Module 3.

Operational Amplifiers & Applications

Introduction to Op-Amp
Op-Amp Input Modes
Op-amp parameters - CMRR
Input Offset Voltage and Current
Input Bias Current
Input and Output Impedance, Slew rate

(12.1, 12.2 of Text 2)

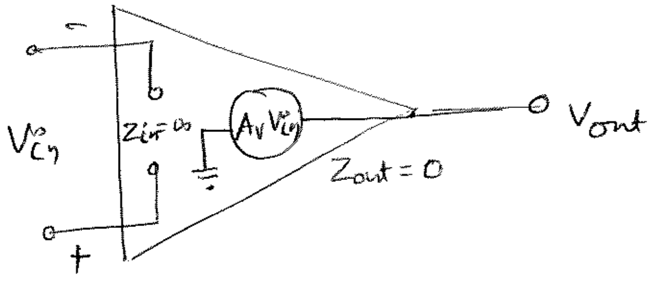
Application of op-amp.
Inverting amplifier
Non-inverting amplifier
Summer
Voltage follower
Integrator
Differentiator
Comparator

(6.2 of Text 1).

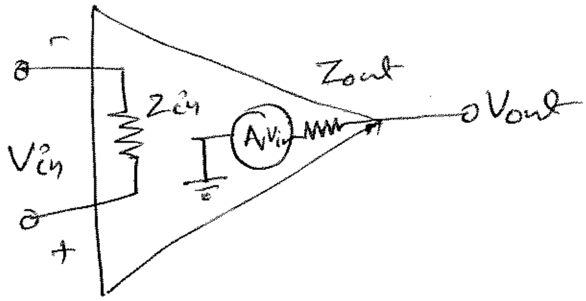
(RBT Levels: L1, L2 & L3)

(1)

Basic op-amp representation



(a) Ideal opamp representation.



(b) practical - op-amp representation.

Op-amp Input modes.

Input signal modes

These are determined by the differential amplifier input stage of the op-amp.

(i) Differential mode:

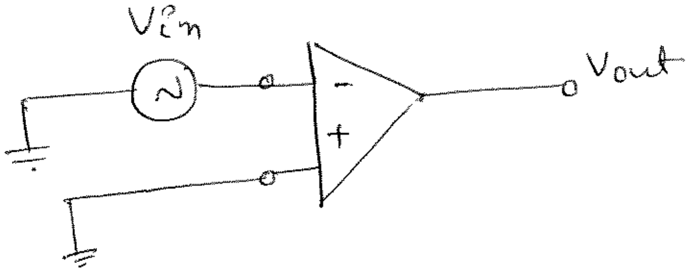
In this mode, either one signal is applied to an input with the other input grounded or two opposite polarity signals are applied to the inputs.

When an op-amp is operated in the single-ended differential mode, one input is grounded and a signal voltage is applied to the other input as shown in figure.

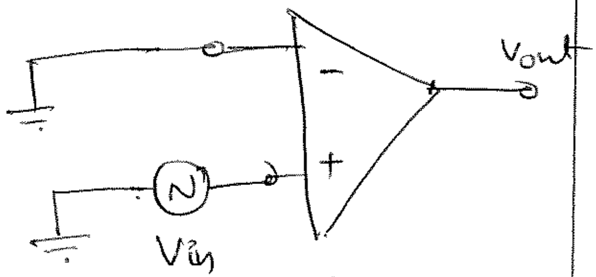
Case (1):- Here the signal voltage is applied to the inverting input, an inverted, amplified signal voltage appears at the output.

Case (2):- Here the signal is applied to the non-inverting input with the inverting input grounded. a non inverted, amplified signal voltage appears at the output

Single ended differential mode [SEDM]



(a) SEDM with input Connected to inverting terminal.



(b) SEDM with input Connected to non-inverting terminal.

In the Double ended differential mode, two Opposite polarity (out of phase) signals are applied to inputs as shown in figure. The amplified difference between the two inputs appear on the output.

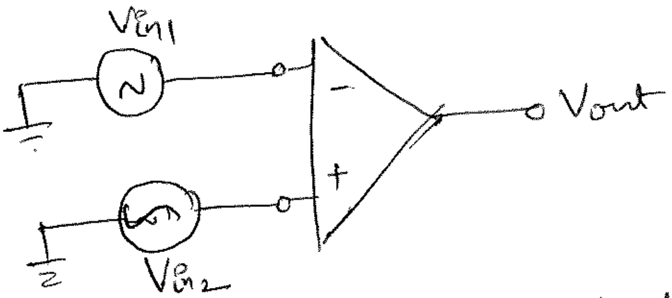


Fig: Double ended Differential mode

Common mode :— In common mode, two signal voltages of the same phase, frequency and amplitude are applied to the two inputs, as shown in figure. when equal input signals are applied to both inputs, they tend to Cancel, resulting in a zero output voltage.

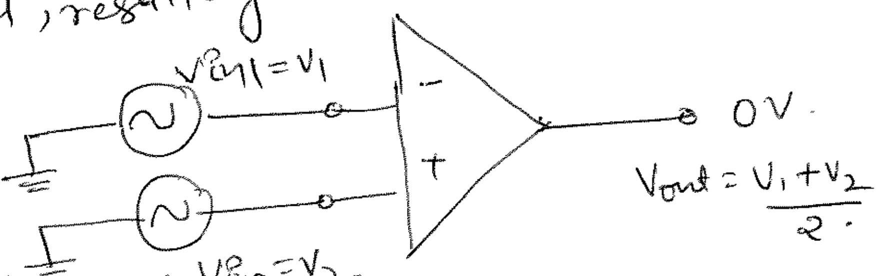


Fig: common mode operation.

Op-Amp parameter

In Common mode operation if same input appears on the both the input then output produced by the op-amp is zero. This is called Common-mode rejection. If any unwanted signal appears commonly on both op-amp inputs, then it rejects.

Common mode rejection means that this unwanted signal will not appear on the output & distort the desired signal. Common mode signals (noise) are the result of the pick-up of radiated energy on input lines, from adjacent lines, the 60Hz power lines, other sources.

Common Mode Rejection Ratio. [CMRR]

Desired signal can appear on only one input or with opposite polarities on both input lines can be amplified & appear on output, but unwanted signal (noise) appearing with the same polarity on both input is cancelled by the op-amp & do not appear on op-amp.

The measure of an amplifier's ability to reject common mode signals is called as Common mode rejection ration [CMRR].

CMRR suggests the measure of the op-amp's performance in rejecting unwanted common-mode signals in the ratio of the open-loop differential voltage gain, A_{dm} to the common-mode gain A_{CM}.

$$CMRR = \frac{A_{dm}}{A_{CM}} =$$

CMRR in decibels (dB)

$$CMRR = 20 \log \left(\frac{A_{dM}}{A_{CM}} \right)$$

Differential mode gain is also called as open loop gain (A_{OL}).

open Loop voltage gain :-

A_{OL}, of an op-amp is the internal voltage gain of the device.

It is the ratio of output voltage to input voltage when there are no external components.

$$\boxed{A_{OL} = \frac{V_o}{V_{in}}}$$

$A_{OL} = 200,000$ (106dB).

Also called as large-signal voltage gain.

CMRR of 100,000 for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common mode).

Problem 1. A certain op-amp has an open-loop differential voltage gain of 100,000 & a common mode gain of 0.2. Determine the CMRR & express it in decibels.

Sol^n: $A_{OL} = 100,000$, $A_{cm} = 0.2$

$$CMRR = \frac{A_{OL}}{A_{cm}} = \frac{100,000}{0.2} = 500,000.$$

$$CMRR = 20\log_{10}(500.000)$$
$$= 114\,dB.$$

(2) Determine the CMRR and express it in dB for an op-amp with an open-loop differential voltage gain of 85,000 & a common-mode gain of 0.25.

Solution:- $A_{OL} = 85,000$, $A_{cm} = 0.25$.

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

$$CMRR = 20\log(\quad) = \quad .$$

Maximum Output Voltage swing [$V_{O(p-p)}$]

With no input signal, the output of an op-amp is ideally 0V. This is called the quiescent output voltage. When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{CC}$.

Input offset voltage:- (V_{OS})

The ideal op-amp produces zero volts output for zero volts input. In a practical op-amp, however, a small dc voltage, Vout (error), appears at the output when no differential input voltage is applied.

The main reason is a slight mismatch of the base-emitter voltage of the differential amplifier input stage of an op-amp.

$V_{OS} \rightarrow$ ideal value 0 volts

$V_{OS} \rightarrow$ practical value 2mV or less.

Input offset voltage, V_{OS}, is the differential dc voltage required between the inputs to force the output to zero volts.

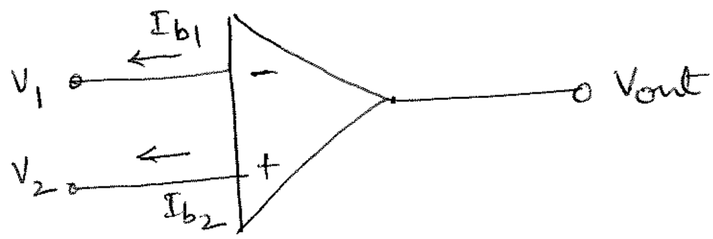
Input Bias Current (I_{Bias})

The input terminals of a bipolar differential amplifier are the transistor bases and, therefore, the input currents are the base currents.

The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage.

Input bias current is the average of both input currents.

$$I_{Bias} = \frac{I_{b_1} + I_{b_2}}{2}$$



$$I_{bias} = \frac{I_{b_1} + I_{b_2}}{2}$$

Figure :- Input bias current is the average of the two op-amp input current.

Input impedance :-

- differential input impedance
- Common input impedance.

Differential input impedance is the total resistance between the inverting and the non-inverting inputs. as shown in fig.

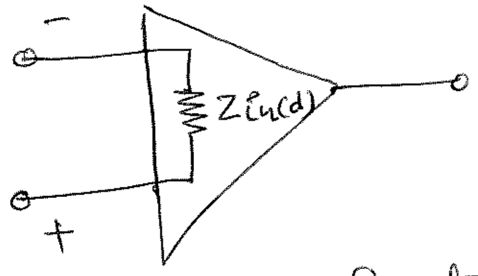
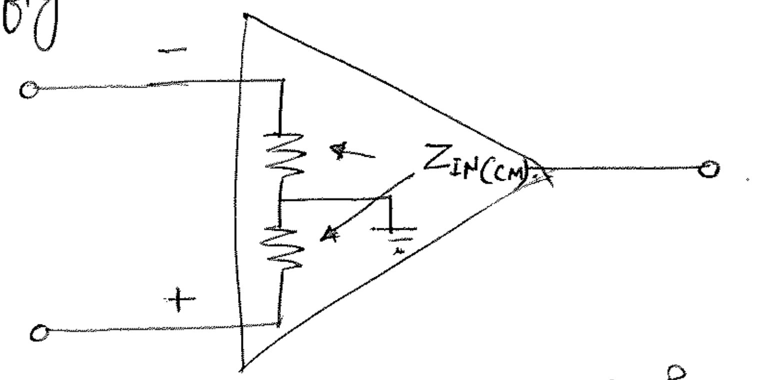


fig :- Differential input impedance

Differential impedance is measured by determining the change in bias current for a given change in differential input voltage.

The common mode input impedance is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage. It is shown in fig



(b) Common-mode input impedance.

<u>Input offset Current</u> :- I_{os}

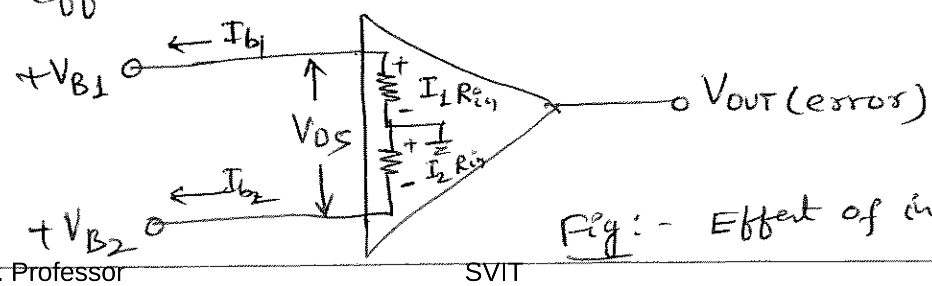
Ideally, the two input bias currents are equal, and thus their difference is zero.

practically op-amp, however, the bias currents are not exactly equal.

• The input offset current, I_{os}, is the difference of the input bias currents, expressed as an absolute value.

$$I_{os} = |I_{b1} - I_{b2}| = |I_{b1} - I_{b2}|$$

The effect input offset current is shown in figure



<u>Fig</u>:- Effect of input offset current.

The offset voltage developed by the input offset current is

$$V_{os} = I_1 R_{in} - I_2 R_{in}$$
$$= (I_1 - I_2) R_{in}$$
$$V_{os} = I_{os} R_{in}$$

The error created by I_{os} is amplified by the gain A_v of the op-amp and appears in the output as

$$V_{OUT(error)} = A_v I_{os} R_{in}.$$

Output Impedance :-

The output impedance is the resistance viewed from the output terminal of the op-amp, as shown in the figure.

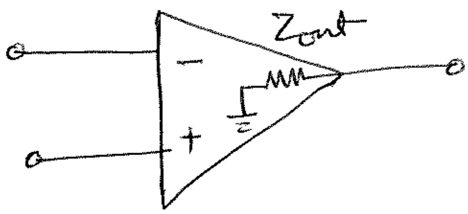


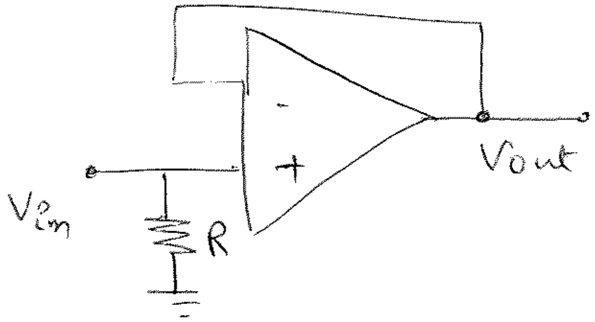
Fig. ~~[illegible]~~ op-amp output impedance

Slew rate :-

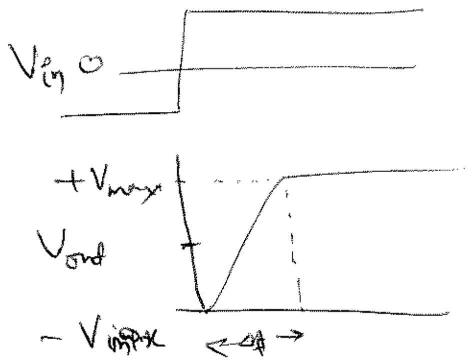
The maximum rate of change of the output voltage in response to a step input voltage is the slew rate of an op-amp.

