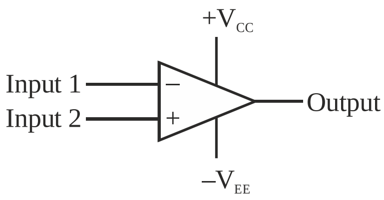
Chapter 6

Operational Amplifier

Symbol:



(+) Non-inverting terminal, (–) Inverting terminal

Input impedance : Few mega Ω (Very high), Output impedance : Less than 100 Ω (Very low)

Differential and Common Mode Operation: One of the more important features of a differential circuit connection as provided in an op-amp is the circuit ability to greatly amplify signals that are opposite at the two inputs while only slightly amplifying signals that are common to both inputs.

An op-amp provides an output component that is due to the amplification of the difference signals applied to the plus and minus input and a component due to the signals common to both inputs.

Since amplification of the opposite input signals is much greater than that of common input signals the circuit provides a common-mode rejection as described by a numerical value called COMMON MODE REJECTION RATIO (CMRR).

Differential Input: When separate inputs are applied to the op-amp, the resulting difference signal is the difference between the two inputs. $\boxed{V_d = V_2 - V_1} = V_+ - V_-$

Common Input: When both input signals applied to an op-amp is common, signal element due to the two inputs can be defined as the average of the sum of the two signals. $\boxed{V_C = \left(\frac{V_1 + V_2}{2}\right)}$.

Output Voltage: Since any signal applied to op-amp in general have both in phase and out of phase components the resulting output can be expressed as $\boxed{V_0 = A_d V_d + A_c V_c}$.

Where V_d = difference voltage, V_C = common mode voltage,

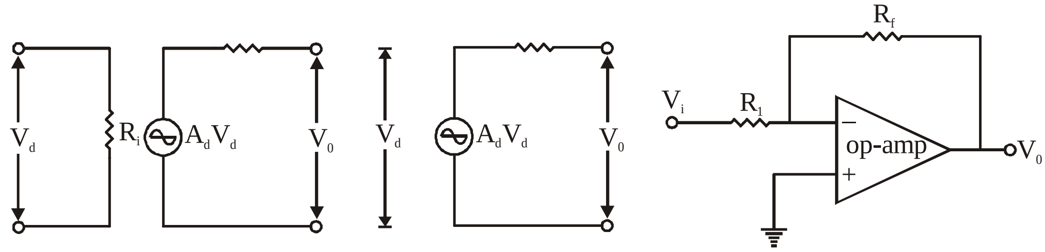
A_d = difference mode gain of the amplifier, A_c = Common mode gain of the amplifier.

CMRR {Common Mode Rejection Ratio}: $\boxed{CMRR = \frac{A_d}{A_c}}$

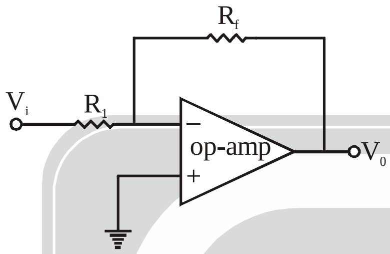
The value of CMRR can also be expressed in log term as

$$\boxed{CMRR(\text{in } d_B) = 20 \log_{10} \frac{A_d}{A_c} (dB)}$$

Equivalent Circuit: While an input to the minus (–) input results in on opposite polarity output. The ac equivalent circuit of the op-amp is shown in figure. As shown the input signal applied between input terminals sees as input impedance Ri typically very high. The output voltage is shown to be the amplifier gain times the input signal taken through output impedance R_0, which is typically very low. An ideal op-amp circuit, as shown in figure would have infinite input impedance zero output impedance and infinite voltage gain.



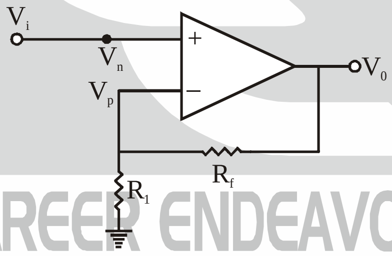
Inverting Amplifier: The most widely used constant gain amplifier circuit is the inverting amplifier.



. We can write $\boxed{V_0 = -\frac{R_f}{R_1} V_1}$

(–) sign represent 180º phase.

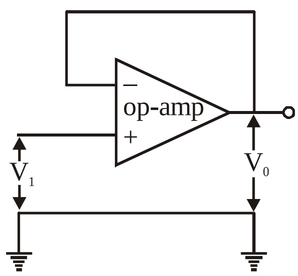
Non-inverting Amplifier: The connection of figures shows an op-amp that works as a non-inverting amplifier or constant gain multiplier. It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability.



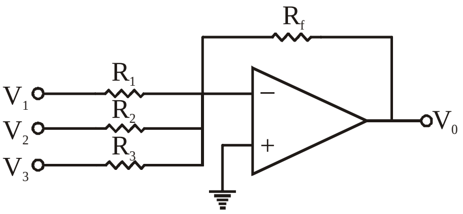
By virtual ground law: $V_n = V_p = V_i$

$$\Rightarrow V_i = \frac{R_1 V_0}{R_1 + R_f} \Rightarrow \frac{V_0}{V_i} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1} \quad \Rightarrow \boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right) V_i}$$

Voltage Follower or Unity Follower: The unity follower circuit as shown in figure provides a gain of unity (1) with number polarity or phase reversal. From the equivalent circuit, it is clear that $\boxed{V_0 = V_1}$ and that the output is the same polarity and magnitude as the input. The circuit operates like an emitter or source follower circuit except that the gain is exactly unity.



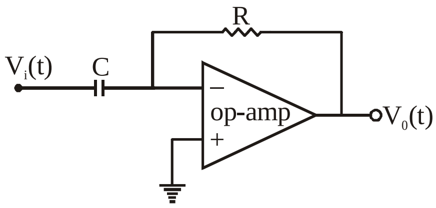
Summing Amplifier: Three input summing amplifier.



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

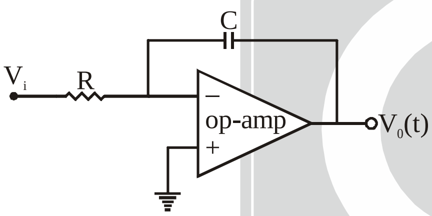
Differentiator : A differentiator circuit is shown in figure while not as useful as the circuit forms covered above the differentiator does provide a useful operation, the resulting far the circuit being

$$V_0(t) = -RC\frac{dV_1(t)}{dt}$$



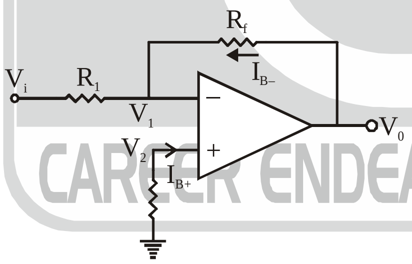
where the scale factor is –RC.

Integrator:



$$V_0(t) = -\frac{1}{RC}\int V_1(t)dt$$

Offset Currents and Voltages {d.c. characteristic of op-amp}:



(1) Input bias current : $\frac{i_B^+ + i_B^-}{2}$

(2) Input offset current: $I_{0s} = |I_B^+| - |I_B^-|$

(3) Input offset voltage : $V_{0s} = V_2 - V_1$

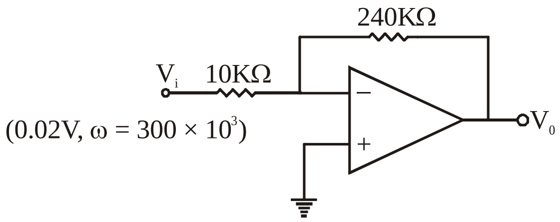
Note: Due to mismatching between V_1 and V_2 output voltage may be positive or negative so we apply offset voltage (V_{os}).

Slew Rate: Another parameter reflecting the op-amp's ability to handling varying signal is slew rate, defined as slew rate = maximum rate at which amplifier output can change in volts per micro second.

$$SR = \frac{\Delta V_0}{\Delta t} V/\mu s$$ with t in μs.

SOLVED PROBLEMS

1. Calculate the slew rate of given circuit.

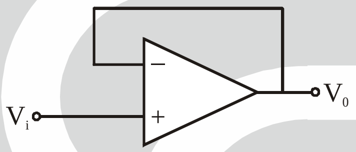


Soln. For a gain of magnitude $A_{CL} = \left|\frac{R_F}{R_1}\right| = \frac{240K\Omega}{10K\Omega} = 24$. The output voltage provides.

$K = A_{CL}, V_i = 24(0.2V) \Rightarrow 0.48V$

$$\omega \le \frac{SR}{K} = \frac{0.5\text{v}/\mu s}{0.48} = 1.1\times10^6 \text{ rad/sec}$$

Voltage Buffer: A voltage buffer circuit provides a means of isolation on input signal from a load by using a stage having unity gain with no phase or polarity inversion.



