OPERATIONAL AMPLIFIER [OP-AMP]

What is an an Operational Amplifier

- An Operational amplifier (or) op-amp, is a direct coupled multistage voltage amplifier with an extremely high gain
- It's behaviour can be controlled by adding a suitable feed back.
- It has a very high input impedance. &
- a very low output impedance.
- The Early op-amps were mainly used for performing mathematical operations such as addition, subtraction, multiplication, Differentiation, and integration.
- Hence the device got the name operational amplifier.

[Now a days op-amps are used for coupling, amplification, impedance matching, delay, Element, buffer]

CIRCUIT SYMBOL OF AN OPAMP AND IT'S TERMINALS

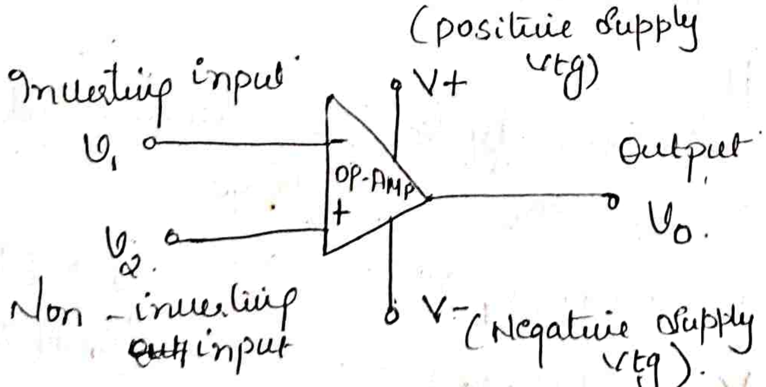


fig: Circuit Symbol for an op-amp

- fig shows the ckt Symbol of an op-amp.
- There are five main terminals, namely.
  1. A Non-inverting i/p terminal denoted by '+' Symbol.
  2. An inverting i/p terminal denoted by '−' Symbol.
  3. An o/p terminal.
  4. A positive supply voltage terminal denoted by V^+
  5. A negative supply Voltage terminal denoted by

V_1 = Voltage at the inverting input.
V_2 = Voltage at the Non-inverting input.
V_0 = output Voltage.

- All these voltages are measured with respect to ground

- Normally, the op-amp operates from a bi-polar dual power supply i.e., two power supplies. one
- One positive & one negative with a common ground terminal.
- The supply voltages are denoted by V^+ & V^- and they are in the range $\pm 9V$ to $\pm 22V$.
- They are typically $\pm 15V$.

- A voltage applied to the Non-inverting input produces an in-phase (or) same polarity vtg at the o/p.
- while a voltage applied to the inverting input produces an out-off phase (or) opposite polarity vtg at the o/p.
- The o/p vtg denoted by V_0 is proportional to the difference b/w the i/p voltages.

i.e., $V_0 \propto (V_2 - V_1)$ (or) $V_0 \propto (V_1 - V_2)$

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

where $A \Rightarrow$ proportionality constant & which is Equal to gain of the differential amplifier.
(or)
A = voltage gain.

Hence, OP-AMP is basically a differential (or) difference amplifier.

OPERATION OF AN-OPAMP [Ideal-op-amp].

The op-Amp is basically a differential amplifier which amplifies the difference b/w its two i/p voltages.

$$V_o = AV_d = A[V_2 - V_1].$$

where $V_d = [V_2 - V_1]$ = differential or difference i/p voltage.
A = open-loop voltage gain.

when a voltage V_1 is applied to the inverting i/p with the non-inverting i/p grounded $[V_2 = 0]$ the o/p voltage is

$$V_o = A[V_2 - V_1]$$

$$V_o = A[0 - V_1]$$

$$\boxed{V_o = -AV_p}$$

This indicates that the o/p voltage will be inverted (phase or polarity reversed) with respect to the input voltage.

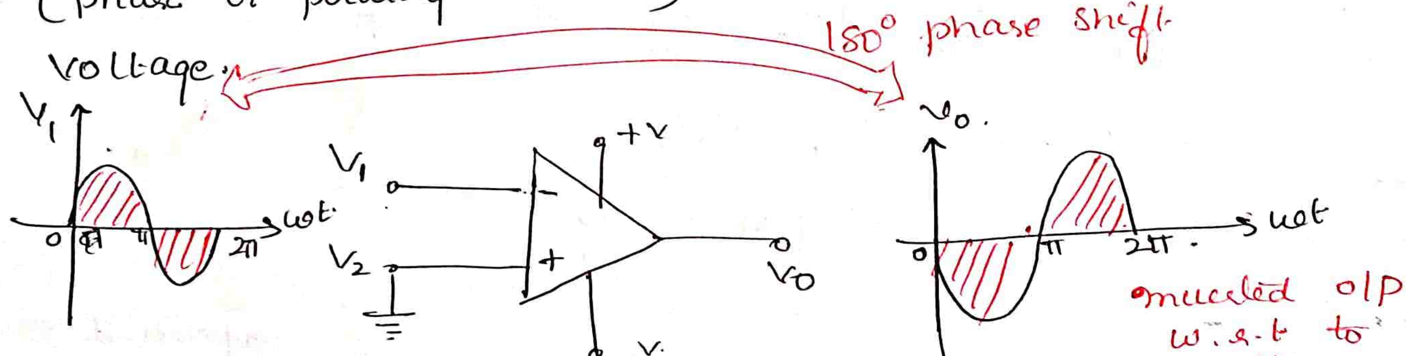


fig: a). Inverting amplifier.

→. On the other hand, when a voltage is applied to the Non-Inverting amplifier input with the inverting input grounded $[V_1 = 0]$ the o/p voltage is

$$V_o = A[V_2 - 0]$$

$$\boxed{V_o = AV_2}$$

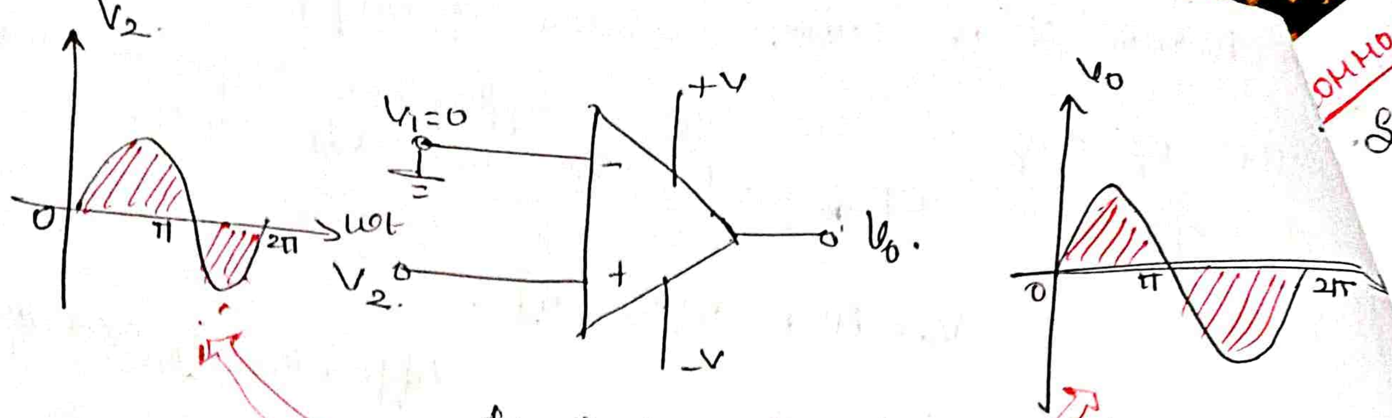


fig: b) Non - inverting amplifier.

Zero Phase Shift

fig a & b: shows Basic operation of an op-amp.

① DIFFERENTIAL GAIN: (A_d).

- Since the differential amplifier amplifies the difference b/w two input ~~sing~~ (voltages) Signals & hence gain provided under this condition is called differential gain.

W.K.T from Eqn. $V_0 = A[V_2 - V_1]$.

where A_d is differential gain.
(differential gain)

let $V_d = [V_2 - V_1]$ is differential voltage

$\therefore V_0 = A_d V_d$

$$\therefore \boxed{A_d = \frac{V_0}{V_d}}$$

Usually the gain is always Expressed in terms of decibels (dB) i.e.,

$$A_d(dB) = 20 \log_{10}\left(\frac{V_0}{V_d}\right)$$
$$= 20 \log_{10}(A_d).$$

COMMON MODE GAIN (A_c).