- The slew rate is dependent upon the high frequency response of the amplifier stages with in the op-amp.
- slew rate is measured with an op-amp connected as shown in figure.

The op-amp used here is the unity gain non inverting configuration.
For step input, the slope on the output is inversely proportional to the upper critical frequency. slope increases as upper critical frequency decreases.



(a) Test circuit.



(b) step input voltage & the resulting output voltage.

Fig:- slew-rate measurement.

A pulse is applied to the input and the resulting ideal output voltage is indicated in figure (b)
The width of the input pulse must be sufficient to allow the output to slew from its lower limit to its upper limit.

Δt is the time interval required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$, once the input step is applied.

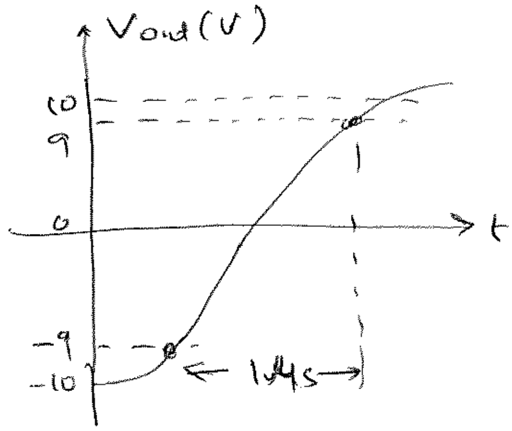
$$\text{slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

where $\Delta V_{out} = (+V_{max} - (-V_{max}))$

unit = V/µs.

problem:-

The output voltage of a certain op-amp appears as shown in figure in response to a step input. Determine the slew rate.



given Data:-

$\Delta t = 1 \mu s$

$V_{max} = 9V$; $-V_{max} = -9V$

$$\text{slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

$$= \frac{+9V - (-9V)}{1 \mu s} = 18 V/\mu s$$

When a pulse is applied to an op-amp, the output voltage goes from $-8V$ to $+7V$ in $0.75 \mu s$. What is the slew rate?

Operational amplifiers & Applications :- ① ECE Dept.

Module - 3 :-

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Introduction to operational amplifiers :-

Ideal OPAMP, Inverting and non inverting OPAMP circuits. OPAMP applications : Voltage follower, Addition, Subtraction, Integration, Differentiation, Numerical example as applicable

Key words : IC : Integrated Circuits

Introduction :-

The op-amp is the common name of operational amplifiers was designed in 1948 using vacuum tubes. In those days, it was used in the analog computers to perform a variety of mathematical operations such as addition, subtraction, multiplication etc. hence the name operational amplifier. Those op-amp are bulky, power consuming and expansive.

The op-amp is perhaps the most important & versatile IC; it is used in analog signal processing and analog filtering.

The IC version of opamp uses BJTs (Bipolar Junction Transistors) and FETs which (Field effect Transistors) which are fabricated using semiconductor chip or wafer. The circuit design becomes very simple. These are low cost, small size, versatility, flexibility & dependability, op-amps are used in the fields of process control, communications, computers, power & signal sources, displays & measuring systems.

The op-amp is an excellent high gain D.C amplifier.

The symbol of an op-amp is shown in figure (1). It has two input terminals, one is inverting terminal (-) and non inverting (+), and one output terminals. also requires The positive supply voltage terminal V_{CC} or +V. The negative supply voltage terminal $-V_{EE}$ or -V.

The op-amp can be defined as high gain, direct Coupled difference amplifier.

$$\text{gain of op-amp} = \frac{\text{output voltage}}{\text{input voltage}}.$$

Direct coupled indicates the op-amp can amplify signals of zero frequency. Zero frequency means DC signals.

Difference amplifier means that the op-amp will have two inputs and the output is proportional to the difference between the two input voltages.

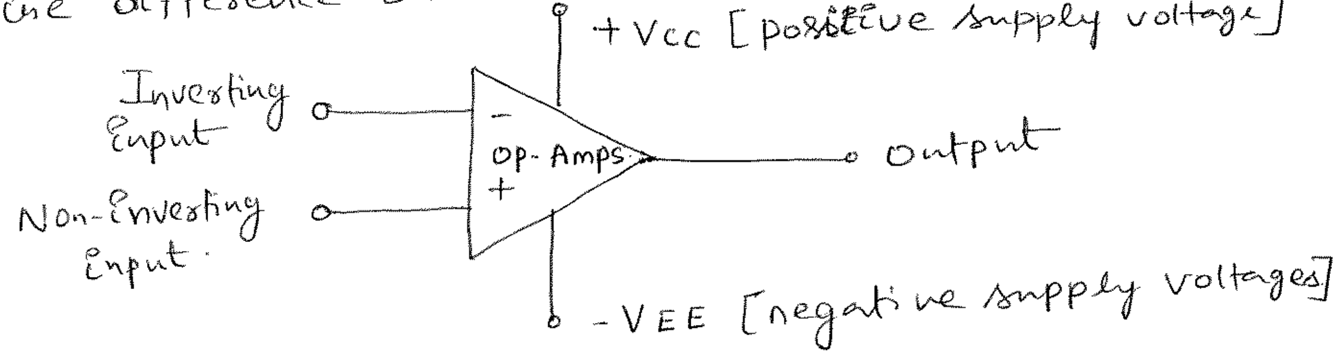
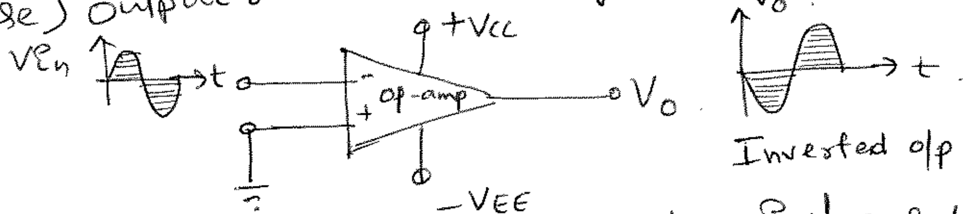


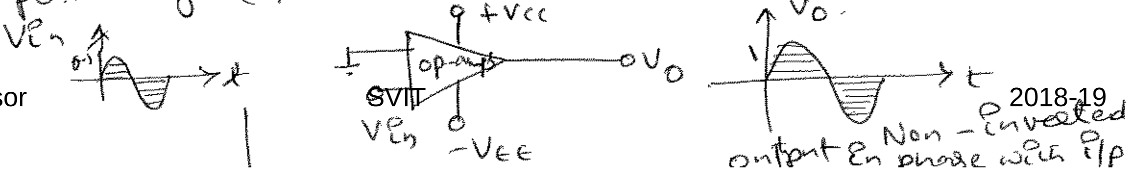
Figure (1) op-amp symbol.

Commercially used power supply voltages are ±15V. Balanced dual supply. popular supply voltages are ±9V, ±12V, ±22V.

- The input at inverting input terminal result in opposite polarity (antiphase) output. as shown in fig ②

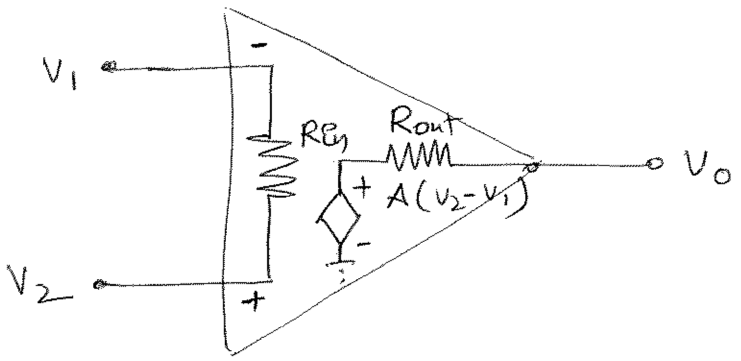


while the input at non inverting input terminal result in same polarity (phase) output. as shown in fig ③.



The simplified circuit model of an op-amp is shown in figure (4). It has a gain of A, input resistance Rin and output resistance Rout.

And ideal op-amp has $A = \infty$, $R_{in} = \infty$ and $R_{out} = 0$.



figure(4). circuit model of op-amp - IC 741

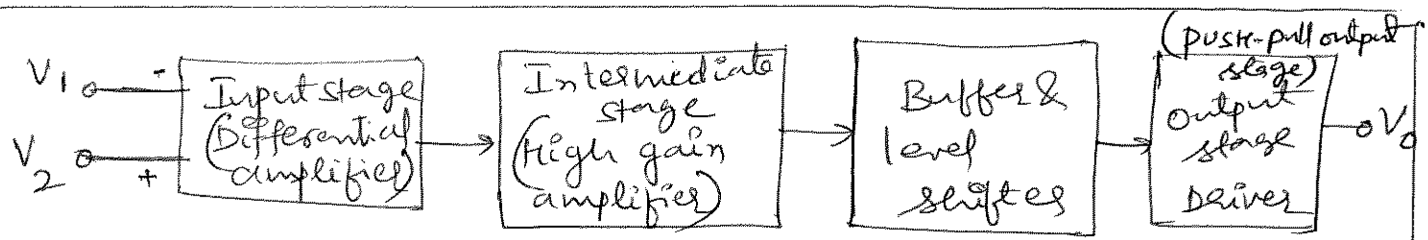
- The resistance R_{in} between the two input terminals is Called input resistance of the op_amp. R_{in} - in MΩ range.
- The voltage source on the output side represents the output of the op-amp.
- The voltage gain 'A' indicated along with the source is called open loop gain. A = in order of 10^6.
- term $V_2 - V_1$ is called difference input voltage. The output proportional to difference between the two input voltages.
- The resistance in series with the voltage source is the output resistance (R_{out}) of the op-amp.

  R_{out} is very low.

op-amp architecture.

Commercial op-amps (IC) consists of four cascaded block as shown in figure (5). It consists of

- Input stage (Differential amplifier).
- Intermediate stage (High-gain amplifier)
- Buffer & Level shifter stage
- (Driver) & output stage.



figure(5) Block diagram of op-amp. IC741.

Input stage :-

• It requires high input impedence to avoid loading on the sources. It requires two input terminals. It also requires low output impedance.

• All these requirements are achieved by using the dual input, balanced output Differential amplifier as input stage.

• function of a Differential amplifier is to amplify the difference b/w the two input signals. It provide Voltage gain of the amplifier. DA consists of two BJT's (MOSFET) with emitter terminal connected together.

Intermediat stage :-

• The output of the input stage drives the next stage which is an intermediate stage. It is also an differential amplifier.

The overall gain requirement of op-amp is very high. The input stage alone cannot provide such a high gain. Intermediate stage provides an additional voltage gain required. This stage consists of Cascaded amplifiers called multistage amplifier used to get high gain.

Buffer & Level shifting stage

The level shifter shifts the level of the output of the intermediate stage. This stage shifts the DC level.

• The level shifter stage brings the d.c. level down to ground potential, when no signal is applied to the input terminals. Then the signal is given to the last stage which is the output stage.

Emitter follower ckt is used.

Output stage :-

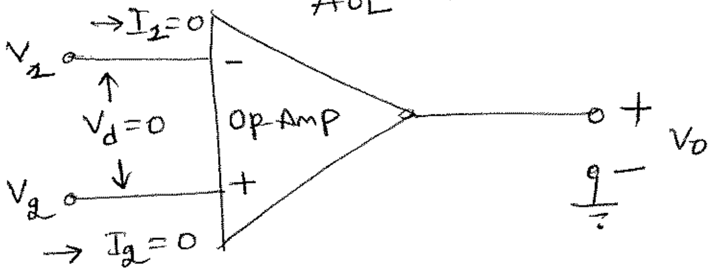
The basic requirements are low output impedance, large a.c output voltage swing and high current sourcing & sinking capability.

push-pull complementary amplifier are used as Driver stage

The output stage provides the required power output. This is also called "power amplifier"

IDEAL OPAMP

$A_{OL} = \infty$



Ideal op-amp.

The figure (6) shows ideal amplifier. It has two input signals V_1 & V_2 applied to non Inverting & Inverting terminals respectively.

The Characteristics of ideal op-amp are.

ⓐ Infinite input impedance ($R_{in} = \infty$)

- The input impedance of the op-amp is infinity.
- The input impedance is defined as the impedance seen at the input terminals of the op-amp. The impedance is a parameter which opposes the flow of current. $R_{in} = \infty$, ensures that no current can flow into an ideal op-amp.

ⓑ. Infinite voltage gain $A_{OL} = \infty$.

The differential open loop gain is infinite for ideal op-amp.

$$A = \frac{V_0}{V_i} = \infty$$

for any input voltage, the output voltage of op-amp becomes infinite.

(c) Zero output Impedance :- ($R_o = 0$)

For ideal op-amp $R_o = 0$. This ensures that the output voltage of the op-amp remains same, irrespective of the value of the load resistance connected.

(d) Infinite CMRR :- ($\rho = \infty$)

The ratio of differential gain & common mode gain is defined as CMRR.

if CMRR = ∞, an ideal op-amp ensures zero common mode gain. Due to this common mode noise output voltage is zero for an ideal op-amp.

(e) Zero input offset voltage ($V_{ios} = 0$)

The presence of the small output voltage though $V_1 = V_2 = 0$ is called an offset voltage. It is zero for an ideal op-amp. This ensures zero output for zero input signal voltage.

(f). Temperature independency :- The characteristics of op-amp do not change with temperature.

(g). Infinite Bandwidth

The range of frequency over which the amplifier performance is satisfactory is called Bandwidth. Bandwidth = ∞. This means that operating frequency range is from 0 to ∞.

This ensures that the gain of the op-amp will be constant over the frequency range from d.c (zero frequency) to infinite frequency. So op-amp can amplify d.c as well as a.c. signals.

(h). Matched Transistors.

The transistors used in difference amplifier are identical.

(i). Infinite Slew rate : ($S = \infty$)

Slew rate indicates ~~___~~ the rate at which the output varies.

"Infinite slew rate indicates that the output voltage can change simultaneously with the changes in the input voltage."

