Chapter-4

Operational Amplifiers

An operational amplifiers is a very high gain differential amplifier with high input impedance and low output impedance. Typical uses of an op-amp are to provide voltage amplitude change, oscillators, filter circuits and many types of instrumentation circuits. An op-amp contains a number of differential amplifier stages to achieve very high voltage gain.

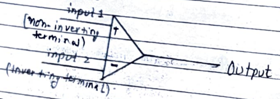
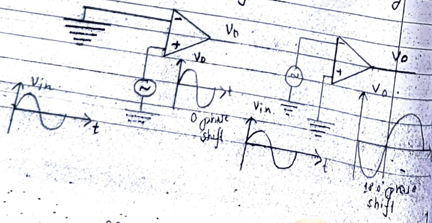
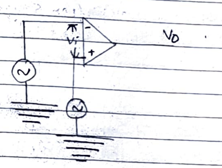


Figure shows a basic op-amp with two inputs and one output. Each input results in either the same or opposite output, depending upon whether the signal is applied to the non-inverting or inverting input respectively.



When the signal is connected to one input with the other input connected to ground (i.e single ended input) the output will be of same polarity (in phase with input) or opposite polarity (i.e cut-off phase) according to the input applied either to the non-inverting input or to the inverting input respectively.

When the input signal is applied to the each of the input, it is known as double-ended input.



Block diagram of an OP-AMP :-

→ multistage amplifier

An op-amp being a multistage amplifier, consists of some basic building blocks as shown in figure below :-

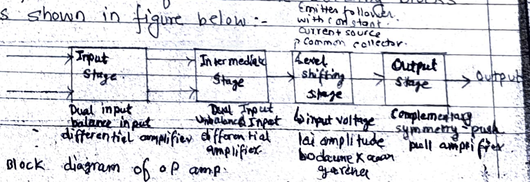


Fig : Block diagram of op amp.

Characteristics of an OP-amp:-

S.N	Parameters	Representation	Ideal OP-amp	Practical OP-amp
1	Open loop voltage gain	A	∞	High
2	Input impedance	R_i	∞	High
3	Output impedance	R_o	0	Low
4	Offset voltage	V_{oos} (output offset)	0	Low
5	Bandwidth	B.W	∞	High
6	Common mode rejection ratio	CMRR	∞	High
7	Slew rate	SR	∞	High

Similarly,

8. It is direct coupled amplifier.
9. It can amplify dc and ac both types of signals.
10. There is virtual short circuit between the two input terminals.

Basic OP-amp circuit:-

The basic OP-amp circuit is shown in figure. An input signal V_1 is applied through the resistor R_1 to the following inverting input terminal.

The output voltage is feedback through resistor R_f to the same input terminal. The non-inverting terminal is connected to the ground since, input voltage is applied to the inverting terminal of an OP-amp-output voltage is opposite in phase to the input signal.

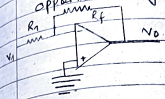


Fig: Basic OP-amp circuit

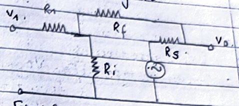
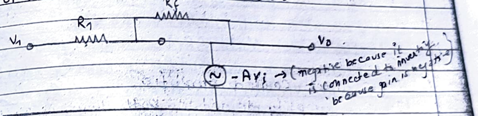
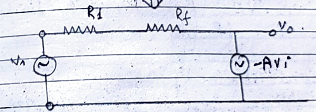


Fig: Equivalent circuit.

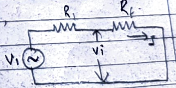
For ideal cases, $R_i = \infty$ and $R_o = 0$.





