Chapter 15. Operational Amplifier > SOLVED PROBLEMS

15.17. SOLVED PROBLEMS

1. The output of an op-amp integrator can swing from +15 V to −15 V. The step input shown in **Fig. 15.100(a)** is v_i = 0 for t < 0 and switched at t = 0 to 5 V. The output voltage v_o = +15 V for t < 0. Plot the waveform.

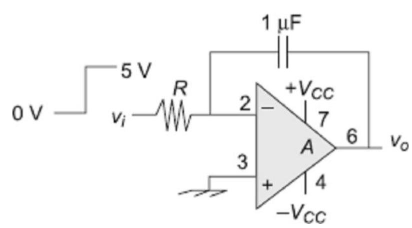
Solution:

$$v_o = -\frac{1}{RC}\int v_i\,dt + C = -\frac{v_i}{RC}t + C$$

At $t \le 0$, $v_i = 0$ and $v_o = +15$ V, $v_o = 15$

$$= -\frac{v_i}{RC} * 0 + C$$

Figure 15.100(a). Figure 15.100(a)



$$0 = -\frac{v_i}{RC}t + 15 \text{ and}$$

$$t = \frac{15}{v_i}RC = \frac{15}{5}1\,\text{K} \times 10^{-6} = 3\text{ ms}$$

The time at wich the v_o = −15

$$= -\left(\frac{v_i}{RC}\right)t + 15$$

$$t = \frac{30}{v_i}RC = \frac{30}{5}1\,\text{K} \times 10^{-6} = 6\text{ ms}$$

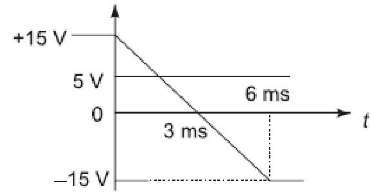
Solution:

Writing node equations at node $v(-)$ of A_1

$$v_1\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = \frac{v_2}{R_3} + \frac{v_3}{R_1}$$

$$C = 15\text{V},\ v_o = -\frac{v_i}{RC}t + 15,$$

Figure 15.100(b). Figure 15.100(b)



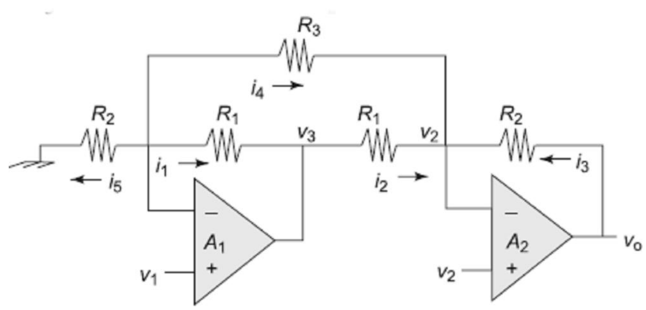
Now the waveform is plotted as in **Fig. 15.100(b)**.

2. For the instrumentation amplifier shown in **Fig. 15.101**, using two ideal op-amps verify the following equation

(GKP Univ. 1994).

$$v_o = \left(1 + \frac{R_2}{R_1} + \frac{2R_2}{R_3}\right)(v_2 - v_1)$$

Figure 15.101. Two op-amp instrumentation amplifier



At node $v_{(-)}$ of A_2

At node $v_{(-)}$ of A_2

$$v_2\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = \frac{v_o}{R_2} + \frac{v_3}{R_1} + \frac{v_1}{R_3}$$

Subtracting this equation from previous one yields

$$\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)(v_1 - v_2) + \frac{1}{R_3}(v_1 - v_2)$$

$$= -\frac{v_o}{R_2}$$

$$\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{2}{R_3}\right)(v_1 - v_2) = \frac{-v_0}{R_2}$$

Solution:

From **Fig. 15.102**

$$v_{o2}^{*} = \frac{KR_2 v_{o2}}{KR_2 + R_2} = \frac{Kv_{o2}}{K+1}$$

$$v_{o1} = v_1 + aR_1 i,\ v_{o2} = v_2 - bR_1 i,$$

$$\text{where, } i = \frac{v_1 - v_2}{R}$$

$$v_{o1} = v_1 + a\frac{R_1}{R}(v_1 - v_2)$$

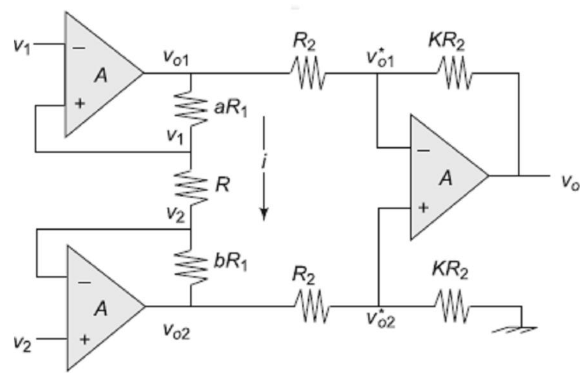
$$= \left(1 + a\frac{R_1}{R}\right)v_1 - a\frac{R_1}{R}v_2$$

$$v_{o2} = v_2 - b\frac{R_1}{R}(v_1 - v_2)$$

$$v_o = \left(1 + \frac{R_2}{R_1} + \frac{2R_2}{R_3}\right)(v_2 - v_1)$$

3. Show that the cross coupled differential voltage follower instrumentation amplifier shown in **Fig. 15.102** produces output voltage $v_o = (1 + a + b)(v_2 - v_1)$.

Figure 15.102. Three op-amp instrumentation amplifier



$$= \left(1 + b\frac{R_1}{R}\right)v_2 - b\frac{R_1}{R}v_1$$

$$v_o = \frac{-KR_2}{R_2}v_{o1} + \left(1 + \frac{KR_2}{R_2}\right)\left(\frac{Kv_{o2}}{1+K}\right)$$

$$= -Kv_{o1} + Kv_{o2} = K(v_{o2} - v_{o1})$$

$$= K\left\{\begin{array}{l}\left(1 + b\frac{R_1}{R}\right)v_2 - b\left(\frac{R_1}{R}\right)v_1 \\ \qquad -\left(1 + a\frac{R_1}{R}\right)v_1 + a\left(\frac{R_1}{R}\right)v_2\end{array}\right\}$$

$$= K\left\{\begin{array}{l}\left(1 + (a+b)\frac{R_1}{R}\right)v_2 \\ \qquad -\left(1 + (a+b)\frac{R_1}{R}\right)v_1\end{array}\right\}$$

$$v_o = (1 + a + b)(v_2 - v_1) \text{ for}$$

$$R = R_1$$

4. Obtain the voltage v_o for the circuit of **Fig. 15.103**. (AMI 1992).

Solution:

Writing node equations as

$$\frac{v_i}{R_1} = -\frac{v_a}{R_2}$$

$$v_a = -\frac{R_2}{R_1} v_i$$

$$\left(\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) v_a = \frac{v_o}{R_3} + \frac{0}{R_2}$$

$$v_o = \left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_4}\right) v_a$$

$$= -\left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_4}\right) \frac{R_2}{R_1} v_i$$

$$\frac{v_O}{v_i} = -\frac{R_F}{R_1} = -\frac{R_2 + R_3 + \frac{R_2 R_3}{R_4}}{R_1}$$

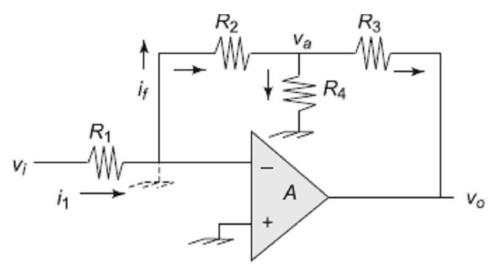
If $R_1 = R_2 = R_3 = 1$ K, $R_4 = 10\ \Omega$,

then $R_F = 2$ K + 1 M/10 = 2 K + 100 K

= 102 K, voltage-gain

$$= A_v = \frac{v_o}{v_i} = -\frac{102\text{ K}}{1\text{ K}} = -102$$

Figure 15.103. Figure 15.103



This illustrates that using only few kilo ohm resistances in the form of *T*-network provides very large feedback resistance resulting into very large gain.

5. Obtain the voltage gain v_o/v_i for **Fig. 15.104(a)**.

Solution:

$$\left(\frac{1}{R} + \frac{1}{R_i + R_1} + \frac{1}{R_F}\right) v_1$$

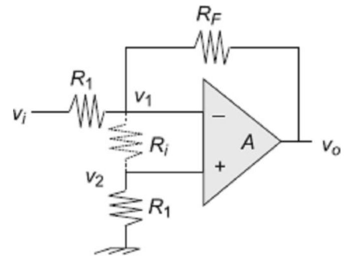
$$= \frac{v_o}{R_F} + \frac{v_i}{R}$$

$$v_2 = \frac{R_1}{R_1 + R_i} v_1$$

$$\text{or } v_2 - v_1 = \frac{R_1}{R_1 + R_i} v_1 - v_1 = -\frac{R_i}{R_1 + R_i} v_1$$

$$\frac{v_O}{A} = v_2 - v_1 = -\frac{R_i}{R_1 + R_i} v_1$$

Figure 15.104(a). Figure 15.104(a)



Combining above equations yield

$$-\frac{v_o}{A}\times\frac{R_i+R_1}{R_i}\times\frac{(R_i+R_1)(R+R_F)+RR_F}{RR_F(R_i+R_1)}-\frac{v_o}{R_F}=\frac{v_i}{R}$$

$$\frac{v_i}{R}=-\frac{(R_i+R_1)(R+R_F)+RR_F+ARR_i}{ARR_FR_i}v_o$$

Hence,

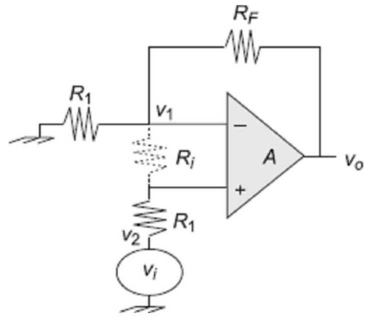
$$\frac{v_o}{v_i}=-\frac{AR_FR_i}{(R_i+R_1)(R+R_F)+RR_F+ARR_i}$$

6. Obtain the voltage gain v_o/v_i for **Fig. 15.104(b)**.

Solution:

$$v_1\left(\frac{1}{R}+\frac{1}{R_1+R_i}+\frac{1}{R_F}\right)$$
$$=\frac{v_o}{R_F}+\frac{v_i}{R_i+R_1}$$
$$v_2=v_i+(v_1-v_i)\left(\frac{R_1}{R_1+R_i}\right)$$
$$=v_1\left(\frac{R_1}{R_1+R_i}\right)+v_i\left(\frac{R_i}{R_1+R_i}\right)$$
$$v_2-v_1=-\frac{R_i}{R_1+R_i}v_1+\frac{R_i}{R_1+R_i}v_i$$
$$=\frac{R_i}{R_1+R_i}(v_i-v_1)$$
$$\frac{v_o}{A}=(v_2-v_1)=(v_i-v_1)\frac{R_i}{R_i+R_1},$$
$$\frac{R_i+R_1}{R_i}\left(\frac{v_o}{A}\right)=(v_i-v_1)$$
$$v_1=-\left(\frac{v_o}{A}\right)\left(\frac{R_i+R_1}{R_i}\right)+v_i$$
$$\left(\frac{v_o}{A}\right)\frac{R_i+R_1}{R_i}$$

Figure 15.104(b). Figure 15.104(b)



$$\times \frac{(R_i + R_1)(R + R_F) + RR_F}{RR_F(R_i + R_1)}$$
$$+ \frac{(R_i + R_1)(R + R_F) + RR_F}{RR_F(R_i + R_1)} v_i$$
$$= \frac{v_o}{R_F} + \frac{v_i}{R_i + R_1}$$
$$- \frac{(R_i + R_1)(R + R_F) + RR_F + ARR_i}{ARR_F R_i} v_o$$
$$= - \frac{(R_i + R_1)(R + R_F)}{RR_F(R_i + R_1)} v_i$$

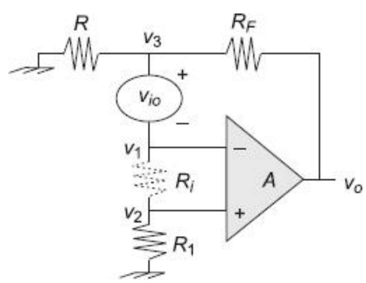
Hence, $\frac{v_o}{v_i}$

$$= - \frac{AR_i(R + R_F)}{(R_i + R_1)(R + R_F) + RR_F + ARR_i}$$

7. Obtain the voltage gain v_o/v_{io} for **Fig. 15.105**.

Solution:

Figure 15.105. Figure 15.105



$$\frac{v_3 - v_{io}}{R_i + R_1} + \frac{v_3}{R} + \frac{v_3 - v_o}{R_F} = 0$$
$$v_3 \left(\frac{1}{R_i + R_1} + \frac{1}{R} + \frac{1}{R_F} \right)$$
$$= \frac{v_{io}}{R_i + R_1} + \frac{v_o}{R_F}$$
$$\frac{RR_F + (R_i + R_1)(R + R_F)}{(R_i + R_1)RR_F} v_3$$

$$= \frac{v_{io}}{R_i + R_1} + \frac{v_o}{R_F}$$

$$v_1 = v_3 - v_{io} \text{ and } v_2 = \frac{v_3 - v_{io}}{R_i + R_1} R_1$$

$$\frac{v_o}{A} = v_2 - v_1 = \frac{v_3 - v_{io}}{R_i + R_1} R_i - v_3 + v_{io}$$

$$v_3 = -\frac{R_i + R_1}{R_i} \times \frac{v_o}{A} + v_{io}$$

$$\left(v_{io} - \frac{v_o}{A} \times \frac{R_i + R_1}{R_i} \right)$$

$$\frac{RR_F + (R + R_F)(R_i + R_1)}{(R_i + R_1)RR_F}$$

$$= \frac{v_o}{R_F} + \frac{v_{io}}{R_i + R_1}$$

$$\frac{v_o}{v_{io}} = \frac{A(R + R_F)R_i}{ARR_i + RR_F + (R + R_F)(R_i + R_1)}$$

8. Prove that the voltage gain and input resistance with feedback in **Fig. 15.106** is given by the expressions $A_{vf} = -\frac{AR_F}{R_1(1+A) + R_F}$ and $R_{if} = \left\{ R_1 + \frac{R_F}{1+A} \right\} || R_i$, where R_i is the internal input resistance of the op-amp

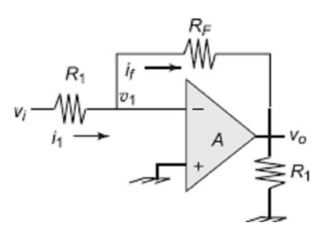
Solution:

$$i_1 = \frac{v_i - v_1}{R_1} = i_f = \frac{v_1 - v_o}{R_F}$$

$$\frac{v_i}{R_1} + \frac{v_o}{R_F} = \left(\frac{1}{R_1} + \frac{1}{R_F} \right) v_1$$

$$\text{and } v_o = -Av_1$$

Figure 15.106. Figure 15.106



$$\frac{v_i}{R_1}+\frac{v_o}{R_F}=\left(\frac{1}{R_1}+\frac{1}{R_F}\right)v_1$$

$$=-\left(\frac{1}{R_1}+\frac{1}{R_F}\right)\frac{v_o}{A},$$

$$\frac{v_i}{R_1}=-\frac{v_o}{R_F}-\left(\frac{1}{R_1}+\frac{1}{R_F}\right)\frac{v_o}{A}$$

$$=-\frac{(1+A)R_1+R_F}{AR_1R_F}v_o$$

$$A_{vf}=\frac{v_o}{v_i}=-\frac{AR_F}{(1+A)R_1+R_F}$$

$$v_i-v_1=R_1i_1$$

$$v_i+\frac{v_o}{A}=R_1i_1=v_i-\frac{AR_Fv_i}{A\{(1+A)R_1+R_F\}}$$

$$R_1i_1=\frac{(1+A)R_1+R_F-R_F}{(1+A)R_1+R_F}v_i$$

$$=\frac{(1+A)R_1}{(1+A)R_1+R_F}v_i$$

$$R_{if}=\frac{v_i}{i_1}=\frac{(1+A)R_1+R_F}{(1+A)R_1}R_1$$

$$=R_1+\frac{R_F}{(1+A)}$$

This input resistance comes in parallel to the op-amp's internal input resistance R_i.

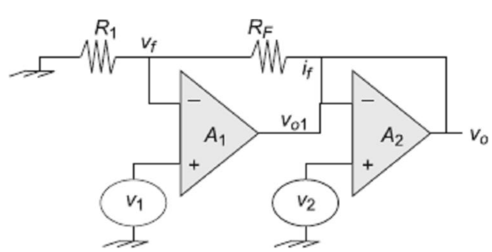
Hence, effective input resistance is equal to $R_{if}=\left\{R_1+\frac{R_F}{(1+A)}\right\}\|R_i$.

9. Show that if $R_i = \infty$, $R_o = 0$ and A_1 and $A_2 < 0$ in **Fig. 15.107**, then $v_o = A_2\{A_1(v_f - v_1) + v_2\}$.

$$\text{where } v_f=v_o\left(\frac{R_1}{R_1+R_F}\right). \text{ If } \frac{A_1A_2R_1}{R_1+R_F}>>1,$$

$$\text{then } v_o=\left(1+\frac{R_F}{R_i}\right)\left(v_1-\frac{v_2}{A_1}\right).$$

Figure 15.107. Figure 15.107



Solution:

The output of first op-amp is expressed as $(v_1 - v_f)\,A_1 = V_{o1}$

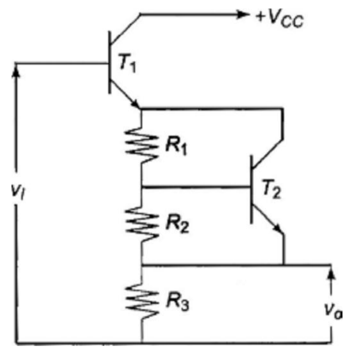
The output of the second op-amp is

$$v_o = A_2(v_2 - v_{o1}) = A_2\{v_2 - A_1(v_1 - v_f)\}$$
$$= A_2\{A_1(v_f - v_1) + v_2\}$$

$$\text{Also, } v_f = \frac{R_1}{R_1 + R_F} v_o$$

$$v_o = A_2 \left\{ A_1 \left(\frac{R_1}{R_1 + R_F} v_o - v_1 \right) + v_2 \right\}$$

Figure 15.108(a). Figure 15.108(a)



$$v_o - A_2 A_1 \left(\frac{R_1 v_o}{R_1 + R_F} \right) = -A_2(A_1 v_1 - v_2)$$

$$\frac{\{(1 - A_2 A_1) R_1 + R_F\} v_o}{R_1 + R_F} = A_2(v_2 - A_1 v_1)$$

$$v_o = \frac{R_1 + R_F}{R_1} \times \left(v_1 - \frac{v_2}{A_1} \right)$$

$$= \left(1 + \frac{R_F}{R_1} \right) \left(v_1 - \frac{v_2}{A_1} \right)$$

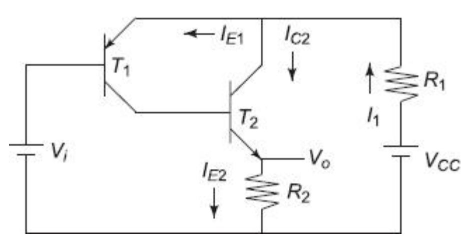
10. For the dc level shifter circuit shown in **Fig. 15.108(a)**, determine the level shift between input and output voltages.