(j) power supply rejection ratio (PSRR = 0)

PSRR is defined as the ratio of the change in input offset voltage due to the change in supply voltage producing it, keeping other power supply voltage constant. It is also called as power supply sensitivity or supply voltage rejection ratio (SVRR).

Ideal value = 0.

unit - mV/V or μV/V

Ideal characteristics table

Sl.No	characteristics	Symbol	Ideal values	practical
1	open loop voltage gain	A_{OL}	∞	2×10^5
2.	Input impedance	R_{in}	∞	2MΩ
3.	Output Impedance	R_o	0	75Ω
4.	I/p offset voltage	V_{ios}	0	2mV.
5.	Bandwidth.	BW	∞	1MHz
6.	CMRR	ρ	∞	90dB.
7.	Slew rate	S	∞	0.5V/μsec
8.	power supply rejection ratio	PSRR	0.	30μV/V.
9.	Input bias current	I_b	0	80nA
10	Input offset ~~voltage~~ current	I_{ios}	0	2mV.

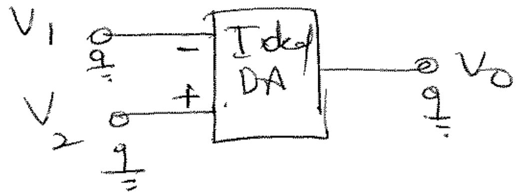
Typical parameter of μA741 IC op-amp are

$A = 2,00,000$ $R_{in} = 2M\Omega$ $R_o = 75\Omega$ CMRR = 80–100dB

$100dB = 10^5$

Ideal op-amp [OP-Amp Input Modes AND parameters]

- Differential amplifier (DA): An amplifier which amplifies the difference between the two input signal. Hence
- it is called Differential (or Difference) amplifier. apply two input signal to DA while V_0 is the single ended output. Each signal is measured with respect to ground.



$$V_0 \propto (V_2 - V_1) \longrightarrow (1)$$

Differential gain (A_d)

From eq^n (1), we can write

$$V_0 = A_d (V_2 - V_1). \qquad A_d \rightarrow \text{Constant of proportionality.}$$

The A_d is the gain with which D.A. amplifies the difference between two input signals. hence it is differential gain. A_d.

let difference Voltage $V_d = V_2 - V_1$.

$$V_0 = A_d V_d.$$

Hence differential gain $= A_d = \dfrac{V_0}{V_d}$.

Differential gain in decibel. (dB)

$$\boxed{A_d = 20 \log_{10} (A_d) \text{ in dB}}$$

Common mode gain. (A_c)

- If we apply two input voltages which are equal in all the respects to the differential amplifier i.e $V_1 = V_2$ then ideally the output voltage must be equal to zero.

- But the output voltage of the practical differential amplifier not only depends on the difference voltage but also depends on the average ~~of~~ common level of the two inputs.

If average level of the two input signal is applied to op-amp denoted as $\boxed{V_C = \frac{V_1 + V_2}{2}}$.

Practically the Differential amplifier produces the output voltage proportional to such common mode signal.

The output voltage

$$V_O = A_C V_C$$

$A_C \rightarrow$ Common mode gain.

$$\boxed{A_C = \frac{V_O}{V_C}}$$

So the total output of any differential amplifier is.

$$\boxed{V_O = A_d V_d + A_C V_C}$$

For ideal op-amp, $\underline{A_d = \infty}$, $\underline{A_C = 0}$. This ensures zero o/p for $V_1 = V_2$.

Common mode Rejection ratio

- The ability of an op-amp to reject a common mode signal is expressed by a ratio called $\underline{CMRR}$. denoted by $\underline{\rho}$.
- It defined as the ratio of differential voltage gain A_d to common mode voltage gain A_C

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

<u>Ideally</u> $A_C = 0$, hence $CMRR = \infty$.

practical DA, A_d is large, A_C is small, hence $CMRR = \underline{\text{very large}}$

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

Important parameter of op-amp [practical]

① $A_{OL} = 10^5$ to 10^6

② $R_i = 1\,M\Omega$ to $100\,M\Omega$

③ $R_o = 1$ & $2\,\Omega$

BW = small

④ Input offset current $I_{ios} = I_{b1} - I_{b2}$

① Input offset Voltage

Differential voltage (V_{os}) needed to make $V_o = 0$.

Typical value $V_{os} = 1\,mV$.

② Input Bias current :-

$$I_B = \frac{I_{B1} + I_{B2}}{2} \text{ to make } V_o = 0,$$

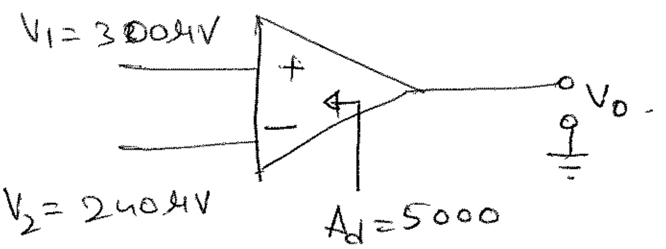
I_{B1} & I_{B2} are base currents of two transistors.

Typical value is 80 nA.

③ Input offset current $I_{ios} = |I_{B1} - I_{B2}|$.

① Determine the output Voltage of an op-amp for the input voltage of 300 µV & 240 µV. The differential gain of the amplifier is 5000 and the value of the CMRR is 10^5. (4M)

$$A_c = \frac{A_d}{CMRR} = \frac{5000}{10^5} = 0.05.$$



$$V_o = A_d V_d + A_c V_c$$

$$= 5000 * (V_1 - V_2) + A_c \frac{(V_1 + V_2)}{2}$$

$$= 5000 * 60 + 0.05 \times 270$$

$$= 300013.5\,\mu V = 300.0135\,mV.$$

we know that

$$V_o = A_d V_d + A_c V_c$$

$$= A_d V_d \cdot \left[1 + \frac{A_c V_c}{A_d V_d} \right]$$

$$\boxed{V_o = A_d V_d \left[1 + \frac{1}{CMRR} \cdot \frac{V_c}{V_d} \right]}$$

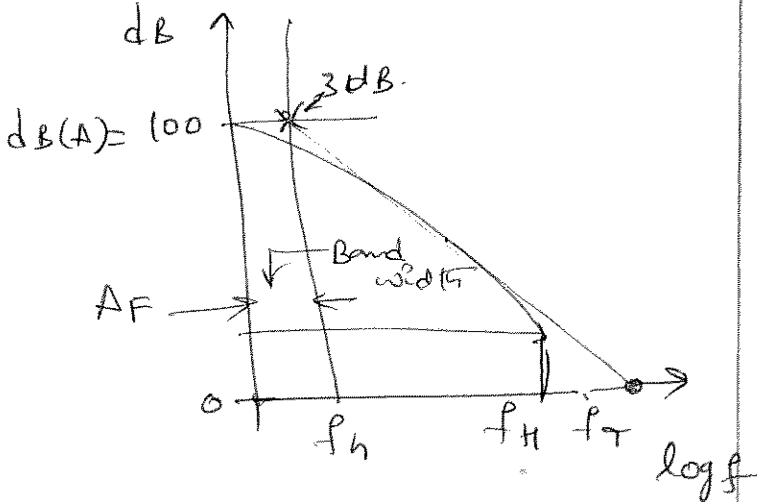
if we know A_d, V_c, V_d & CMRR we can easily calculate V_o, with out knowing $A_c \rightarrow$ Common mode voltage gain.

Slew Rate and Frequency response

Frequency response.

Some RC Couplings are provided in an op-amp circuit so as to reduce the gain at high frequencies. otherwise, a positive feedback occurs from stray Capacitances causing high frequency Oscillations. The op-amp acts like a Low-pass filter with a break frequency at $f_h = 10Hz$.

Typical frequency response is shown in fig using Bode plot.



op-amp LPF frequency response.

From Bode plot

$$20\log\frac{f_T}{f_h} = dB(A) = 20\log A$$

$$\therefore \frac{f_T}{f_h} = A.$$

$$Af_h = f_T = \text{unity gain (0dB) frequency} = \text{Constant}.$$

$A f_h$ = gain Bandwidth product

If negative feedback around op-amp it reduces the gain to A_F, then

$$A_F f_H = f_T$$

(or) $$f_H = \frac{f_T}{A_F} >> f_h$$

Due to reduction in gain caused by feedback, the bandwidth increases from f_h to f_H.

Slew rate :-

Because of presence of capacitances, which is RC combination it can charge at a limited rate, & the rate of change of output of the op-amp is limited to

$$\text{Slew rate } S = \left.\frac{dv_o}{dt}\right|_{max}$$

Its typical value is 0.5 V/μs as shown in figure

For a sinusoidal signal

$$V_o = V_m \sin\omega$$

$$S = \left.\frac{dV_o}{dt}\right|_{max} = V_m\omega$$

or $S = 2\pi f V_m$

or It is a combination of frequency & peak value of output.

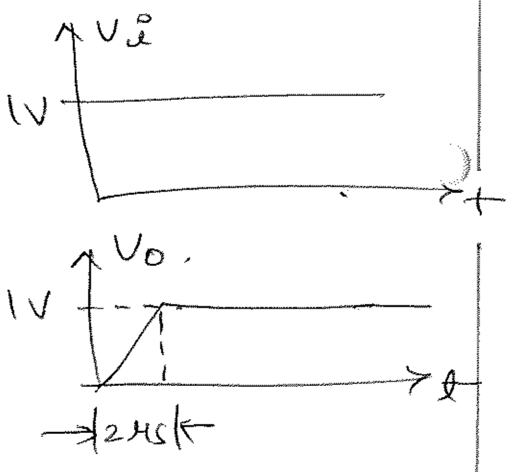


Fig. Effect of slew rate

The two assumptions are.

1. Zero input current :-
The current draw by either of the input terminals (inverting & non inverting) is zero.

2. Virtual ground.
This means that differential input v/g V_d b/w non inverting & inverting input terminals is essentially zero.
Due to large open loop gain of op-amp, if V_o = few volts,

$$V_d = 0 = V_1 - V_2$$

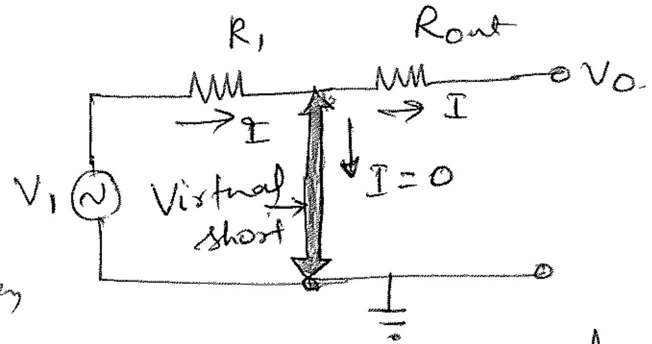
$$V_o = V_d A_{OL} \quad \text{i.e.} \quad V_d = \frac{V_o}{A_{OL}} = \underline{0}, \quad A_{OL} = \text{very high } \infty$$

$$V_d = (V_1 - V_2) = 0$$

$$\boxed{V_1 = V_2}$$

Thus under linear range of operation there is virtually short circuit between the two input terminals, in the sense that their voltages are same.

Fig shows the concept of the virtual ground. The thick line indicates the virtual short circuit between the input terminals.



Concept of virtual ground.

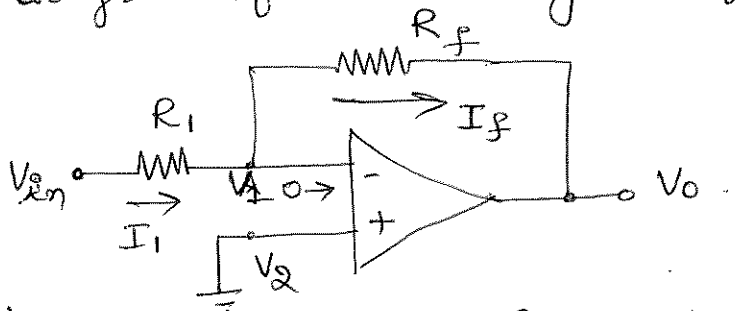
• Now if the non-inverting terminal is grounded by the concept of virtual short, the inverting terminal is also at ground potential, though there is no physical connection b/w the inverting terminal & the ground. This is principle of virtual ground.

It is defined as phenomenon by which the potential difference between the two input terminal is zero.

Inverting op-amp circuits.

An amplifier which provides a phase shift of 180° between input & output is called inverting amplifier.

- The basic circuit diagram of an inverting amplifier is shown in figure.



Connect input signal Vin to the

- non-inverting terminal through a resistor R_1. The non inverting terminal is grounded.
- The resistance R_f connects the output terminal to inverting terminal to provide the negative feedback.

Note: - all amplifier should have negative feedback.

When (+) terminal is grounded, the (−) terminal is virtually at ground potential. step1: V/g at V_2 terminal. $V_2 = 0$ because connected ground.

"step2" - The input impedance of op-amp is $R_{in} = \infty$ hence current into an op-amp terminal is zero. From virtual ground concept $V_1 = 0$.

Step3: $V_2 = V_1 = 0 \rightarrow (1)$

applying KCL to inverting terminal $I_f = I_1 \rightarrow (2)$ replace

Step 4: current by ohms law

Here $I_f = \dfrac{V_1 - V_o}{R_f} = \dfrac{-V_o}{R_f}$

$I_1 = \dfrac{V_{in} - V_1}{R_1} = \dfrac{V_{in}}{R_1}$

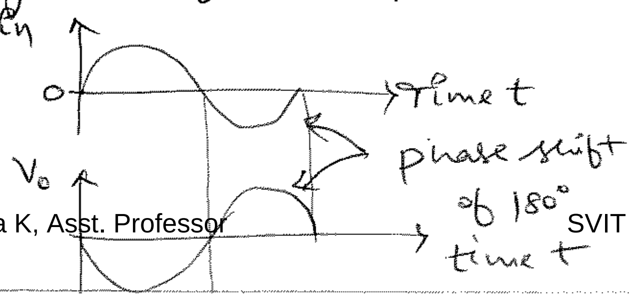
$$\frac{0 - V_o}{R_f} = \frac{V_{in}}{R_1}$$

The gain is.

$$A_V = \underset{\text{gain}}{\text{voltage}} = \frac{V_o}{V_{in}} = -\frac{R_F}{R_1}$$

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

Here the output voltage is the negative of the input voltage, i.e it is inverted.



Waveform of inverting amplifier.