For V_i, using superposition theorem,

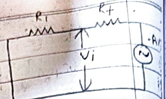
considering source V_1 only,



Here,

$$I = \frac{V_1}{R_1 + R_f}$$

$\therefore V_{i1} = IR_f = \frac{V_1}{R_1+R_f} R_f$ —(I)



Again, considering source → AV_i only,

$\therefore V_{i2} = -\frac{AV_i}{R_1+R_f} \times R_1$ —(II)

Base OP-AMP circuit :-

The total voltage,

$V_i = V_{i1} + V_{i2}$

or, $V_i = \frac{V_1 R_f}{R_1+R_f} - \frac{AV_i R_1}{R_1+R_f}$

or, $V_i + \frac{AR_1 V_i}{R_1+R_f} = \frac{V_1 R_f}{R_1+R_f}$

or, $V_i(R_1+R_f) + AR_1 V_i = V_1 R_f$

or, $V_i(R_1+R_f+AR_1) = V_1 R_f$

$\therefore V_i = \frac{R_f}{(R_1+R_f+AR_1)} \cdot V_1$ —(III)

If $A >> 1$ and $AR_1 >> R_f$, then,

$V_i = \frac{R_f}{AR_1} \times V_1$ —(IV).

we know, $A = \frac{-V_0}{V_i}$

or, $V_0 = -AV_i = -\cancel{A} \times \frac{R_f}{\cancel{A}R_1} \times V_1$

$\therefore \boxed{\frac{V_0}{V_1} = \frac{-R_f}{R_1}}$ —(V)

Offset voltages:

i) Output offset voltage :-

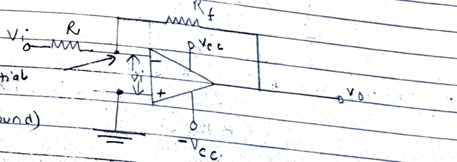
The output offset voltage is the dc voltage (positive or negative) present at the output terminal when two input terminals are grounded. Ideally, the offset voltage is zero, but practically there exists a small voltage even though both the inputs are grounded.

ii) Input offset voltage :-

The voltage which is to be applied between the input terminals to make output voltage equal to zero is known as input offset voltage.

IMP.

Virtual Ground:



zero potential (virtual ground)

$A = 10^5$

$V_{cc} = 15V$

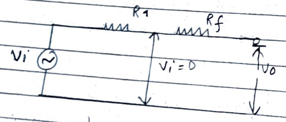
$A = \frac{V_{cc}}{V_i}$

$V_i = \frac{V_{cc}}{A} = \frac{15}{10^5} = 150\mu V$

Since, $A_v = \frac{V_o}{V_i}$, the value of V_i is very small, may be considered as 0V as compared to all other input and output. The fact $V_i \cong 0V$ leads to the concept that at the amplifier input there exist a virtual short circuit or virtual ground.

The concept of virtual short implies that although the voltage is nearly zero, there is no current through the amplifier input to ground.

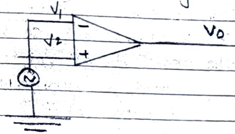
The figure below depicts the virtual ground concept. The heavy line is used to indicate that a short circuit exist with $V_i \approx 0$ but that is virtual short so no current flows through the short to ground.



The current goes only through resistor R1 and Rf as shown in figure.

Common Mode Rejection Ratio (CMRR) :-

When the same input signal are applied to the both input, common mode operation results. A significant features of a differential connection is that the signals that are ~~opera~~ opposite at inputs are highly amplified whereas those signals that are ~~known~~ common to the two inputs are only slightly amplified. An op-amp amplify the different signal while rejecting the common signal at the two input. This operating feature is referred to as common-mode rejection.



Common mode operation.

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

ie $CMRR = \frac{|A_d|}{|A_c|}$

In dB, $CMRR_{dB} = 20 \log \frac{|A_d|}{|A_c|}$

Ideally, $CMRR = \infty$. This means that the common signal like noise are perfectly rejected by the amplifier.

Here,

Common mode gain (Ac) $= \frac{V_o}{V_{CM}} = \frac{V_o}{\frac{V_1 + V_2}{2}}$

Differential mode gain (Ad) $= \frac{V_o}{V_1 - V_2}$.

Now, the total output of any differential amplifier can be expressed as:

$$V_o = A_d V_d + A_c V_{CM}$$

where,

$$V_d = V_1 - V_2.$$

$$V_{CM} = \frac{V_1 + V_2}{2}$$

For ideal case, $A_d = \infty$ and $A_c = 0$

max frequency also measured

Slew Rate:

Measurement of how fast output voltage change from small to large.
It is measured in (V/µs)

The slew rate of an op-amp is a measure of how fast the output voltage can change and is measured in volt per microsecond (V/µs).

