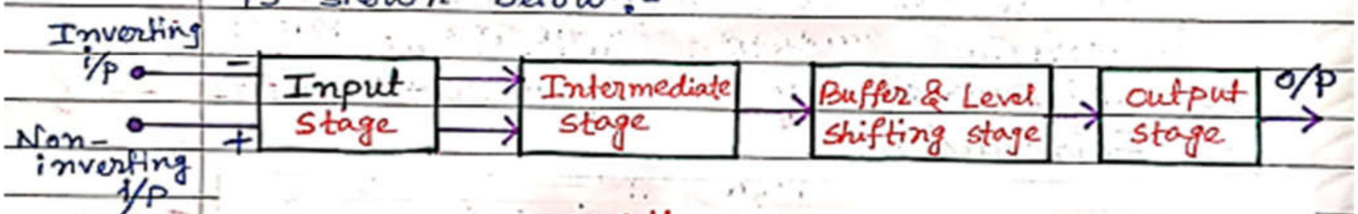
CMR Institute of Technology, Bengaluru
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

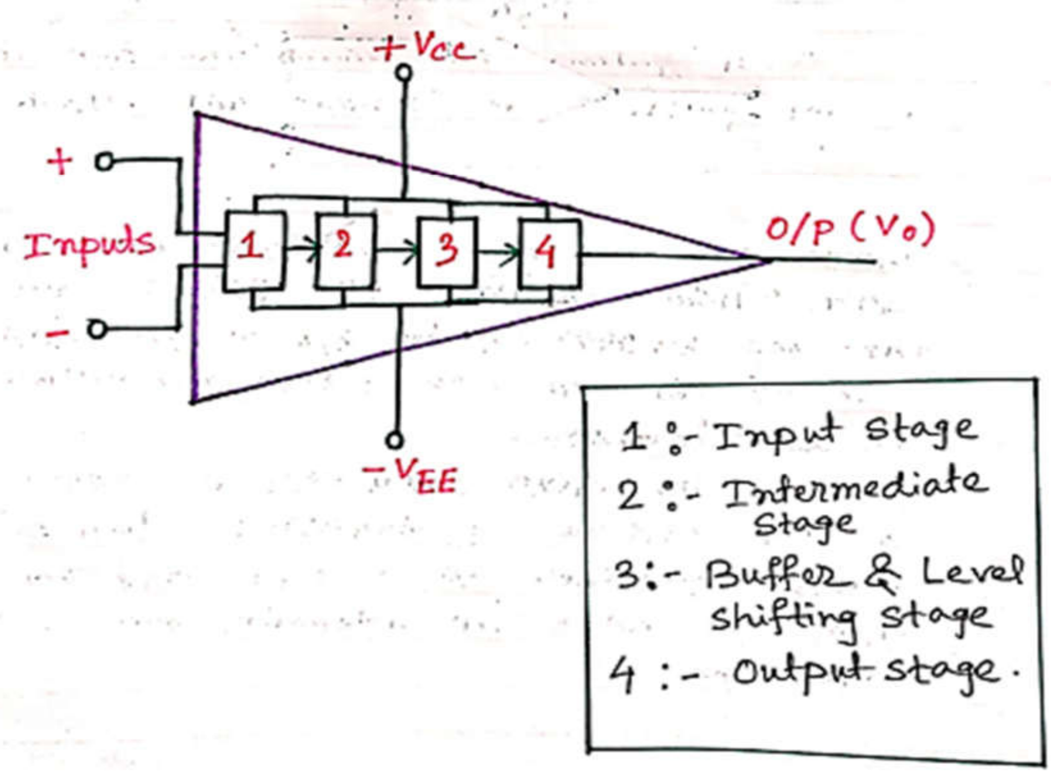
Solutons of Internal Assesment Test – I
Subject: OPERATIONAL AMPLIFIERS AND LINEAR ICS (18EE46)
Semester: 4A

1. (a) Draw the block diagram of Op-amp and explain each stage

Solution:

⇒ The op-amps are available in an integrated circuit form. Commercial integrated circuit op-amps usually consists of four cascaded blocks. The block diagram representation of op-amp is shown below:-





1) Input Stage:-

→ The input stage is a dual i/p balanced o/p (two o/ps) differential amplifier.

→ It provides most of the voltage gain of the amplifier and establishes the high i/p impedance.

→ This stage also rejects the noise by eliminating the common mode signal.

2) Intermediate stage:-

→ The o/p of the input stage is directly fed to the intermediate stage. This is another differential amplifier with dual i/p and unbalanced o/p (i.e single ended o/p).

→ The input stage alone cannot provide such a high gain. The main function of this stage is to provide an additional voltage gain.

3) Buffer and Level shifting stage:-

Since the i/p stage amplifier and the intermediate stage amplifier are directly coupled, so the dc voltage at the o/p of the intermediate stage tends to rise above the ground, which is not desirable.