Problem (1)

An inverting amplifier has $R_1 = 2K\Omega$ $R_f = 10K\Omega$. for an input voltage of 1.5 V, find the output voltage of the circuit.

$R_1 = 2K\Omega$ $R_f = 10K\Omega$ $V_{in} = 1.5V$ $V_o = ?$

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

$$= -\left(\frac{10\times10^3}{2\times10^3}\right) * 1.5$$

$$= -7.5 \text{ Volts}$$

(2). Design an inverting amplifier to provide an output voltage of −9 V for an input of 2V.

given $V_{in} = 2V$ $V_o = -9V$

Find R_1, R_2.

$$A_V = \frac{V_o}{V_{in}} = \frac{-9}{2} = 4.5$$

$$A_V = -\frac{R_f}{R_1} = \quad \text{let } R_1 = 1K\Omega$$

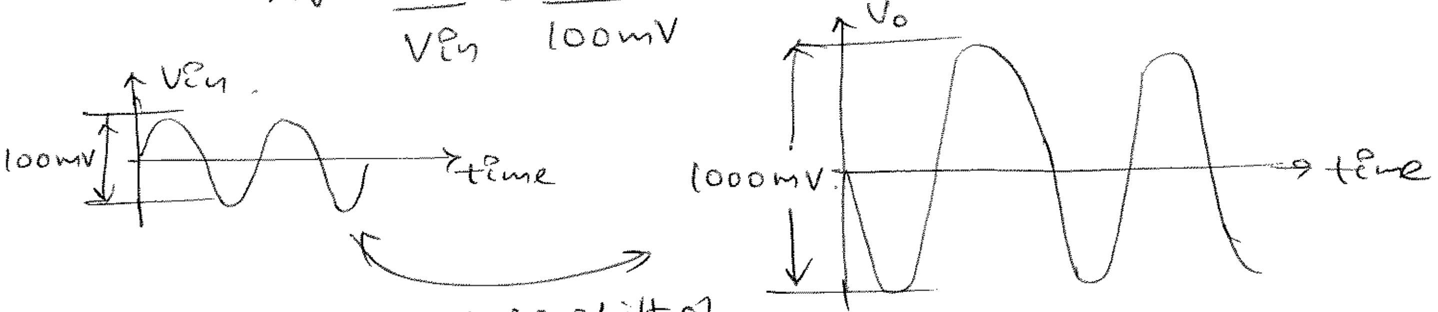
$$-4.5 = -\frac{R_f}{1K\Omega} \qquad \boxed{R_f = +4.5K\Omega}$$

(3). An op-amp is used as an inverting amplifier to amplifier an input sine wave of amplitude 100mV. (peak to peak) The input Resistance $R_1 = 1K\Omega$ and feedback resistance $R_f = 10K\Omega$. Calculate the voltage gain & Sketch the output waveform to scale.

given:- $V_{in} = 100mV$, $R_1 = 1K\Omega$ $R_f = 10K\Omega$. $A_V = ?$

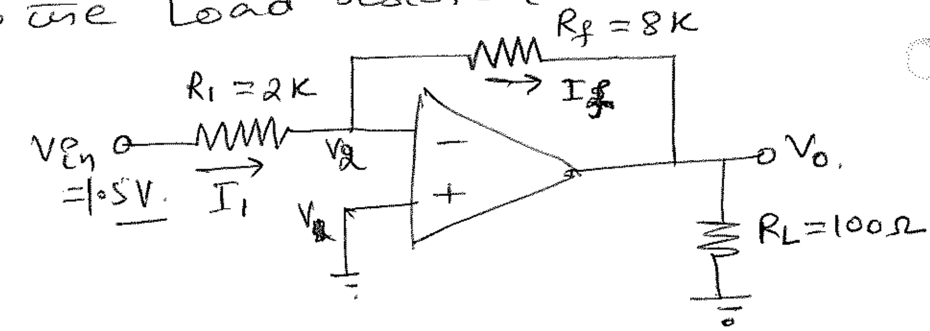
$$V_o = -\left(\frac{R_f}{R_1}\right) * V_{in} = \frac{-10\times10^2}{1\times10^2} * 100mV = -1V$$

$$A_V = \frac{-V_o}{V_{in}} = \frac{-1\ V}{100\ mV} = -10.$$



phase shift of 180°.

4. In the following op-amp circuit find voltage gain, input current (current drawn from the source), output voltage, the current through the Load resistor, power delivered to the Load resistor.



given Data:-

$R_f = 8K.$

$R_1 = 2K$

$R_L = 100\ \Omega$

$V_{in} = 1.5\ V$

Find $A_V, I_{in}\ V_o, I_L, P_o$

$$A_V = \frac{-V_o}{V_{in}} = \frac{R_f}{R_1} = \frac{-8}{2} = -4.$$

$$I_{in} = \frac{V_{in}}{R_1} = \frac{1.5}{2K} = 750\ \mu A = 0.75\ mA.$$

$$V_o = A_V V_{in} = (-4) * 1.5 = -6\ V.$$

$$P_o = (V_o)^2 / R_L = (-6)^2 / 100$$

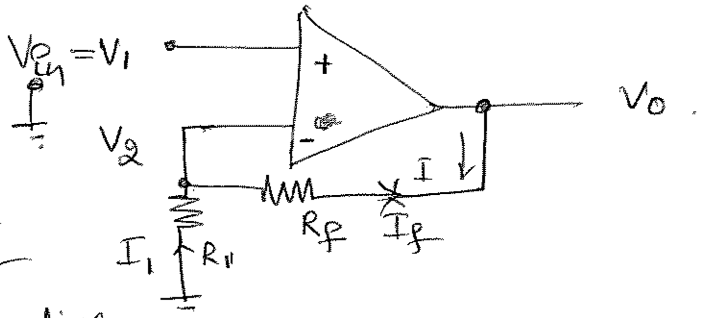
$$= 0.36\ W.$$

$$I_L = \frac{V_o}{R_L} = \frac{-6}{100} = -0.06\ A.$$

Non-inverting amplifier :-

An amplifier which amplifies the input without producing any phase shift between input & output is called Non-inverting amplifier.

The circuit Diagram is shown in figure.



Input signal is applied to the non-inverting terminal.

The resistance R_f connects the output terminal to inverting terminal to provide the negative feedback.

Feedback circuit is completed by connecting it to resistance R_1 and following ground.

Step ①
The voltage V_1 at the non-inverting terminal.

$$V_{in} = V_1$$

Step ②
From the concept of virtual ground, $\boxed{V_1 = V_2 = V_{in}}$

Step ③
By applying KCL at the inverting terminal. Let I_1 is the current through resistor R_1. I_f is the current through ~~the current~~ the resistor R_f.

$$I_1 = I_f$$

Step ④ Replace current by ohms law.

$$\frac{0 - V_2}{R_1} = \frac{V_2 - V_o}{R_f} \Rightarrow \frac{-V_2}{R_1} = \frac{V_2}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_2}{R_f} + \frac{V_2}{R_1}$$

$$\frac{V_o}{R_f} = V_2\left[\frac{R_1 + R_f}{R_f R_1}\right] \qquad V_2 = V_1$$

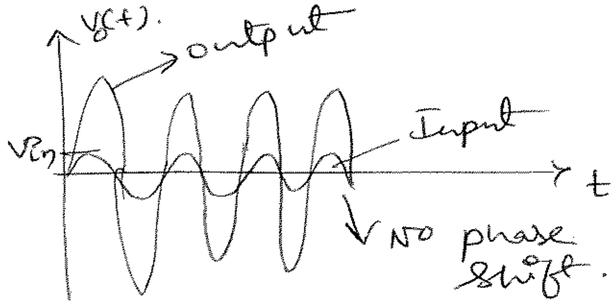
$$\frac{V_o}{R_f} = V_1\left[\frac{R_1 + R_f}{R_f R_1}\right]$$

$$A_V \text{ Voltage gain} = \frac{V_o}{V_1} = \cancel{R_f}\left[\frac{R_1+R_f}{R_1 \cancel{R_f}}\right] = \left[1+\frac{R_f}{R_1}\right]$$

if $R_1 = \infty$ then $\boxed{A_V = 1}$ The ckt is then Voltage follower.

or $R_f = 0$ then also $A_V = 1$ unity gain.

Waveform of non-inverting amplifier.



Problems:-

(1) A non-inverting amplifier has $R_1 = 2K\Omega$, $R_f = 10K\Omega$. for an input voltage of 1.5V, Find the output voltage of the circuit.

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

$$= \left[1 + \frac{10}{2}\right] 1.5 = 9\,V$$

$$A_V = \frac{V_o}{V_{in}} = \frac{9V}{1.5V} = 6$$

(2) Design a non-inverting amplifier to provide an output voltage of 9V for an input of 2V.

given. $V_o = 9V$ $V_{in} = 2V$.

$$A_V = \frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}$$

$$\frac{9}{2} = 1 + \frac{R_f}{R_1}$$

if $R_1 = 1K\Omega$.

$$\frac{R_f}{R_1} = 4.5 - 1$$

$$R_f = 3.5 * R_1$$

$$\boxed{R_f = 3.5K\Omega} \qquad R_1 = 1K\Omega.$$

The open loop voltage gain of op-amp is A_V and due to finite gain the concept of virtual ground cannot be used.

$$V_d = V_1 - V_2 = V_{in} - V_2$$

$$\& \quad V_o = A_V V_d = A_V (V_{in} - V_2) \rightarrow (1)$$

Here R_f & R_1 forms a voltage divider.

$$V_2 = R_1 * \frac{V_o}{R_1 + R_f} = \beta V_o$$

$$\beta = \frac{R_1}{R_1 + R_f} = \text{feedback factor}$$

$$V_o = A_V [V_{in} - \beta V_o]$$

$$V_o = A_V V_{in} - A_V \beta V_o \quad \text{i.e} \quad V_o(1 + A_V \beta) = A_V V_{in}$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{A_V}{1 + A_V \beta}}$$

But $\frac{V_o}{V_{in}}$ is called closed loop voltage gain denoted as A_{vf}

$$\boxed{A_{vf} = \frac{A_V}{1 + A_V \beta}}$$

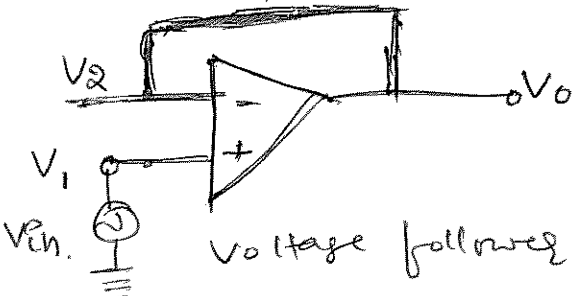
23.10.11

* Voltage follower :-

A circuit in which the output voltage follows the input voltage is called voltage follower circuit.

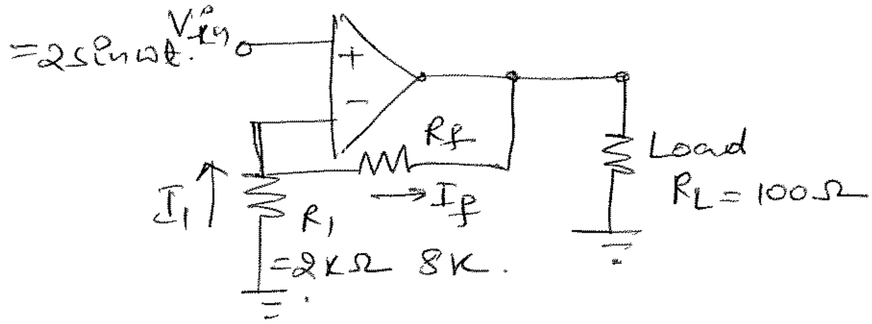
A voltage follower is a circuit with non-inverting configuration. The voltage gain is unity.

- Input signal V_1 is connected to the non inverting terminal
- The output terminal is connected to inverting terminal directly to provide the negative feedback.



Voltage follower.

(3) In the following op-amp circuit find voltage gain, current drawn from the source, output voltage, the current through the Load resistor. power delivered to the Load resistor.



given.

$R_1 = 2K\Omega$

$R_f = 8K\Omega$

$V_{in} = 2\sin\omega t$.

Find A_V, I_{in}, V_0, I_L, P_0.

$$A_V = 1 + \frac{R_f}{R_1} = 1 + \frac{8}{2} = 5.$$

$$I_{in} = \frac{V_{in}}{R_1} = \frac{2}{2K\Omega} = 1mA \text{ (peak value)}.$$

$$V_0 = A_V V_{in} = (5)\,2 = 10V$$

$$V_0(rms) = \frac{V_0}{\sqrt{2}} = \frac{10}{\sqrt{2}} = 7.07V.$$

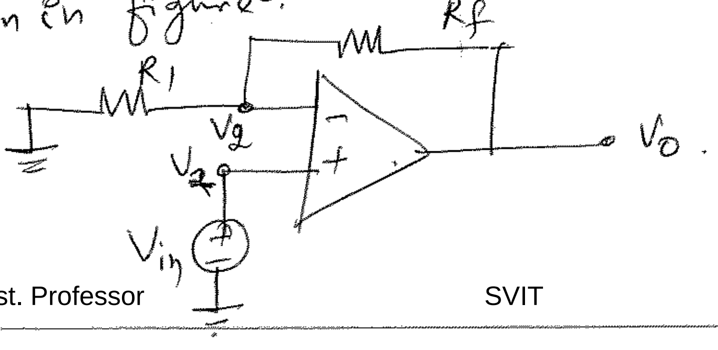
$$P_0 = \frac{V_0^2}{R_L} = (7.07)^2/100 = 0.5 \text{ Watts}.$$

Question

Draw the non-inverting Voltage amplifier circuit using an op-amp & show that the closed loop voltage gain is given by $A_{vt} = \dfrac{A_V}{1 + A_V \beta}$ When $A_V \rightarrow$ open loop Voltage gain of an op-amp.

$\beta \rightarrow$ feedback factor.

Ans:- The non-inverting amplifier is shown in figure.