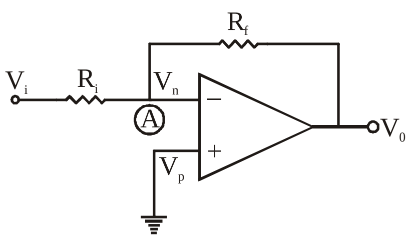
$$\boxed{V_0 = V_i}$$

Controlled Sources: Op-amp can be used to form various types of controlled sources. An input voltage can be used to control on output voltage or current or an input current can be used to control on output voltage or current. There type of connections are suitable far use in various instrument system (circuit). It has four types:

(1) Voltage Controlled Voltage Source
(2) Voltage Controlled Current Source
(3) Current Controlled Current Source
(4) Current Controlled Voltage Source

(1) Voltage Controlled Voltage Source: An ideal form of a voltage source whose output V_0 is controlled by on input voltage V_J is shown in figure. The output voltage is seen to be independent on the input voltage. This type of circuit can be built using an op-amp as shown in figure.

(i) Inverting op-amp:

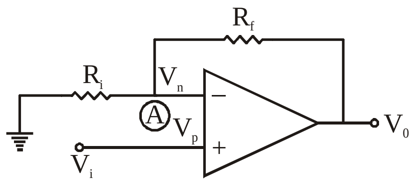


$$\boxed{K = -\frac{R_f}{R_i}}$$

By virtual ground condition $V_n = V_p = 0$

Now KCL at point A, $\frac{V_i - 0}{R_i} = \frac{0 - V_0}{R_f} \Rightarrow \boxed{\frac{V_0}{V_i} = -\left(\frac{R_f}{R_i}\right)}$

(ii) Non-inverting op-amp:



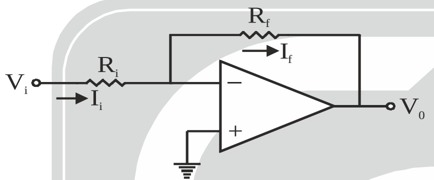
$$\boxed{K = 1 + \frac{R_f}{R_i}}$$

By virtual ground condition $V_p = V_n = V_i$
Now KCL at point A

$$\frac{O - V_i}{R_i} = \frac{V_i - V_o}{R_f} \Rightarrow \frac{V_0}{R_f} = \left(\frac{R_f + R_i}{R_f + R_i}\right)V_i \Rightarrow \boxed{\frac{V_0}{V_i} = 1 + \frac{R_f}{R_i}}$$

(2) Voltage Controlled Current Source: An ideal form of circuit providing an output current controlled by an input voltage is that of figure. The output current is dependent on the input voltage.

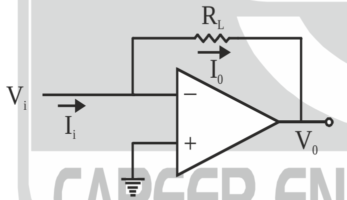
Practical Circuit:



$$\boxed{I_i = \frac{V_i}{R_i}}$$

(3) Current Controlled Voltage Source: An ideal form of a voltage source controlled by a input current is shown in figure. The output voltage is dependent on the input current.

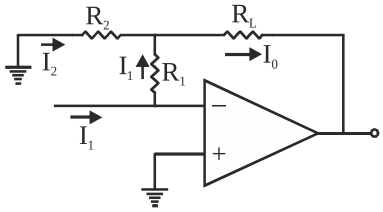
Practical Circuit:



$$\boxed{V_0 = -I_i R_L}$$

(4) Current Controlled Current Source: An ideal form of a circuit providing on output current dependent on an input current is shown in figure. In this type of circuit on output current is provided dependent on the input current.

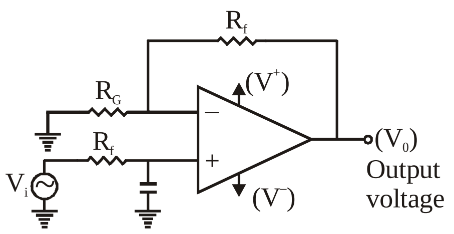
Practical Circuit:

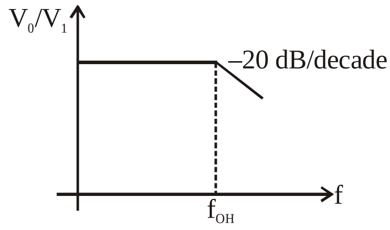


$$I_0 = I_1 + I_2 = I_1 + \frac{I_1 R_1}{R_2} = \left(1 + \frac{R_1}{R_2}\right)I_1 = K\,I_1$$

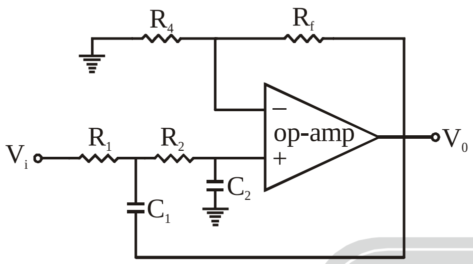
Low Pass Filter: A 1st order, low pass filter using resistor and capacitor as in figure shown has a practical slope of –20 dB per decade as shown in figure (rather them the ideal response of figure). The voltage gain below the cutoff frequency is constant at

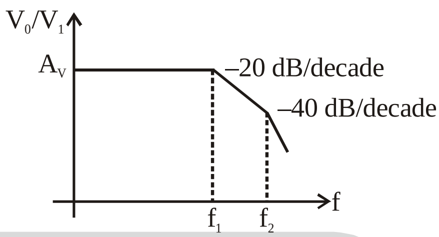
$\boxed{A_v = 1 + \frac{R_f}{R_G}}$, at a cut off frequency of $\boxed{f_{OH} = \frac{1}{2\pi R_1 C_1}}$





Second Order Filter: Connecting two sections of filter as in given figure result in a second order low pass filter with cut off at 40 dB decade closer to the ideal characteristic.

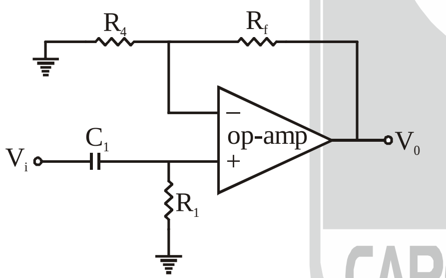


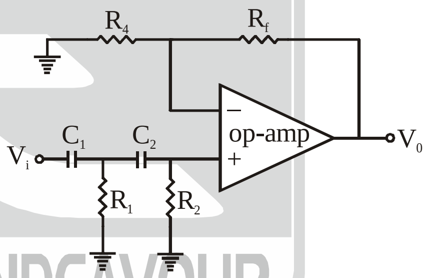


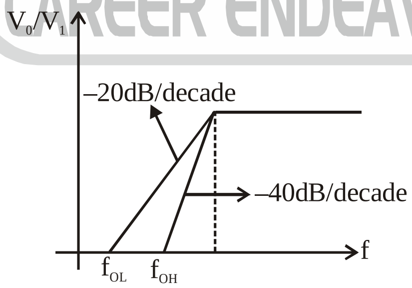
$\boxed{f_2 > f_1}$

High-Pass Active Filter: First and second order high-pass active filter can be built as shown in figure.

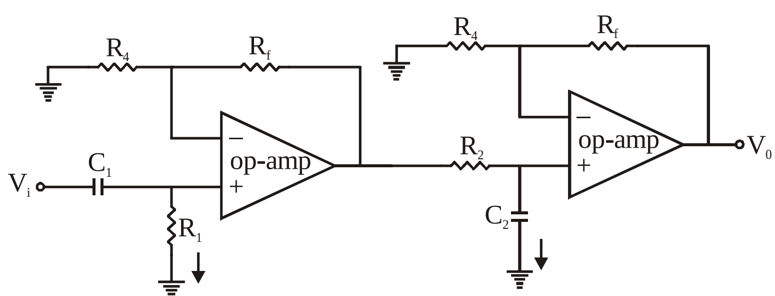
The amplifier cut off frequency is $\boxed{f_{OL} = \dfrac{1}{2\pi R_1 C_1}}$ with a second order filter $R_1 = R_2$ and $C_1 = C_2$ result is the same cut off frequency as in figure.





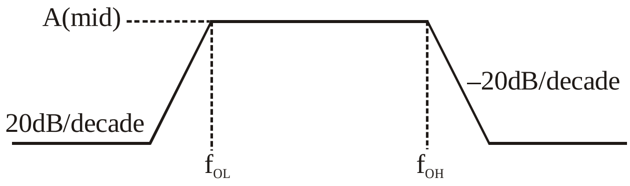


Band Pass Filter: Figure shows a band pass filter using two stages. The 1st a high pass filter and the second a low pass filter. The combined operation being the desired band pass response.