If the slew rate of an OP-amp is 0.5 V/µs, it means that the amplifier can change the output from the amplifier by 0.5V every microsecond.

Slew rate can be expressed as

$$SR = \left.\frac{dV_{out}}{dt}\right|_{max}.$$

Since, frequency is a function of time, the slew

rate can be used to determine the maximum operating frequency of an OP-amp as:

$$f_{max} = \frac{\text{Slew rate}}{2\pi \times V_p}$$

where, V_p = peak output voltage

Note

Now,

$V_o = V_p \sin wt$ using calculus in this eqn.

Maxm rate of change,

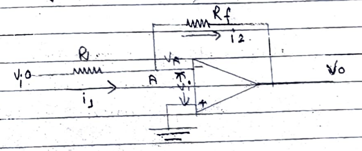
$$roc(max) = V_p w$$

$$V_p w \le SR$$

$$\text{or, } 2\pi f V_p \le SR$$

$$f = \frac{SR}{2\pi \times V_p}$$

Inverting Amplifier:



An input signal is applied through resistor R_1 to the inverting input. The o/p is feedback to the same inverting input through feedback resistor R_f. The non-inverting input is grounded. Since, the input signal is applied to the inverting input, the O/P will be inverted as compared to the input. Hence, the name inverting amplifier

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

$$\therefore i_1 = \frac{V_i}{R_i} \quad [\because V_A = 0]$$

$$i_2 = \frac{V_A - V_0}{R_f}$$

$$\therefore i_2 = \frac{-V_0}{R_f}$$

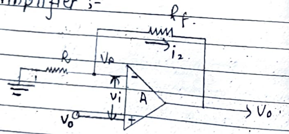
Applying KCL at node A,

$$i_1 = i_2$$

$$\text{or, } \frac{V_i}{R_i} = \frac{-V_0}{R_f}$$

$$\text{or, } \frac{V_0}{V_i} = -\frac{R_f}{R_i} \qquad \therefore A_v = -\frac{R_f}{R_i}$$

Non-inverting Amplifier :-



When an o/P signal has to produce the same polarity as the input signal, OP-amp is connected as non-inverting amplifier as shown in figure.

$$i_1 = \frac{V_A}{R_i}$$

$$i_2 = \frac{V_A - V_0}{R_f}$$

We have,

$$V_i = V_1 - V_A$$

From virtual ground, $V_i = 0$

$$\therefore \boxed{V_1 = V_A}$$

Then, $i_1 = \frac{V_1}{R_i}$, $i_2 = \frac{V_1 - V_0}{R_f}$.

Applying KCL at node A,

$$i_1 + i_2 = 0.$$

$$\text{or, } \frac{V_1}{R_i} + \frac{V_1 - V_0}{R_f} = 0$$

$$\text{or, } V_1\left[\frac{1}{R_i} + \frac{1}{R_f}\right] = \frac{V_0}{R_f}$$

$$\text{or, } V_1\left[\frac{R_f + R_i}{R_i \cancel{R_f}}\right] = \frac{V_0}{\cancel{R_f}}$$

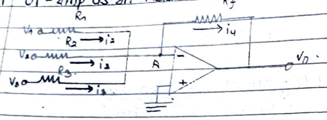
$$\text{or, } \frac{V_0}{V_1} = \frac{R_i + R_f}{R_i}$$

$$\text{or, } \frac{V_0}{V_1} = 1 + \frac{R_f}{R_i}.$$

$$\boxed{\therefore A_v = 1 + \frac{R_f}{R_i}}$$

Application of operational Amplifier :

1. OP-amp as an Adder :-



Here,

$$i_1 = \frac{V_1 - V_A}{R_1},\ i_2 = \frac{V_2 - V_A}{R_2},\ i_3 = \frac{V_3 - V_A}{R_3},\ i_4 = \frac{V_A - V_0}{R_f}$$

Now, Applying KCL at node A,

$$i_1 + i_2 + i_3 = i_4$$

or, $$\frac{V_1 - V_A}{R_1} + \frac{V_2 - V_A}{R_2} + \frac{V_3 - V_A}{R_3} = \frac{V_A - V_0}{R_f}.$$

Since, $V_A = 0$, due to virtual ground,

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

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

If $R_1 = R_2 = R_3 = R$,

$$\therefore V_0 = \frac{-R_f}{R}\left[V_1 + V_2 + V_3\right] \quad \text{—(I)}$$

Hence, O/P voltage is proportional to algebraic sum of three input voltages multiplied by a constant gain factor.