To bring down this dc voltage to zero, a level shifter is employed. This is usually an emitter follower which also acts as a buffer with very large i/p resistance and low o/p resistance.

4) Output stage:-

The o/p stage consists of complementary push-pull amplifier, which helps to increase the o/p voltage swing and the current supplying capacity of the op-amp.

[push-pull amplifiers use two complementary & matching transistors, one being NPN and another PNP type with common input signal together i.e equal in magnitude but opposite in sign].

1. (b) Define the following terms: CMRR, PSRR

Solution:

i) CMRR :- The ability of a differential amplifier to reject a common mode signal is expressed by a factor called common mode rejection ratio (CMRR). It is expressed as the ratio of differential gain (A_d) to the common mode gain (A_c)

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

Many times, CMRR is expressed in decibel (dB).

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

Ideally, the common mode voltage gain (A_c) is zero, hence the ideal value of CMRR is infinite.

But, for a practical differential amplifier, A_d is large and A_c is small, hence the value of CMRR is also very high. For IC 741 the value of CMRR is 90 dB.

NOTE :- A good op-amp should always have a very high CMRR value. So that it can cancel the common mode signal.

ii) POWER SUPPLY REJECTION RATIO (PSRR) :-

PSRR is defined as the ratio of the change in input offset voltage to the change in supply voltage, keeping other power supply voltage constant.

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

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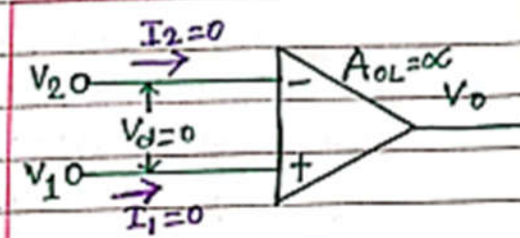
The PSRR value for IC 741 is 30 µV/V.

PSRR is also called as supply voltage Rejection Ratio (SVRR).

2. (a) Explain the ideal characteristics of op-amp

Solution:

⇒ An ideal op-amp would exhibit the following characteristics:-



1. Infinite open loop voltage gain ($A_{OL}=\infty$)
2. Infinite input resistance so that almost any signal source can drive it and there is no loading effect.
3. Zero output resistance so that the o/p can drive an infinite number of other devices.
4. Zero input offset voltage ($V_{ios}=0$)
5. Zero input bias current ($I_B=0$)
6. Zero input offset current ($I_{ios}=0$)
7. Infinite common-mode rejection ratio (CMRR) so that the o/p common-mode noise voltage is zero.
8. Infinite slew rate so that the o/p voltage changes occur simultaneously with i/p voltage changes.
9. Power supply rejection ratio (PSRR) is zero.
10. Infinite Bandwidth so that any frequency signal from 0 to ∞ Hz can be amplified without attenuation.
11. No effect of temperature.

2. (b) Deduce the expression for a closed loop voltage gain of non-inverting amplifier

Solution:

An amplifier which amplifies the input without producing any phase shift between input and output is called non-inverting amplifier. The basic circuit diagram of a non-inverting amplifier using op-amp is shown in the Fig. 1.16.1. The input is applied to the non-inverting input terminal of the op-amp.

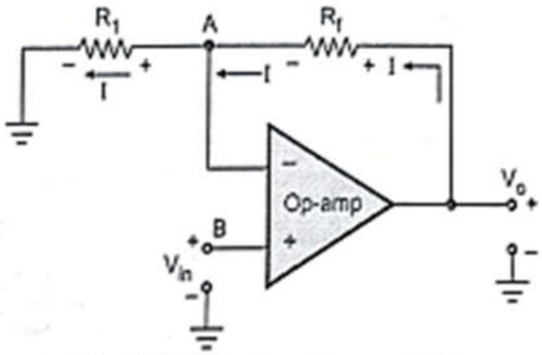


Fig. 1.16.1 Non-inverting amplifier

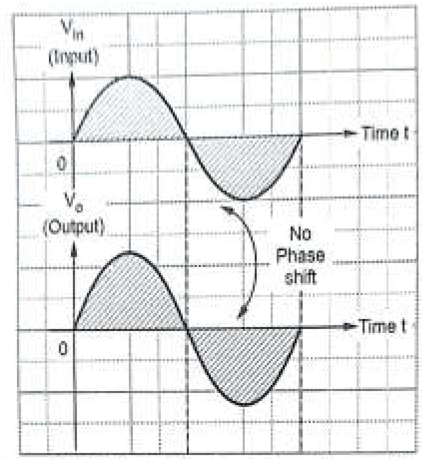


Fig. 1.16.2 Waveforms of non-inverting amplifier

Derivation of closed loop gain :

The node B is at potential V_{in}, hence the potential of point A is same as B which is V_{in}, from the concept of virtual share.

$$\therefore \quad V_A = V_B = V_{in} \qquad \text{... (1.16.1)}$$

From the output side we can write,

$$I = \frac{V_o - V_A}{R_f}$$

$$\therefore \quad I = \frac{V_o - V_{in}}{R_f} \qquad \text{... (1.16.2)}$$

At the inverting terminal,

$$I = \frac{V_A - 0}{R_1} \quad \text{i.e.} \quad I = \frac{V_{in}}{R_1} \qquad \text{... (1.16.3)}$$

Entire current passes through R_1 as input current of op-amp is zero.

