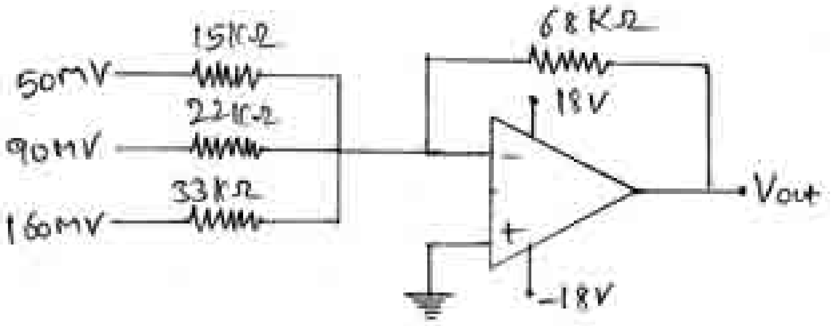
16) An op-amp has slew rate of $8 V/\mu s$. What is the power bandwidth for a peak output voltage of 5V?

Sol: Given $SR = 8V/\mu s$, $V_m = 5V$, $f_{max} = ?$

Highest freq @ power bandwidth,

$$f_{max} = \frac{SR}{2\pi V_M} = \frac{.8/10^{-6}}{2\pi \times 5} = 254.64\,KHz$$

17 In fig 17, what is the ac output voltage? If a compensating resistor needs to be added to non-inverting input, what size should it be?



Sol:

AC output Voltage,

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

$$= \left[\frac{68K}{15K}(50\times10^{-3}) + \frac{68K}{22K}(90\times10^{-3}) + \frac{68K}{33K}(160\times10^{-3})\right]$$

$$= 834.53\,mV$$

Compensating resistor,

$$R_c = R_1 \| R_2 \| R_3$$

$$= \frac{1}{\frac{1}{15K} + \frac{1}{22K} + \frac{1}{33K}}$$

$$= 7.02\,K\Omega$$

[If a summing circuit needs to be compensated by adding an equal resistance to the non-inverting input, the resistance is the Thevenin resistance looking from the inverting input back to the sources]

18 What is the initial slope of a sine wave with a frequency of 15KHz & a peak value of 2V? What happens to the initial slope if the frequency increases to 30KHz?

Sol: Given ⓐ $f = 15\,KHz$, $V_m = 2V$, $S_s(SR) = ?$

Initial slope of a sine wave.