2. OP-amp as a substractor :-

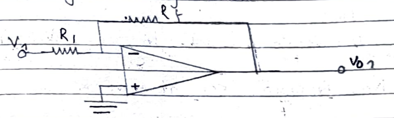
It provides as output proportional to or equal to the difference of two input signals. According to superposition theorem

$$V_0 = V_{01} + V_{02} \quad \text{—(I)}.$$

where,

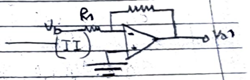
V_{01} = O/P produced by V_1 alone.

V_{02} = O/P produced by V_2 alone.



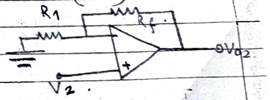
Now, considering V_1 alone,

$$V_{01} = -\frac{R_f}{R_1} V_1 \quad \text{—(II)}$$



Considering V_2 alone,

$$V_{02} = \left(1 + \frac{R_f}{R_1}\right) V_2 \quad \text{—(III)}$$



Now, From Eqn (I),

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

$$= -\frac{R_f}{R_1} V_1 + \frac{R_f}{R_f} V_2 \quad \left[\because \frac{R_f}{R_1} >> 1, \text{So, } 1 + \frac{R_f}{R_1} \simeq \frac{R_f}{R_1}\right]$$

~~Logic Circuits~~

~~Tutorial - 3~~

~~Boolean Algebra & Logic Gates~~

~~1) Realize all the basic gates using NAND and NOR gate.~~

$$\boxed{\therefore V_0 = \frac{R_f}{R_1}(V_2 - V_1)} \quad \text{— (IV)}$$

3 OP-amp as a differentiator :-

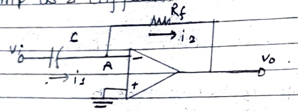


Fig : OP-amp as a differentiator

It's function is to provide O/P which is proportional to the rates of change of input voltage.

$$i_1 = C\frac{d(V_i)}{dt} \qquad \text{or, } C\frac{dV_i}{dt} = -\frac{V_0}{R_f} \quad [\because V_A = 0]$$

$$i_2 = \frac{V_A - V_0}{R_f} \qquad \boxed{\therefore V_0 = -R_f C\frac{dV_i}{dt}}$$

Applying KCL at node A,

$$i_1 = i_2$$

$$\frac{Cd(V_i)}{dt} = \frac{V_A - V_0}{R_f}$$

4) OP-amp as an integrator :-

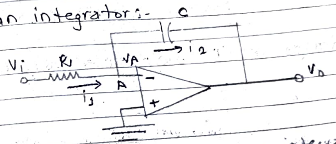


Fig: OP-amp as an integrator.

It provides an output voltage proportional to the integral of input voltage.

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

$$i_2 = C\frac{dV_c}{dt} = -C\frac{dV_0}{dt} \quad [\because V_c = -V_0]$$

Applying KCL at node A,

$$i_1 = i_2$$

$$\text{or, } \frac{V_i - V_A}{R_1} = -C\frac{dV_0}{dt}$$

$$\text{or, } \frac{V_i}{R_1} = -C\frac{dV_0}{dt} \quad [\because V_A = 0]$$

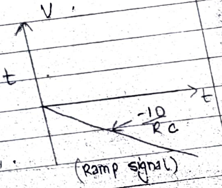
$$\text{or, } dV_0 = -\frac{1}{RC} V_i dt$$

Integrating both sides,

$$\therefore V_0 = -\frac{1}{RC}\int_0^t V_i dt$$

Let $V_i = 10$ V dc.

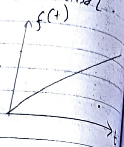
$$\therefore V_0 = -\frac{1}{RC}\int_0^t 10 dt$$



$$= \frac{-10}{RC} t$$

Thus, ~~volta~~ if dc voltage is applied to an integrator it will give a ramp voltage at the output terminal.

Ramp function, $f(t) = 0$ if $t < 0$
$= mt$ if $t > 0$



VVI for 5 marks.