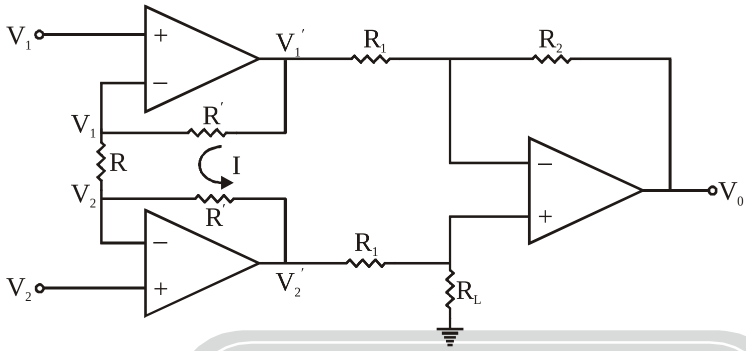


High Pass Section

Low Pass Section



Instrument Amplifier:



Calculation of output voltage:

$$V_0 = \frac{R_2}{R_1}(V_2' - V_1') \qquad I = \frac{V_1 - V_2}{R} \qquad \dots (1)$$

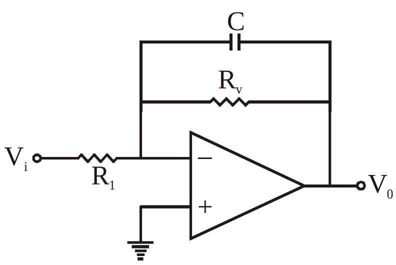
$$V_1' - V_1 = IR' \qquad \dots (2)$$

$$V_2 - V_2' = IR' \qquad \dots (3)$$

$$V_1' - V_2' = 2IR' + V_1 - V_2 \qquad I = \frac{V_1 - V_2}{R}$$

$$\Rightarrow V_1' - V_2' = \frac{(2R' + R)(V_1 - V_2)}{R} \qquad \Rightarrow \boxed{V_0 = \left(1 + \frac{2R'}{R}\right)\left(\frac{R_2}{R_1}\right)(V_2 - V_1)}$$

2. An Active filter shown in figure. The DC gain and 3dB out off frequency are nearly.



$R_1 = 15.9\text{K}\Omega$, $R_2 = 159\text{K}\Omega$, C = 1nF

(a) 40dB, 3.14KHz (b) 40dB, 1KHz (c) 20dB, 628KHz (d) 20dB, 1KHz

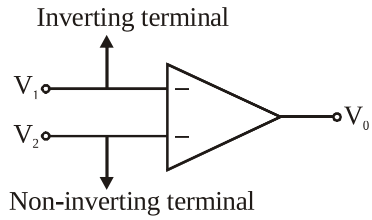
Soln: $$\frac{V_{D(s)}}{V_{i(S)}} = \frac{-R_2/(1 + R_2C_1S)}{R_1} = \frac{-R_2}{R_1(1 + R_2C_1S)}$$

$$A_V = -\frac{R_2}{R_1} = 10 = 20\log_{10}10 = 20dB\ \{\log_{10}10 = 1\}$$

At 3dB frequency $\left|\frac{V_{0(S)}}{V_{1(S)}}\right| = \frac{1}{\sqrt{2}};\ \frac{1}{\sqrt{1+(R_2C_1\omega)^2}} = \frac{1}{\sqrt{2}}$ Since, DC gain $\boxed{\omega = 0}$

On putting the value of R_2, C_1 and comparing L.H.S. and R.H.S. ω = 1KHz

3. In the given op-amp find, the value of output voltage. Given $V_1 = 2\mu V$ d.c. and $V_2 = 4\mu V$ d.c., $A_{OL} = 2 \times 10^5$, $V_{CC} = \pm 15V$.



Soln: Let A_{OL} is open loop voltage gain. In this care $V_0 = (V_2 - V_1)A_{OL}$

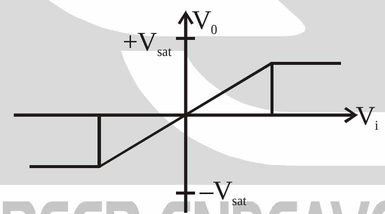
$\Rightarrow V_0 = (4.2) \times 2 \times 10^5 \times 10^{-6} \Rightarrow 4 \times 10^{-1} = 0.4V$

[$V_{sat} \rightarrow$ output will vary between $+V_{sat}$ and $-V_{sat}$]

If $V_1 = -2\mu V$, $V_2 = \pm 4\mu V$

$V_0 = (4 + 2) \times 2 \times 10^5 \times 10^{-6} = 12 \times 10^{-1} = 1.2V$

For Ideal Op-amp (Open Loop): Input and output voltage characteristic of open loop Op-amp.

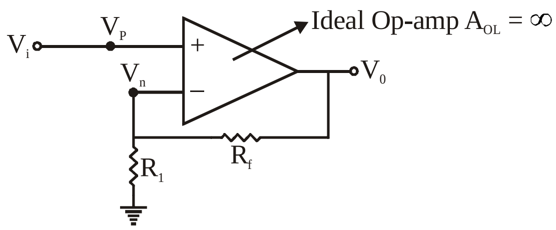


It is clear that open loop op-amp is able to amplify signals of very small amplitude. So, practically, open loop Op-amp is not used.

For Ideal Op-Amp (Open loop):

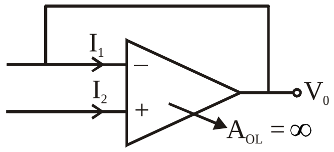
(i) $R_i = \infty$, (ii) $A_{OL} = \infty$, (iii) $R_0 = 0$, (iv) Slew rate = ∞ (v) CMRR = ∞

(vi) Band width = ∞



$$\Rightarrow\ V_0 = A_{OL}(V_p - V_n)\ \Rightarrow\ (V_p - V_n) = \frac{V_0}{A_{OL} \rightarrow \infty}\qquad \boxed{V_p = V_n}$$

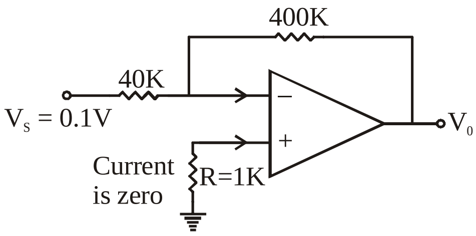
Concept of Virtual Ground:



$$V_1 - V_2 = \frac{V_0}{A_{OL} \to \infty (\text{ideal case})} = 0 \Rightarrow \boxed{V_1 = V_2}$$

In ideal case, $I_1 = I_2 = 0$

4. In the given op-amp circuit. Find the output voltage.

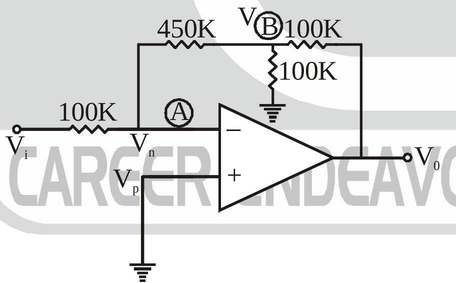


Soln. The given op-amp is inverting amplifier. By the inverting amplifier gain formula

$A = \frac{V_0}{V_i} = -\frac{R_f}{R_1}$. Given, R_f = 400K, R_1 = 40K, V_i = 0.1V

$$\Rightarrow V_0 = -\frac{400}{40} \times 0.1 = -1V$$

5. For the given op-amp circuit. Find voltage gain $\left(\frac{V_0}{V_i}\right)$.



Soln. Applying KCL at point A.

$$\frac{V_i - 0}{100} = \frac{0 - V}{450} \Rightarrow \frac{V_i}{V} = \frac{-100}{450} \Rightarrow V = -4.5V_i \qquad \text{(i)}$$

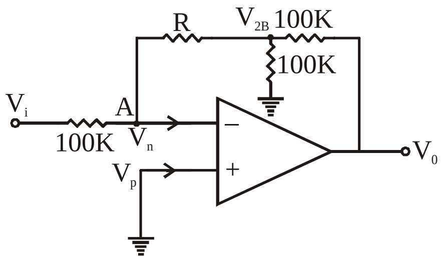
Now KCL at point B.

$$\frac{0 - V}{450} = \frac{V}{100} + \frac{V - V_0}{100} \qquad \text{(Now by equation (i) V = –4.5 V}_i\text{)}$$

$$\Rightarrow \frac{+4.5V_i}{450} = \frac{-4.5V_i}{100} \frac{-4.5V_i - V_0}{100}$$

On solving $\Rightarrow \frac{-V_0}{100} = \frac{4.5V_i}{450} + \frac{4.5V_i}{100} + \frac{4.5V_i}{100} \quad \Rightarrow \frac{V_0}{V_i} = \frac{20}{9}$