Solution:

$$V_i = V_{BE1} + V_{R_1} + V_{R_2} + V_o,$$

$$V_{BE2} = V_{R_2} = \frac{V_{E_1E_2}}{R_1 + R_2} R_2$$

Figure 15.108(b). Figure 15.108(b)



$$V_o = V_i - V_{BE1} - V_{E1E2}$$
$$= V_i - V_{BE1} - \left(1 + \frac{R_1}{R_2}\right) V_{BE2}$$
$$V_{BE1} = V_{BE2} = V_{BE}$$
$$V_o = V_i - V_{BE}\left(1 + 1 + \frac{R_1}{R_2}\right)$$
$$= V_i - V_{BE}\left(2 + \frac{R_1}{R_2}\right)$$

11. Obtain the level shift V_o in **Fig. 15.108(b)**.

Solution:

$$I_1 = I_{E1} + I_{C2} = I_{C1} + I_{B1} + I_{C2}$$
$$= I_{C1} + I_{B1} + \beta I_{B2}$$
$$= I_{C1} + I_{B1} + \beta I_{C1}$$
$$= I_{B1} + (1 + \beta) I_{C1} \cong (1 + \beta) I_{C1}$$
$$V_{CC} = I_1 R_1 + V_{BE1} + V_i = R_1(1 + \beta) I_{C1}$$
$$+ V_{BE1} + V_i$$
$$I_{C1} = \frac{V_{CC} - V_i - V_{BE1}}{(1 + \beta) R_1}$$
$$V_o = R_2 I_{E2} = R_2(1 + \beta) I_{B2}$$
$$= R_2(1 + \beta) I_{C1}$$
$$= \frac{(V_{CC} - V_i - V_{BE1})(1 + \beta) R_2}{(1 + \beta) R_1}$$
$$V_o = \frac{(V_{CC} - V_i - V_{BE1}) R_2}{R_1}$$

12. Draw the output wave shapes of the voltage follower using op-amp with 1 V/ms slew rate with the square wave input shown in **Fig. 15.109(a)**.

Solution:

It is seen from the wave shapes of v_o that remarkable distortion occurs for slew rate at high frequency. **Fig. 15.109(b)** is100 Hz signal that does not produce appreciable distortion. A 10 kHz signal produces appreciable distortion as shown in **Fig. 15.109(c)**. A 1 MHz signal becomes sawtooth wave as in **Fig. 15.109(c)**.

Figure 15.109(a). Figure 15.109(a)

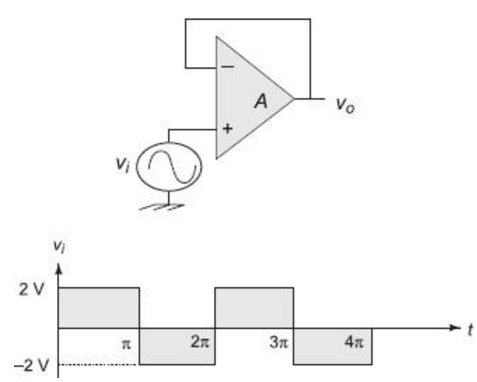


Figure 15.109(b). Figure 15.109(b)

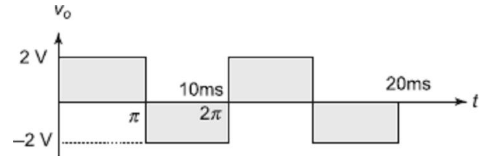
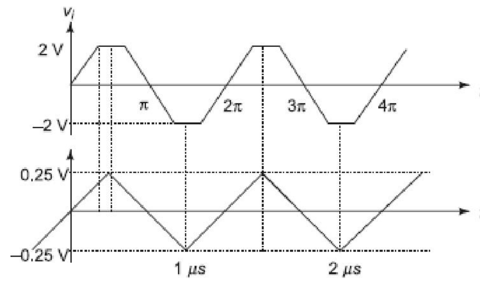


Figure 15.109(c). Figure 15.109(c)

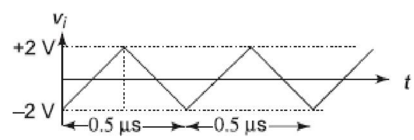


13. A square wave input of 8 V peak to peak magnitude and frequency 2 MHz is applied to a voltage follower which produces the triangular output as shown in **Fig. 15.110**. What is its slew rate?

Solution:

$$\text{SR} = \frac{4\text{ V}}{(0.5/2)\,\mu s} = 16\text{ V}/\mu\text{s}$$

Figure 15.110. Figure 15.110



14. The 741 op-amp is used as an inverting amplifier with its gain = 50. What would be the maximum input signal magnitude applied to it if its voltage gain is flat upto 100 kHz?

Solution:

$$\text{Slew rate of the } 741 = 0.5\text{ V}/\mu\text{s},$$

$$SR = 2\pi f V_m = \frac{2\pi f V_{i(\text{pp})}}{10^6},$$

$$V_{i(\text{pp})} = \frac{SR\,(V/\mu s)\times 10^6}{6.28\times 100\times 10^3} = \frac{0.5\times 10}{6.28}$$

$$= 0.796\text{ V}$$

The maximum input signal to get undistorted output should be $= \dfrac{0.796}{50}$ = 15.9 mV.

15. A peak to peak input signal of 500 mV has to produce a peak to peak undistorted output voltage of 3 V with a rise time of 4 ms. Can 741 be used for such application?

Solution:

Rise time = 3 V (90% − 10%) = 3 V (0.90 − 0.10) = 2.4 V

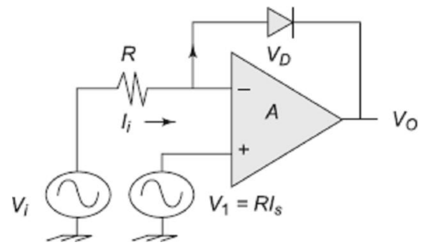
$$SR = \frac{2.4}{4\mu s} = 1.8\text{ V}/\mu\text{s}$$

The 741 cannot be used.

16. The characteristic of the diode is given by the relationship as $I_D = I_S(e^{qV/\eta KT} - 1)$, where V is the forward voltage and η is the ideality factor = 1 (Ge) and 2 (Si). Express V_o as a function of V_i. What is the value of input voltage to result in output voltage V_o

$= 0$, if $R = 100\ K\Omega$, $I_S = 1\ \mu A$ and $\frac{KT}{q} = 26$ mV.