Instrumentation Amplifier:

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Instrumentation Amplifier:

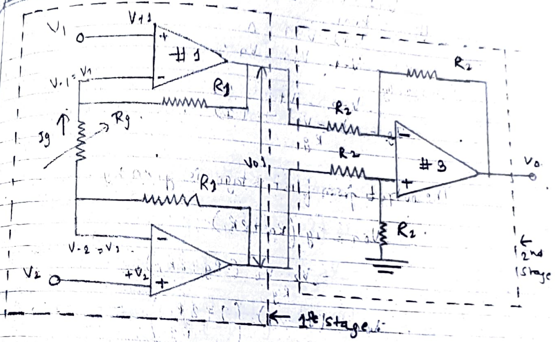

Fig: Instrumentation Amplifier.

It consist of two stage, 1st stage consists of two OP-amp. The two inputs V_1 and V_2 are applied to the non-inverting terminal of OP-amp 1 and 2 respectively and the output from 1st stage is taken through string of resistor (R_1, R_g, R_1). The two resistor R_1 and R_1 are connected internal to the IC whereas R_g is connected externally. By changing the value of R_{g}, the gain of I.A can be changed. So, R_g is known as gain setting resistor. Second stage is a unity gain differential amplifier.

$$V_{+1} = V_1$$

As we know,

$$V_{+1} - V_{-1} = 0$$

$$V_{-1} = V_{+1} = V_1$$

Similarly

$$V_{-2} = V_{+2} = V_2$$

$$I_g = \frac{V_2 - V_1}{R_g} \quad \text{—(I)}$$

The output from first stage is given by:

$$V_{o1} = I_g (R_g + 2R_1)$$

$$= \frac{V_2 - V_1}{R_g} (R_g + 2R_1)$$

$$\therefore V_{o1} = (V_2 - V_1)\left(1 + \frac{2R_1}{R_g}\right) \quad \text{— II}$$

As a second stage is a unity gain differential amplifier, hence, the output is given by:

$$V_o = -V_{o1}$$

or, $V_o = -(V_2 - V_1)\left(1 + \frac{2R_1}{R_g}\right)$

Or, $\frac{V_o}{V_2 - V_1} = -\left(1 + \frac{2R_1}{R_g}\right)$

$$\therefore A_v = \frac{V_o}{V_2 - V_1} = -\left(1 + \frac{2R_1}{R_g}\right) \quad \text{—(III)}$$

Thus by changing the value of R_g, the

gain can be changed ie for higher value of R_g, the gain will be low and vice-versa.

Application of Instrumentation Amplifier:-

The IA along with the transducer bridge can be used in many applications such as:-

i) Data acquistion system.
ii) Temperature controller
iii) Temperature Indicator.
iv) Light Intensity System.

i) Data acquistion system:-

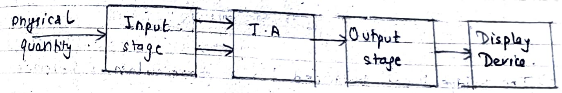

Fig:- Block diagram of Data acquistion System

The transducer bridge converts physical quantity to an electrical signal. The signal is then passed to the IA.

The O/P stage consists of a display device or some other conditioning circuit.

$V_{+1} = V_1$

As we know,

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$$\text{or, } V_o = -(V_2 - V_1)\left(1 + \frac{2R_1}{R_g}\right)$$

$$\text{Or, } \frac{V_o}{V_2 - V_1} = -\left(1 + \frac{2R_1}{R_g}\right)$$

$$\therefore A_v = \frac{V_o}{V_2 - V_1} = -\left(1 + \frac{2R_1}{R_g}\right) \quad \text{—(III)}$$

Thus by changing the value of R_g, the

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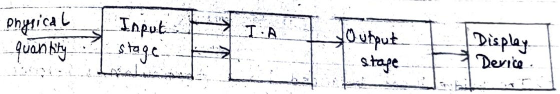

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The transducer bridge converts physical quantity to an electrical signal. The signal is then passed to the IA.

→ The O/P stage consists of a display device or some other conditioning circuit.