$$S_s = 2\pi f V_m \qquad (\because SR = S_s = 2\pi f V_m)$$

$$= 2\pi \times 15\times10^3 \times 2$$

$$= 188.49\,mV/\mu s$$

ⓑ $f = 30\,KHz$, $V_m = 2V$, $S_s = ?$

$$S_s = 2\pi f V_m = 2\pi \times 30\times10^3 \times 2 = 376.99\,mV/\mu s$$

19 Find V_{out} in fig ⑲, if $R = 10k\Omega$, $V_1 = -20mV$ & $V_2 = -30mV$

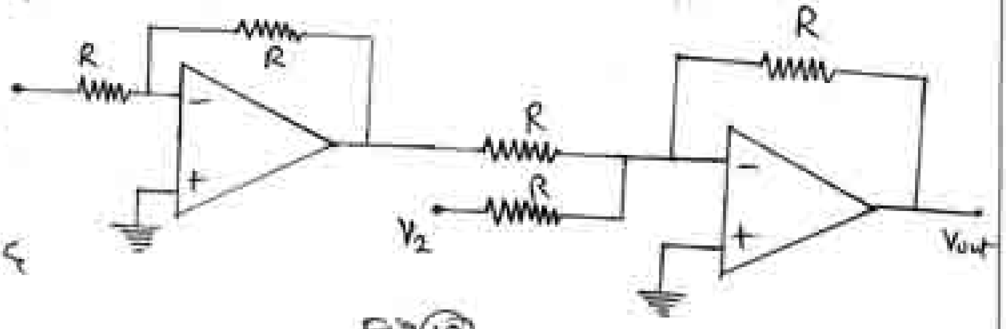
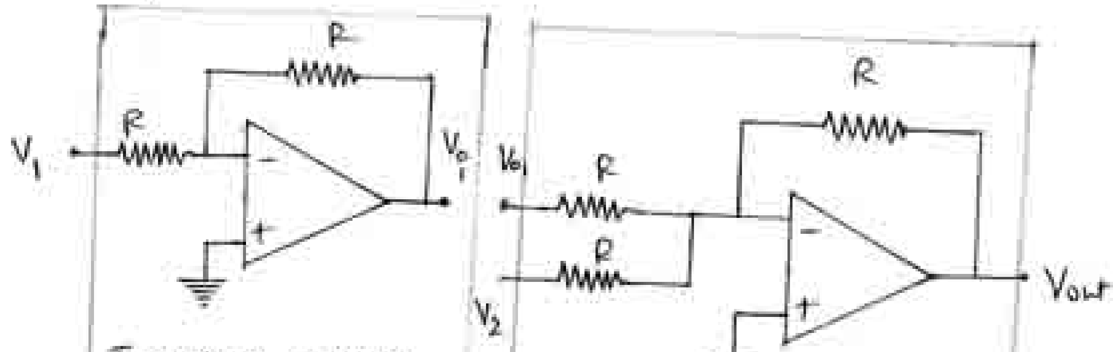


Fig ⑲

Sol:

The given circuit is redrawn



Inverting amplifier circuit ①

Inverting summer circuit ②

From circuit ①,

$$V_{o_1} = -\frac{R}{R} V_1$$

$$= -(-20mV)$$

$$= 20mV$$

From circuit ②

$$V_{out} = -\left(\frac{R}{R} V_{o_1} + \frac{R}{R} V_2\right) \qquad V_{out} = V_2 - V_{o_1}$$

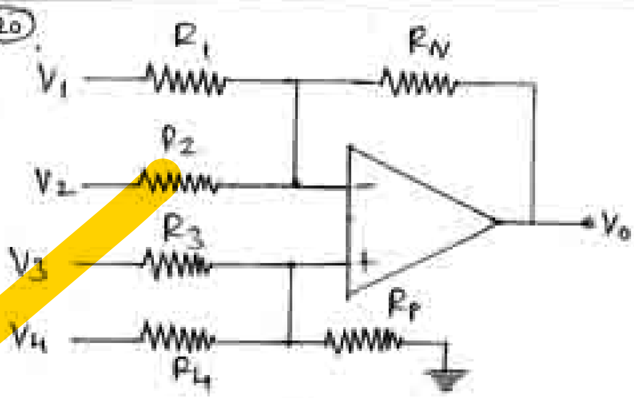
$$= -(20mV - 30mV)$$

$$= -20mV + 30mV$$

$$V_{out} = 10mV$$

The given circuit is a subtractor

2) In the op-amp circuit of fig(20), show that $V_o = (V_3+V_4)-(V_1+V_2)$ if all resistances are equal.



Fig(20)

Sol:

Let us use superposition theorem.