Step ① The voltage V_1 at non-inverting terminal is $V_1 = V_{in}$

Step ② The node V_1 is also at the same potential as V_2 i.e V_{in} according to the concept of virtual ground.

$$V_1 = V_2 = V_{in}.$$

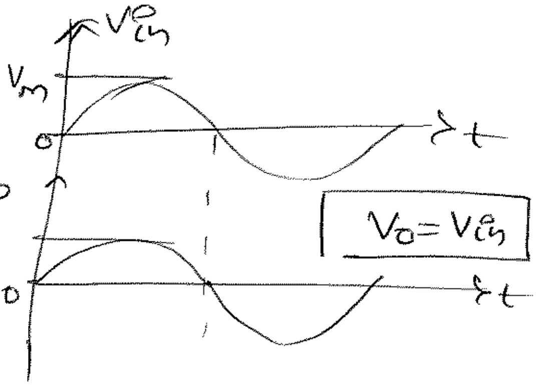
Step ③ Since the node V_2 is connected to the output terminal directly, the voltage at the output terminal is same as the inverting terminal.

$$\therefore V_0 = V_1 = V_2.$$

It is also called source follower, unity gain amplifier, buffer amplifier or isolation amplifier.

The output voltage is said to be following the input voltage. $\therefore$ the circuit is called a voltage follower.

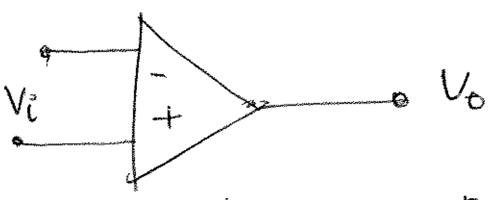
The waveform shown in figure.



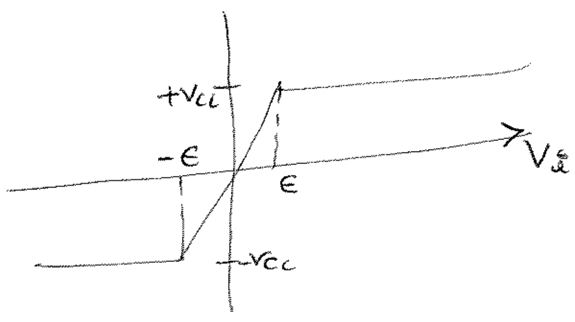
- Voltage follower has large bandwidth.
- Very large input resistance, in MΩ
- Low output impedance, almost zero.
- The o/p follows the input exactly without any phase shift.

Transfer characteristics of op-amp.

An op-amp is linear with high gain over a very small value of $V_i = \epsilon$ as shown in fig. beyond which it saturates, $V_0 = V_{CC}$



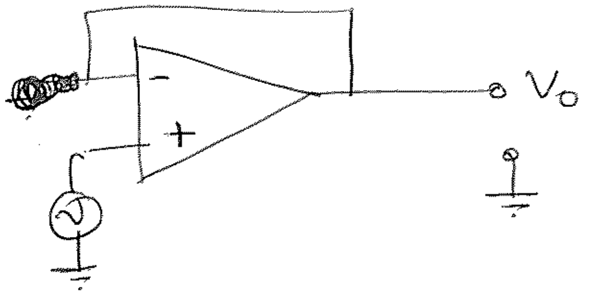
ⓐ open loop op-amp.



ⓑ Transfer characteristics

Problem ① The input to the op-amp is $10 \sin 10t$ volts. Draw the output waveform indicating time period & maximum value.

Ans:- the ckt is v/g follower



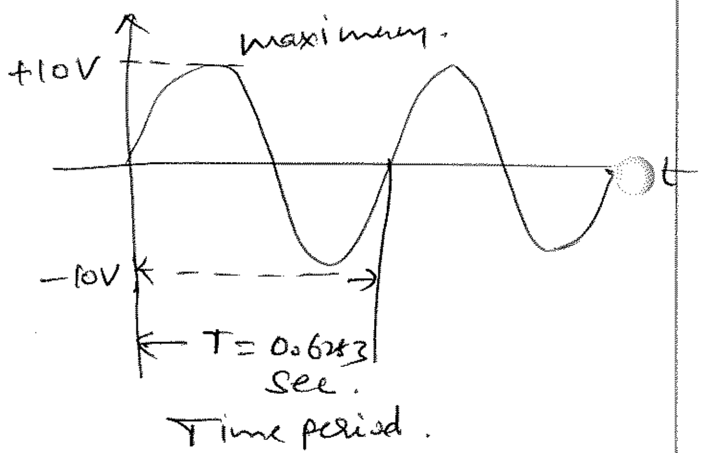
$V_o = V_{in}$

$= 10 \sin 10t$.

maximum value $= 10V$

$\omega = 10 = \frac{2\pi}{T}$

$T = 0.6283$ sec.



Addition or Summer circuit :-

An op-amp circuit in which the output voltage is proportional to the sum of the all the input voltages can be defined as summer circuit.

Two types of summer circuit

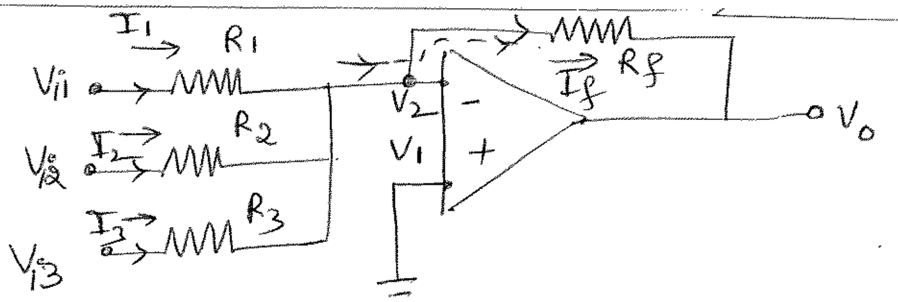
① Inverting Summer circuit

② Non inverting summer circuit.

Classification made depending upon the sign of the output.

Inverting Summing amplifier

- In this circuit, all the input signal to be added are applied to the inverting input terminal of the op-amp. The circuit with three input signal is shown in figure.



Summer circuit.

Step 1:- The non inverting terminal is grounded. $\therefore V_1 = 0$.

Step 2:- using the concept of virtual ground, the voltage V_2 at the inverting terminal is equal to V_1

$$V_2 = V_1 = 0.$$

Step 3:- From KCL -
At the inverting terminal

$$I_1 + I_2 + I_3 = I_f.$$

[KCL states that the sum of the currents entering a terminal must be equal to the current leaving the terminal.]

Step 4:- Replace each current by ohm's law.

$$\frac{V_{i1} - V_2}{R_1} + \frac{V_{i2} - V_2}{R_2} + \frac{V_{i3} - V_3}{R_3} = \frac{V_2 - V_o}{R_f} \quad ; \text{put } V_2 = 0.$$

$$\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} + \frac{V_{i3}}{R_3} = \frac{-V_o}{R_f}$$

let $R_1 = R_2 = R_3 = R$.

$$V_o = \frac{-R_f}{R}\left[V_{i1} + V_{i2} + V_{i3}\right]$$

if $R = R_f$.

$$V_o = -\left[V_{i1} + V_{i2} + V_{i3}\right]$$

The significance of the negative sign is that the input signal & output signals are out of phase by 180°.

problem: (1) Calculate the output of Summing amplifier with $R_1 = 200K\Omega$, $R_2 = 250K\Omega$, $R_3 = 500K\Omega$, $R_f = 1000K\Omega$

$V_{i1} = -2V$, $V_{i2} = 2V$, & $V_{i3} = 1V$.

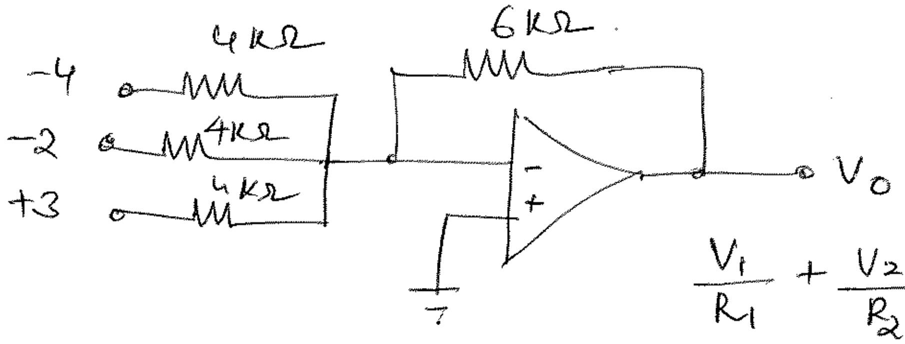
$$\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} + \frac{V_{i3}}{R_3} = \frac{-V_o}{R_f}.$$

$$\frac{-2}{200} + \frac{2}{250} + \frac{1}{500} = \frac{-V_o}{1000}.$$

$$\left[-0.01 + 0.008 + 0.002\right] * 1000 = -V_o.$$

$$\boxed{V_o = 0}$$

(2) Find the output voltage of the 3-input adder circuit shown below.



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

$$\frac{-4}{4} - \frac{2}{4} + \frac{3}{4} = \frac{-V_o}{6} \Rightarrow$$

$$6(-1 - 0.5 + 0.75) = -V_o.$$

$$6(-0.75) = -V_o.$$

$$\boxed{V_o = 4.5}$$

(3) Design a adder circuit to get an output voltage of $V_o = -(3V_1 + 4V_2 + 5V_3)$ choose $R_f = 30K$.

Then given expression is $V_o = -(3V_1 + 4V_2 + 5V_3)$. $\rightarrow$ (1)

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

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

By comparing eq^n (1) & (2).

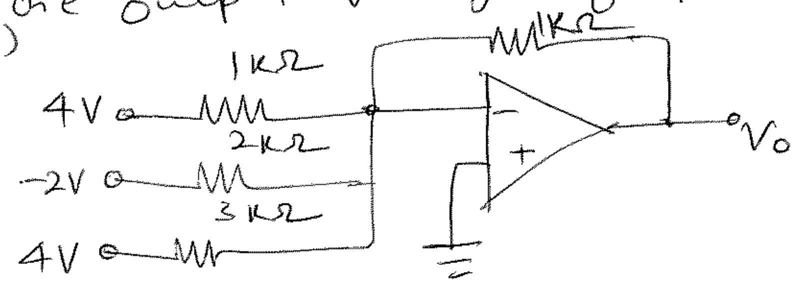
$$\frac{R_f}{R_1} = 3 \quad \frac{R_f}{R_2} = 4 \quad \frac{R_f}{R_3} = 5. \qquad \text{let } R_f = 30K.$$

$$\frac{30}{R_1} = 3 \quad \frac{30}{R_2} = 4 \quad \frac{30}{R_2} = 5.$$

$$\boxed{R_1 = 10K\Omega} \quad \boxed{R_2 = 7.5K\Omega} \quad \boxed{R_3 = 6K\Omega}$$

(4). * Find the output voltage of op-amp circuits given VTU, June 2012 (4 Marks)

(a)



inverting summer with $R_f = 1k\Omega$.

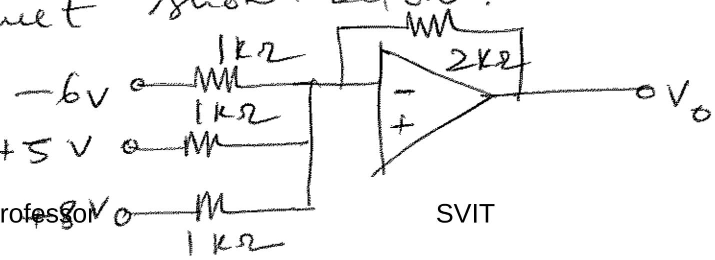
here $R_1 = 1K\Omega$, $R_2 = 2K\Omega$, $R_3 = 3k\Omega$ $V_1 = 4V$ $V_2 = -2V$ $V_3 = 4V$.

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

$$= -\left[\frac{1\times10^3}{1\times10^3} * 4V + \frac{1}{2} * (-2) + \frac{1}{3} * 4\right]$$

$$= \left[4V - 1V + 1.33V\right] = 4.33V.$$

(b). Determine the output voltage of the op-amp circuit shown below. VTU: June 12. 4 Marks.

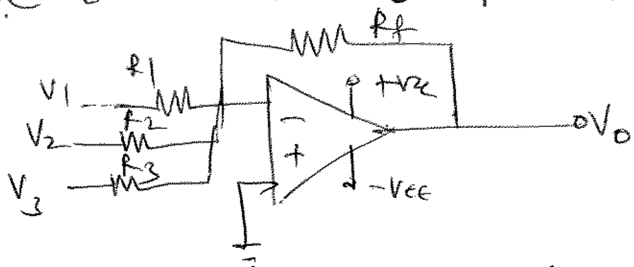


$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

$$= -\left(\frac{2}{1}\times(-6) + \frac{2}{1}\times5 + \frac{2}{1}\times8\right)$$

$$= -14V$$

(7) Calculate the ~~output~~ voltages of the circuit given below. VTU Jan 13 (5M)



let $V_o = -(0.1 V_1 + 0.5 V_2 + 20 V_3)$

$R_f = 10 k\Omega$

The output of inverting summer is

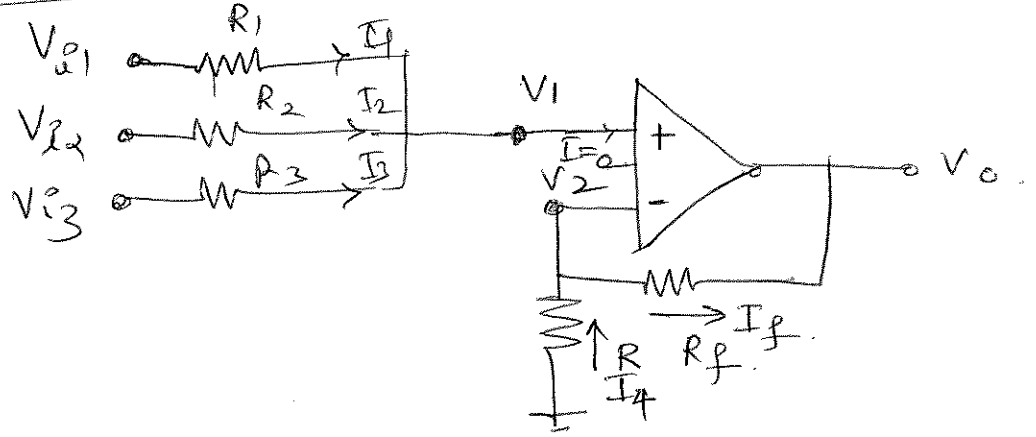
$$V_o = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right]$$

$$= -0.1 V_1 + 0.5 V_2 + 20 V_3.$$

$\frac{R_f}{R_1} = 0.1$ $\frac{R_f}{R_2} = 0.5$ $\frac{R_f}{R_3} = 20.$ if $R_f = 10 k\Omega$.