Equating equations (1.16.2) and (1.16.3),

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

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

$$\therefore \quad \frac{V_o}{R_f} = V_{in}\left[\frac{(R_1 + R_f)}{R_1 R_f}\right]$$

$$\therefore \quad \frac{V_o}{V_{in}} = \frac{(R_1 + R_f) R_f}{R_1 R_f} = \frac{R_1 + R_f}{R_1}$$

$$\therefore \quad \boxed{A_{VF} = \frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}} \qquad \text{... (1.16.4)}$$

3. (a) Show that the output of a subtractor is equal to the difference between the two input voltages

Solution:

Similar to the summer circuit, the subtraction of two input voltages is possible with the help of op-amp circuit, called subtractor or difference amplifier circuit.

The circuit diagram is shown in the Fig. 1.19.1.

To find the relation between the inputs and output let us use **Superposition principle.**

Let V_{o1} be the output, with input V_1 acting, assuming V_2 to be zero. And V_{o2} be the output, with input V_2 acting, assuming V_1 to be zero.

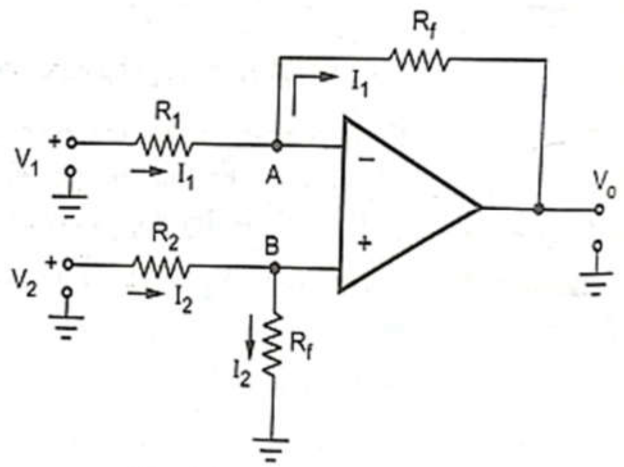


Fig. 1.19.1 Subtractor circuit

Case 1 : With V_2 zero, the circuit acts as an inverting amplifier. Hence we can write, $V_{o1} = -\frac{R_f}{R_1} V_1$ ... (1.19.1)

Case 2 : While with V_1 as zero, the circuit reduces to as shown in the Fig. 1.19.2.

Let potential of node B is V_B. The potential of node A is same as B i.e. $V_A = V_B$.

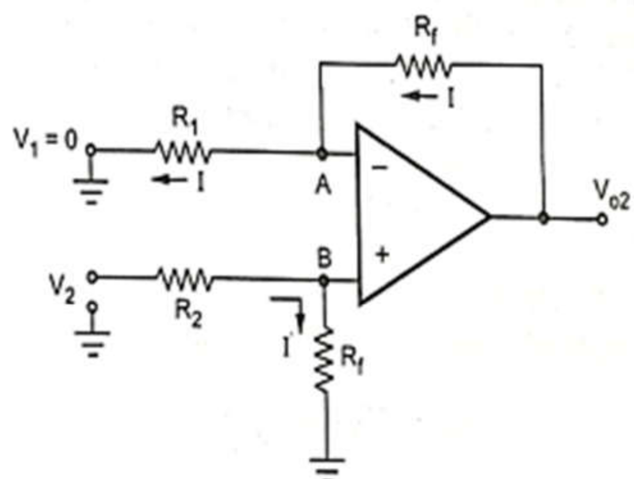


Fig. 1.19.2

Applying voltage divider rule to the input V_2 loop,

$$V_B = \frac{R_f}{R_2 + R_f} V_2 \qquad \text{... (1.19.2)}$$

Now
$$I = \frac{V_A}{R_1} = \frac{V_B}{R_1} \qquad \text{... (1.19.3)}$$

And
$$I = \frac{V_{o2} - V_A}{R_f} = \frac{V_{o2} - V_B}{R_f} \qquad \text{... (1.19.4)}$$