6. In the given figure of OP-amp. Find the value of resistance R. $\boxed{\text{Given } \frac{V_0}{V_i} = -10}$



Soln. By virtual ground condition $V_p = V_n = 0$

KCL at point A

$$\frac{V_i - 0}{100K} = \frac{0 - V_2}{R} \Rightarrow \frac{V_i}{100K} = \frac{-V_2}{R}$$

$$\Rightarrow V_2 = \frac{-R.V_i}{100K} \quad \text{... (i)}$$

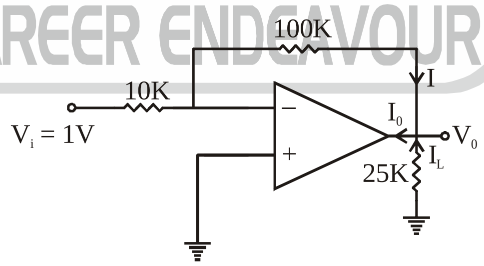
Now KCL at point B

$$\frac{0 - V_2}{R} = \frac{V_2 - V_0}{100K} + \frac{V_2}{100K} \quad \text{... (ii)}$$

$$\frac{V_0}{V_i} = -10 \text{ (Given)} \quad \text{... (A)}$$

By equation (i), (ii) and (A), R = $450K\Omega$

7. In the given circuit of op-amp. Find I_0 and I_L.



Soln. This is inverting amplifier $\frac{V_0}{V_i} = -\left(\frac{R_f}{R_i}\right) = -\left(\frac{100}{10}\right) = -10$

$V_0 = -10V$

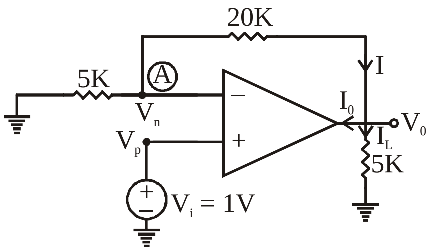
$\Rightarrow$ For current I_L $\quad 0 - (-10) = I_L \times 25K\Omega$

$\Rightarrow I_L = \frac{10}{25} = 0.4mA \quad \Rightarrow$ For current I,

$\Rightarrow \; 0 - (-10) = 100K \times I \quad \Rightarrow$ I = 0.1mA

$\Rightarrow I_0 = I + I_L = 0.4 + 0.1 \Rightarrow 0.5$ mA

8. Based on Non-inverting amplifier.



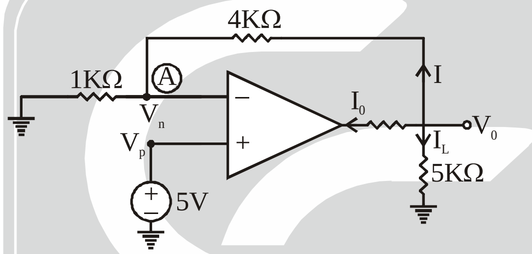
. From the above given op-amp. Find I_L and I_0?

Soln. By VGP, $V_n = V_p = 1V$. KCL at point A, $\frac{0-1}{5} = \frac{1-V_0}{20} \Rightarrow V_0 = 5V$

$I_L = 1mA = \frac{5}{5} = 1mA$, $I = \frac{1-5}{20} = -0.2mA$, $I_0 = I - I_L = -(1 + 0.2) = -(1.2)mA$

So, the current direction of I and I_0 will be reverse.

9. In the given figure of op-amp. Find the value of I_0 and I_L?



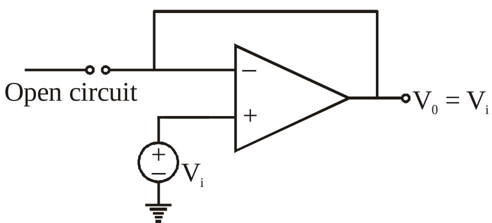
Soln. This is non-inverting amplifier. $V_p = V_n = 5V$ by VGP.

Now, KCL at point A,

$$\frac{0-5}{1K} = \frac{5-V_D}{4K} \Rightarrow V_D = 25V,\ I_L = \frac{25}{5K} = 5mA,\ I = \frac{5-25}{4K} = -\frac{20}{4} = -5mA$$

$$I_0 = I - I_L = -5-5 = -10mA$$

Voltage Follower: Means a unity gain non-inverting op-amp.



(a) $R_f = 0, R_1 = 0$ (b) $R_f = 0, R_1 = \infty$ (c) $R_f = 0,$ any value of R_1

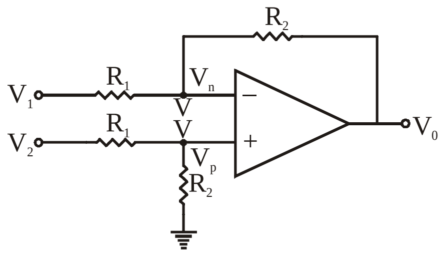
(d) $R_f = R_1$

For which value of R_f and R_1 it makes voltage follower.

Voltage Follower: $\left\{\begin{matrix} R_{in} = \text{Very high} \\ R_{out} = \text{Very low} \end{matrix}\right\}$

This resistance range is used for impedance matching or used as buffer.

Difference Amplifier:



In the above given op-amp figure. Find the value of output voltage in term of V_1 and V_2.

Soln. By the VGP condition $V_p = V_n = V$.

For the upper loop, $\dfrac{V_1 - V}{R_1} = \dfrac{V - V_0}{R_2}$ ... (i)

For the lower loop, $\dfrac{V_2 - V}{R_1} = -\dfrac{V}{R_2}$ ... (ii)

$$\Rightarrow \frac{V_2}{R_1} = V\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \Rightarrow V\left(\frac{R_2 - R_1}{R_1 R_2}\right)$$

$$\Rightarrow V = \frac{V_2 . R_2}{(R_2 - R_1)} \quad \text{... (A)}$$

Now putting the value of equation (A) in equation (i)

$\boxed{V_0 = \dfrac{R_2}{R_1}(V_2 - V_1)}$ for ideal subtractor circuit CMRR is ∞

Super Position, Principle: Let V_1 be at ground, then $V_2 = \left(1 + \dfrac{R_2}{R_1}\right)V$

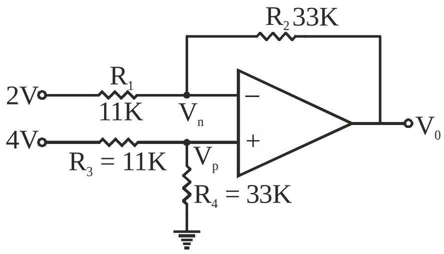
$$V = \frac{R_2 V_2}{R_1 + R_2} \quad \therefore V_{02} = \left(1 + \frac{R_2}{R_1}\right) . \frac{R_2 V_2}{R_1 + R_2}$$

$$\Rightarrow V_{02} = \frac{(R_1 + R_2)}{R_1} . \frac{R_2 V_2}{(R_1 + R_2)}; \; V_{02} = \frac{R_2}{R_1} V_2$$

Now, when V_2 be at ground, then, $V_{01} = -\dfrac{R_2}{R_1} . V_1; V_0 = V_{01} + V_{02}$

Total $\boxed{V_0 = \dfrac{R_2}{R_1}(V_2 - V_1)}$

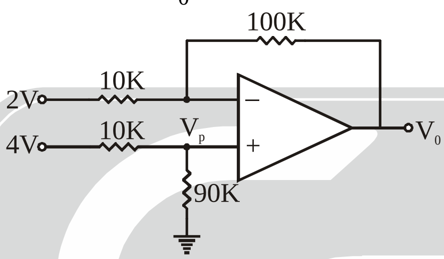
10. In the given op-amp circuit. Find the output voltage V_0?



Soln. $V_0 = 3(4-2)$, $V_0 = 6$ volt

Hence, $\frac{R_2}{R_1} = \frac{R_4}{R_3}$, then $V_0 = \frac{R_2}{R_1}(V_1 - V_2)$ or $V_0 = \frac{R_4}{R_3}(V_1 - V_2)$

11. In the given op-amp circuit. Find the value of V_0.

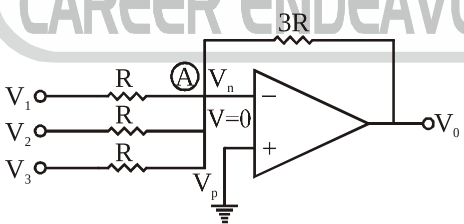


Soln. Firstly, considering first inverting loop, $V_{01} = -\frac{R_f}{R_1}V_i \Rightarrow \frac{-100}{10} \times 2 = -20V$

Now, considering non-inverting loop $V_P = \frac{4\times 90}{90+10} \Rightarrow \frac{360}{100} \Rightarrow 3.6V$

$\Rightarrow V_{02} = \left(1+\frac{100}{10}\right)3.6 \Rightarrow 39.6$ $\quad \therefore V_0 = (39.6 + (-20V)) \Rightarrow 19.6 Volt$

Adder:

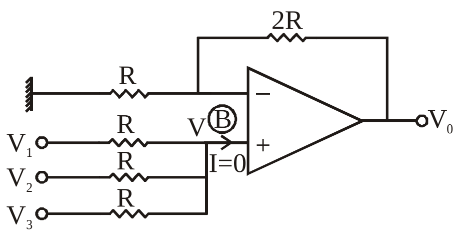


Soln: By VGP $\Rightarrow V_n = V_p = 0$

KCL at point A $\frac{V_1}{R} + \frac{V_2}{R} + \frac{V_3}{R} = \frac{0 - V_0}{3R}$ $\Rightarrow \boxed{V_0 = -3(V_1 + V_2 + V_3)}$

So, the above op-amp is working as a inverting adder.