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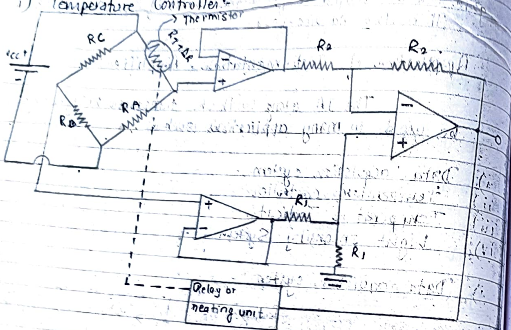
i) Temperature Controller:-



→ The bridge is set balanced for a particular reference temperature

→ For any change in temperature, the T.A produce the output voltage.

→ This voltage can be used to drive the relay which in turn controls the ON-OFF of the heating unit to control the temperature.

iii) Temperature Indicator:-

Above figure can be used as a temperature indicator

→ The bridge is kept balanced at some reference temp when $V_0 = 0V$.

→ As the temperature changes, the amplifier output also changes.

→ The meter connected at output can be calibrated to indicate the desired temperature range by selecting the appropriate gain of the amplifier.

(iv) Light intensity meter:-

→ The circuit shown in figure above can be used as a light intensity meter if the thermister is replaced by a photocell.

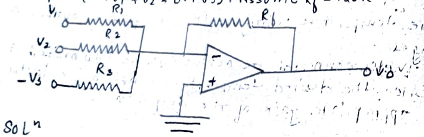
→ The bridge is set balanced for dark condition

→ When light falls on the photocell, it's resistance changes and produces the output.

→ The meter connected at the output can be calibrated in terms of LUX to measure the light intensity.

Numerical :

Design an OP-amp adder circuit that will produce an output $(-4V_1 + V_2 - 0.1V_3)$. Assume $R_f = 100K$



Sol^n

The O/P voltage of adder circuit is given by :-

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

Given,

$$V_0 = -(4V_1 + V_2 - 0.1V_3) \text{ --- (II)}$$

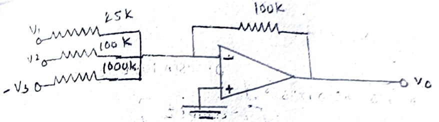
Comparing eq^n (I) and (II), we get

$\frac{R_f}{R_1} = 4$, $\frac{R_f}{R_2} = 1$, $\frac{R_f}{R_3} = 0.1$ [∵ since resistor cannot be -ve, V_3 is made -ve]

$\therefore R_1 = \frac{100}{4} = 25k$

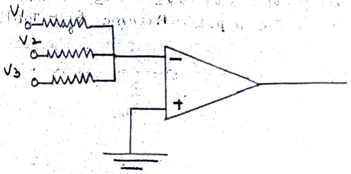
$R_2 = 100k$.

$R_3 = 100/0.1 = 1000K$.

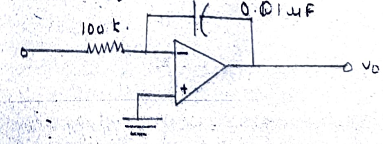


* Design an OP-amp circuit that will produce an output voltage equal to $-V_1 + 2V_2 - 3V_3 + V_4)$, where V_1, V_2, V_3 & V_4 are input. Assume $R_f = 100k$.

$$V_0 = -V_1 + 2V_2 - 3V_3 + V_4.$$
$$= -(V_1 - 2V_2 + 3V_3 - V_4)$$



* Find the peak value of the output of an ideal integrator where $R_1 = 100k$, $R_f = 100k$, $C = 0.01\ \mu F$ and $V_{in} = 0.5 \sin 100t$



$$v_0 = \frac{-1}{RC}\int v_{in}(t)\,dt$$

$$= \frac{-1}{100\times10^{-3}\times0.01\times10^{-6}}\int 0.5\sin 100t\,dt$$

$$= \frac{-0.5}{10^{5}\times0.01\times10^{-6}}\left[\frac{-\cos 100t}{100}\right]$$

$$= 5\cos 100t$$

$\therefore$ Peak value $= 5V$

7) Design an OP-amp circuit that will produce an output voltage equal to $V_0 = 2V_1 + 6V_2 + 4V_3 - 12V_4$, where V_1, V_2, V_3 & V_4 are input. Assume $R_f = 100K$.