Case(i): Let $V_2 = V_3 = V_4 = 0$

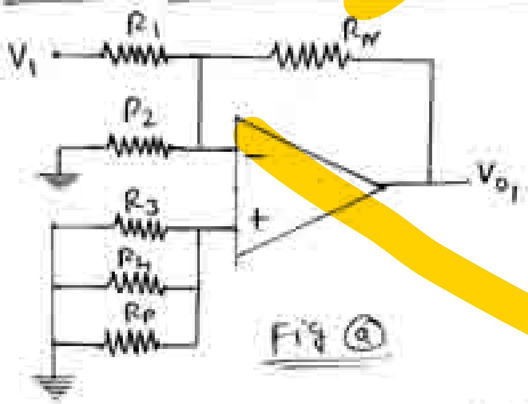


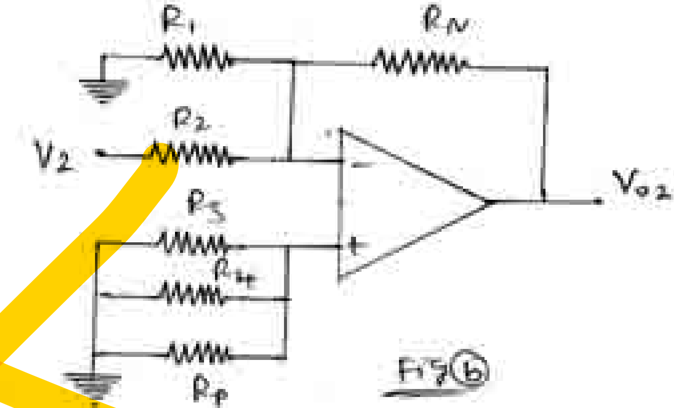
Fig (a)

The resulting circuit is shown in fig (a). The circuit is inverting amplifier. op V?? is,

$$\therefore V_{o_1} = -\frac{R_N}{R_1} V_1$$

$$\boxed{V_{o_1} = -V_1} \quad (\text{Let } R_1 = R_N) \quad -(1)$$

Case(ii): Let $V_1 = V_3 = V_4 = 0$



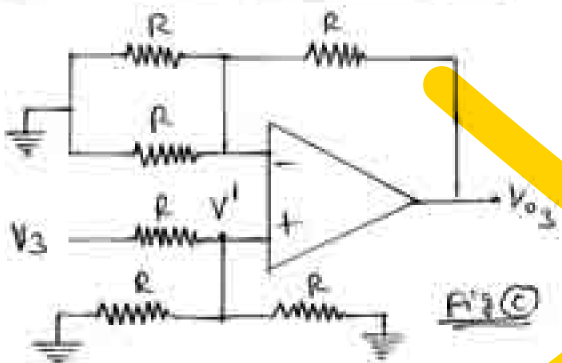
Fig(b)

The output voltage V_{o_2} is,

$$V_{o_2} = -\frac{R_N}{R_2} V_2$$

$$\boxed{V_{o_2} = -V_2} \quad -(2) \quad (\text{Let } R_2 = R_N)$$

Case(iii): Let $V_1 = V_2 = V_4 = 0$

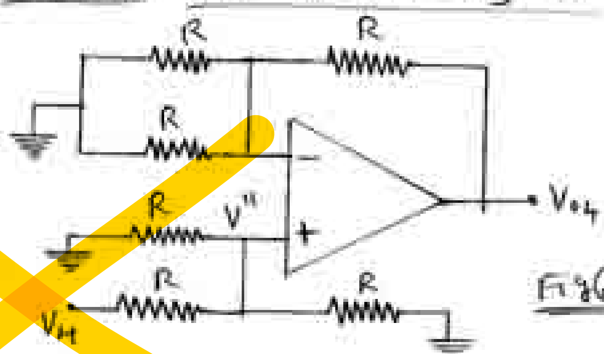


Fig(c)

From potential divider rule.

$$V' = \frac{V_3\,(R\,||\,R)}{R + (R\,||\,R)}$$

Case(iv): Let $V_1 = V_2 = V_3 = 0$



Fig(d)

From potential divider rule.

$$V'' = \frac{V_4\,(R\,||\,R)}{R + (R\,||\,R)}$$

$$V' = \frac{V_3 \frac{RR}{R+R}}{R + \frac{RR}{R+R}}$$

$$= \frac{V_3 \frac{R^2}{2R}}{R + \frac{R^2}{2R}}$$

$$= \frac{V_3 R/2}{3R/2}$$

$$= \frac{V_3}{3} \quad \text{—} (*)$$

Now Fig © can be redrawn as

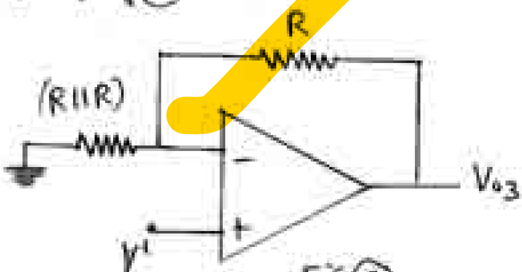


Fig ©

The resulting circuit shown in fig © is non-inverting amplifier

∴ The output voltage V_{o3} is

$$V_{o3} = \left[1 + \frac{R}{(R\|R)}\right] V' \quad \text{—} (***)$$

using (*) in (***)