Equating the equations (1.19.3) and (1.19.4),

$$\frac{V_B}{R_1} = \frac{V_{o2} - V_B}{R_f} \quad \text{i.e.} \quad V_{o2} = \frac{R_1 + R_f}{R_1} V_B$$

$$\therefore \quad V_{o2} = \left[1 + \frac{R_f}{R_1}\right] V_B \quad \text{... (1.19.5)}$$

Substituting V_B from equation (1.19.2) in equation (1.19.5) we get,

$$\boxed{V_{o2} = \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_f}{R_2 + R_f}\right] V_2} \quad \text{...(1.19.6)}$$

Hence using Superposition principle,

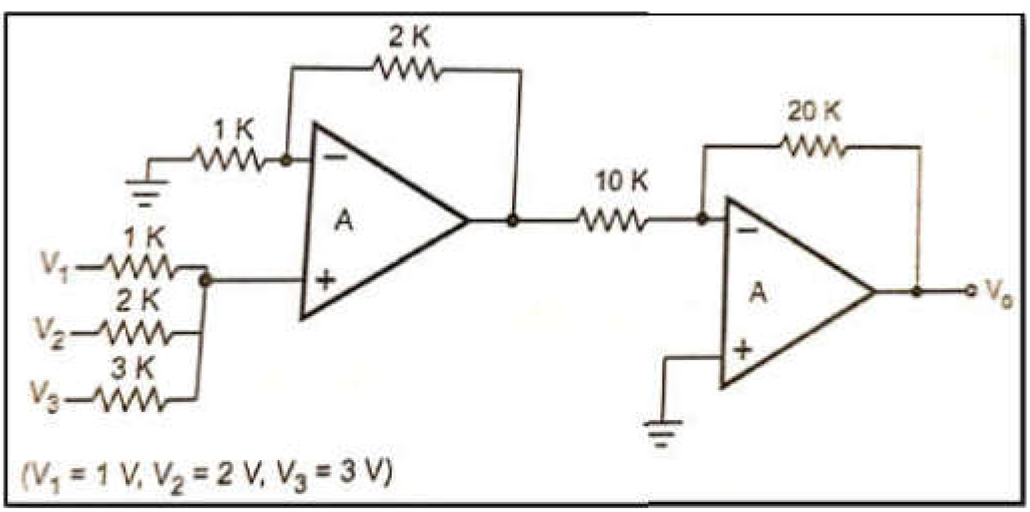
$$V_o = V_{o1} + V_{o2} = -\frac{R_f}{R_1} V_1 + \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_f}{R_2 + R_f}\right] V_2 \quad \text{... (1.19.7)}$$

Now if the resistances are selected as $R_1 = R_2$,

$$V_o = -\frac{R_f}{R_1} V_1 + \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_f}{R_1 + R_f}\right] V_2 = -\frac{R_f}{R_1} V_1 + \frac{R_f}{R_1} V_2$$

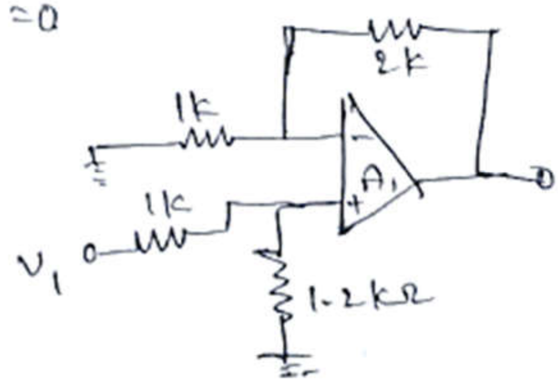
$$\therefore \quad \boxed{V_o = +\frac{R_f}{R_1}(V_2 - V_1)} \quad \text{...(1.19.8)}$$

3. (b) Find the output voltage for the following circuit:



Solution:

Case 1 :- V_1 = present , $V_2 = V_3 = 0$



$$R_{eq} = \frac{2\times3}{2+3} = 1.2$$

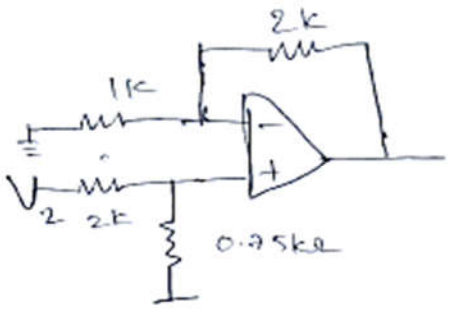
$$V_{B_1} = V_1 \cdot \frac{1.2}{1+1.2}$$

$$V_{B_1} = 0.5454\ V_1$$

$V_1 = 1V$,

$$\boxed{V_{B_1} = 0.5454\ V}$$

Case 2 :- V_2 = present , $V_1 = V_3 = 0$.