$R_f = 10 k\Omega$, $R_1 = 100 k\Omega$ $R_2 = 20 k\Omega$, $R_3 = 0.5 k\Omega$.

Non-inverting summing circuit



non-inverting summing circuit.

Here multiple input signals are connected to the non-inverting terminal. Each input signal is connected to a seperate resistor.

- The output terminal is connected to inverting terminal through a resistor. Rf: it provides negative feedback.
- The inverting terminal is also connected to ground through a resistor.

Step 1 : The voltage V_1 at the non-inverting terminal.

many inputs are connected to the non-inverting terminals. The voltage V_1 found by applying KCL. KCL states that sum of the currents entering terminal must be equal to the current leaving the terminal.

$$I_1 + I_2 + I_3 = 0.$$

$$\frac{V_{i1} - V_1}{R_1} + \frac{V_{i2} - V_1}{R_2} + \frac{V_{i3} - V_1}{R_3} = 0.$$

let $R_1 = R_2 = R_3 = R$.

$$\frac{V_{i1} - V_1}{R} + \frac{V_{i2} - V_1}{R} + \frac{V_{i3} - V_1}{R} = 0$$

$$3V_1 = V_{i1} + V_{i2} + V_{i3}.$$

$$\boxed{V_1 = \frac{V_{i1} + V_{i2} + V_{i3}}{3}}$$

Step 2 :- using the concept of virtual ground, the Voltage V_2 at the inverting terminal is equal to V_1.

$$V_2 = V_1 = \frac{V_{i1} + V_{i2} + V_{i3}}{3}.$$

Step 3 :- apply KCL at the inverting terminal. let I_4, I_f are the current through resistors R_1, R_f respectively.

$$I_4 = I_f.$$

Step 4 :- Replace each current by ohm's law.

$$\frac{0 - V_2}{R} = \frac{V_2 - V_0}{R_f}$$

$$\frac{-V_2}{R} = \frac{V_2}{R_f} - \frac{V_o}{R_f}.$$

$$\frac{V_o}{R_f} = \frac{V_2}{R_f} + \frac{V_2}{R}.$$

$$\frac{V_o}{R_f} = V_2\left[\frac{R+R_f}{R_f * R}\right].$$

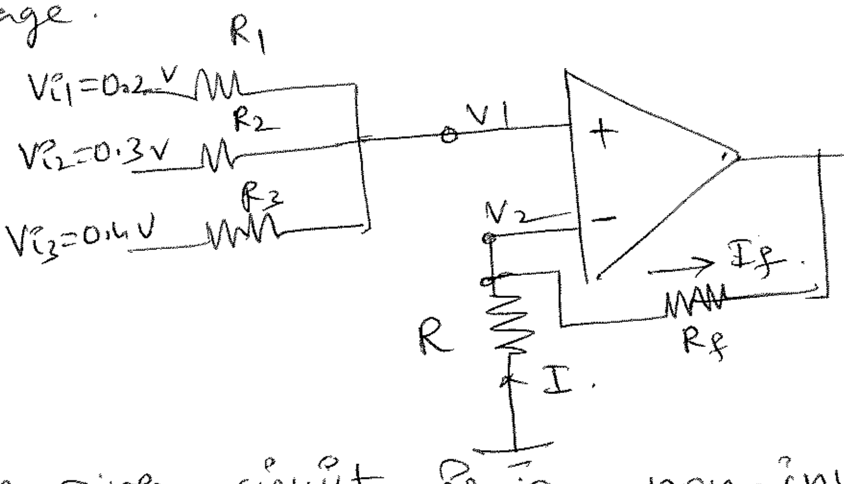
$$V_o = V_2\left[\frac{R+R_f}{\cancel{R_f} * R}\right]\cancel{R_f}$$

$$V_o = V_2\left[1 + \frac{R_f}{R}\right]$$

$$V_o = \left(\frac{V_{i1}+V_{i2}+V_{i3}}{3}\right)\cdot\left(1+\frac{R_f}{R}\right).$$

If $\boxed{R_f = 2R_1}$, Then $\boxed{V_o = V_{i1} + V_{i2} + V_{i3}}$

problem ① for the following circuit, find output voltage.



$R_1 = R_2 = R_3 = 2K$.

$R_f = 10K$

$R_1 = 2K$

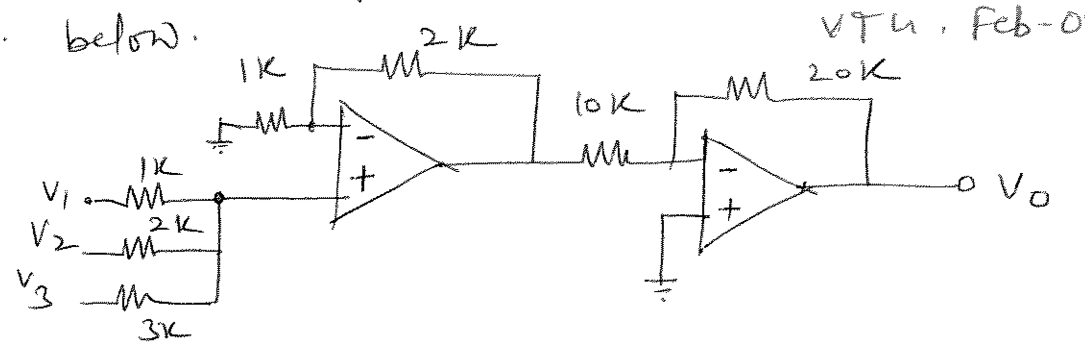
The given circuit is an non-inverting summer.

$$V_o = \left\{\frac{V_{i1}+V_{i2}+V_{i3}}{3}\right\}\left[1+\frac{R_f}{R}\right]$$

$$V_o = \frac{0.9}{3} \times \left[1 + \frac{10}{2}\right]$$

$$\boxed{V_o = 1.8\,V}$$

② Calculate the output voltage of the circuit given in fig. below. VTU, Feb-09, (8M)



$V_1 = 1V$, $V_2 = 2V$ $V_3 = 3V$.

Sol^n:- By using super position theorem, & consider each input acting seperately.

Case ①. V_1 acting V_2 & V_3 grounded.

This is non inverting amplifier with $R_f = 2k\Omega$, $R_1 = 1k\Omega$.

Then $2k\Omega \parallel 3k\Omega = \frac{2\times3}{2+3} = \frac{6}{5} = 1.2\,k\Omega$

$$V_B = \frac{V_1(2k\Omega \parallel 3k\Omega)}{1 * k\Omega + [2k\Omega + 3k\Omega)} = \frac{V_1 * 1.2\,k}{1K + 1.2\,K}$$

$$\boxed{V_B = 0.5454\,V_1}$$

$$V_{01} = \left[1 + \frac{R_f}{R_1}\right] V_B.$$

$$= \left[1 + \frac{2}{1}\right] * 0.5454\,V_1 = 1.6363\,V_1$$

Case ②:- V_2 acting V_1 & V_3 grounded. $1k\Omega \parallel 3k\Omega = 750\Omega$.

$$V_B = \frac{V_2 \times 750}{2K + 750} = 0.2727\,V_2.$$

$$V_{02} = \left[1 + \frac{R_f}{R_1}\right] V_B = \left[1 + \frac{2\times10^3}{1\times10^3}\right] 0.2727\,V_2$$

$$= 0.8181\,V_2.$$

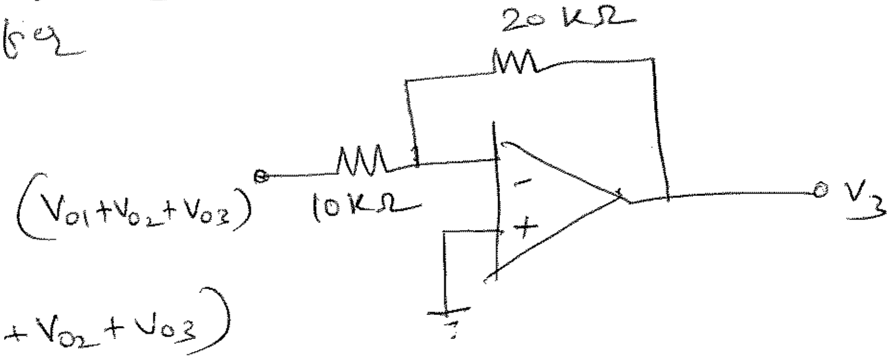
Case ③:- V_3 acting V_1 & V_2 grounded, $1k\Omega \parallel 2k\Omega \parallel = 666.67\Omega$

$$V_B = \frac{V_3 * 666.67}{[3\times10^3 + 666.67]} = 0.1818\,V_3.$$

$$\therefore V_{03} = \left[1 + \frac{R_f}{R_1}\right] V_B = \left[1 + \frac{2\times10^3}{1\times10^3}\right] \times 0.1818\,V_3$$

$$\boxed{V_{03} = 0.5454\,V_3}$$

Now the voltage $(V_{01}+V_{02}+V_{03})$ is applied to inverting terminal of amplifier



$$\therefore V_0 = \frac{-R_f}{R_1}(V_{01}+V_{02}+V_{03})$$

$$= \frac{-20}{10}\left[1.6363V_1 + 0.8181V_2 + 0.5454V_3\right)$$

$$\therefore V_0 = (-3.2726V_1 - 1.6362V_2 - 1.0909V_3)$$

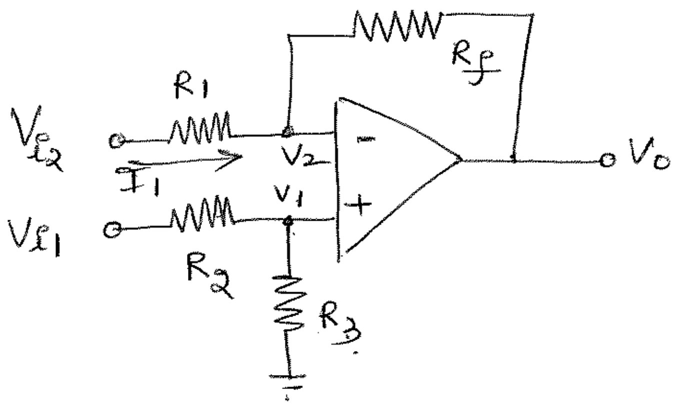
with $V_1 = 1V$, $V_2 = 2V$ $V_3 = 3V$.

$$\boxed{\therefore V_0 = -9.8178\ V}$$

Subtractor or Difference amplifier

VTU, Aug 04,05 (M-S)

The circuit diagram of subtractor is shown in figure.



Difference amplifier.

- One of the input voltage is connected to the non inverting terminal through a potential divider network R_2 and R as shown in figure.
- Another input voltage is connected to the inverting terminal through a resistor R_1
- The resistor R_f connects the output terminal to inverting input terminal to provide negative feed back.

Step 1 :- At the non-inverting terminal, two resistor are connected. The voltage across one of the resistor is found by applying voltage divider rule.

$$V_1 = V_{i1} \frac{R_3}{R_2 + R_3}$$

step 2 :- using the concept of virtual ground, the voltage V_2 at the inverting terminal is equated to the voltage at non inverting terminal.

$$V_2 = V_1 = V_{i1} \frac{R_3}{R_2 + R_3}.$$

step 3 :- By applying KCL at the inverting terminal. Let I_1, I_f are the current through resistors R_1, R_f.

$$I_1 = I_f.$$

step 4 : Replace the each current by ohm's law.

$$\frac{V_{i2} - V_2}{R_1} = \frac{V_2 - V_0}{R_f}$$

$$\frac{V_{i2}}{R_1} - \frac{V_2}{R_1} = \frac{V_2}{R_f} - \frac{V_0}{R_f}.$$

$$\frac{V_0}{R_f} = \frac{V_2}{R_f} + \frac{V_2}{R_1} - \frac{V_{i2}}{R_1}$$

$$\frac{V_0}{R_f} = V_2\left[\frac{R_f + R_1}{R_f * R_1}\right] - \frac{V_{i2}}{R_1}$$

$$V_0 = V_2\left[\frac{R_f + R_1}{R_1}\right] - V_{i2}\frac{R_f}{R_1}$$

$$V_0 = V_{i1}\left(\frac{R_3}{R_2 + R_3}\right)\left(\frac{R_f + R_1}{R_1}\right) - V_{i2} \cdot \frac{R_f}{R_1} \quad ; \text{ let } R_3 = R_f \quad R_2 = R_1$$

$$V_0 = V_{i1}\left(\frac{R_f}{\cancel{R_1 + R_f}}\right)\left(\frac{\cancel{R_f + R_1}}{R_1}\right) - V_{i2} \cdot \frac{R_f}{R_1} = \frac{R_f}{R_1} V_{i1} - V_{i2}\frac{R_f}{R_1}$$

$$\boxed{V_0 = \frac{R_f}{R_1}\left(V_{i1} - V_{i2}\right)}$$

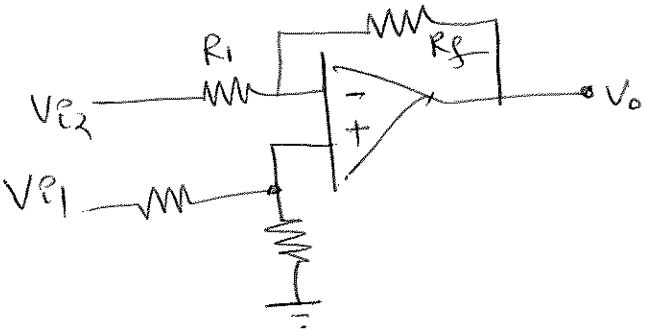
$\frac{R_f}{R_1}$ = Voltage gain

If $R_f = R_1$, the voltage gain becomes unity, then the circuit is subtractor circuit.

If $R_f > R_1$, then voltage gain becomes greater than unity and the circuit is called difference amplifier.

Problem.

① For the given op-amp circuit find the output voltage. Take $R_f = R_3 = 12K\Omega$ $R_1 = R_2 = 3K\Omega$, $V_{i1} = 2.1V$, $V_{i2} = -0.9V$.