For the given op-amp circuit. Find the value of output voltage.

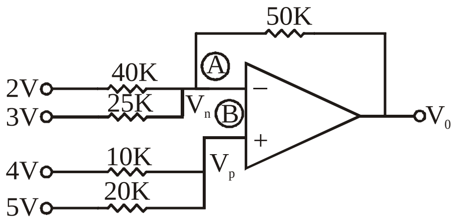


Soln. KCL at point B $\frac{V_1 - V}{R} + \frac{V_2 - V}{R} + \frac{V_3 - V}{R} = 0$ or $\boxed{V = \frac{1}{3}(V_1 + V_2 + V_3)}$

$\therefore V_0 = \left(1 + \frac{2R}{R}\right)V \Rightarrow V_0 = (1+2).\frac{1}{3}(V_1 + V_2 + V_3)$ $\boxed{V_0 = (V_1 + V_2 + V_3)}$

So, this is non-inverting adder.

12. In the given op-amp figure. Find the output voltage.



Soln. By VGP condition (Virtual Ground Position) ($V_p = V_n$)

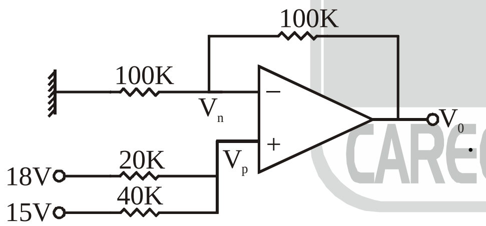
Let $V_p = V_p = V$.

Now, KCL at point B, $\frac{4 - V_p}{10} + \frac{5 - V_p}{20} = 0 \Rightarrow V_p = \frac{13}{3} Volt$

Now, KCL at point A, $\frac{2 - V_n}{40} + \frac{3 - V_n}{25} = \frac{V_n - V_0}{50}$, $\frac{2}{40} + \frac{3}{25} = \frac{V_n}{40} + \frac{V_n}{25} + \frac{V_n}{50} - \frac{V_0}{50}$

Now putting the value of V_n, $\frac{2}{40} + \frac{3}{25} = \frac{13}{120} + \frac{13}{75} + \frac{13}{150} - \frac{V_0}{50} \Rightarrow V_0 = 9.9V \quad \because V_n = V_p$

13.



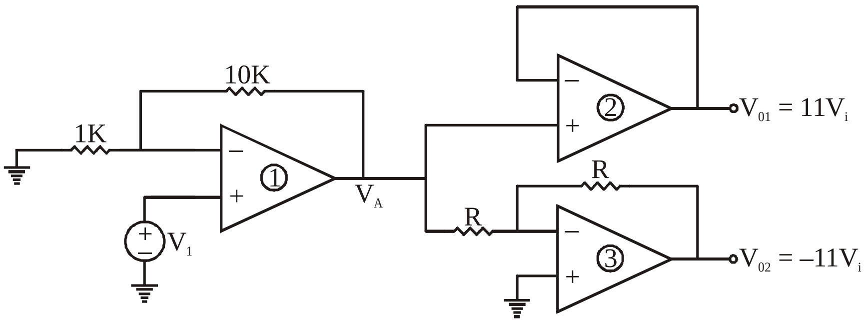
In the above given op-amp circuit, find output voltage.

Soln. $V_p = V_n = V$ (By VGP)

KCL at positive terminal, $\frac{18 - V}{20} + \frac{15 - V}{40} = 0 \Rightarrow V = \frac{41}{3} Volt$.

KCL at positive terminal, $\Rightarrow \frac{0 - \frac{41}{3}}{100K} = \frac{\frac{41}{3} - V_0}{100} \Rightarrow V_0 = \frac{82}{3} Volt$

14. For the given op-amp circuits. Find $\frac{V_{01}}{V_{02}}$.



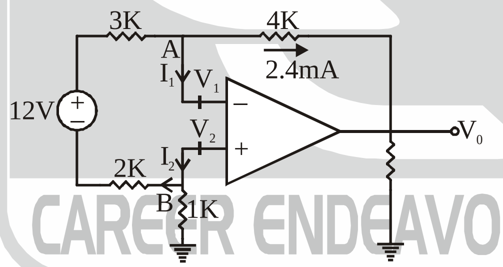
Soln. For the op-amp ... (1), this is non-inverting amplifier.

$V_A = \left(1+\frac{10}{1}\right)V_i = 11V_i$ $\Rightarrow$ Op-amp (2) is working like buffer, $V_{01} = 11V_i$

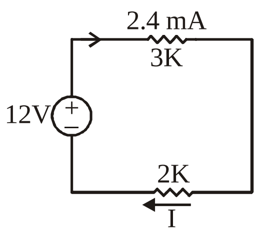
$\Rightarrow$ Op-amp (3) is working like inverting amplifier, $V_{02} = \frac{-R}{R}11V_i = -11V_i$

$\Rightarrow \frac{V_{01}}{V_{02}} = -\frac{11V_i}{11V_i} = -1$

15. In the given op-amp circuit find output voltage.



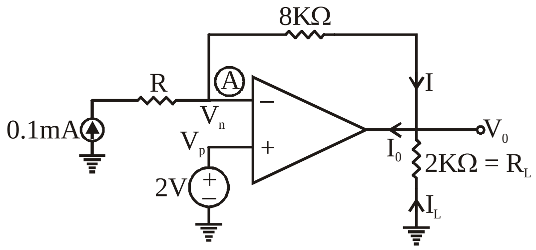
Soln. Because $I_1 = I_2 \Rightarrow V_1 - V_2 = 0$



$I = \frac{12}{5} = 2.4mA;\ V_B = 0 - 2.4\times 1 = -2.4V$, $V_A = -2.4V;$

$\Rightarrow \frac{-2.4 - V_0}{4} = 2.4 \Rightarrow \boxed{V_0 = -12.0V}$

16. In the given op-amp circuit find V_0 and I_0.

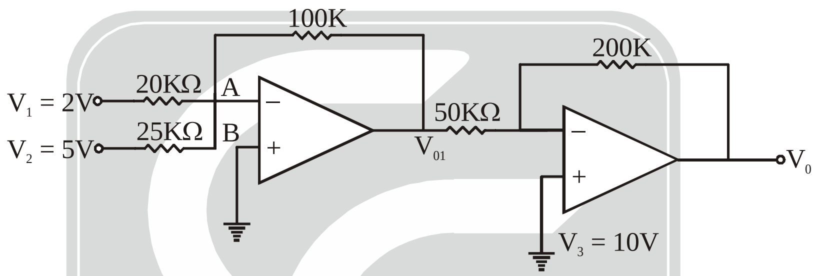


Soln: By VGP $\rightarrow$ $V_n = V_p = 2V$

Now, KCL at point A

$0.1 = \dfrac{2-V_0}{8} \Rightarrow V_0 = -2.8 Volt$, $I_L = \dfrac{2.8}{R_L} = 1.4mA$, $I_0 = 1.4 + 0.1 = 1.5mA$

17. In the given op-amp figure. Find the output voltage.

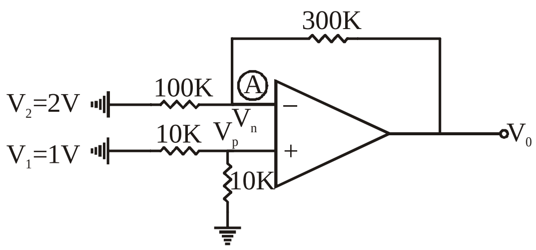


Soln. By VGP, $V_B = V_A = 0$, Now, KCL at point A, $\dfrac{2}{20} + \dfrac{5}{25} = \dfrac{0-V_0}{100} \Rightarrow V_{01} = -30 Volt$

Now, KCL at second OP-amplifier $\dfrac{10-(-30)}{50} = \dfrac{V_0 - 10}{200}; \dfrac{40}{50} = \dfrac{V_0 - 10}{200}$

$\therefore V_0 = 1T_0\, Volt$

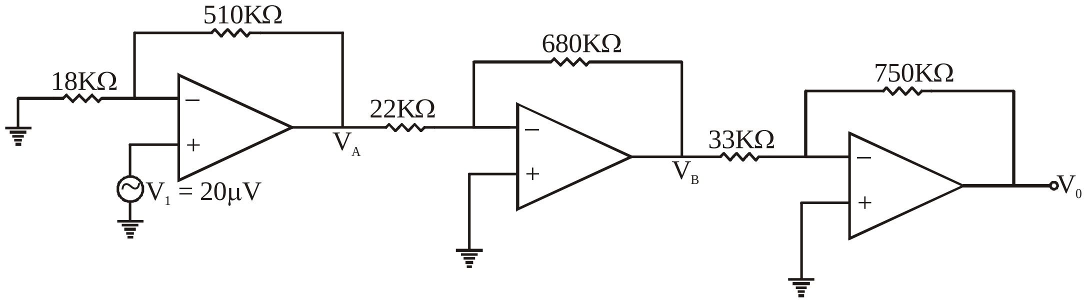
18. In the given Op-amp circuit. Find V_0?