Suppose the two i/p signals given to the two i/p terminals of differential amplifier, are which are Equal in all respect that is Equal amplitudes, Equal frequencies and Equal in phases, then the o/p of ideal differential amplifier is Equal to zero.

$$\therefore V_0 = A_c [V_2 - V_2].$$

$\frac{V_2 - V_2}{A_c 0}$

But $V_1 = V_2$. $\Rightarrow$ [Same vtg applied

$$\therefore \boxed{V_0 = 0.}$$

- But the o/p voltages of practical amplifier not only depends on the difference b/w two i/p voltages, but also depends on the average common level of the two i/p signal.
- Such average level of the two i/p signals is called common-mode signal and is denoted as V_c.

$$\therefore V_c = \frac{V_1 + V_2}{2}$$

- practically, the differential amplifier produces the output voltage proportional to common mode signal.
- the gain with which it amplifies the common mode signal to produce the o/p is called common mode gain denoted as 'A_c' and is given by

$$V_0 = A_c V_c.$$

$$\therefore \boxed{A_c = \frac{V_0}{V_c}.}$$

∴ The total o/p vtg of any differential amp expressed as sum of o/p vtgs under differential & o/p vtg under common mode.

$$\therefore \boxed{V_o = A_d V_d + A_c V_c}$$

COMMON MODE Rejection Ratio (CMRR)

→ CMRR is the ability of differential amplifier to reject a common mode signals.

→ The CMRR is defined as the ratio of differential mode gain to the common mode gain.

It is denoted as 'ρ'

$$CMRR = \rho = \left|\frac{A_d}{A_c}\right|.$$

- As w.k.t for ideal differential amplifier $A_d = \infty$ & $A_c = 0$.

- ∴ Hence the CMRR is also Equal to infinity.

- Many a times CMRR is also expressed into dB

∴ $$CMRR\ (dB) = 20 \log_{10} \left|\frac{A_d}{A_c}\right| dB.$$

PIN DIAGRAM OF OP-AMP IC μA 741 & ITS SIGNIFICANCE:

why it's named as 741 IC.

[out of 8 pins]

- 7 means 7 pins are connected. could in the next page.
- '4' are considered as i/p i.e, two are i/p's & two are supply voltages.
- 1 is o/p pin
- 2 pins are offset null.

(7)

∴ It is named as 741 IC.

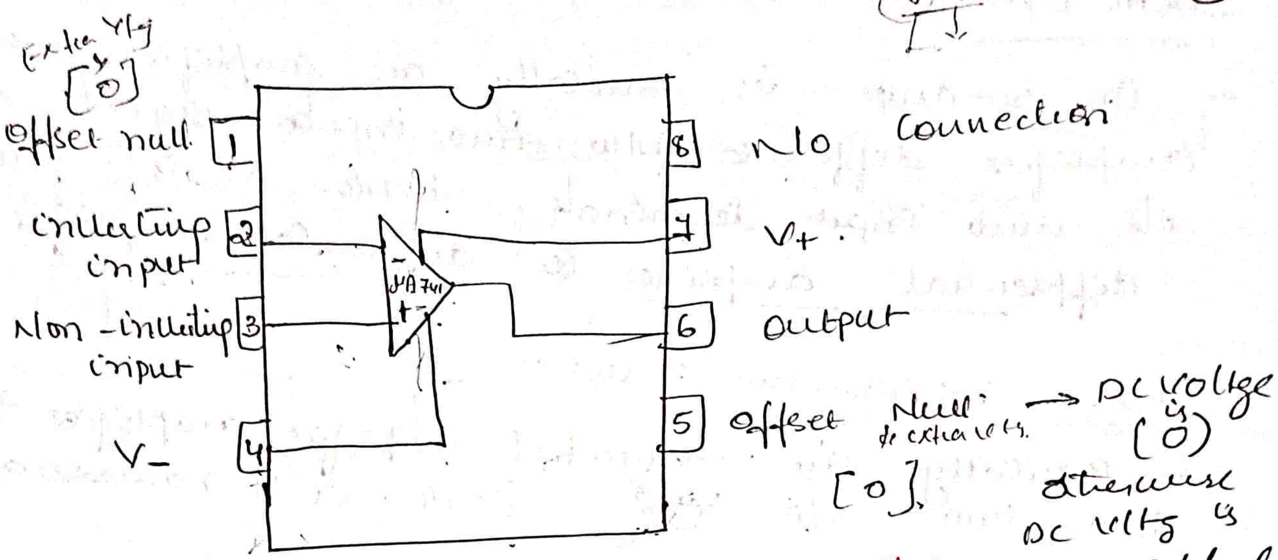


fig:. pin diagram of IC 741.

- An integrated circuit (IC) is an electronic circuit in which all the components such as transistors, diodes etc., resistors etc., are produced and interconnected during manufacturing process on a single piece of silicon waffer called a chip
- A very popular and widely used IC version of Op-Amp is μA 741. which is 8 pin IC available in dual-in-line package (OR) DIP packages.
- The pin diagram of μA 741 is as shown in fig.
- pin 1 & 5 are used to null or balance the offset voltages.
  [offset voltages is the o/p voltage that occurs even when both the input voltages are zero].
- pin 2 is the inverting i/p terminal.
- pin 3 is the non-inverting input terminal.
- pin 4 & 7 are the supply voltage pins.
  ['+' to pin '7' & '–' to pin 4]
- pin 8 is dummy to which No connection is made
- pin 6 is the o/p terminal.

IDEAL OP-AMP:

- An op-amp is basically an amplifier which amplifies difference b/w two inputs signals applied its two input terminals, hence it is called as differential amplifier (or) difference amplifier

IDEAL DIFFERENTIAL AMPLIFIER:

- Basically the differential amplifier amplifies the difference b/w two i/p vtgs. Hence it is named as differential amplifier.

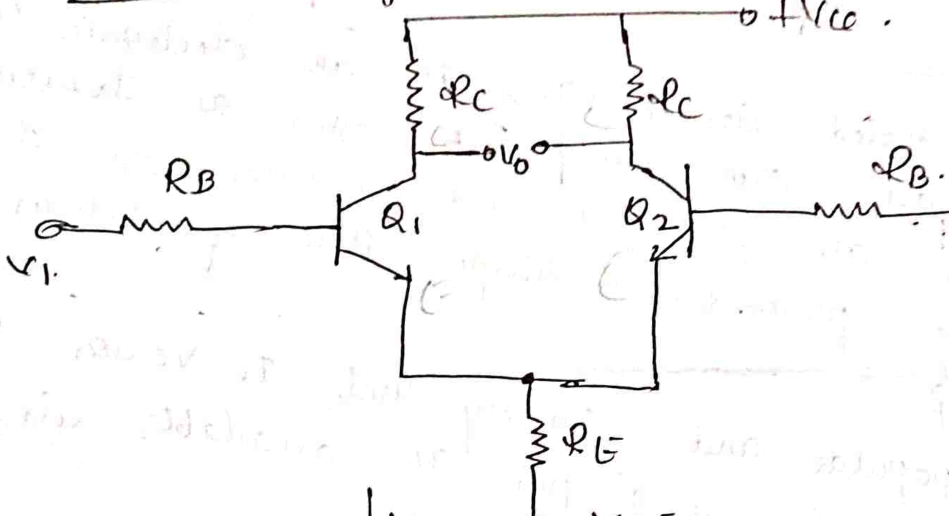


fig a:

- Let us consider differential amplifier ckt is shown in fig (a).
- The ckt consists of two transistors connected back-to-back as shown in the fig (a)
- The two i/p's are given to the base of each transistor and o/p is taken b/w two collectors of of two transistors.

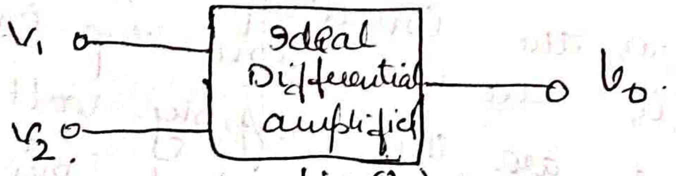


fig (b)

- fig shows the symbolic representation of differential amplifier.

V_1 and V_2 are the two i/p voltages and 'V_0' is the ~~unit~~ o/p vtg.

In an ideal differential amplifier the o/p vtg is directly proportional to difference b/w two i/p voltages.

i.e., $V_0 \propto (V_2 - V_1)$

$V_0 = A(V_1 - V_2)$

A = proportionality const and which is equal to gain of the differential amplifier.