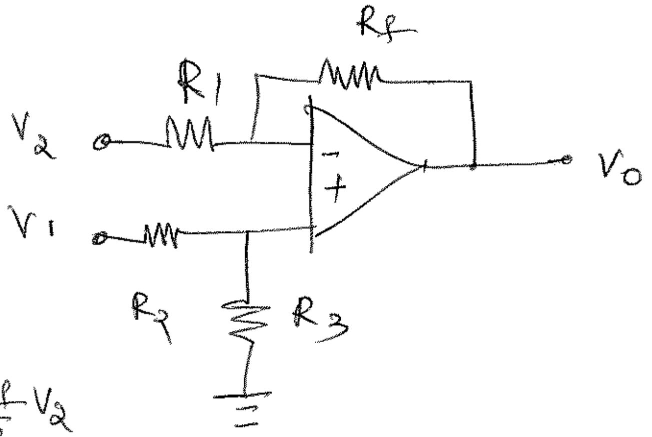


The given circuit is a difference amplifier.

$$V_o = \frac{R_f}{R_1}\left[V_{i1} - V_{i2}\right]$$

$$= \frac{12K}{3K}\left[2.1-(-0.9)\right] = \underline{12V}.$$

② Design a suitable circuit to realize the given expression $V_o = 0.4V_1 - 8V_2$. where V_1 & V_2 are the input voltages. Draw the circuit.



The expression for the output voltage is.

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

$\boxed{\frac{R_f}{R_1} = 8}$ $\boxed{R_f = 8R_1}$ let $R_1 = 10K\Omega$ $R_f = 80K\Omega$.

Comparing the coefficient of V_1 we get.

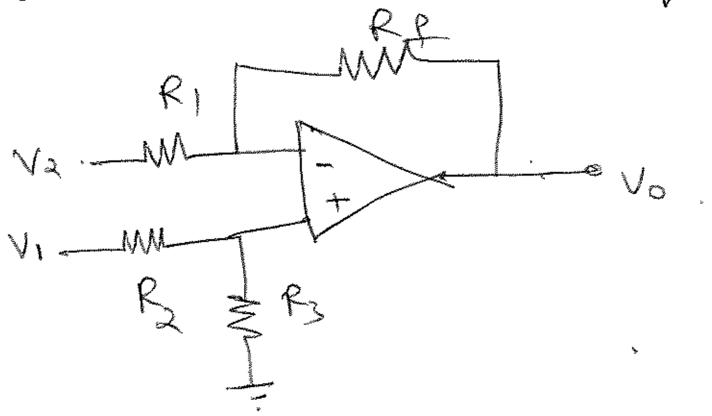
$$\frac{R_3}{R_2+R_3}\left[\frac{R_1+R_f}{R_1}\right] = 0.4. \quad \frac{R_3}{R_2+R_3}\left[\frac{10+80}{10}\right] = 0.4$$

$\frac{R_3}{R_2+R_3} = \frac{0.4}{9} = 0.044$, $\frac{R_2+R_3}{R_3} = 22.72$ $1+\frac{R_2}{R_3} = 22.72$ if $R_3 = 10K\Omega$

$\boxed{R_2 = 217.2K\Omega}$

(3) Design an op-amp circuit to get the required expression $V_0 = 8(V_1 - V_2)$. $\rightarrow$ (*)

Since the 2 input voltages are subtracted, the required circuit is as follows.



Since the coefficient of V_1 & V_2 are same.

choose $R_1 = R_2$

$R_f = R_3$.

$$V_0 = \frac{R_f}{R_1}(V_1 - V_2) \rightarrow (1)$$

By comparing eqn (*) & (1)

$\frac{R_f}{R_1} = 8$ $\quad R_f = 8 * R_1$ $\quad$ let $\boxed{R_1 = 10k\Omega \\ R_f = 80k\Omega}$

---

(4) Design the op-amp circuit which can give the output as $V_0 = 2V_1 - 3V_2 + 4V_3 - 5V_4$

The positive & negative terms can be added seperately using two adder then subtractor.

$2V_1 + 4V_3$, $\rightarrow$ (*) let $R_{f_1} = 100k\Omega$.

$$V_{01} = -\left(\frac{R_{f_1}}{R_1}V_1 + \frac{R_{f_1}}{R_3}V_3\right)$$

Comparing with (*)

$\frac{+R_{f1}}{R_1} = 2$ $\quad \frac{R_{f1}}{R_3} = 4$.

$R_1 = 50k\Omega$ $\quad R_3 = 25k\Omega$.

$3V_2 + 5V_4$, let $R_{f_2} = 120k\Omega$

$$V_{02} = -\left\{\left(\frac{R_{f2}}{R_2}\right)V_1 + \left(\frac{R_{f2}}{R_4}\right)V_3\right\}$$

$$\frac{R_{f2}}{R_2} = 3 \quad \text{hence } R_2 = 40\,K\Omega$$

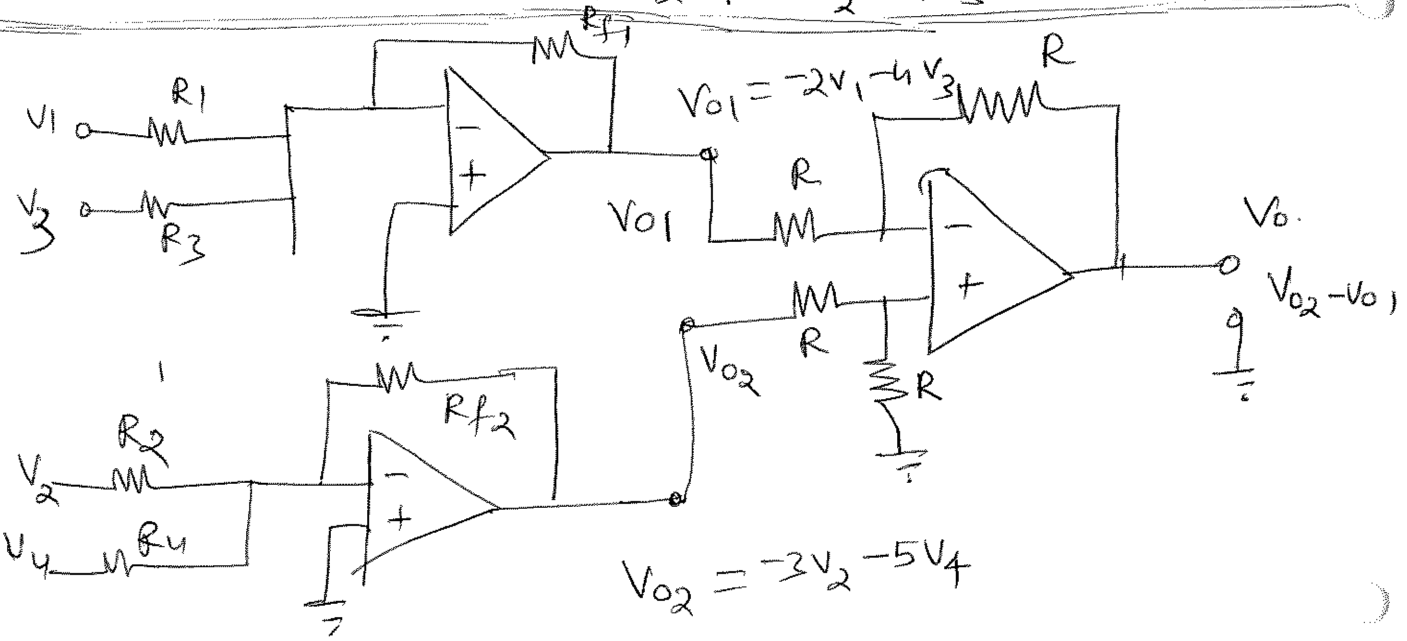
$$\frac{R_{f2}}{R_4} = 5 \quad \text{hence } R_4 = 24\,K\Omega.$$

use the subtractor with all the resistances of same value of $R = 100\,K\Omega$.

Here $V_o = V_{o2} - V_{o1}$, where V_{o2} & V_{o1} are the two inputs of the subtractors.

$$V_o = V_{o2} - V_{o1} = -3V_2 - 5V_4 - (-2V_1 - 4V_3)$$

$$= 2V_1 - 3V_2 + 4V_3 - 5V_4.$$



Integrator: -

VTU - mar 01, 05
Feb 03, 04
June 13.
Jan-08 - 11.

Any circuit whose output voltage is proportional to the integral of the input voltage can be defined as an integrator.

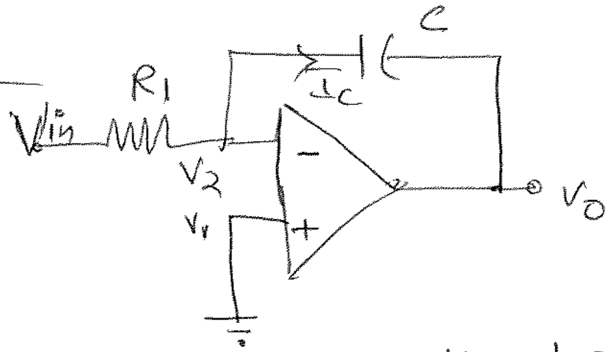
A capacitor is used for realizing the integrator. The voltage across the capacitor is.

$$V_c = \frac{1}{C}\int i_c \cdot dt.$$

$i_c \rightarrow$ is the current through the capacitor

18

Here the output voltage is an integration of the input voltage.



- passive integrator
- Active integrator.

The input signal is connected to the inverting terminal through a resistance R. It is inverting integrator.

- For the circuit to behave as an integrator, a capacitor is necessary. ∴ the capacitor is connected in the feedback path between the output terminal & the inverting terminal.
- The non-inverting terminal is connected to ground.

Step 1:- The voltage V_1 at the non-inverting terminal is grounded $V_1 = 0$. Since the non-inverting virtual ground,

Step 2:- From the concept of virtual ground,

$$V_2 = V_1 = 0.$$

Step 3:- apply KCL at the inverting terminal. let I_1 be the current through R_1 & i_c is the current through capacitor.

$$I_1 = i_c$$

Step 4:- replace current (by I_1) by ohms law.

$$\frac{V_i - 0}{R} = i_c$$

$$\boxed{i_c = \frac{V_i}{R}}$$

The output voltage is $V_O = -V_C$.

$$= -\frac{1}{C}\int i_c \cdot dt$$

$$V_O = -\frac{1}{C}\int \frac{V_i}{R} \cdot dt = \frac{-1}{RC}\int V_i \cdot dt.$$

Thus output voltage is proportional to the integral of the input voltage & hence the circuit can be called integrator :-

applications :-

In analog computer

Solving the differential equation

In ramp generators

In ADCs.

Various signal wave shaping circuits.

problem :-

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

For an ideal integrator,

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

Now $R_1 = 100k\Omega$ & $C_f = 1\mu F$, $V_{in} = V_m \sin \omega t$

where $V_m = 6mV$ $\omega = 2\pi f = 2\pi \times 10^3 \times 2$

$= 4\pi 10^3$ rad/sec.

$$V_o = \frac{1}{R_f C_f}\int_0^t V_{in} \cdot dt$$

$$= \frac{1}{100\times10^3 \times 1\times10^{-6}}\int_0^t 6\times10^{-3} \sin(4\pi \times 10^3) \cdot dt$$

$$= -0.06 \left[\frac{-\cos(4\pi\times10^3 t)}{4\pi\times10^3}\right]_0^t$$

$$= 4.77 \times 10^{-6} \{\cos(4000\pi t) - 1\} \; V$$

$$\boxed{V_o = 4.77\times10^{-6} [\cos(4000\pi t)]}$$

Differentiator :-

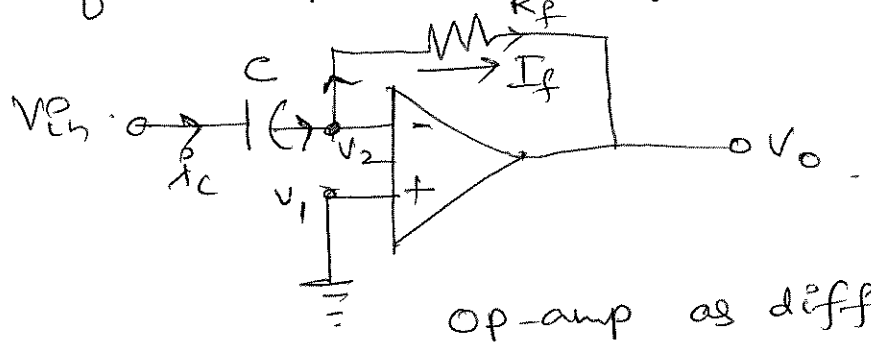
Any circuit whose output voltage is proportional to the derivative of the input voltage can be defined as a differentiator.

A capacitor is used to realize the differentiator. The voltage across the capacitor is

$$V_C = \frac{1}{C}\int i_C \cdot dt .$$

$$i_C = C \cdot \frac{d}{dt}(V_C).$$

Thus, the current through the capacitor is proportional to the derivative of the capacitor voltage.



Op-amp as differentiator.

- V_{in} is connected to inverting terminal through the capacitor C. The Resistor R_f is connected in the feedback path between the output terminal & the inverting terminal.
- The non-inverting terminal is connected to ground.

Step 1: The voltage V_1 at the non-inverting terminal is $V_1 = 0$, since non-inverting terminal is grounded.

Step 2:- From the concept of virtual ground, the

$$V_2 = V_1 = 0 .$$

Step 3:- apply KCL at the inverting terminal.

Let I_f is the current through resistor R_f & i_c is the current through the capacitor

$$i_c = I_f ,$$

Replace the current by ohm's law

$$\frac{V_2 - V_o}{R_f} = i_c = \frac{0 - V_o}{R_f}.$$

$$i_c = -\frac{V_o}{R_f}$$

let V_c is the voltage across the capacitor

$$V_c = V_{in} - V_2.$$

$$V_c = V_{in} - 0$$

$$\boxed{V_c = V_{in}}$$

$$i_c = C \cdot \frac{d}{dt} V_c \qquad \text{w.r.t} \quad i_c = -\frac{V_o}{R}$$

$$-\frac{V_o}{R} = C \frac{d}{dt} \cdot V_c$$

$$\boxed{V_o = -RC \cdot \frac{d}{dt}(V_c)} \qquad V_c = V_{in}$$

$$\boxed{V_o = -RC \frac{d}{dt}(V_{in})}$$

Note:- appl^n of differentiator

- In the wave shaping circuits to detect the high frequency components in the input signal.
- As a rate of change of detector in FM demodulators.

Thus, the output voltage is proportional to the derivative of the input voltage & hence the circuit can be called a differentiator.