$$V_{o3} = \left[1 + \frac{R}{(RR/R+R)}\right] \frac{V_3}{3}$$

$$= \left(1 + \frac{R}{R^2/2R}\right)\left(\frac{V_3}{3}\right)$$

$$= (1+2)\frac{V_3}{3}$$

$$\boxed{V_{o3} = V_3} \quad \text{—} (3)$$

$$\Rightarrow V'' = \frac{V_4 (RR/R+R)}{R + (RR/R+R)}$$

$$\Rightarrow V'' = \frac{V_4}{3} \quad \text{—} (**)$$

$$|||^{ly} \quad V_{o4} = \left[1 + \frac{R}{(R\|R)}\right] V''$$

$$\boxed{V_{o4} = V_4} \quad \text{—} (4)$$

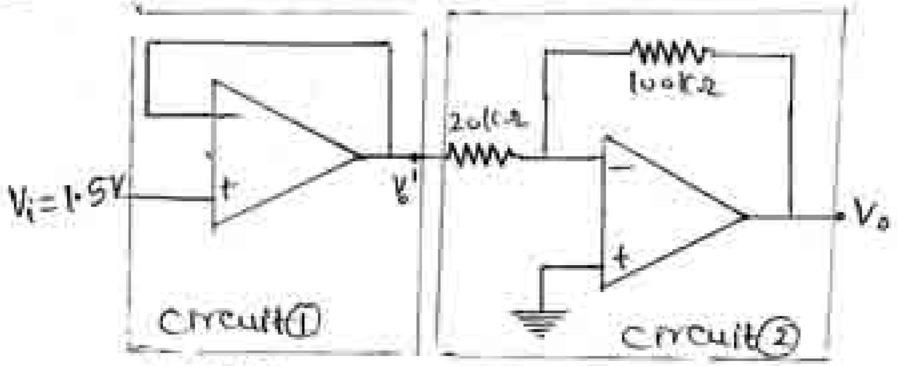
From Superposition theorem, the output voltage is

$$V_o = V_{o1} + V_{o2} + V_{o3} + V_{o4} = (V_3 + V_4) - (V_1 + V_2)$$

1) For the fig (21), determine V_o

Fig (21)

Sol:



Voltage follower — Inverting amplifier

From circuit (1), o/p of voltage follower is,

$$V_o' = V_i = 1.5V$$

From circuit (2), output V_o is,

$$V_o = -\left(\frac{100K}{20K}\right)V_o' = -5(1.5) = \underline{-7.5V}$$

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

Sol: Given $I_1 = 8.3\mu A$, $I_2 = 7.9\mu A$, $I_{ib} = ?$, $I_{io} = ?$

Input bias current, $I_{ib} = \frac{I_1 + I_2}{2} = \frac{8.3 + 7.9}{2} = 8.1\mu A$ //

Input offset current, $I_{io} = |I_1 - I_2| = |8.3 - 7.9| = 0.4\mu A$ //

3) How long does it take the output voltage of an op-amp to go from −8V to 7V, if the slew rate is 0.5V/μs?