Figure 15.111. Figure 15.111



$$e^{qV/KT} = \frac{I_D}{I_S} + 1,\ V = \frac{KT}{q}\ln\left(\frac{I_D}{I_S} + 1\right)$$

$$= 0.026\ln\left(\frac{I_D}{I_S} + 1\right)$$

$$V_D = 0.026\left[\ln\left(\frac{I_D}{I_S}\right) + \ln 1\right]$$

$$= 0.026\left[\ln\left(\frac{I_D}{I_S}\right) + 0\right]$$

$$V_O = V_D = 0.026\ln\left(\frac{I_D}{I_S}\right),\ I_D = \frac{V_i}{R} = I_i$$

$$\text{(a) } V_O = V_D = 0.026\ln\left(\frac{V_i}{RI_S}\right) = 0$$

$$= \ln\left(\frac{V_i}{RI_S}\right) = \ln 1,$$

$$V_i = RI_s = 10^5 \times 10^{-6} = 0.1\text{ V}$$

17. In the circuit of **Fig. 15.112** the output voltage V_o is initially zero. The switch is connected first to *A* to charge the capacitor C_1 to the voltage *V*. It is then connected to point *B*. This process repeats *f* times per second. Calculate (a) transfer of charge per second from *A* to *B*, (b) Derive the average rate of change of the output voltage V_o, (c) If the switch and capacitor are removed and a resistor is connected between point *A* and *B*, what will be the value of resistor to get the same average rate of change the output voltage, (d) If the repetition rate of the switching action is 10^4 times per second, $C_1 = 100$ pF, $C_2 = 10$ pF and $V = 10$ mV, what is the average rate of change of the output voltage?

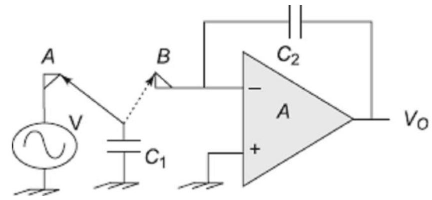
Solution:

(a) When the switch changes from *B* to *Af* times per second, the charge transferred to the capacitor $C_1 = Qf = C_1Vf$. The capacitor charges exponentially, but the time constant of charging is zero and hence capacitor charges instantaneously.

$$V = V_{SS}(1 - e^{-t/RC}) = V_{SS}(1 - e^{-t/0})$$

$$= V_{SS} = \frac{Q}{C_1}$$

Figure 15.112. Figure 15.112



(b)

$$i = -C_2 \frac{dV_o}{dt}, \frac{dV_o}{dt} = -\frac{i}{C_2},$$

$$dV_O = -\frac{idt}{C_2} = -\frac{Q}{C_2} = -\frac{C_1 Vf}{C_2}$$

(c)

$$i = V/R, dV_o = -\frac{idt}{C_2} = -\frac{Vdt}{RC_2}$$

$$= -\frac{V}{RC_2} \text{ in one second}$$

Equating dV_o yields as $-\frac{V}{RC_2} = -\frac{C_1 Vf}{C_2}, \; R = \frac{1}{C_1 f}$,

The integration of the steady input voltage gives ramp (rate of change) voltage.

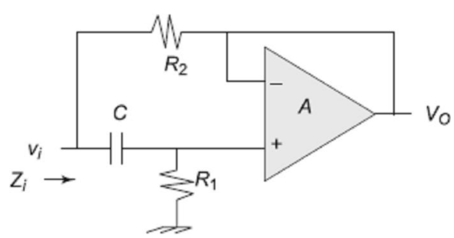
(d)

$$dV_o = -\frac{C_1 Vf}{C_2}$$

$$= -10 \times 10^{-3} \times 10^4 \frac{100}{10} = -1000 \text{ V}$$

18. Show that the circuit in **Fig. 15.113** simulates an inductance across its input terminals.

Figure 15.113. Figure 15.113



Solution:

$$i_i = \frac{v_i - v_o}{R_2} + SC(v_i - v_+) \text{ , } v_+ = v_o$$

$$\text{(as unity gain)}, \ v_+ = \frac{SCR_1 v_i}{1+SCR_1}$$

$$i_i = \left(\frac{1}{R_2}+SC\right)v_i - \left(\frac{1}{R_2}+SC\right)v_+$$

$$= \frac{1+SCR_2}{R_2}v_i - \frac{1+SCR_2}{R_2}v_+$$

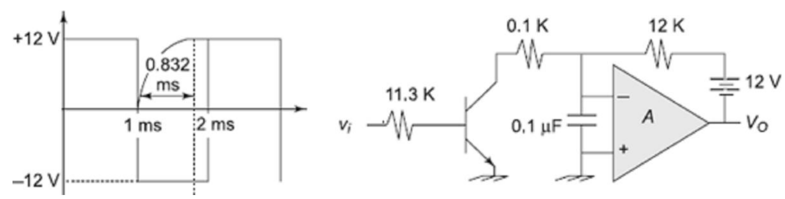
$$= \frac{1+SCR_2}{R_2}v_i - \left(\frac{1+SCR_2}{R_2}\right)\frac{SCR_1}{1+SCR_1}v_i$$

$$= \frac{1+S^2C^2R_1R_2+SC(R_1+R_2) - SCR_1 - S^2C^2R_1R_2}{R_2(1+SCR_1)}v_i$$

$$= \frac{1+SCR_2}{R_2(1+SCR_1)}v_i$$

$$\text{Hence, } Z_i = \frac{v_i}{i_i} = \frac{(1+SCR_1)R_2}{1+SCR_2}$$

Figure 15.114. Figure 15.114



Solution:

When input is changing from −12 V to +12 V, the capacitor gets charged to the maximum voltage exponentially with the time constant = 12 K × 0.1 × 10^{-6} = 1.2 ms. In order to find out the time taken by the capacitor to reach final value = 12 V, we have to see the following expression $V_C = V_F - (V_F - V_i)e^{-t/RC}$,

$$= \frac{(1+j\omega CR_1)R_2}{1+j\omega CR_2}$$

$$= \frac{(1+j\omega CR_1)R_2(1-j\omega CR_2)}{(1+j\omega CR_2)(1-j\omega CR_2}$$

$$= \frac{(1+\omega^2C^2R_1R_2+j\omega C(R_1-R_2)R_2}{1+\omega^2C^2R_2^2}$$

$$= R + j\omega L$$

$$\text{where, } R = \frac{(1+\omega^2C^2R_1R_2)R_2}{1+\omega^2C^2R_2^2},$$

$$\text{and } L = \frac{C(R_1-R_2)R_2}{1+\omega^2C^2R_2^2}$$

19. Draw the waveform of $v_o(t)$ as function of v_i. Specifying the output voltage $v_o(t)$, determine the voltage levels and time constants involved.

$$e^{-t/RC} = \frac{V_F - V_C}{V_F - V_i},$$

$$t = RC\ln\frac{V_F - V_i}{V_F - V_C} = RC\ln\frac{12-(-12)}{12-0}$$

$$= RC \text{ In } 2$$

$$= 12 \times 10^3 \times 0.1 \times 10^{-6} \times 0.693$$

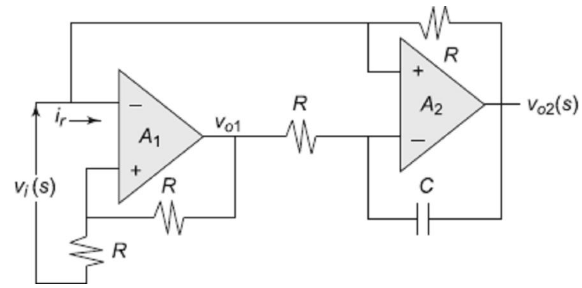
$$= 0.832 \text{ ms}$$

As the capacitor gets charged from −12 V to slightly above 0 V, the output amplifier gets saturated.