$$V_{B_2} = V_2 \cdot \frac{0.75}{2+0.75}$$

$\boxed{V_2 = 2V}$

$$V_{B_2} = 2 \cdot \frac{0.75}{2.75}$$

$$\boxed{V_{B_2} = 0.5454\ V}$$

Case 3 :- V_3 present , $V_1 = V_2 = 0$

$$R_{equ} : \frac{1\times2}{1+2} = 0.666$$

$$V_{B_3} = V_3 \cdot \frac{0.66}{3+0.66}$$

$V_3 = 3V$.

$$V_{B_3} = 3 \cdot \frac{0.66}{3.66}$$

$$\boxed{V_{B_3} = 0.5459\ V}$$

totally $v_B = v_{B1} + v_{B2} + v_{B3}$

$= 0.5454 + 0.5459 + 0.5459$

$v_B = 1.6367\ V.$

Non inverting amplifier :-

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

$$V_o' = V_B\left(1 + \frac{R_f}{R}\right) = 1.6367\left(1 + \frac{2}{1}\right)$$

$$\boxed{V_o = 4.9101\ V}$$

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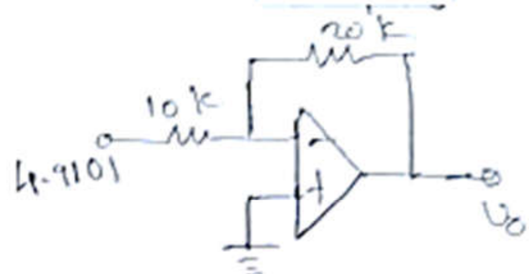
at second op-amp

$V_o = 4.9101\ V$ is input

$V_{in} = 4.9101\ V.$



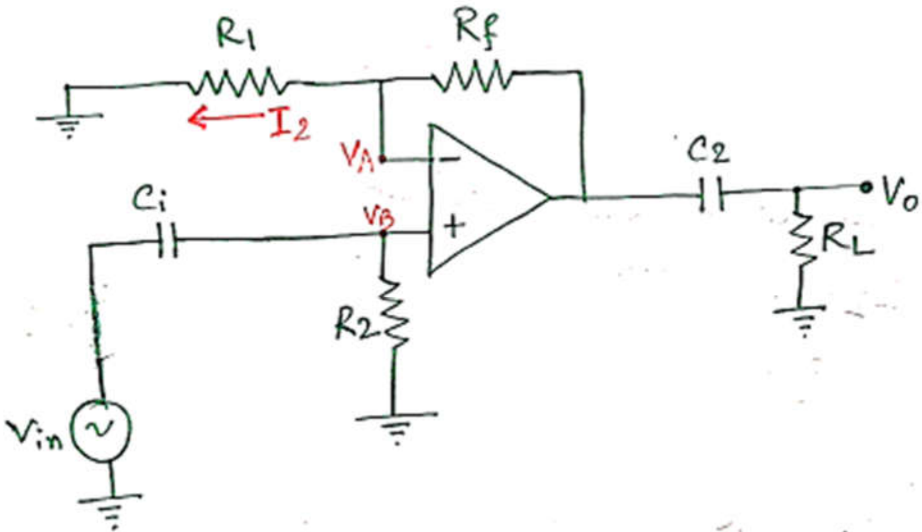
$$\frac{V_o}{V_{in}} = \frac{-R_f}{R}$$

$$V_o = -4.91010 \times \frac{20}{10}$$

$$\boxed{V_o = -9.82\ V}$$

4. Design a capacitor coupled AC non-inverting amplifier for the frequency of 120 Hz, voltage gain of 5, and input voltage of 1V using 741 op-amp.

Solution:



In IC741 op-amp, $I_{B\,max} = 500\,nA$.

$$R_{2\,max} = \frac{0.1 \times V_{BE}}{I_{B\,max}} = \frac{0.1 \times 0.7}{500\,nA} \quad [\because V_{BE} = 0.7]$$

$$\therefore R_{2\,max} = \frac{0.1 \times 0.7}{500 \times 10^{-9}}$$

$\boxed{R_2 = 140\,K\Omega}$ → This is the max^m value of R_2. You can consider any value which is less than $140\,K\Omega$.