Soln. $V_p = \dfrac{10 \times 1}{10+10} = 0.5V$, By VGP condition, $V_n = V_p = 0.5V$

Now, KCL at point A, $\Rightarrow \dfrac{2-0.5}{150} = \dfrac{0.5 - V_0}{300} \Rightarrow V_0 = -2.5 Volt$

19. In the given Op-amp circuit. Find output voltage.

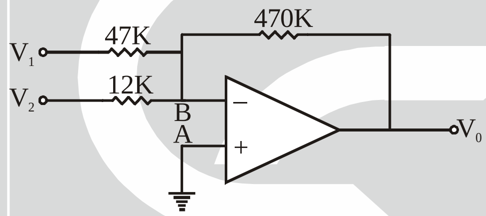


Soln. We will 1st calculate V_A, $\dfrac{20\times10^{-6}-0}{18}=\dfrac{V_A-20\times10^{-6}}{510}$

$$\Rightarrow 20\times10^{-6}\left[\frac{1}{18}+\frac{1}{510}\right]=\frac{V_A}{510};V_A=\frac{528}{18}\times20\times10^{-6},\ V_A=5.86\times10^{-4}Volt$$

Similarly on solving, $V_B=\dfrac{-680}{22}\times5.86\times10^{-4}V$, $V_B=-0.081Volt$, $V_0 = 0.409$ Volt

20. Calculate the output voltage for the circuit with input $V_1 = 40mV$, $V_2 = 20mV$.

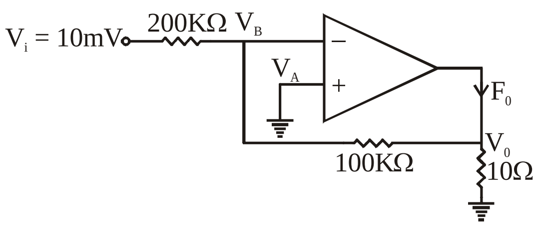


Soln. $V_A = V_B = 0$, Now applying KCL in inverting loop

$$\frac{V_1-0}{47}+\frac{V_2-0}{12}=\frac{0-V_0}{470},\ \Rightarrow\frac{40}{47}+\frac{20}{12}=-\frac{V0}{470}\Rightarrow V_0=\frac{-(40\times12+20\times47)\times470}{47\times12}$$

$$\Rightarrow\therefore V_0=\frac{-(480+940)\times5}{6}=\frac{7100}{6}=-1183.93mV\ \Rightarrow V_0=-1.183Volt$$

21. Calculate the output current I_0 in the given circuit.

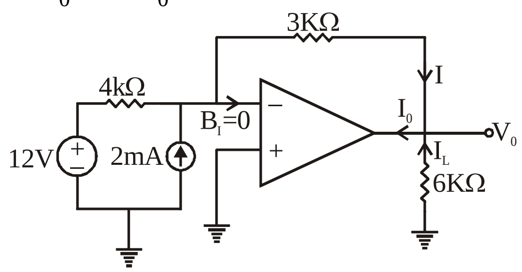


Soln. Potential at A and B points are equal by VGP. i.e. $V_A = V_B = 0$
Now applying KCL in inverting loop

$$\frac{V_i-0}{200}=\frac{0-V_0}{100K}\Rightarrow V_0=\frac{10\times100\times10^{-3}\times10^3}{200}V_0\Rightarrow 5V$$

Now, $I_0=\dfrac{5}{10}+\dfrac{5}{100k\Omega}=0.5+0.00005\simeq0.5A$

22. In the given Op-amp circuit. Find I_0 and V_0?

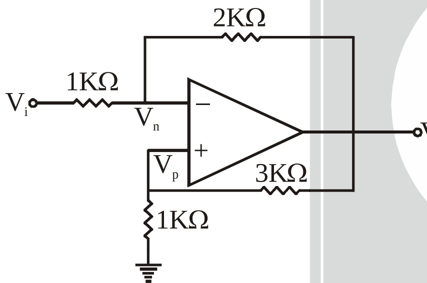


Soln. Applying KCL at point B, $2\times10^{-3}+\frac{12}{4K}=\frac{0-V_0}{3K}$

$$\Rightarrow 2\times10^{-3}+3\times10^{-3}=\frac{-V_0}{3K}\Rightarrow V_0=-(15Volt)$$

$$I_L=\frac{V_0}{6}=2.5m\,Amp,\quad I=\frac{0+15}{3K}=5mA,\ I_0=I+I_L\Rightarrow 7.5mA$$

23. In the given circuit find voltage gain $\frac{V_0}{V_i}$.

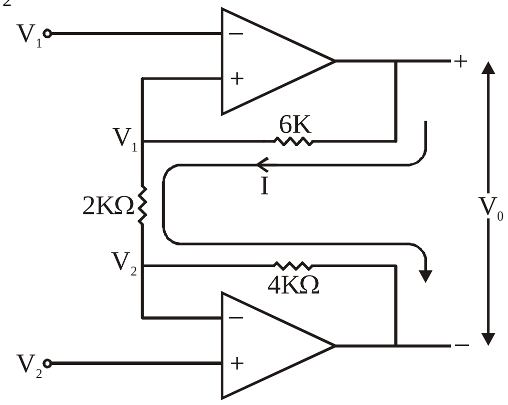


Soln. In the non-inverting loop applying KCL let $V_p = V_n = V$

In the $\frac{0-V}{1}=\frac{V-V_0}{3}\Rightarrow V_0=4V,\boxed{V=\frac{V_0}{4}}$.

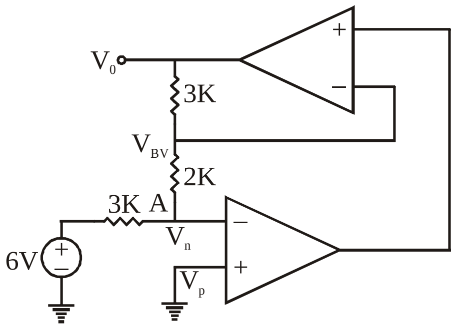
In the inverting loop applying KCL, $\frac{V_i-V}{1}=\frac{V-V_0}{2}\Rightarrow V_i-\frac{V_0}{4}=\frac{\frac{V_0}{4}-V_0}{2}\ \Rightarrow\boxed{\frac{V_0}{V_i}=-8}$

24. In the given circuit. Find $\frac{V_0}{V_1-V_2}$?



Soln. $V_0=6I+2I+4I=12I;\ V_1-V_2=2I \quad \therefore \frac{V_0}{V_1-V_2}=\frac{12I}{2I}=6$

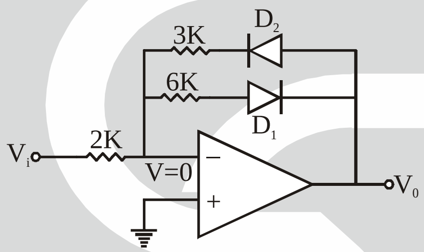
25. In the given circuit find V_0?



Soln. $V_n = V_p = 0$ {VGP}, Now, KCL at point A, $\frac{6-0}{3} = \frac{0-V_B}{2} \Rightarrow V_B = -4V$

Now, KCL at point B, $\frac{0-V_B}{2} = \frac{V_B - V_0}{3} \Rightarrow \because V_B = -4V$, $\frac{4}{2} = \frac{-4-V_0}{3} \Rightarrow \boxed{V_0 = -10V}$

26. In the circuit calculate the output voltage V_0?



(i) If $V_i = 3V$, then V_0? (ii) If $V_i = -3V$, then V_0?

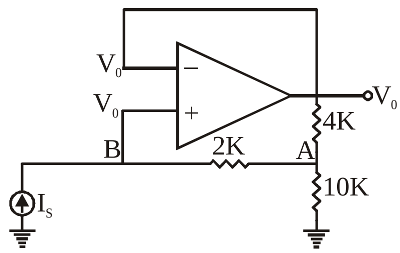
Soln. (i) When $V_i = 3V$, diode D_1 will on, Now KCL in D_1 loop

$$\frac{3-0}{2} = \frac{0-V_0}{6} \Rightarrow V_0 = -9Volt$$

(ii) When $V_i = -3V$, diode D_2 will on, Now, KCL in D_2 loop

$$\frac{V_i - 0}{2} = \frac{0-V_0}{3} \Rightarrow -\frac{3}{2} = -\frac{V_0}{3} \Rightarrow V_0 = 4.5Volt$$

27. In the given circuit calculate $\frac{V_0}{I_S}$.



Now, KCL at point A.