When the capacitor is charged to +12 V, the capacitor starts discharging through saturated transistor with a time constant = 100 × 0.1 × 10^{-6} = 0.01 ms

20. Show that circuit of **Fig. 15.115** simulates an inductor i.e. $\frac{v_i(s)}{i_i(s)}$ is inductive.

Figure 15.115. Figure 15.115



Solution:

$$v_{o1} = v_i\left(1+\frac{R}{R}\right) = 2v_i$$

$$v_{o2} = -\frac{1}{CR}\int v_{o1}dt = -\frac{v_{o1}}{SCR} = -\frac{2v_i(s)}{SCR}$$

$$\text{or,}\quad v_{o2} = -i_iR = -\frac{2v_i(s)}{SCR}$$

$$\text{or,}\quad \frac{v_i(s)}{i_i(s)} = SCR^2/2 = j\omega CR^2/2 = j\omega L$$

$$\text{where}\qquad L = CR^2/2$$

21. How much is the output voltage in the circuit of **Fig. 15.116**.

Solution:

Writing node equation at the inverting input terminal of the op-amp results as

$$\frac{v_i - v_-}{5\text{ K}} = \frac{v_- - v_o}{10\text{ K}}\ ,\ \left(\frac{1}{5\text{ K}}+\frac{1}{10\text{ K}}\right)v_-$$

$$= \frac{v_i}{5\text{ K}}+\frac{v_o}{10\text{ K}}$$

$$\text{or, } v_- = \frac{10v_i}{15}+\frac{5v_o}{15} = v_+ \cong \frac{10}{100}v_o$$

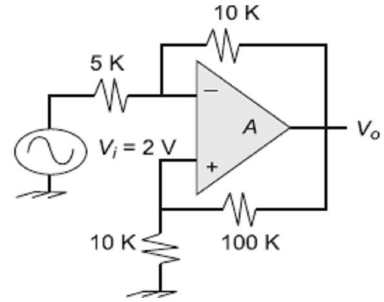
$$\left(\frac{1}{10}-\frac{5}{15}\right)v_o = \left(\frac{15-50}{150}\right)v_o$$

$$= \left(\frac{-35}{150}\right)v_o = \frac{10\times 2}{15}$$

$$v_o = -\frac{10\times 2}{15}\times\frac{150}{35} = -\frac{10\times 2\times 10}{35}$$

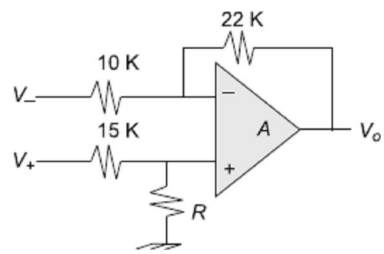
$$= -6.5\text{ V}$$

Figure 15.116. Figure 15.116



22. Obtain the value of resistor R for the condition that both inputs V_- and V_+ should be amplified by the same amount in **Fig. 15.117**.

Figure 15.117. Figure 15.117



$$\text{For } V_- = 0,\ V_O = \left(1 + \frac{22}{10}\right)\frac{R}{R+15}V_-$$

$$= \frac{3.2R}{R+15}V_+$$

$$\text{For } V_+ = 0\ ,\ V_O = -\frac{22}{10}V_- = -2.2\text{ V}$$

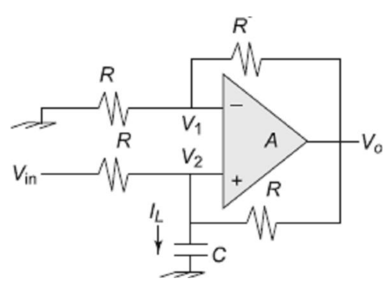
$$\frac{V_O}{V_+} = \frac{3.2R}{R+15} = \frac{V_O}{V_-} = 2.2\ ,$$

$$3.2\text{R} - 2.2\text{R} = 33$$

$$\text{or, } R = 33\text{ K}\Omega$$

23. Derive a relationship between the input and output voltages for the circuit shown in **Fig. 15.118**. Also obtain the output waveform for a symmetrical square wave input voltage of amplitude V_p and frequency f.

Figure 15.118. Figure 15.118



Solution:

$$V_1 = \frac{R}{2R}V_o = \frac{V_o}{2}, \frac{V_{in} - V_2}{R} + \frac{V_o - V_2}{R}$$
$$= I_L, V_1 = V_2$$
$$\frac{V_{in}}{R} - \frac{V_o}{2R} - \frac{V_o}{2R} + \frac{V_o}{R} = I_L$$
$$\text{or, } I_L = \frac{V_{in}}{R} = C\frac{dV_2}{dt}, V_2 = \frac{1}{RC}\int V_{in}dt$$
$$V_o = 2V_2 = \frac{2}{RC}\int V_{in}dt$$

If the input voltage is square wave, the output voltage is a triangular wave of magnitude $\pm V_P$ and frequency *f*.

24. Find out the value of two resistors used in a non-inverting op-amp to result in the voltage gain of 21 dB.

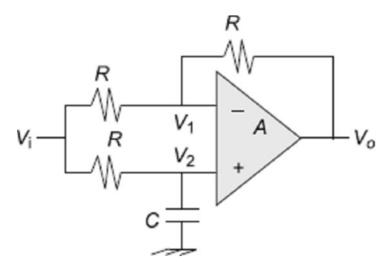
Solution:

$$21\text{dB} = 10^{21/20} = 10^{1.05} = 11.22$$
$$= 1 + \frac{R_2}{R_1}, R_2 = 10.22 R_1$$

If R_1 is selected to be 10 KΩ, R_2 = 102.2 KΩ

25. Obtain the transfer function between input and output voltages of **Fig. 15.119**. What will be the value of the capacitor required to yield a phaseshift of 270° at a frequency of 1 kHz with R = 10 K?