PROBLEM:

1. For a differential amplifier with input voltage are 600μV and 480μV. The differential gain of the amplifier is 10,000. Find the output voltage for the following CMRR. i) CMRR = 200 ii) CMRR = 10^8

Soln Given that $V_1 = 600\mu V$, $V_2 = 480\mu V$ and $A_d = 10000$ (differential gain)

i) For CMRR = 200,

$$CMRR = \left|\frac{A_d}{A_c}\right|$$

$$\therefore 200 = \frac{10000}{A_c}$$

$$\therefore A_c = \frac{10000}{200} = 50$$

$$V_c = \frac{V_1 + V_2}{2} = \frac{600\mu V + 480\mu V}{2}$$

$$\boxed{V_c = 540\mu V}$$

$|||^{ly}$ $V_d = V_1 - V_2 = 600\mu V - 480\mu V = 120\mu V$

$\therefore$ The o/p vtg of a differential amplifier is given by

$$V_0 = A_d V_d + A_c V_c$$

$$V_0 = 10000 \times 120 \times 10^{-6} + 50 \times 540 \times 10^{-6}$$

$$V_0 = 1227\ mV \quad \text{or} \quad 1.227V$$

ii) $CMRR = 10^8$

$\therefore A_c = \frac{A_d}{CMRR} = \frac{10000}{10^8} = \underline{10^{-4}}$

$V_c = 540\,\mu V$

$V_d = 120\,\mu V$

$\therefore$ O/P vltg is

$V_o = A_d V_d + A_c V_c$

$V_o = 10000 \times 120 \times 10^{-6} + 10^{-4} \times 540 \times 10^{-6}$

$\underline{V_o = 1.2V}$

(2) An op-amp has a differential gain of 500 and a CMRR of 80dB. If the common mode i/p signal is $2 \sin 100\pi t$ V, calculate the common-mode o/p vltg

Solⁿ

CMRR in dB $= 20 \log \left|\frac{A_d}{A_c}\right|$

i.e. $80dB = 20 \log \left|\frac{A_d}{A_c}\right|$

or $\frac{A_d}{A_c} = \text{antilog}\left(\frac{80}{20}\right) = \text{antilog}(4)$

$\therefore \frac{A_d}{A_c} = 10000$

(or) $A_c = \frac{A_d}{10000} = \frac{500}{10000} = \underline{0.05}$

$\therefore$ O/P vltg of common-mode o/p vltg is

$\boxed{A_c V_c = 0.05 \times 2 \sin 100\pi t}$

CHARACTERISTICS OF AN IDEAL OP-AMP.

1. An ideal op-amp does not draw any current from the voltage sources connected to its O/P terminals. Thus its input resistance is infinite i.e., $R_i = \infty$.
   → very high
2. The O/P vtg of an ideal op-amp is independent of the current drawn from it. This means that it has zero O/P resistance i.e., $R_0 = 0$. ⟹ [O/P vtg is high].
3. The voltage gain of an ideal op-amp is infinite, $A = \infty$. This implies that, for a given O/P voltage, the differential input voltage is essentially zero.
4. An ideal opamp amplifies signals of any frequency with a constant gain, which ~~amplifies~~ implies that it has an infinite bandwidth, $B.W = \infty$.
5. When equal voltages are applied to both the inputs of an ideal opamp, its output voltage is zero. Thus, it has a perfect balance.
6. The common-mode rejection ratio of an ideal opamp is infinite. i.e., $CMRR = \infty$.
7. An ideal opamp has infinite slew-rate i.e, $SR = \infty$. This implies that the O/P vtg change simultaneously with the I/P voltages.
8. The characteristics of an ideal opamp do not change with temperature.
9. The supply voltage (or) power supply rejection ratio of an ideal op-amp is zero, i.e., $PSRR = 0$.

CHARACTERISTICS OF PRACTICAL OP-AMPS are:

practical (or) non - ideal op-Amps differs from the ideal

The Characteristics are:

1. The open-loop voltage gain is not infinite, but is generally in the range of 10^4 to 10^6 (or) more.
2. The i/p resistance is not infinite, but is high & is of the order of megaohms.
3. The output resistance is not zero, but is of the order of 100Ω or less.
4. The B.W is not infinite, but is in the range of 1 to 100 MHZ.
5. The common-mode rejection ratio is not infinite, but is of the order of 90dB.
6. +ve & -ve voltage swings (o/p voltages) are limited by the supply voltages namely, V^+ & V^- [-ve feedback]

COMPARISON B/W IDEAL & PRACTICAL OPAMP:

NO	PARAMETER	SYMBOL	IDEAL VALUE	(PRACTICAL) TYPICAL value for μA741
1.	open loop voltage gain	A & (A_{OL})	∞	2×10^5 (max
2.	input resistance (impedance)	R_i (Z_{in})	∞	$2M\Omega$ [$100M\Omega$]
3.	o/p resistance (impedance)	R_o (Z_{out})	0	75Ω → (min) (1Ω)
4	o/p offset current	I_{io}	0	20nA [0.1nA]
5	i/p Bias current	I_B	0	80nA [100nA]
6.	i/p offset voltage	V_{io}	0	2mv [1mv].
7.	common-mode rejection ratio	CMRR, ρ	∞	90dB
8.	Band width	B.W	∞	1MHz (at unity gain)
9	slew rate	SR	∞	0.5 V/μs
10	power supply rejection ratio	PSRR	0	30μV/V. (20μV/V)

[these values only for open loop op-amps]

IDEAL and

IDEAL CHARACTERISTICS [derivations].

ideal

Infinite voltage gain ($A_{OL} = \infty$)

- Since for an ideal op-amp the differential o/p ($V_d = V_2 - V_1 = 0$). V_d is zero with a very small o/p vtg i.e.,

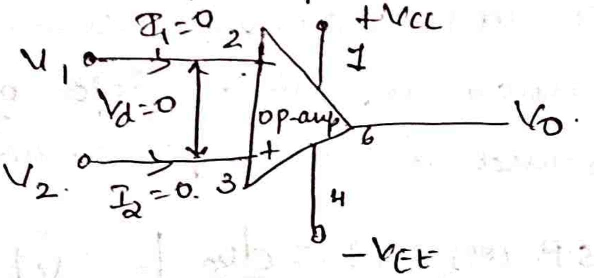
$$A_{OL} = \frac{\text{finite o/p vtg}}{\text{zero difference vtg}} = \frac{V_o}{V_d} = \frac{V_o}{0} = \infty$$

$$\therefore \boxed{A_{OL} = \infty}$$

NOTE: A_{OL} is also called open loop gain.

b) Infinite input impedance (or Resistance) ($R_i = \infty$)

- Even if we apply two i/p signals to two input terminals the current drawn at the i/p terminal is zero. i.e., $I_1 = I_2 = 0$. It indicates the inverting & non - inverting terminals are open circuited, hence open circuit impedance is very high & it is approximate as ∞ for ideal op-amp.



$R_{in} = \infty$

$\therefore I_1 = I_2 = 0$.

c) Zero output impedance ($R_o = 0$)

The o/p impedance (R_o) of an ideal op-amp is zero. this Ensures that the o/p vtg of op-Amp remains same irrespective of the load resistance connected at the o/p terminal.

d) Input off-set Voltage ($V_{ios}=0$)

The presence of small o/p voltage even when the i/p voltages are at ground potential (or) zero

i.e., $V_1 = V_2 = 0$ is called as off set voltage

$$\boxed{V_{ios}=0}$$

e) Infinite Bandwidth (B.W = ∞)

It is the range of frequencies over which the amplifier performance is satisfactory.

- The B.W ~~is~~ for ideal-opamp is ∞.

f) CMRR (ρ)

- It is the ratio of differential mode gain to common mode gain

$$\boxed{\rho = \infty}$$

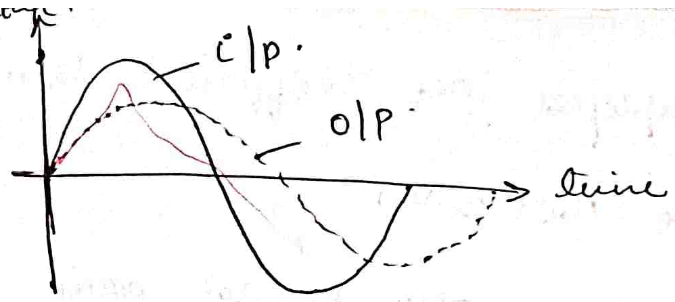
$$CMRR(\rho) = \frac{A_d}{A_c}$$

g) SLEW RATE :

The slew rate (or) maximum slew-rate of the op-amp is defined as the maximum ~~time~~ rate of change change of its o/p vtg, expressed in volts per microsecond.

$$SR \text{ (or) } MSR = \left.\frac{dv_o}{dt}\right|_{max} \; V/\mu sec$$

- Slew-rate is a measure of how fast the op-amp's output can change in response to changes in the input signal.
- It limits the maximum operating frequency.
- If the frequency of the input signal exceeds a particular value then the output will not be able to follow the i/p faithfully & the o/p waveform will be distorted. The o/p in such situation is referred to as the slew-rate limited o/p.



dig: Effect of slew rate.

ii) power supply rejection ratio (PSRR=0).