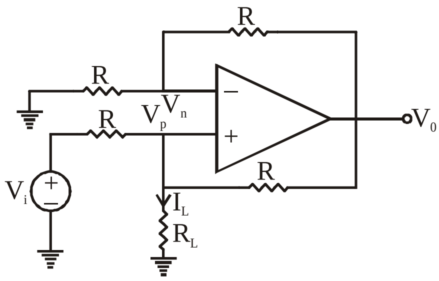
$$\frac{V-V_0}{4} + \frac{V-V_0}{2} + \frac{V}{10} = 0 \Rightarrow 5(V-V_0) + 10(V-V_0) + 2V = 0$$

$$\Rightarrow 5V - 5V_0 + 10V - 10V_0 + 2V = 0 \quad \Rightarrow 17V = 15V_0 \Rightarrow V = \frac{15V_0}{17}$$

Now, KCL at point A

$$\frac{V_0 - V}{2} + (-I_S) = 0 \Rightarrow V_0 - V - 2I_S = 0 \quad \Rightarrow V_0 - \frac{15V_0}{17} = 2I_S \quad \Rightarrow \frac{2V_0}{17} = 2I_S \Rightarrow \frac{V_0}{I_S} = 17$$

28. In the given circuit find value of I_L.



Soln. By VGP, $V_n = V_p = V$. Firstly, KCL in non-inverting terminal

$$\frac{V_i - V}{R} = I_L + \frac{V - V_0}{R} \qquad \text{... (i)}$$

Similarly, KCL in inverting terminal

$$\frac{0 - V}{R} = \frac{V - V_0}{R} \Rightarrow V_0 = 2V \Rightarrow V = \frac{V_0}{2} \qquad \text{... (ii)}$$

Now, putting value of (ii) in equation (i)

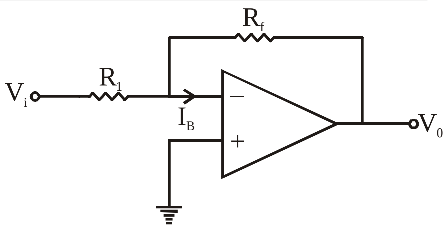
$$\frac{V_i - \frac{V_0}{2}}{R} = I_L + \frac{\frac{V_0}{2} - V_0}{R}, \quad V_i - \frac{V_0}{2} = I_L R + \frac{V_0}{2} - V_0 \Rightarrow \boxed{I_L = \frac{V_i}{R}}$$

DC Characteristic of Op-amp:

(i) Input bias current (For DC analysis)

(ii) Input offset current

(iii) Input offset voltage



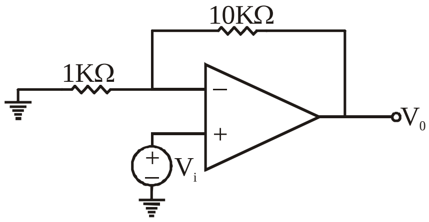
(i) Input bias current = $\frac{|I_B^+| + |I_B^-|}{2}$. Let $|I_B^+| = |I_B^-|$, $0 - V_0 = |I_B^-| R_f$; $\boxed{V_0 = |I_B^-| R_f}$

To compensate effect of input bias current R_{comp} is used. $\therefore$ $\boxed{R_{comp} = R_1 \| R_f}$

(ii) Input offset current; $I_{OS} = |I_B^+| - |I_B^-|$, $V_0 = R_f I_{OS} \rightarrow$ output if $V_i = 0$, due to input offset current.

(iii) Input offset voltage; $V_{OS} = V_1 - V_2$, output to input offset; $V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{OS}$.

29.



Calculate I_L, Given V_{OS} = 10mV, $|I_B^-|$ = 300nA, I_{OS} = 100pA.
Find (a) Calculate maximum output voltage due to V_{OS} and I_B^-. (b) Calculate R comperate.
(c) Calculate output voltage if R_{comp} is connected.

Soln. (i) If we are considering input bias current then I_{OS} = 0, as we have already assumed $|I_B^+| = |I_B^-|$.

(ii) If R_{comp} is connected, then input bias current will not considered, only I_{OS} will be considered.
If R_{comp} is connects then for zero input = zero output.

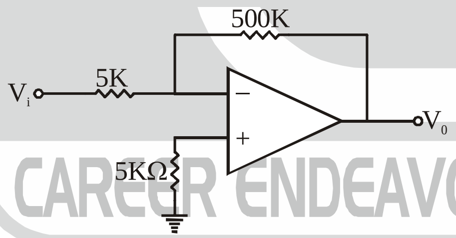
(a) $V_0 = \left(1+\frac{R_f}{R_1}\right).V_{OS} + R_f.I_B^- = \left(1+\frac{10}{1}\right).10 + 10.300nA = 110 + 3mV = 113mV$

(b) $R_{comp} = R_1 \,||\, Rf = \frac{10}{11} K\Omega$

(c) $V_0 = \left(1+\frac{R_f}{R_1}\right).V_{OS} + R_f I_{OS} = \left(1+\frac{10}{1}\right)\times 10mV + 10K \times 100\,pA$

$= 110mV + 0.001mV = 110.001mV$

30. If input offset voltage = 4mV, input offset current = 150nA, input bias current = 300nA.



Soln. $V_0 = \left(1+\frac{R_f}{R_1}\right)V_{OS} + R_f.I_{OS} = \left(1+\frac{500}{5}\right).4mV + 500K \times 150nA$ = 101 × 4 + 75

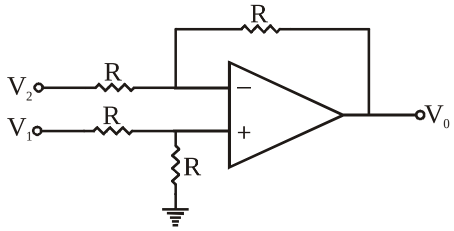
= 404 + 75 = 479mvolt.

Calculation of CMRR

$\boxed{CMRR = \frac{A_d}{A_C}}$ A_d = differential mode gain, A_C = Common mode gain

$\boxed{V_0 = A_d V_d + A_C V_C}$ $V_d = V_1 - V_2,\ V_C = \frac{V_1 + V_2}{2},\ A_d = \left.\frac{V_0}{V_d}\right|_{V_C = 0,}\ A_C = \left.\frac{V_0}{V_C}\right|_{Vd=0}$

31. In the given circuit. Find the value of CMRR?



Soln. $V_0 = \frac{R}{R}(V_1 - V_2)$, $V_0 = (V_1 - V_2)$ $\therefore V_d = V_1 - V_2, \Rightarrow A_d = 1$

For $A_C, V_1 = V_2. \Rightarrow A_C = 0$ $\therefore CMRR = \frac{1}{0} = \infty$

32. In the op-amp circuit, CMRR = 40dB and A_d = 50dB. Find A_C.

Soln. Here, CMRR = Common Mode Rejection Ratio

A_d = Difference Mode gain, A_C = Common Mode gain

CMRR and A_d are given in dB. First off all we will change it in normal value.

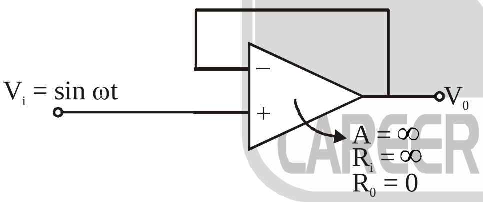
40dB = 20 $\log_{10}$ CMRR

$\Rightarrow$ CMRR = $(10)\frac{40}{20} = 10^2 = 100$ $\Rightarrow$ 50dB = 20$\log_{10}$ A_d

$\Rightarrow$ A_d = $10^{2.5}$ = 316.22 $\Rightarrow$ CMRR = $\frac{A_d}{A_C}$ $\Rightarrow$ A_C = $\frac{A_d}{CMRR} \Rightarrow \frac{316.27}{100}$

A_C = 3.16

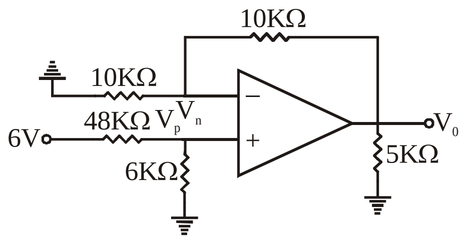
Slew Rate:



33. What is the maximum value of input voltage given to an voltage follower so, that there is no distortion (Slew rate is given).