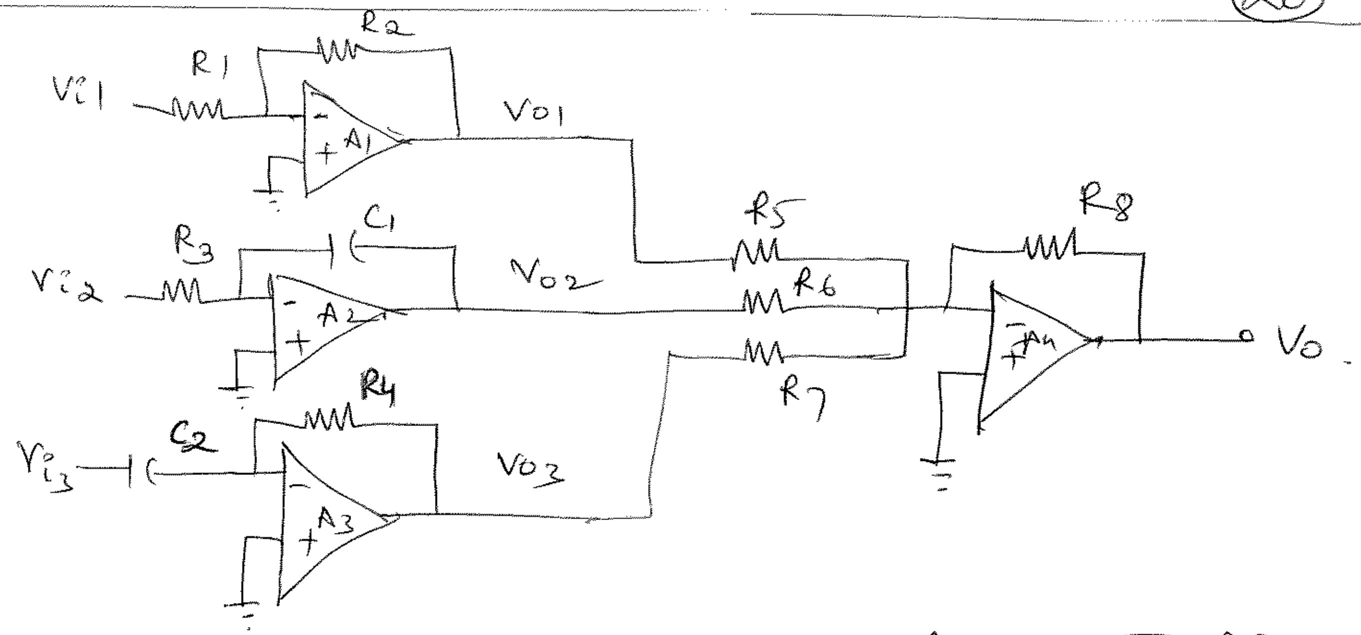
-ve sign shows that the op-amp is connected as an inverting configuration.

Problem "Extra sloved Examples"

(1). For the following circuit find the expression for the output voltage.

given. $R_1 = R_2 = R_5 = R_6 = R_7 = R_8 = 1 k\Omega$

$R_3 = R_4 = 1 M\Omega \quad C_1 = C_2 = 1 \mu F.$



The op-amp A_1 is an inverting amplifier. Therefore the output of A_1 can be written as

$$V_{o1} = -\frac{R_2}{R_1} V_{i1} = -V_{i1}.$$

The op-amp A_2 is an inverting integrator.

The output of A_2

$$V_{o2} = -\frac{1}{R_3 C_1}\int V_{i2} \cdot dt$$

$$= -\frac{1}{1\times10^{6}\times1\times10^{-6}}\int V_{i2} \cdot dt$$

$$= -\int V_{i2} \cdot dt$$

The op amp A_3 is an inverting differentiator. The output of A_3 is

$$V_{o3} = -R_4 C_2 \frac{d}{dt}(V_{i3})$$

$$= -1\times10^{6}\times1\times10^{-6}\frac{d}{dt}(V_{i3})$$

$$V_{o3} = -\frac{d}{dt}(V_{i3})$$

The op-amp A_4 is inverting summer.

the output of A_4 is.

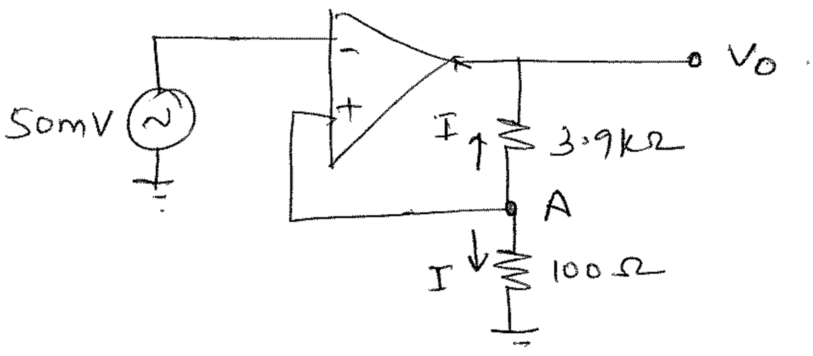
$$V_o = \frac{-R_8}{R_5}\left[V_{o1}+V_{o2}+V_{o3}\right] \qquad R_8 = R_5$$

$$= \left[-V_{i1} + \left(-\int V_{i2}\cdot dt\right) + \frac{d}{dt}(-V_{i3})\right]$$

$$\boxed{V_o = V_{i1} + \int V_{i2}\cdot dt + \frac{d}{dt} V_{i3}}$$

Problems.

① Find the output & closed loop gain of the op-amp circuit.



$V_{in} = 50mV$.

$$\underset{(100\Omega)}{I} = \frac{50}{100} = 0.5\ mA.$$

No current flows into the +ve terminal

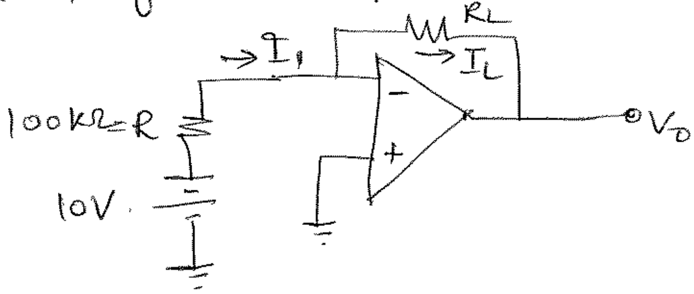
$$I\,(3.9k) = 0.5\ mA$$

$$V_o = V_A + 3.9 \times 0.5 \times 10^3 \times 10^{-3}$$

$$= 50m + 1950m = \underline{2000mV}.$$

$$A_F = \frac{V_o}{V_{in}} = \frac{2000}{50} = \underline{\underline{40}}.$$

(2) In the figure R_L is the transducer resistance which can vary from $1k\Omega$ to $10k\Omega$. Determine the range of variation of the output voltage.



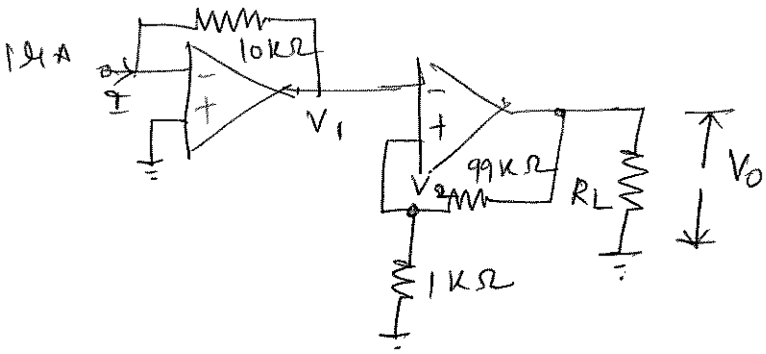
$$I_1 = I_L$$

$$\frac{10}{100} = -\frac{V_o}{R_L}$$

$$V_o = \frac{-R_L}{10}$$

$R_L = 1k\Omega,\ V_o = -0.1V$
$R_L = 10k\Omega,\ V_o = -1V$ } range.

(3). Find the V_o op-amp circuit of figure below.



$$V_1 = -1\times10^{-6}\times10\times10^{3} = -0.01V.$$

because virtual ground concept

$$V_2 = V_1 = -0.01V.$$

Applying KCL at node (2)

$$\frac{V_2}{1k} + \frac{V_2 - V_0}{99k} \Rightarrow V_0 = (99+1)V_2$$

$$= 100 * -0.01$$

$$= -1.0V \quad \text{Independent of } R_L$$

An op-amp has a slew rate of 0.8 V/µs. What is the maximum amplitude of undistorted sine wave that the op-amp can produce at a frequency of 40 KHz? What is the maximum frequency of the sine wave that op-amp can reproduce if the amplitude is 3 V?

(a) $S = 2\pi f V_m$.

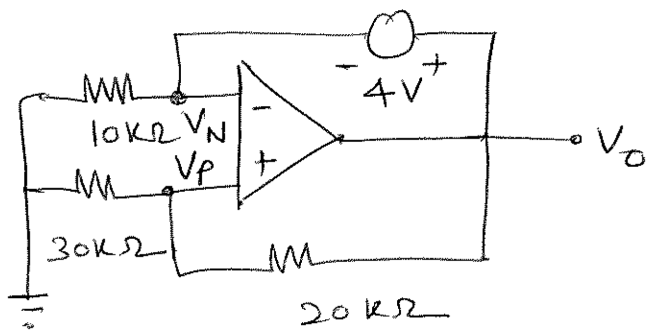
$0.8 \times 10^6 = 2\pi \times 40 \times 10^3 V_m$

$\boxed{V_m = 3.18 V}$

$0.8 \times 10^6 = 2\pi f \times 3$.

$\boxed{f = 42.44 KHz}$

For an op-amp circuit of figure below determine V_P, V_N, V_0 and also power supplied / absorbed by the 4V source.



$V_P = \frac{30}{30+20} \cdot V_0 = 0.6 V_0$.

$V_N = V_P = 0.6 V_0$.

$V_N + 4 = V_0 \Rightarrow 0.6 V_0 + 4 = V_0$

$\boxed{V_0 = 10 V}$

$V_P = 0.6 V_0 = 0.6 \times 10 = 6 V = V_N$

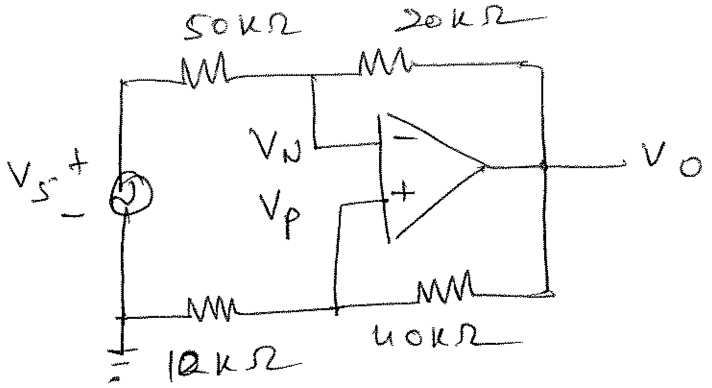
$i(10K) = \frac{6}{10} = 0.6 mA$

i(4 V source) = 0.6 mA entering at +ve terminal

power absorbed $= P = 4 \times 0.6$ mA

$\boxed{= 2.4 mW}$

For an op-amp circuit of figure find V_o if $V_s = 9V$. All resistance are in kΩ.



Sol^n :-

$$V_p = \frac{10}{10+40} \cdot V_o = 0.2 V_o$$

$$V_N = 0.2 V_o$$

By applying KCL at V_N node.

$$\frac{V_s - V_N}{50} = \frac{V_N - V_o}{20}$$

$$\frac{9 - 0.2 V_o}{50} = \frac{0.2 V_o - V_o}{20}$$

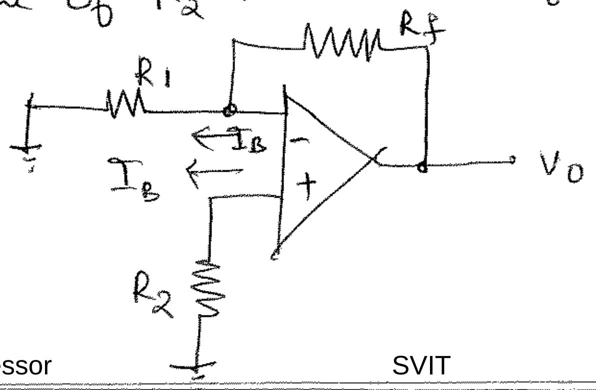
$$(9 - 0.2 V_o) 20 = (0.2 V_o - V_o) 50$$

$$180 - 4 V_o = 10 V_o - 50 V_o$$

$$180 = 10 V_o - 50 V_o + 4 V_o$$

$$180 = -36 V_o \Rightarrow V_o = -5 \text{ As}$$

Fig below shows the effect of bias current ($I_{B_1} = I_{B_2} = I_B$) on the output for an inverting op-amp circuit. what value of R_2 will make $V_o = 0$?



$$V_+ = R_2 I_B$$

at the −ve terminal

$$I_B = \frac{V_+}{R_1} + \frac{V_+ - V_0}{R_f}$$

$$V_0 = 0$$

$$\boxed{R_2 = R_1 \parallel R_F}$$

The two input voltages of an op-amp are 2V & 3V. The Common output Voltage is 2mV. The difference mode o/p voltage is 9V. Find CMRR.

$V_1 = 2V \quad V_2 = 3V \qquad A_C = A_D = ?$

$V_{C\cdot MO} = 2mV \qquad V_{dmo} = 9V$

$$A_C = \frac{V_{CM\cdot O}}{V_{CM\,in}} = \frac{2mV}{(2+3)/2} = 0.8 \times 10^{-3}$$

$$A_d = \frac{V_{dM\cdot O}}{V_{dM\cdot in}} = \frac{9V}{(3V - 2V)} = 9$$

$$CMRR = \frac{A_d}{A_C} = 9/0.8\times10^{-3} = 11250.$$

(7) An operational amplifier has two input voltage of 6V and 3V. The difference mode output voltage is 10V find the total output Voltage. Find the common mode voltage gain & total output voltage. Take CMRR = 10,000.

$V_{id} = V_1 - V_2 = 3V \qquad A_d = \frac{V_{od}}{V_{id}} = \frac{10}{3} = 3.33$

$V_{iCM} = \frac{V_1 + V_2}{2} = 4.5V$

$CMRR = \frac{A_d}{A_C}$

$A_C = \frac{3.33}{1000} = 3.33\times10^{-4}$

$V_0 = V_{ocm} + V_{od}$

$= (3.33 \times 10^{-4})4.5 + 3.33 \times 3$

$= 0.00149 + 9.99$

$= 9.[illegible] V$