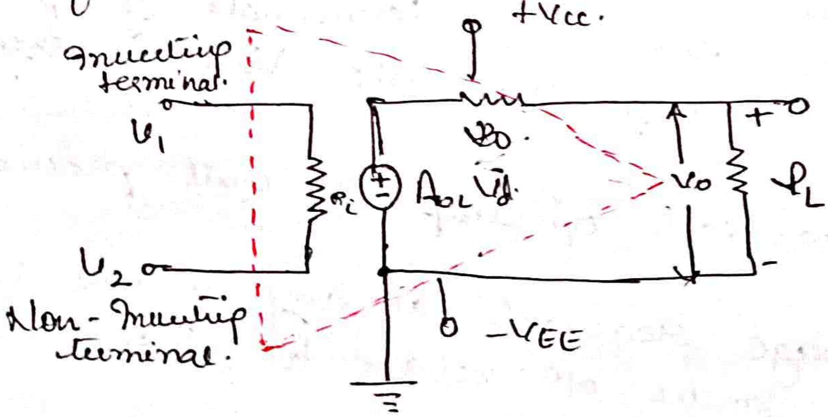
- The PSRR is defined as the ratio of change in i/p off-set voltage due to change in any one supply voltage by keeping other as const.
- The PSRR is also called power supply sensitivity.
- we are using two biasing voltages +Vcc and -VEE.
- PSRR is expressed as

$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{cc}}\Big|_{V_{EE}=const} \quad (or) \quad PSRR = \frac{\Delta V_{ios}}{\Delta V_{EE}}\Big|_{V_{cc}=const}.$$

- PSRR is expressed in terms of mv/v or μv/v and it is zero for ideal op-amp.

PRACTICAL OP-AMP CHARACTERISTICS.

for practical considerations the op-amp is replaced by its Equivalent ckt as shown below



W.K.T op-amp amplifies the difference b/w two signals.

$$\therefore V_0 = A_{OL} V_d = A_{OL}(V_2 - V_1)$$

1. **Open loop gain (A_{OL}):** It is the voltage gain of the op-amp with no feedback element connecting b/w i/p to o/p terminals. practically it is several thousands.

2. **Input Impedance (or) Resistance (R_i):** - It is the impedance looking from i/p terminals of op-amp.
   - It is a finite value typically 1MΩ. when we design op-amp with transistors and it may be several hundreds of MΩ when we design with FET'S.

3. **Output impedance (R_o):** - It is the impedance looking from o/p terminals of op-amp.
   - It is typically few hundred ohms.
   - with the help of -ve feedback, it can be reduced to a very small value like 1 or 2 Ω's.

4. **Bandwidth (BW):** - the Bandwidth of an practical op-amp under open loop configuration is very small.
   - with the help of -ve feedback it can be increased to desired value.

5. **Input - offset value:**
   - whenever both the i/p terminals of op-amp are grounded, ideally the o/p voltage should be zero.
   - But for the practical op-amp it will provide a small o/p vtg.
   - The o/p voltage required at any of the i/p terminals to make this small o/p voltage to zero is called i/p offset voltage.
   - Normally voltage required is in millivolts.
   - the i/p offset voltage depends on temperature.

6) INPUT BIAS CURRENT: (I_b).

- ~~As we~~ the i/p bias current is defined as the average of two i/p currents.

$$I_b = \frac{|I_{b1}| + |I_{b2}|}{2}$$

7. Input offset current (I_{ios}):

- The difference between two inputs currents is called input offset current.

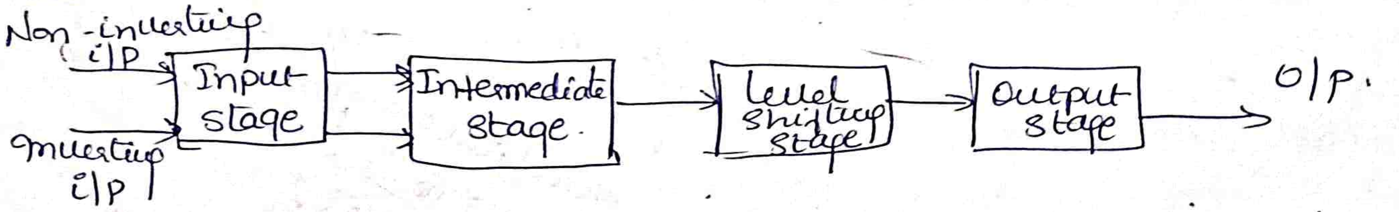
$$I_{ios} = I_{b2} - I_{b1}$$

8. PSRR: It is defined as the ratio of the change in the o/p offset vtg due to the change in the one power supply vtg keeping the other power supply vtg const:

$$PSRR = \left.\frac{\Delta V_{ios}}{\Delta V_{cc}}\right|_{\text{const } V_{EE}}$$

9) Slew Rate: [Same explanation of ideal]

10 * BLOCK DIAGRAM OF A TYPICAL OP-AMP:



- Block diagram consists of the following stages
1. Input stage 2. Intermediate stage 3. level shifting stage
4. output stage.

* * *

1. Input stage is a Dual - input, Dual input it can handle two inputs. - and balanced O/P differential amplifier.

- Balanced O/P means, the O/P is zero when two inputs are Equal or set to zero.
- It provides most of the gain of the op-amp and decides the input impedance of Op-amp.

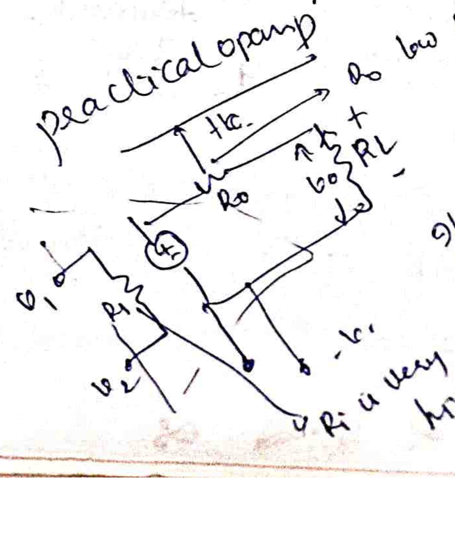
2. Intermediate stage: is a dual - input, unbalanced amplifier.

- unbalanced O/P means, the O/P is non-zero, when the two O/P's are Equal.
- Intermediate stage contains one or more differential amplifiers to achieve higher differential gain.

3. LEVEL SHIFTING: → This stage amplifies both dc & ac signals due to absence of coupling capacitors. It is usually a CC configuration, used to shift the d.c level at the O/P of the intermediate stage downward to zero w.r.t ground.

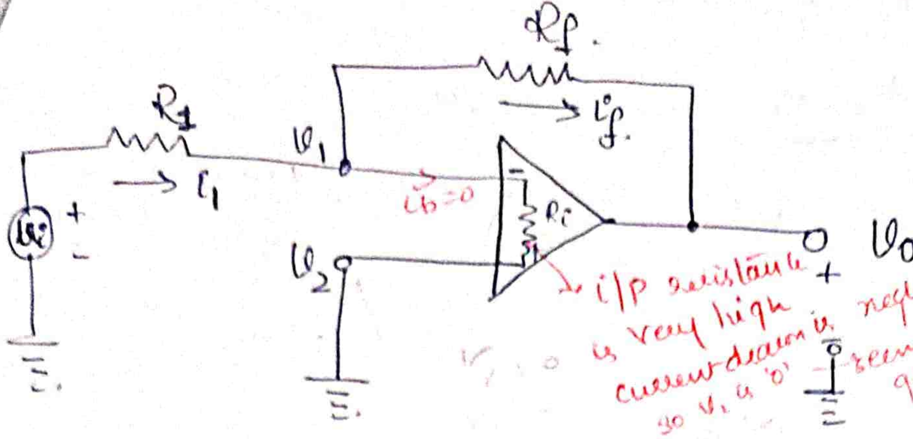
4. OUTPUT STAGE: the O/P stage is basically a power amplifier that is used to increase the O/P current supplying capability of the op-amp.

- It decides the O/P impedance of op-amp
- It is desirable to have very low O/P impedance.



If V_2 is grounded then drop across R_o is zero, so V_1 is also zero

CONCEPT OF VIRTUAL SHORT IN AN OP-AMP:



If V_2 is grounded then the drop across R_1 is zero so V_1 is zero

$V_2 = 0,\ V_1 = 0$

$\therefore V_2 = V_1$

- the above fig shows the ckt of op-amp inverting amplifier which employs -ve' of Vb.