$V_B = V_{in}$

$\because V_A = V_B$

$\therefore V_A = V_{in}$

At the inverting terminal, we can write,

$$I_2 = \frac{V_A - 0}{R_1}$$

$$\text{or, } I_2 = \frac{V_A}{R_1}$$

$$\text{or, } I_2 = \frac{V_{in}}{R_1}$$

Also, we know, ~~Gain = $\frac{V_o}{}$~~

$$I_2 = 100 \times I_{Bmax}$$
$$= 100 \times 500\, nA$$
$$= 50\, \mu A$$

$$\therefore I_2 = \frac{V_{in}}{R_1}$$

or, $$R_1 = \frac{V_{in}}{I_2}$$

$$= \frac{1}{50 \times 10^{-6}}$$

$$\boxed{\therefore R_1 = 20\, K\Omega}$$

We know that, Gain $= \frac{V_o}{V_{in}}$

For non-inverting, $\frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}$

As per Question, Gain $= 5$

$$\therefore 5 = 1 + \frac{R_f}{R_1}$$

$$\therefore R_f = 4 R_1$$

$$\therefore R_f = 4 \times 20\, K\Omega$$

$$\boxed{R_f = 80\, K\Omega}$$

Also, we know,

$$X_{Ci} = \frac{R_2}{10}$$

or, $$\frac{1}{2\pi f C_i} = \frac{R_2}{10}$$

or, $$\frac{1}{2\pi f C_i} = \frac{140\, K\Omega}{10}$$

or, $$C_i = \frac{1}{2\pi \times 120 \times 14 \times 10^3}$$

or, $$\boxed{C_i = 0.09\, \mu F}$$

$$X_{C_2} = R_L$$

or, $$\frac{1}{2\pi f C_2} = 2.2 \times 10^3$$

or, $$C_2 = \frac{1}{2\pi \times 120 \times 2.2 \times 10^3}$$

or, $$\boxed{C_2 = 0.6\, \mu F}$$

5. (a) In a AC inverting amplifier, The following parameters are given: Source Resistance (R_{in})= 50Ω, Coupling capacitor (C_i)=0.1 μF, Input Resistance (R_1)=100Ω, Feedback Resistance (R_f) = 1KΩ, Load Resistance (R_L)= 10KΩ, Supply voltage= 15V. Find the bandwidth of the amplifier. (UGB = 10^6, K=0.909 for 741 IC).

Solution : For an inverting amplifier, $R_{iF} \approx R_1 = 100\ \Omega$

$$R_{in} = R_s = 50\ \Omega,\ C_i = 0.1\ \mu F,\ R_f = 1\ k\Omega$$

$$\therefore \quad f_L = \frac{1}{2\pi C_i (R_s + R_{iF})} = \frac{1}{2\pi \times 0.1 \times 10^{-6} \times (50+100)} = 10.61\ kHz$$

$$A_F = -\frac{R_f}{R_1} = -\frac{1\times 10^3}{100} = -10$$

$$\therefore \quad f_H = \frac{UGB \times K}{A_F} = \frac{10^6 \times 0.909}{10} = 90.9\ kHz$$

$$\therefore \quad BW = f_H - f_L = 80.29\ kHz$$

5. (b) With neat diagram, explain the working of Peaking amplifier.

Solution:

The circuit which gives out the frequency response which exhibits a peak at a certain frequency is called as a **peaking amplifier.** Such a circuit is possible with the help of parallel LC network along with the op-amp. This parallel LC network must be connected in the feedback path as shown in the Fig. 1.27.1.

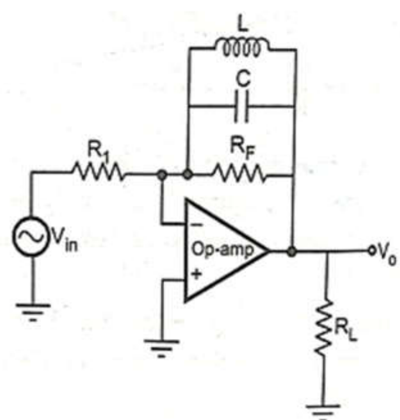


Fig. 1.27.1 Peaking amplifier

When the input frequency is changed, at a particular frequency, the parallel LC circuit shows the resonance. Hence the circuit output shows the peak in the frequency response. Such a frequency is called **resonant frequency** or **peak frequency** denoted by f_r. It is totally dependent on the values of L and C and is given by

$$\boxed{f_r = \frac{1}{2\pi\sqrt{LC}} \quad \text{if } Q_{coil} \geq 10} \quad \text{where } Q_{coil} = \text{Quality factor of coil} \qquad \text{... (1.27.1)}$$

$$\boxed{Q_{coil} = \frac{\omega L}{R}} \qquad \text{... (1.27.2)}$$

At resonance the impedance of the parallel LC circuit is very large hence the gain of the circuit is also at its maximum. This is the reason why amplifier shows peak at the output.

The gain of the amplifier at resonance is given by,

$$\boxed{A_F = -\frac{R_f \parallel R_p}{R_1}} \quad \text{... (1.27.3)}$$

where R_p = Equivalent parallel resistance of tank circuit

$$\boxed{R_P = Q_{coil}^2 \, R} \quad \text{where } R = \text{Internal resistance of the coil} \quad \text{... (1.27.4)}$$

Below and above the resonating frequency the gain of the amplifier is less than the $(R_f \parallel R_p)/R_1$ as the impedance of the parallel LC circuit is less than R_p.