Sol: Given $dV_o = 7 - (-8) = 15V$, $SR = \frac{0.5}{10^{-6}}$ V/s, $dt = ?$

We have $SR = \frac{dV_o}{dt} \Rightarrow dt = \frac{dV_o}{SR} = \frac{15}{0.5/10^{-6}} = \underline{30\mu s}$

4) For the inverting amplifier, $R_1 = 20k\Omega$, $R_f = 100k\Omega$ & $V_{in} = 1mV$, Calculate
ⓐ Closed-loop gain ⓑ Input resistance seen by source ⓒ output voltage ⓓ Input current ⓔ current entering the op-amp input terminals ⓕ current through feedback

Sol: Given, $R_1 = 20k\Omega$, $R_f = 100k\Omega$, $V_{in} = 1mV$, A (or A_d) = ?,
$R_{in} = ?$, $I_{in} = ?$, $V_o = ?$, $I_{op\text{-}amp} = ?$, $I_f = ?$

ⓐ We have,
$$A = -\frac{R_f}{R_1} = -\frac{100\times10^3}{20\times10^3} = -5$$

ⓑ $R_{in} = R_1 = \underline{20k\Omega}$

ⓒ Output Voltage, $V_o = +AV_{in} = -5\times1\times10^{-3} = \underline{-5mV}$

ⓓ $I_{in} = \dfrac{V_{in}-V_1}{R_1} = \dfrac{1\times10^{-3}-0}{20\times10^3} = 50nA$ $\left[\because \text{From virtual ground } V_1 = V_2 = 0\right]$

ⓔ $I_{op\text{-}amp} = 0$ ($\because$ No current flows into op-amp input terminals)

ⓕ $I_f = I_{in} = \underline{50nA}$

5) A sinusoidal signal with peak value 6mV & of 20KHz is applied to the input of an ideal op-amp integrator with $R = 100k\Omega$ & $C = 1\mu F$. Find the output voltage.

Sol: Given $R = 100k\Omega$, $C = 1\mu F$, $V_m = 6mV$, $f = 20KHz$, $V_o = ?$
$V_{in} = V_m \sin\omega t = 6\times10^{-3}\sin(2\pi f t) = 6\times10^{-3}\sin(40000\pi t)$

Output Voltage,
$$V_o = -\frac{1}{RC}\int_0^t V_{in}\,dt + V_o(0)$$
$$= -\frac{1}{100\times10^3\times1\times10^{-6}}\int_0^t 6\times10^{-3}\sin(40000\pi t)$$

Assume $V_o(0) = 0$
Initial Vtg across capacitor = 0

$$= -10\left[(6\times10^{-3})\left(\frac{-\cos 40000\pi t}{40000\pi}\right)_0^t\right]$$

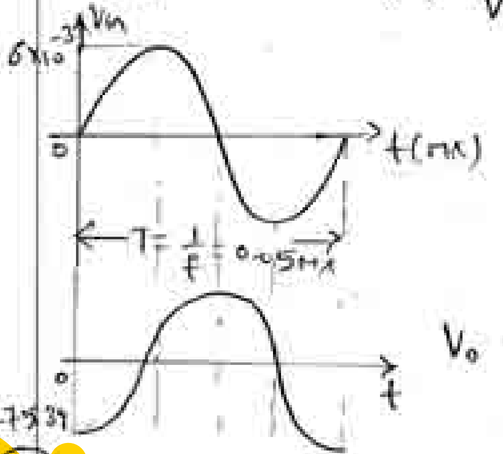
$$V_o = 477.46\,[\cos(40000\pi t) - 1]\ nV$$

(26) The input to a ideal differentiator is a sinusoidal voltage of peak voltage 6mV & frequency 20KHz. Find the output voltage, Given $R = 100K\Omega$ & $C = 1\mu F$.

Sol: Given $R = 100K\Omega$, $C = 1\mu F$, $V_m = 6mV$, $f = 20KHz$

$$V_{in} = V_m \sin(\omega t) = 6\times10^{-3}\sin(40000\pi t)$$

output voltage, $V_o = -RC\dfrac{dV_{in}}{dt}$



$$= -100\times10^{3}\times1\times10^{-6}\frac{d}{dt}\left[6\times10^{-3}\sin(40000\pi t)\right]$$

$$= -0.1\times6\times10^{-3}\cos(40000\pi t).40000\pi$$

$$V_o = -75.39\cos(40000\pi t)\ V$$

(27) Determine the output Voltage of a Ideal differentiator for the input shown in fig (27). Given $RC = 1ms$.