- Ri represents the i/p resistance of op-amp measured b/w the inverting and non-inverting i/p terminals.

- the o/p vtg 'V_0' is given by

$$V_0 = A[V_2 - V_1]$$

$$(\text{or})\quad V_2 - V_1 = \frac{V_0}{A} \qquad \text{——} \ (1)$$

$V_1 = V_2 + \text{drop a/c } R_i$

$V_1 = V_2 = 0.$

- W.K.T where A = is the open loop vtg gain of op-amp.

- the o/p voltage 'V_0' cannot exceed the D.C supply vtg given to the op-amp.

[For Ex:- for μA 741, typically supply vtg is 12V & the open loop vtg gain A is 2×10^5.

- To get an o/p vtg of 10V, the required differential i/p vtg ie $V_2 - V_1 = \frac{10V}{2\times10^5} = 0.5\mu V$

- This value is very small compared to the i/p & o/p vtges].

- For this reason it is considered as 0V

$V_2=0,\ V_1=0$

$\therefore V_2 - V_1 = 0$

i.e., $V_2 - V_1 \simeq 0V$ (or)

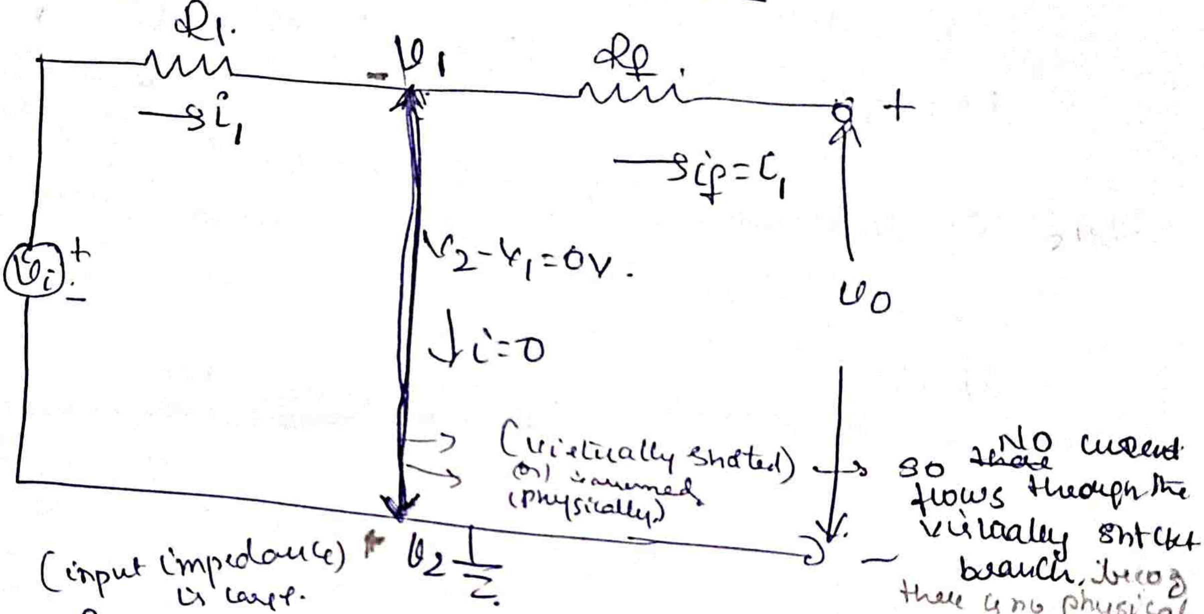
$V_2 = V_1$ ——— ②

$V_2 \simeq V_1$

- From Eqn ② we find that the inverting and non-inverting i/p terminals are at the same potential

- i.e., they appear to be shorted.

- $\therefore$ voltage across R_i is zero



- W.K.T R_i is very large [2 MΩ for μA741] current flowing through R_i is almost zero

- If two terminals are physically shorted, the vltg b/w the two terminals will be zero & a large current flows through this short.

- Since the vltg b/w the o/p terminals is zero & no current flows through the short to the ground we say that as a virtual short exists b/w the i/p terminals of op-amp.

- The virtual short is also called as the virtual ground

* → W.K.T gain of opamps is very large & o/p is very low then we say that the potential at inverting i/p is equal to potential at Non-inverting i/p & there exists a short called virtual gro

the ~~the~~ virtual ground is indicated by thick line b/w the i/p terminals. (11)

(10)

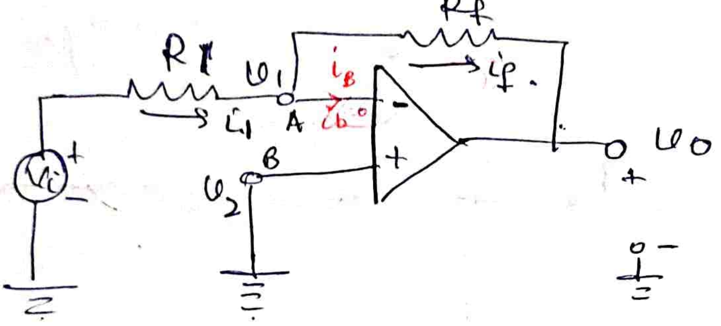
- Note that same current flows through R_1 and R_f

- the concept of virtual short is very much useful in the analysis of op-amp circuits.

[N. the difference b/w the real short & virtual short is that the current flows b/w two pts which are really shorted but current cannot flow b/w two pts which are virtually shorted. the concept of virtual gnd is applicable only to op-amp with -ve feedback

·OP-AMP APPLICATIONS

1. op-amp inverting amplifier.



['-' terminal inverting]

['+' terminal Non-inverting.]

KCL

$i_1 = i_B + i_f$ (Bias current)

$i_1 \approx i_f$

- fig shows the ckt of an op-amp inverting amplifier.
- one i/p signal v_i is applied to the inverting i/p terminal through the resistor R_1.
- Non-inverting i/p terminal is grounded.
- feed back from o/p to the inverting i/p terminal is provided through the f/b resistor R_f.
- since the o/p is applied to the inverting i/p terminal, v_o & v_i are of opposite polarity & hence the f/b is -ve.

- Since the non-inverting i/p terminal is grounded, $V_2 = 0$

- But due to the virtual ground concept at the i/p of op-amp, the inverting & non-inverting i/p terminals are at the same potential

$$\therefore V_1 = V_2 = 0.$$

- W.K.T the i/p impedance of the op-amp is very high, the current flowing into its inverting i/p terminal is zero

- $\therefore$ same current flows through R_1 and R_f

i.e $\quad i_1 = i_f$ —— (1)

But $i_1 = \frac{V_i - V_1}{R_1} = \frac{V_i}{R_1}$ —— (2)

& $i_f = \frac{V_1 - V_o}{R_f} = -\frac{V_o}{R_f}$ —— (3)

$\therefore$ using Eqn (1) we have

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

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

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

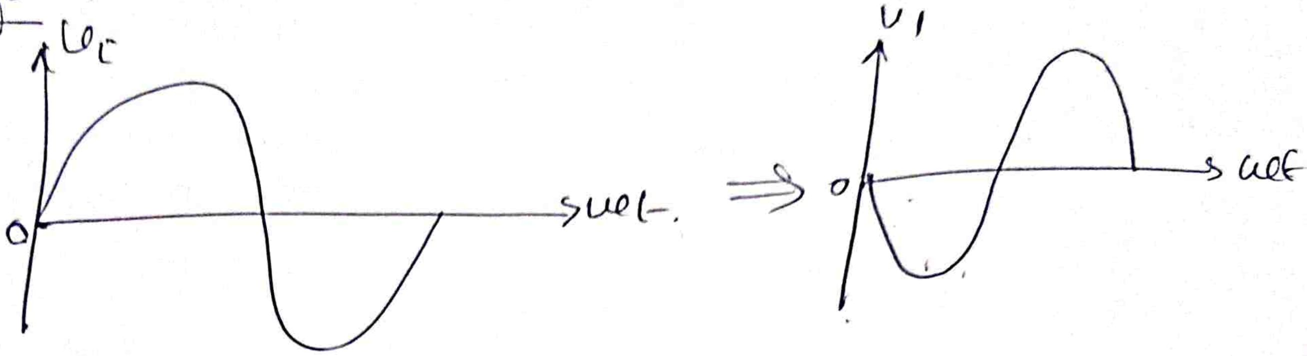
$$\boxed{A_f = \frac{-R_f}{R_1}}$$

$\therefore$ where A_f is the closed open loop Vtg gain

Note that A_f depends only on the External resistors R_f and R_1

- the -ve ' sign implies that v_o & v_i are of opposite polarity.

waveform



⇒

Example 1: A 200 mV peak to peak sine waveform vtg is applied to an op-amp inverting amplifier with $\frac{R_f}{R_1} = 10$. Sketch the o/p.