Figure 15.119. Figure 15.119



Solution:

$$v_2 = \frac{v_i / SC}{R + \frac{1}{SC}} = \frac{v_i}{1 + SCR},$$
$$\frac{v_i - v_1}{R} = \frac{v_1 - v_o}{R},$$
$$2v_1 = v_i + v_o$$
$$\frac{v_i + v_o}{2} = \frac{v_i}{1 + SCR},$$
$$v_o + v_i = \frac{2v_i}{1 + SCR},$$
$$v_o = \frac{2v_i}{1 + SCR} - v_i$$
$$v_o = \frac{(2 - 1 - SCR)v_i}{1 + SCR} = \frac{(1 - SCR)v_i}{1 + SCR}$$

$$\text{or, } \frac{v_o}{v_i} = \frac{1 - SCR}{1 + SCR} = \frac{1 - j\omega CR}{1 + j\omega CR}$$

$$= \frac{\sqrt{1 + (\omega CR)^2}}{\sqrt{1 + (\omega CR)^2}} = 1$$

$$\text{Phase shift} = -\tan^{-1} \omega CR - \tan^{-1} \omega CR$$

$$= -2 \tan^{-1} \omega CR = 270°$$

$$\text{or, } -\tan^{-1} \omega CR = 135°, \tan 135 = -1$$

$$= -\omega CR$$

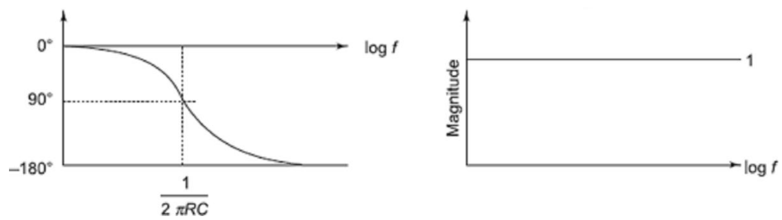
$$C = \frac{1}{2\pi \times 1000 \times 10\text{K}} = \frac{0.159}{10^7}$$

$$= 0.159 \times 10^{-7}$$

$$C = 0.159 \times 10^{-7} = 0.0159\ \mu\text{F}$$

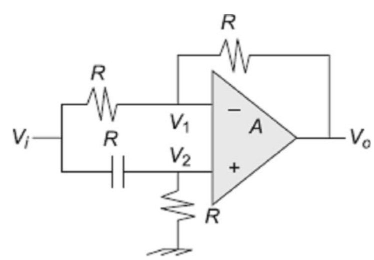
The plots of magnitude and phase shift are shown in **Fig. 15.120**.

Figure 15.120. Phase and magnitude plot of given circuit



26. Obtain the transfer function between input and output voltages of **Fig. 15.121**.

Figure 15.121. Figure 15.121



Solution:

$$v_2 = \frac{v_i R}{R + \frac{1}{SC}} = \frac{v_i SCR}{1 + SCR}, \frac{v_i - v_1}{R}$$

$$= \frac{v_1 - v_o}{R}, 2v_1 = v_i + v_o$$

$$\frac{v_i + v_o}{2} = \frac{v_i SCR}{1 + SCR},$$

$$v_o + v_i = \frac{2v_i SCR}{1 + SCR},$$

$$v_o = \frac{2v_i SCR}{1 + SCR} - v_i$$

$$= \frac{(2SCR - 1 - SCR)v_i}{1 + SCR}$$

$$= \frac{(SCR - 1)v_i}{1 + SCR}$$

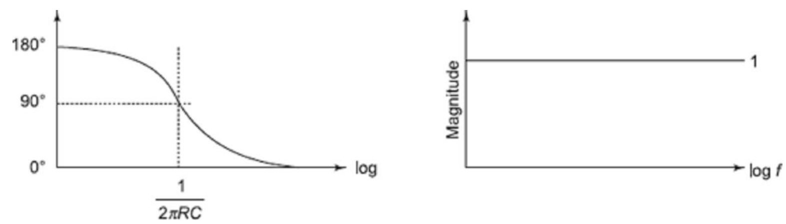
$$\text{or, } \frac{v_o}{v_i} = \frac{SCR - 1}{1 + SCR} = \frac{-1 + j\omega CR}{1 + j\omega CR}$$

$$= -\frac{\sqrt{(-1)^2 + (\omega CR)^2}}{\sqrt{1+(\omega CR)^2}} = 1$$

Phase shift = 180° − $\tan^{-1} \omega CR$ − $\tan^{-1}\omega CR$ = 180° − 2 $\tan^{-1} \omega CR$

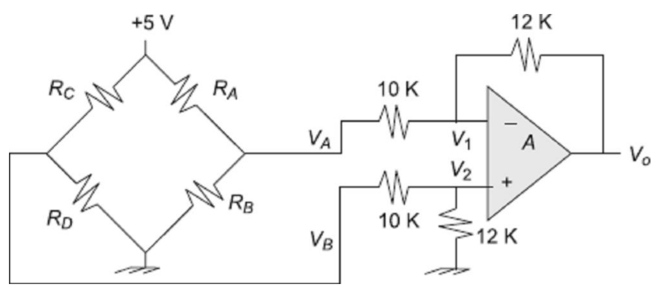
The plots of its magnitude and phase-shift are shown in **Fig. 15.122**.

Figure 15.122. Phase and magnitude plot of given circuit



27. What value of the resistance R_B will provide balance of the bridge yielding V_o = 0 for R_A = R_C = R_D = 1 KΩ. What will be the value of output voltage, if now R_B is set to 0.5 K?

Figure 15.123. Figure 15.123



Solution:

$$V_B = \frac{5VR_D}{R_C + R_D} = 2.5 \text{ V}$$

$$V_A = \frac{5VR_B}{R_A + R_B} = \frac{5VR_B}{1\text{K} + R_B}$$

$$V_2 = \frac{V_B 12}{12+10} = \frac{12V_B}{22}$$

$$\frac{V_A}{10} + \frac{V_o}{12} = V_1\left(\frac{1}{10\text{ K}} + \frac{1}{12\text{ K}}\right)$$

$$V_1 = \frac{12V_A}{22} + \frac{10V_o}{22} = \frac{12V_B}{22},\ 10V_o$$

$$= 12(V_B - V_A)\ ,\ V_o = 1.2\ (V_B - V_A),$$

For the condition $V_o = 0$

$$= 1.2\left(2.5 - \frac{5R_B}{R_A + R_B}\right),\ R_A + R_B = 2R_B,$$

$$R_A = R_B = 1\ \text{K}\Omega$$

$$V_O = 1.2\left(2.5 - \frac{5 \times 0.5}{1.5}\right) = 1.2(2.5 - 1.67)$$

$$= 0.996 \text{ V}$$

28. Sketch the waveform of the output voltage for the circuit of **Fig. 15.124**. What portion of the current i_o coming out from the operational amplifier flow as the load current i_L?