The frequency response of the peaking amplifier is shown in the Fig. 1.27.2.

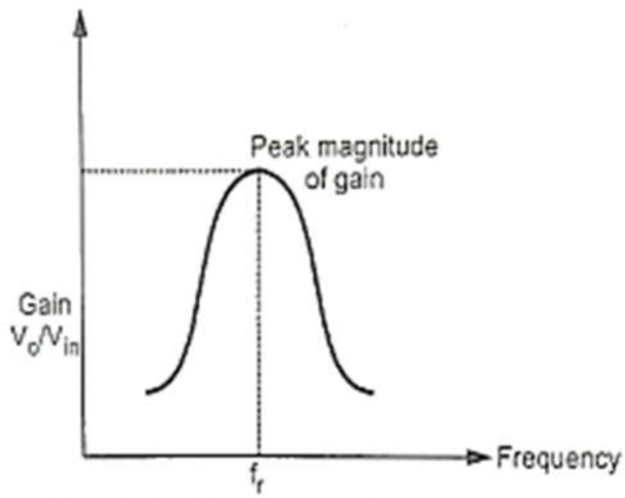


Fig. 1.27.2 Frequency response of peaking amplifier

The bandwidth of the peaking amplifier is given by,

$$\boxed{BW = \frac{f_r}{Q_L}} \quad \text{... (1.27.5)}$$

where f_r = Resonating frequency

Q_L = Loaded quality factor of parallel resonating circuit

$$\boxed{Q_L = (R_f \parallel R_p) / X_L} \quad \text{... (1.27.6)}$$

6. What is Instrumentation amplifier? Find the expression for the output of three op-amp Instrumentation amplifier.

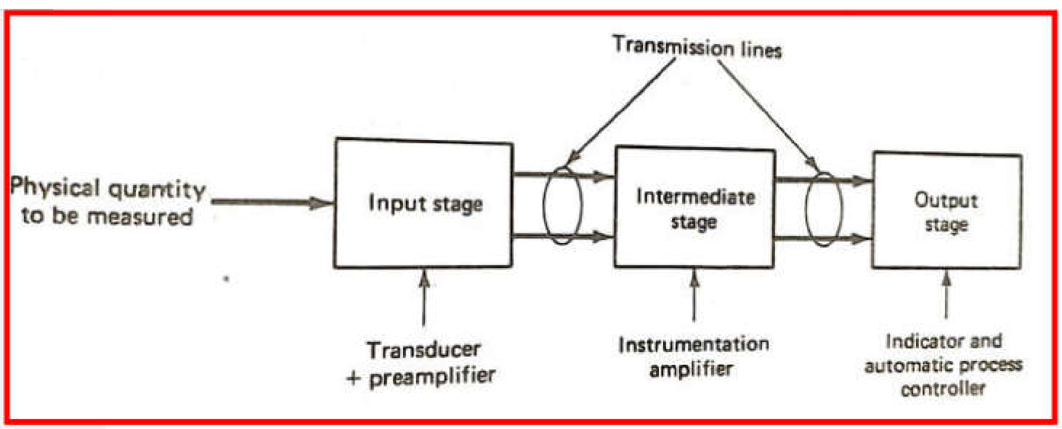
Solution:

- It is a high gain differential amplifier with high CMRR value and also allows to adjust the gain of the amplifier circuit without having to change more than one resistor value.

- This is mainly used in industries where the accurate measurement and control of physical parameters (like temperature, humidity, pressure etc.) are very important.

- For example: 1. Maintaining a constant temperature and humidity inside a dairy or meat plant is very important. 2. Precise temperature control of plastic furnace is needed to produce a particular type of plastic. In both the cases Instrumentation amplifier is used.

- In short, Instrumentation Amplifier is intended for precise and low level sig nal amplification with low noise, high CMRR, high slew rate, low thermal and time drift, high input impedance, and accurate closed-loop gain.