Soln peak-to peak i/p vtg

$2V_m = 200\ mV$.

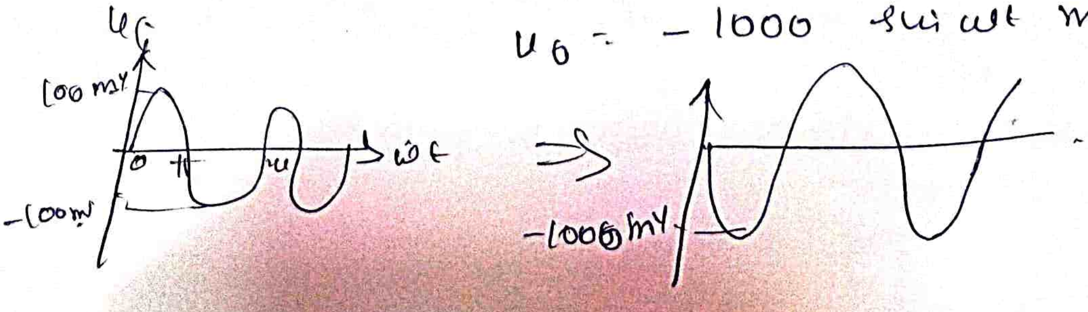
$\boxed{V_m = 100\ mV.}$

i/p vtg $v_i = V_m \sin \omega t$ mV

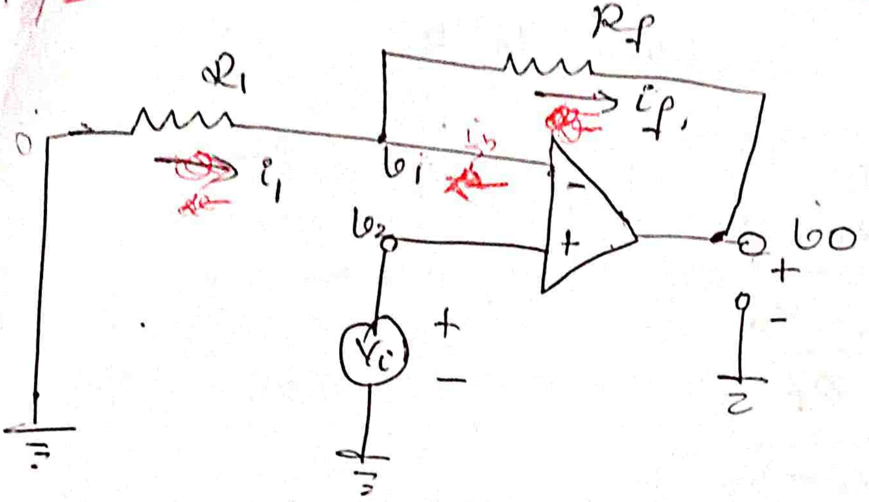
$v_o = -\frac{R_f}{R_1} \times v_i$

$v_o = -10 \times 100 \sin \omega t$ mV

$v_o = -1000 \sin \omega t$ mV. = - sine



OP-AMP NON-INVERTING AMPLIFIER:



- Feedback resistor 'R_f' appears b/w o/p terminal & inverting i/p terminal.
- R_1 connects the inverting terminal to ground.
- The i/p signal 'v_i' is applied at the Non-inverting i/p terminal.

$$\therefore V_2 = V_i \quad \text{——} \quad ①$$

- W.K.T. Due to virtual ~~ground~~ (short) at the inverting & non-inverting i/p of op-amp, the terminals are at the same potential. ——— ②.

$$\therefore v_1 = v_2$$

Equating Eq^n^s ① & ②

$$\therefore v_1 = v_i \quad \text{———} \quad ③$$

- W.K.T Due to high - i/p impedance of op-amp the current flowing into its inverting i/p terminal is zero
- As a result same current flows through R_1 & R_f

$$i_1 = i_f \quad \text{————} \quad ④$$

$$i_1 = \frac{0 - V_i}{R_1}$$ when $v_1 = v_i$

$$\boxed{i_1 = -\frac{v_i}{R_1}} \quad \text{—— 5}$$

and $$i_f = \frac{V_1 - V_o}{R_f}$$

$$\boxed{i_f = \frac{V_i - V_o}{R_f}} \quad \text{—— 6.}$$

using 5 & 6 Eqn in Eqn 5.

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

$$\frac{V_o}{R_f} = V_i\left[\frac{1}{R_1} + \frac{1}{R_f}\right].$$

$$\frac{v_o}{R_f} = v_i\left[\frac{1}{R_1} + \frac{1}{R_f}\right]$$

$$v_o = v_i R_f\left[\frac{R_f + R_1}{R_1 R_f}\right].$$

$$v_o = v_i \cancel{R_f}\left[\frac{R_f + R_1}{R_1 \cancel{R_f}}\right]$$

$$\frac{\cancel{R_f}}{R_1 \cancel{R_f}} + \frac{\cancel{R_1}}{R_1 \cancel{R_1}}$$

$$A_{f1} = \frac{v_o}{v_i} = \left[\frac{R_f}{R_1} + \frac{R_1}{R_1}\right]$$

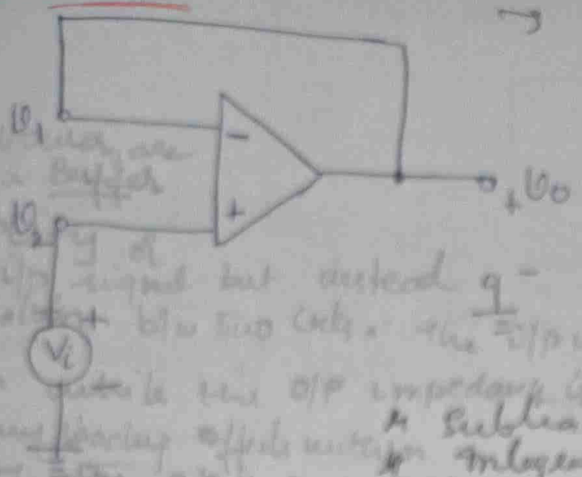
$$1 + \frac{R_f}{R_1}$$

$$\frac{v_o}{v_i} = 1 + \frac{R_f}{R_1}.$$

$$\boxed{A_f = \frac{v_o}{v_i} = 1 + \frac{R_f}{R_1}} \quad \text{—— 8}$$

→ A_f is the closed loop v/g gain or voltage gain with -ve' f/b

AGE FOLLOWER:



→ When an opamp is used for linear applications, the o/p & i/p vtgs are related by a linear fn. (2)

- Some of the linear applications of op-amps:
  - Subtracter
  - Integrator
  - Differentiator
  - Voltage follower
  - Summer

- A voltage follower is a ckt that the o/p voltage (V_0) follows the i/p voltage V_i

- Note that the voltage gain of voltage follower is unity — since $V_0 = V_i$

- The ckt of voltage follower can be derived from the non-inverting amplifier by shorting circuiting R_f & open circuiting R_1

  i.e., by setting $R_f = 0$ & $R_1 = \infty$.

- Since the i/p vtg V_i is directly applied to the non-inverting i/p terminal

$$V_2 = V_i \text{ ——— } (1)$$

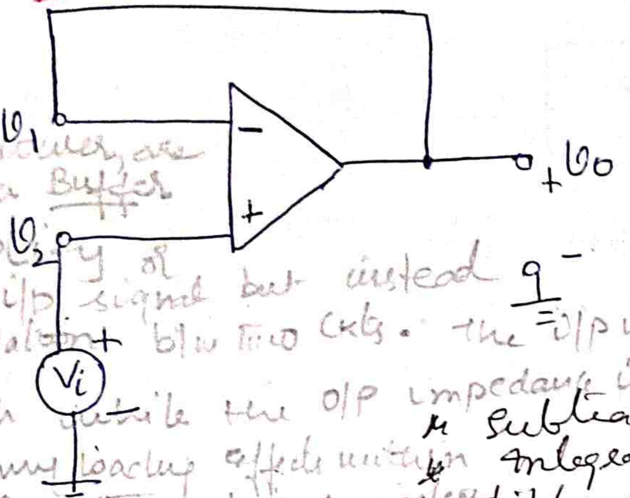
- Due to virtual short at the i/p of op-amp, the inverting & non-inverting i/p terminals are at the same potential.

$$\therefore V_1 = V_2 \text{ ——— } (2)$$

- Note that the inverting i/p terminal is directly tied to the o/p terminal.

$$\therefore V_0 = V_1 \text{ ——— } (3)$$

AGE FOLLOWER:



Voltage followers are also called a Buffer. They do not amplify or power the i/p signal but instead provides isolation b/w two ckts. The i/p impedance is very high while the o/p impedance is low avoiding any loading effects within the ckt. As the o/p is connected back directly to one of its i/p, the overall gain of the buffer is +1 and $V_o = V_{in}$

→ When an op-amp is used for linear applications, the o/p & i/p vtgs are related by a linear fn. — Some of the linear applications of op-amps
* Subtracter
* Integrator
* differentiator
* Voltage follower
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the o/p voltage (3)

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  $\therefore V_1 = V_2$ ——— (2)

- Note that the inverting i/p terminal is directly tied to the o/p terminal.
  $\therefore V_o = V_1$ ——— (3)

$V_1 - V_2 - V_1$

∴ combining all these '3' Eqns. we have.

$$\boxed{V_0 = V_i} \quad \text{—— (4)}.$$

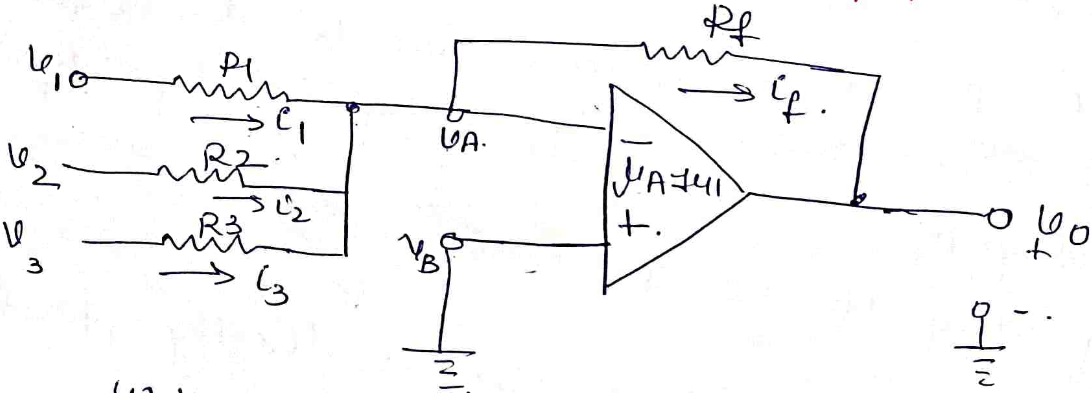
$V_0 = V_1$
$V_0 = V_2$
$V_2 = V_0$

- from Eqn (4) we can find that o/p vtg. follows the i/p voltage.
- the closed loop vtg gain is given by.

$$\boxed{A_f = \frac{V_0}{V_i} = 1} \quad \text{—— (5)}.$$

- NOTE that the closed loop vtg gain is unity.

4) OPAMP SUMMER (OR) SUMMING AMPLIFIER:



W.K.T
- ~~Since~~ the non-inverting i/p terminal of op-amp is grounded $V_B = 0$.
- Due to virtual short at the i/p of op-amp, the inverting & non-inverting i/p terminal are at the same potential.

$$\therefore V_A = V_B = 0. \quad \text{—— (1)}. \quad \cancel{i_f = i_1}$$

$$i_f = i_1 + i_2 + i_3 \Rightarrow \text{[By applying KCL at node 'A']} \quad \cancel{i_1 = i_f}$$

$$i_1 = \frac{V_1 - V_A}{R_1} = \frac{V_1}{R_1} \quad \text{—— (2)}$$

$$i_2 = \frac{V_2 - V_A}{R_2} = \frac{V_2}{R_2} \quad \text{—— (3)}$$

$$i_3 = \frac{V_3 - V_A}{R_3} = \frac{V_3}{R_3} \quad \text{—— (4)}$$

$$i_f = \frac{V_A - V_o}{R_f} = \frac{-V_o}{R_f} \quad \text{—— (5)}$$

Due to the high i/p impedance of the op-amp, the current flowing into its inverting o/p terminal is zero.

~~Applying Kirchoff's~~

∴ substituting i_1, i_2 & i_3 in i_f we have.

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

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

∴ If we choose $R_f = R_1 = R_2 = R_3$, then

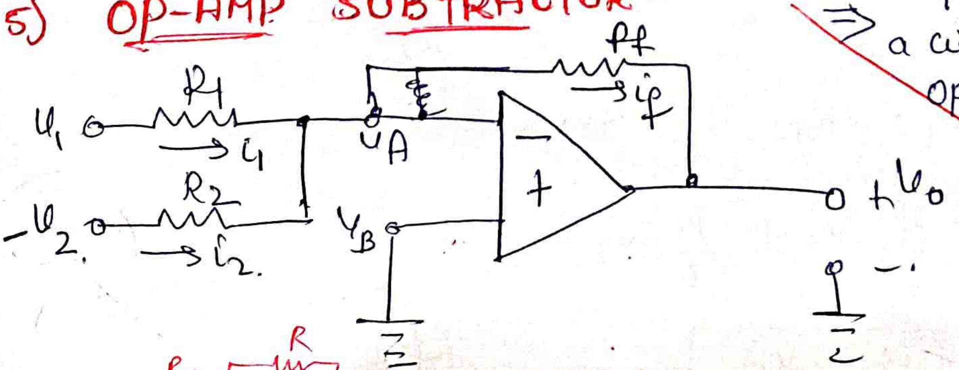
$$V_o = -\left[\frac{\cancel{R_1}}{\cancel{R_1}}V_1 + \frac{\cancel{R_2}}{\cancel{R_2}}V_2 + \frac{\cancel{R_3}}{\cancel{R_3}}V_3\right]$$

$$\boxed{V_o = -[V_1 + V_2 + V_3]}$$

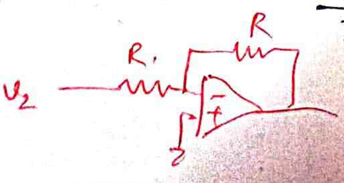
NOTE: that the O/P ~~of~~ vtg ~~is~~ Equal to the -ve' of the sum of the i/p vtgs. due to the -ve sign

- The ckt is called inverting summer

5) OP-AMP SUBTRACTOR

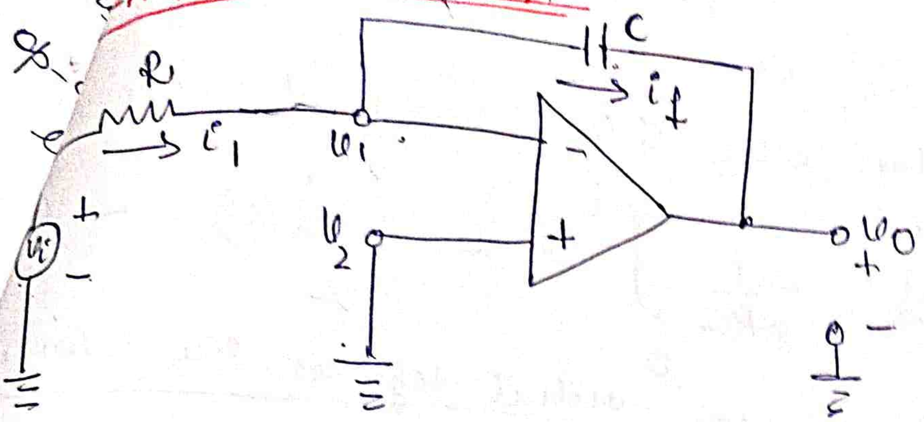


⇒ ||^{le} to Summer circuit, a circuit is designed with op-Amp such that its O/P is difference b/w two vtg i/p vtg's. Such circuits are called Subtractor



$$V_o = V_1 + V_2 = V_1 - V_2$$

OP-AMP AS AN INTEGRATOR:



- Fig shows an op-amp as an integrator. It has a capacitor in the f/b loop.
- Since the non-inverting i/p terminal of op-amp is grounded $v_2 = 0$.
- Due to virtual short of ~~the~~ the i/p of op-amp, the inverting and non-inverting i/p terminals are at the same potential.

$$v_1 = v_2 = 0 \quad \text{——— (1)}$$

- Due to high i/p impedance of op-amp, the current flowing into ~~at~~ its inverting i/p terminal is zero
- $\therefore$ same ~~the~~ current flows through R and C.

$$\text{i.e.} \quad i_1 = i_f \quad \text{——— (2)}$$

But $\quad i_1 = \dfrac{v_i - v_1}{R} = \dfrac{v_i}{R} \quad$ ——— (3).