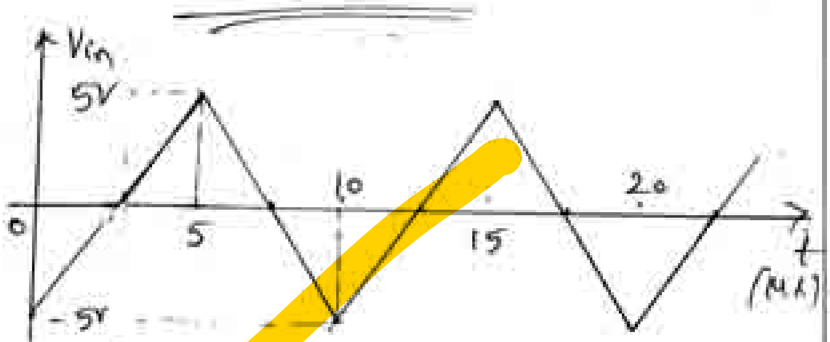


Fig (27)

Sol: Given $RC = 1ms$

case(1): For $0 < t < 5ms$

$$\frac{dV_{in}}{dt} = \frac{5-(-5)}{(5-0)} = 2V/ms \quad (a)$$

$x_2\,y_2$
(5,5)

(0,-5)
$x_1\,y_1$

$$\frac{y_2-y_1}{x_2-x_1} = \frac{y-y_1}{x-x_1}$$

$$\Rightarrow y = 2x-5$$

(or) $V_{in} = 2t-5$

Diff w.r.t t

$$\frac{dV_{in}}{dt} = 2V/ms$$

$$\therefore V_o = -RC\frac{dV_{in}}{dt} = -1\times10^{-6}\frac{2}{10^{-6}} = \underline{-2V}$$

Case (ii): For $5\mu s < t < 10\mu s$

$$\frac{dV_{in}}{dt} = \frac{-5-5}{(10-5)} = \frac{-10}{5} = -2V/\mu s \quad (a)$$

x_1, y_1 (5,5)

x_2, y_2 (10,-5)

$$\frac{-5-5}{10-5} = \frac{y-5}{x-5}$$

$$\frac{-10}{5} = \frac{y-5}{x-5}$$

$$y-5 = -2x+10$$

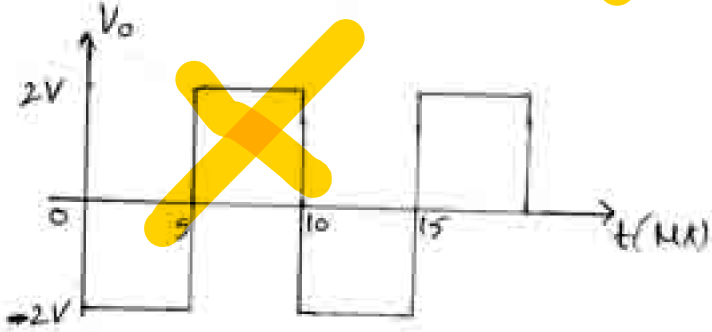
$$y = -2x+15$$

$$\frac{dy}{dx} = -2\ V/\mu s$$

$$\therefore V_o = -RC\frac{dV_{in}}{dt}$$

$$= -1\times10^{-6}\left(-\frac{2}{10^{-6}}\right)$$

$$= \underline{2V}$$



28) Calculate

(a) The output offset voltage due to input offset voltage = 1.2mV

(b) The output offset voltage due to input offset current = 100nA.

(c) The output offset voltage due to input offset voltage = 4mV & input offset current = 150nA.