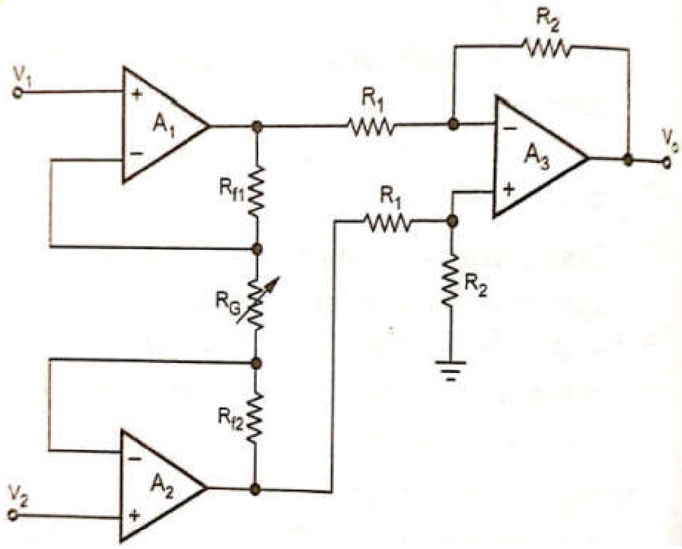


- **Input Stage:** It is a combination of transducer and preamplifier. A transducer is a device which converts one form of energy into another. Most of the transducer outputs are as low as few mV or μV.
- **The intermediate stage:** It consists of Instrumentation amplifier whose input is connected to the output of the Input stage. The Instrumentation amplifier will amplify the low level signal from the transducer unit. For the rejection of noise, amplifiers must have high common-mode rejection ratio (CMRR).
- **The output stage:** It consists of devices like Meters, Oscilloscpes, Charts, Magnetic records etc.

3 Op-amp Instrumentation Amplifier

- The op-amps A1 & A2 are the non-inverting amplifier forming the first stage of the Instrumentation Amplifier.

- The op-amp A3 is the normal difference amplifier forming the output stage of the Instrumentation Amplifier.



It can be seen that the output state is a standard basic difference amplifier. So if the output of the op-amp A_1 is V_{o1} and the output of the op-amp A_2 is V_{o2}, we can write,

$$V_o = \frac{R_2}{R_1}(V_{o2} - V_{o1}) \quad \dots (1.30.1)$$

Let us find out the expression for V_{o2} and V_{o1} interms of V_1, V_2, R_{f1} and R_{f2} and R_G.

Consider the first stage as shown in the Fig. 1.30.3.

The node A potential of op-amp A_1 is V_1. From the realistic assumption, the potential of node B is also V_1. And hence potential of G is also V_1.

The node D potential of op-amp A_2 is V_2. From the realistic assumption, the potential of node C is also V_2. And hence potential of H is also V_2.

The input current of op-amp A_1 and A_2 both are zero. Hence current I remains same through R_{f1}, R_G and R_{f2}.

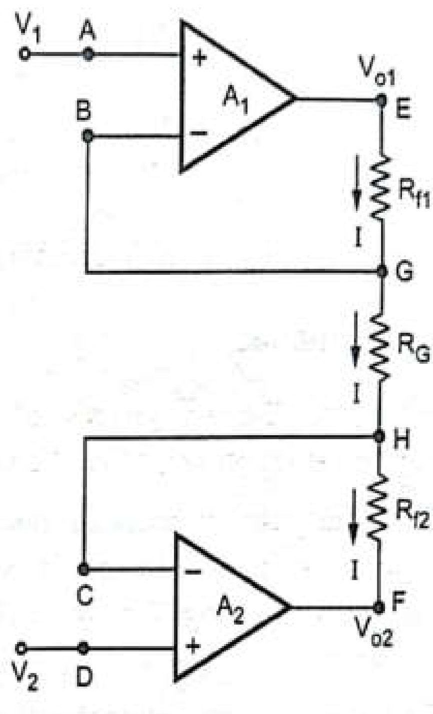


Fig. 1.30.3

Applying Ohm's law between the nodes E and F we get,

$$I = \frac{V_{o1} - V_{o2}}{R_{f1} + R_G + R_{f2}} \quad \text{... (1.30.2)}$$

Let $$R_{f1} = R_{f2} = R_f \quad \text{... (1.30.3)}$$

$$\therefore \quad I = \frac{V_{o1} - V_{o2}}{2R_f + R_G} \quad \text{... (1.30.4)}$$

Now from the observation of nodes G and H,

$$I = \frac{V_G - V_H}{R_G} = \frac{V_1 - V_2}{R_G} \quad \text{... (1.30.5)}$$

Equating the two equations (1.30.4) and (1.30.5),

$$\frac{V_{o1} - V_{o2}}{2R_f + R_G} = \frac{V_2 - V_1}{R_G} \quad \text{... (1.30.6)}$$

$$\frac{V_{o2} - V_{o1}}{2R_f + R_G} = \frac{V_1 - V_2}{R_G} \quad \text{... (1.30.7)}$$

$$V_{o2} - V_{o1} = \frac{(2R_f + R_G)(V_2 - V_1)}{R_G} \quad \text{... (1.30.8)}$$

Substituting the $V_{o2} - V_{o1}$, in the equation (1.30.1),

$$V_o = \frac{R_2}{R_1} \cdot \left[\frac{2R_f + R_G}{R_G}\right](V_2 - V_1) \quad \text{... (1.30.9)}$$

$$\boxed{V_o = \frac{R_2}{R_1} \cdot \left(1 + \frac{2R_f}{R_G}\right)(V_2 - V_1)} \quad \text{... (1.30.10)}$$