Soln: $V_0 = V_m \sin \omega t$, Slew Rate = $Vm.\omega \cos \omega t$, S.R. = $Vm.\omega$ $\therefore V_m = \frac{S.R}{2\pi f}$

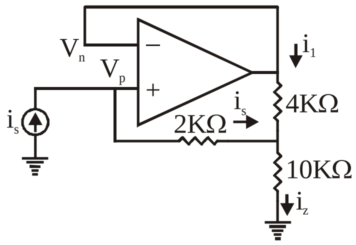
34. For the circuit shown below the value of V_0 is



(a) $\frac{4}{3}$V (b) $-\frac{2}{3}$V (c) $\frac{2}{3}$V (d) $-\frac{4}{3}$V

Soln. $V_p = \dfrac{6\times 6}{48+6} = \dfrac{2}{3}V$, $V_0 = \left(1+\dfrac{R_f}{R_1}\right)V_p = \left(1+\dfrac{10}{10}\right).\dfrac{2}{3} = (2)\times\dfrac{2}{3} = \dfrac{4}{3}$

35. For the circuit shown below the input resistance is

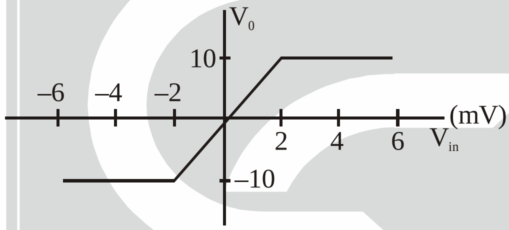


(a) $38K\Omega$ (b) $17K\Omega$ (c) $25K\Omega$ (d) $47K\Omega$

Soln. Since op-amp is ideal, $V_n = V_p, 2k\,i_s = 4k\,i_1 \Rightarrow i_s = 2i_1, V_s = 2k\,i_s + 10k\,i_2,\; i_2 = i_s + i_1$

$$V_s = 2k\,i_s + 10k(i_s + i_1) \because i_1 = \frac{i_s}{2} \;\Rightarrow V_s = 2k\,i_s + 10k\left(i_s + \frac{i_s}{2}\right) \Rightarrow \frac{V_s}{i_s} = 17K = R_{in}$$

36. The voltage transfer characteristic of an operation amplifier is shown in figure. What are the values of gain and offset voltage for this op-amp.



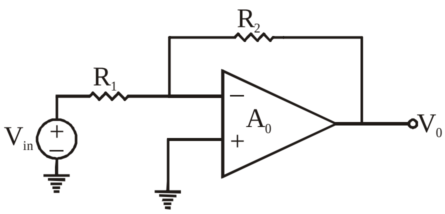
(a) 10, 1mV (b) 7500, –1mV (c) 20, 2mV (d) 7500, –2mV

Soln. $V_0 = A_V(V_{in} + V_{OS}),\; V_{OS} \rightarrow \text{Offset Voltage},\; A_V \rightarrow \text{Voltage Gain}$

$A_V = \dfrac{dV_0}{dV_{in}} = \dfrac{10-(-5)}{(2-0)mV} = 7500$, When $V_0 = 0$, $V_{in} = -V_{OS}$

Offset voltage is $V_{OS} = -V_{in} / V_0 = 0 = -1mV$

37. An inverting operational amplifier shown in figure has an open gain of 1000 and closed loop gain of 4, gain error is

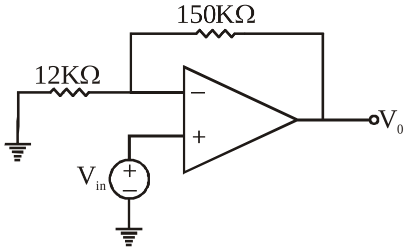


(a) 0.4% (b) 0.5% (c) 2.5% (d) 2%

Soln. Gain error is given as $\Delta g = \dfrac{1}{A_0}\left(1+\dfrac{R_2}{R_1}\right)$, $A_0 = 1000$ (Open loop gain)

$\dfrac{R_2}{R_1} = 4$ (Closed loop gain), $\Delta g = \dfrac{1}{1000}(1+4) = 0.5\%$

38. In the following non-inverting amplifier. The op-amp has an open loop gain of 86dB, gain error is



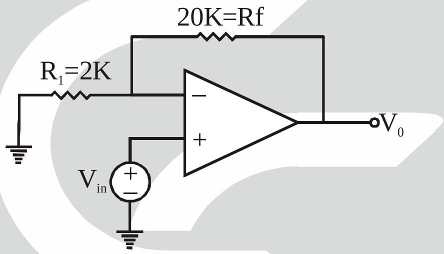
(a) 0.0125% (b) 0.13% (c) 0.930% (d) 0.0675%

Soln. Gain error for non-inverting amplifier is given by $\Delta g = \dfrac{1}{A_0}\left(1+\dfrac{R_2}{R_1}\right)$

where $A_0 \rightarrow$ open loop gain $20\log_{10} A_0 = 86\text{(given)}$ $A_0 \simeq 20,000$, $R_2 = 150\,K\Omega$, $R_1 = 12\,K\Omega$

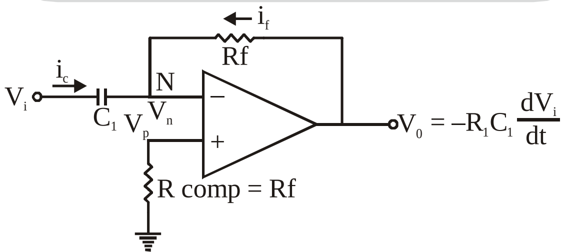
So, gain error is $\Delta g = \dfrac{1}{20,000}\left(1+\dfrac{150}{2}\right) = 6.75\times10^{-4}$ or $\Delta g = 0.0675\%$

39. Op-Amp of a given figure has open loop gain of 45. What is closed loop gain of an op-amp.



Soln. For non-inverting $A_{CL} = \dfrac{\left(1+\dfrac{R_f}{R_1}\right)}{1+\dfrac{\left(1+\dfrac{R_f}{R_1}\right)}{A_{OL}}} \Rightarrow \dfrac{\left(1+\dfrac{20}{2}\right)}{1+\dfrac{\left(1+\dfrac{20}{2}\right)}{45}} = \dfrac{11}{1+\dfrac{11}{45}} = \dfrac{4\times11}{56} \Rightarrow 8.95$

Differentiator:



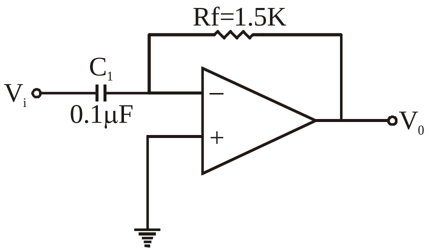
By VGP, $V_p = V_n = 0$, Now, KCL at point N, $i_C = C_1\dfrac{d}{dt}(V_i - V_N) = C_1\dfrac{dV_i}{dt}$, this is far capacitor current.

For feedback resistor Rf. $i_f = \dfrac{V_0}{R_f} \Rightarrow C_1\dfrac{dV_i}{dt} + \dfrac{V_0}{R_f} = 0 \Rightarrow \boxed{V_0 = -RfC_1\dfrac{dV_i}{dt}}$

We may now write the magnitude of gain A of the differentiator as,

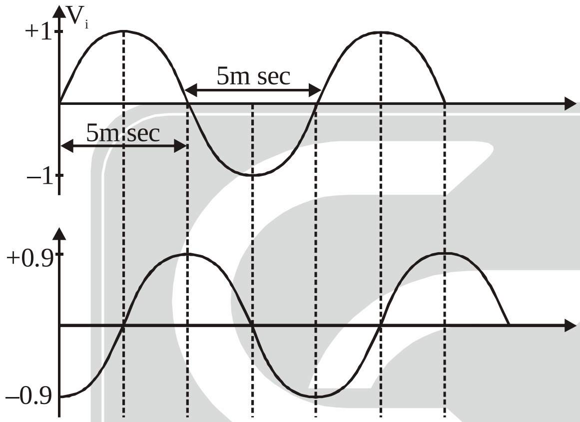
$|A| = \left|\dfrac{V_0}{V_i}\right| = |-J\omega RfC_1| = \omega RfC_1$ or $|A| = \dfrac{f}{f_a}$ where $\boxed{f_a = \dfrac{1}{2\pi RfC_1}}$

40. In the given differentiator, if $V_i = \sin(2\pi \times 10^2 t)$. Draw wave form of V_0.

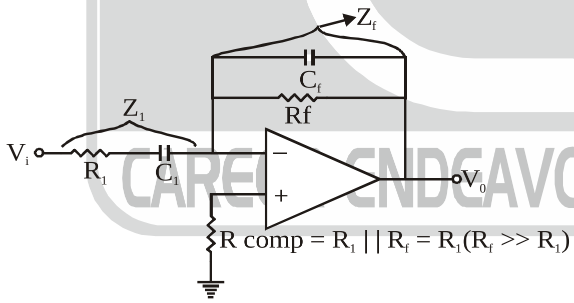


Soln. $V_0 = -CR_f \dfrac{dV_i}{dt}$, $V_0 = -0.1\times10^{-6}\times1.5\times10^{3}.\cos(2\pi\times10^{2}t).2\pi\times10^{2}$

$$V_0 = -3\pi\times10^{-2}\cos(2\pi\times10^{2}t) = -0.09\cos(2\pi\times10^{2}t)$$



Practical Differentiator:



This is inverting op-amp: $\dfrac{V_{0(s)}}{V_{i(s)}} = -\dfrac{Z_f}{Z_i} = -\dfrac{SR_fC_1}{(1+SRf(f))(1+SC_1R_1)}$

For $R_fC_f = R_1C_1$, we get $\dfrac{V_{0(S)}}{V_{i(S)}} = -\dfrac{SR_fC_1}{(1+SR_1C_1)^2} = -\dfrac{SR_fC_1}{\left(1+j\dfrac{f}{f_b}\right)^2}$

Where, $\boxed{f_b = \dfrac{1}{2\pi R_1C_1}}$