$i_f = C\dfrac{dv_c}{dt} \rightarrow$ V_c is the vtg across the capacitor

and $\quad i_f = C\dfrac{d}{dt}\left[V_1 - V_0\right]$

$$i_f = -C\frac{dv_0}{dt}. \quad \text{——— (4)}$$

substitute in eqn (1) $\quad \dfrac{v_i}{R} = -C\dfrac{dv_0}{dt}$

$$-\frac{V_i}{RC} = \frac{dv_0}{dt}. \rightarrow \text{integrating both side}$$

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

Integrating both sides w.r.t 't' we have

$$v_o = -\frac{1}{RC}\int_0^t v_i \, dt + \underbrace{v_o(0)}_{\text{const}} \quad \text{--- (5)}$$

- where $v_o(0)$ is the initial vtg on the capacitor at $t=0$.
- Note that $v_o(0)$ represents the const of integration
- from Eqn (5) we find that the o/p vtg v_o is Proportional to the integral of the i/p vtg v_i
- If the initial vtg on the capacitor at $t=0$, i.e. $v_o(0) = 0$

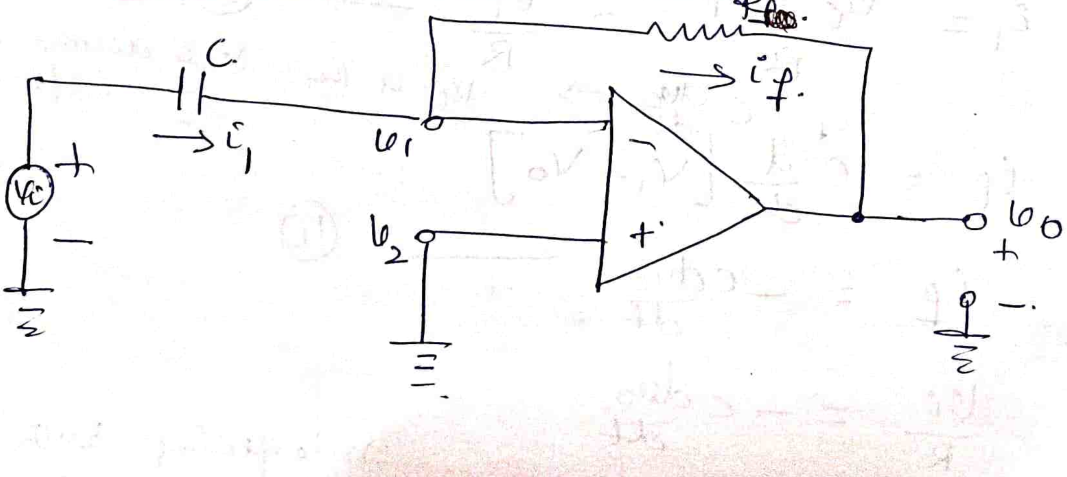
Now Eqn (5) can be written as

$$\boxed{v_o = -\frac{1}{RC}\int_0^t v_i \, dt} \quad \text{--- (6)}$$

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

7) OP-AMP AS DIFFERENTIATOR:

[differentiation of i/p so we given 'C' to i/p]



(5)

Fig shows the op-amp differentiator.

- The circuit of op-amp differentiator can be obtained from op-amp integrator ckt by simply interchanging the positions of 'R' and 'C'.

- Since the non-inverting terminal of op-amp is grounded $v_2 = 0$.

- Due to the virtual short of the i/p terminal of op-amp,

- the inverting & non-inverting i/p terminals are at the same potential. —— (1).

$$\therefore v_1 = v_2 = 0$$

- Due to the high i/p impedance of op-amp i/p terminal the current flowing into its inverting is zero.

- $\therefore$ the current flows through 'R' and 'C'. —— (2).

i.e, $i_1 = i_f$.

But $i_1 = C\frac{d}{dt}[v_i - v_1]$

$$i_1 = C\frac{dv_i}{dt} \quad \text{—— (3)}.$$

& $$i_f = \frac{v_1 - v_0}{R} = -\frac{v_0}{R}. \quad \text{—— (4)}.$$

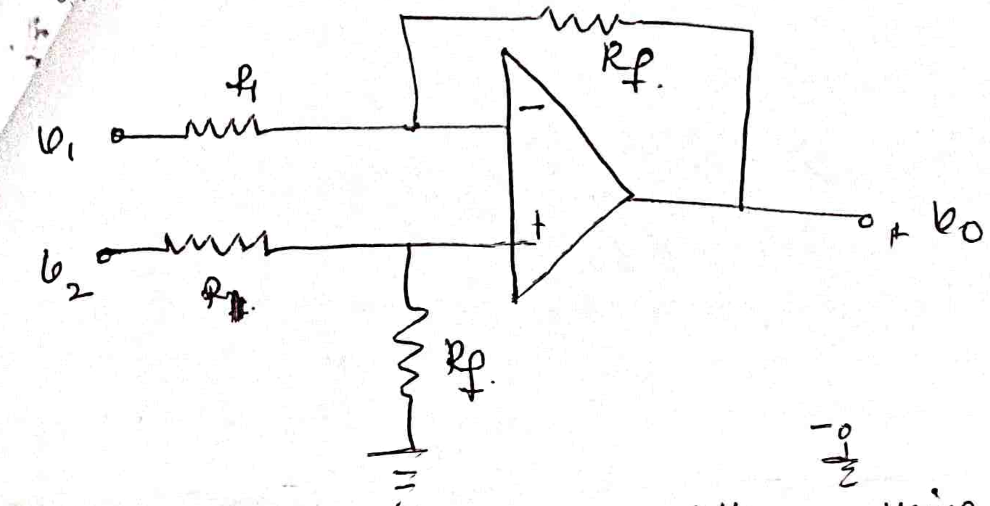
Let's eqn (3) & (4) can be substituted in eqn (2)

$$C\frac{dv_i}{dt} = -\frac{v_0}{R}$$

$$\boxed{v_0 = -RC\frac{dv_i}{dt}} \quad \text{—— (5)}.$$

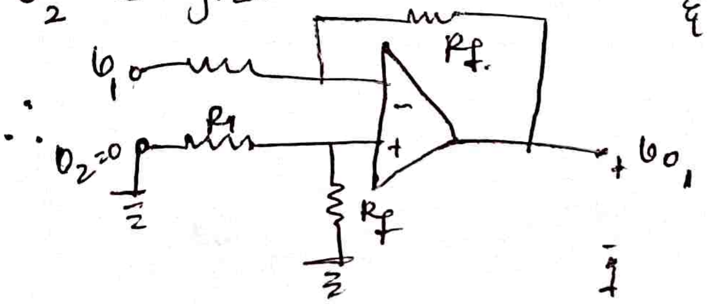
∴ Eq ③ shows the o/p vtg V_o is proportional to time derivative of the i/p vtg V_i.

Op-amp as subtractor



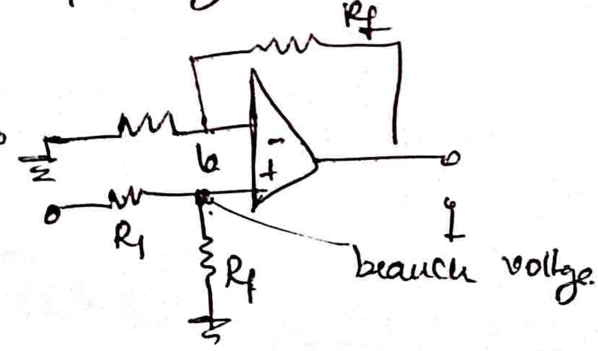
→ let us obtain the o/p vltg v_o using superposition principle by applying the following steps

Step 1: v_2 to gnd and i/p to v_1 & find v_{o_1} [nothing but an inverting amplifier]



$$\therefore v_{o_1} = -\left[R_f/R_1\right]v_1$$

Step 2: now v_1 to zero (Gnd) and find v_{o_2}. (nothing but an non-inverting amplifier)



$v_{o_2} = v \times$ Gain of non-inverting amplifier

$$= v \times \left[1 + \frac{R_f}{R_1}\right] \quad \text{—(1)}$$

where 'v' is the voltage drop across Rf. using voltage division rule

$$v = v_2\left[\frac{R_f}{R_1 + R_f}\right]$$

$$v = v_2\left[\frac{R_f}{R_1\left[1 + \frac{R_f}{R_1}\right]}\right]$$

Substitute in eq (1)

$$v = v_2\left[\frac{R_f}{R_1\left[1 + \frac{R_f}{R_1}\right]}\right]\left[1 + \frac{R_f}{R_1}\right]$$

$$v_o = v_2\left[\frac{R_f}{R_1}\right]$$

∴ the o/p vltg given by superposition principle

$$v_o = v_{o_1} + v_{o_2}$$

$$\therefore = -\frac{R_f}{R_1}v_1 + \frac{R_f}{R_1}v_2$$

$$\boxed{v_o = \frac{R_f}{R_1}\left[v_2 - v_1\right]}$$