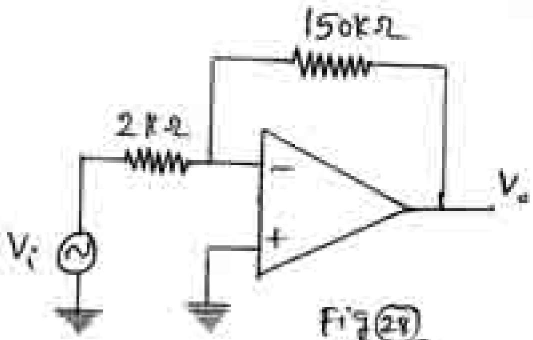


Fig (28)

Sol: (a) Given $V_{io} = 1.2mV$

output offset voltage.

$$V_{oo}(\text{due to } V_{io}) = V_{io}\left(\frac{R_1+R_f}{R_1}\right) = 1.2\times10^{-3}\left(\frac{2k+150k}{2k}\right)$$

$$V_{oo}(\text{due to } V_{io}) = \underline{91.2mV}$$

(b) $V_{oo}(\text{due to } I_{io}) = I_{io} R_f = 100\times10^{-9} \times 150\times10^{3} = 15\,mV$

(c) $V_{oo} = V_{oo}(\text{due to } V_{io}) + V_{oo}(\text{due to } I_{io})$

$$= V_{io}\left(1 + \frac{R_f}{R_1}\right) + I_{io} R_f$$

$$= 4\times10^{-3}\left(1 + \frac{150k}{2k}\right) + 150\times10^{-9}(150k)$$

$$= 304\times10^{-3} + 22.5\times10^{-3}$$

$$= 326.5\,mV$$

29) Calculate the input bias currents at each input of an op-amp having input bias current = 30nA & Input offset current = 5nA

Sol:
We have, $I_1 = I_{ib} + \frac{I_{io}}{2}$ & $I_2 = I_{ib} - \frac{I_{io}}{2}$

$$= 30\times10^{-9} + \frac{5\times10^{-9}}{2} \qquad = 30\times10^{-9} - \frac{5\times10^{-9}}{2}$$

$$= 32.5\,nA \qquad = 27.5\,nA$$

30) For an op-amp having a slew rate of $2\,V/\mu s$, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5V in $10\mu s$?

Sol: We have $V_o = A\,V_{in}$

$$\Rightarrow dV_o = A\,dV_{in}$$

$$\Rightarrow \frac{dV_o}{dt} = A\frac{dV_{in}}{dt}$$

$$\Rightarrow A = \frac{dV_o/dt}{dV_{in}/dt} = \frac{SR}{dV_{in}/dt} = \frac{2/10^{-6}}{0.5/10\times10^{-6}} = 40$$

Maximum closed-loop voltage gain = 40

31) For the signal & circuit of fig (31), determine the max frequency that may be used. Op-amp slew rate = 0.5 V/μs.

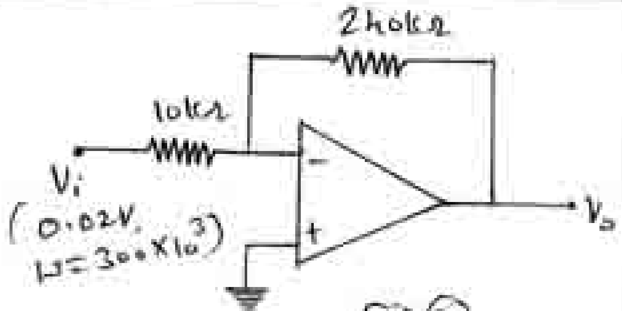


Fig (31)

sol: Gain $A = \left|\frac{R_f}{R_1}\right| = \frac{240\times10^3}{10\times10^3} = 24$

Output voltage (maximum)

$$V_m = A V_i = 24 \times 0.02 = 0.48V$$

We have $\omega_m \le \frac{SR}{V_m}$ (or) $f_m \le \frac{SR}{2\pi V_m}$

$$\le \frac{0.5/10^{-6}}{0.48} \qquad \le \frac{0.5/10^{-6}}{2\pi \times 0.48}$$

$$\omega_m \le 1.041\times10^6 \text{ rad/s} \text{ (or) } f_m \le 165.78 \text{ KHz}$$

Since the signal's frequency ($\omega = 300\times10^3$ rad/s) is less than the maximum freq ω_m; no output distortion will result.

2) For the circuit shown in fig (32).

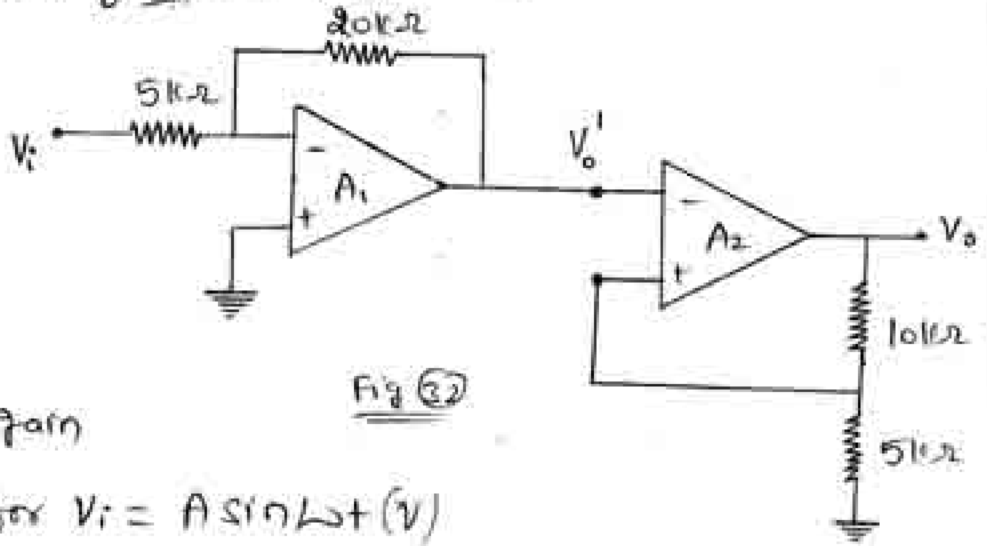


Fig (32)

(a) Calculate A_1

(b) Calculate A_2

(c) Find the total gain

(d) Find V_o' & V_o for $V_i = A\sin\omega t$ (V)

sol:

(a) $A_1 = -\frac{20k\Omega}{5k} = -4$ (b) $A_2 = 1 + \frac{10k}{5k} = 3$

(c) $A = A_1 A_2 = -12$

(d) $V_o' = (-2)\, A \sin\omega t = -2A\sin\omega t\ (V)$

$\therefore V_o = A_2 V_o' = 3(-2A\sin\omega t) = -6A\sin\omega t\ (V)$

33 Design an op-amp circuit for $V_o = 2V_1 - 3V_2 + 4V_3 - 5V_4$

Sol: $V_o = 2V_1 - 3V_2 + 4V_3 - 5V_4$

$\Rightarrow V_o = (2V_1 + 4V_3) - (3V_2 + 5V_4)$

$\boxed{V_o = V_{o1} - V_{o2}} \rightarrow (1)$ where $V_{o1} = 2V_1 + 4V_3$

$V_{o2} = 3V_2 + 5V_4$

Eqn (1) is the expression for output voltage of subtractor.

Consider

$V_{o1} = 2V_1 + 4V_3$

Comparing with,

$V_{o1} = \frac{R_{f1}}{R_1} V_1 + \frac{R_{f1}}{R_3} V_3$

$\Rightarrow \frac{R_{f1}}{R_1} = 2, \quad \frac{R_{f1}}{R_3} = 4$

Let $R_{f1} = 100k\Omega$.

$\therefore R_1 = 50k\Omega, \; R_3 = 25k\Omega$

Consider

$V_{o2} = 3V_2 + 5V_4$, Comparing with

$V_{o2} = \frac{R_{f2}}{R_2} V_2 + \frac{R_{f2}}{R_4} V_4$

$\Rightarrow \frac{R_{f2}}{R_2} = 3, \quad \frac{R_{f2}}{R_4} = 5$

Let $R_{f2} = 150k\Omega$

$\therefore R_2 = 50k\Omega, \quad R_4 = 30k\Omega$

The op-amp circuit is shown below

Let $R = 20k\Omega$