Solution:

$$\text{For } V_{in} = 0,\ V_o = \frac{-10 \times 12}{120} = -1\ \text{V},$$

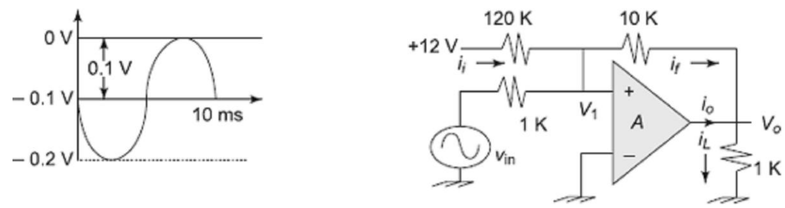
$$T = \frac{1}{100} = 10\ \text{ms}$$

$$V_{in} = 12 = 0,$$

$$V_o = \frac{-10 \times 0.1 \cos 2\pi \times 100t}{1}$$

$$= -1(\cos 2\pi \times 100t)V$$

Figure 15.124. Figure 15.124



$$i_L = \frac{v_o}{R_L} = i_o + i_f = i_o + \frac{v_o}{R_F},$$

$$i_o = \frac{V_o}{R_L} - \frac{V_o}{R_F} = \frac{V_o}{1\text{K}} - \frac{V_o}{10\text{K}} \cong \frac{V_o}{R_L}$$

$$i_o = \frac{V_o}{R_L} = \frac{R_F i_f}{R_L}$$

$$= \frac{R_F}{R_L} \times \frac{V_i}{R_1}$$

$$= \frac{10\text{K}}{1\text{K}} \times \frac{12}{120\text{K}} = 1\ \text{mA (max)},$$

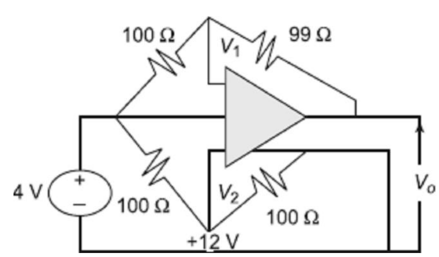
$$i_i = \frac{12}{120\text{K}} = 0.1\ \text{mA} = i_f,$$

$$i_L = i_o - i_f = 1\ \text{mA} - 0.1\ \text{mA} = 0.9\ \text{mA}$$

Hence, i_o = 1mA cos $2\pi \times 100t$, now $i_L = i_o$ (max) − i_f = 1 mA − 0.1 mA = 0.9 mA
Hence, total i_L(max) = 0.9 mA + 0.9 mA = 1.8 mA.

29. Determine the output voltage v_o for the circuit shown in **Fig. 15.125**.

Figure 15.125. Figure 15.125



Solution:

$$V_2 = \frac{4V \times 100}{200} = 2\ \text{V},\ \frac{V_I - V_1}{100} = \frac{V_1 - V_0}{99}$$

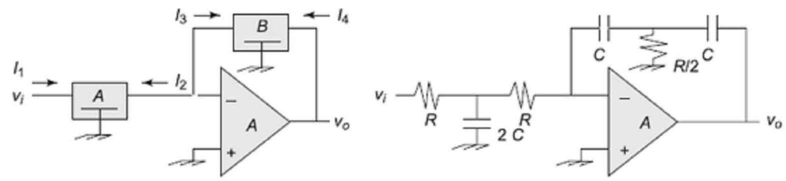
$$V_1\left(\frac{1}{100} + \frac{1}{99}\right) = \frac{4}{100} + \frac{V_o}{99}$$

$$\text{or, } V_1 = \frac{4 \times 99}{199} + \frac{V_o \times 100}{199} = 2\ \text{V}$$

or, V_o = (2 − 1.99)1.99 = 0.02 V

30. Show that the system shown in **Fig. 15.126** is a double integrator. In other words, prove that the transfer gain is given by $\frac{v_o}{v_i} = \frac{-1}{C^2R^2S^2}$, assume an ideal op-amp.

Figure 15.126. Figure 15.126



Solution:

$$I_2 + I_3 = 0,\ Y_{21A} = \frac{I_2}{V_i},\ I_2 = Y_{21A}V_i,$$

$$\frac{I_3}{V_o} = Y_{12B},$$

$$I_3 = Y_{12B}V_o,\ V_iY_{21A} + V_oY_{12B} = 0$$

$$\text{or, } \frac{V_O}{V_i} = -\frac{Y_{21A}}{Y_{12B}}.\ \text{In } T\text{-network, } Z_1$$

and Z_2 are series elements and Z_1 is shunt element.

$$Y_{12} = Y_{21} = -\frac{Z_3}{\Delta Z}$$

$$= -\frac{Z_3}{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}$$

Now,

$$Y_{21A} = -\frac{1/2SC}{R^2 + \frac{R}{2SC} + \frac{R}{2SC}}$$

$$= -\frac{1/2SC}{R^2 + \frac{2R}{2SC}} = -\frac{1}{2R(SCR+1)}$$

$$Y_{12B} = -\frac{R/2}{\frac{1}{S^2C^2} + \frac{R}{2SC} + \frac{R}{2SC}}$$

$$= -\frac{R/2}{\frac{1}{S^2C^2} + \frac{R}{SC}} = -\frac{R/2}{\frac{1+SCR}{S^2C^2}}$$

$$= -\frac{RS^2C^2}{2(1+SCR)}$$

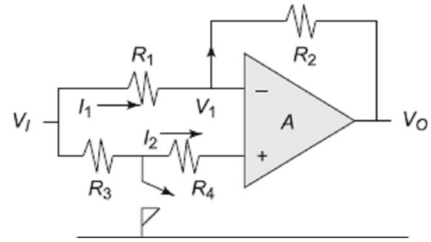
$$\text{Hence, } \frac{V_O}{V_i} = -\frac{Y_{21A}}{Y_{12B}}$$

$$= -\frac{2(SCR+1)}{2R(SCR+1)RS^2C^2} = -\frac{1}{R^2S^2C^2}$$

31. Obtain the voltage transfer function between output and input voltages of **Fig. 15.127**. When switch is open, the opamp does not draw any current and hence $I_2 = 0$.

Solution:

Figure 15.127. Figure 15.127



$$\frac{V_i - V_1}{R_1} = \frac{V_1 - V_O}{R_2},\ V_1 = \frac{V_i R_2}{R_1 + R_2}$$

$$+ \frac{V_O R_1}{R_1 + R_2}$$

$$V_1 = V_i = \frac{V_i R_1}{R_1 + R_2} + \frac{V_O R_1}{R_1 + R_2}$$

$$\frac{V_i(R_1 + R_2 - R_2)}{R_1 + R_2} = \frac{V_O R_1}{R_1 + R_2}$$

$$\text{or, } \frac{V_O}{V_i} = \frac{R_1}{R_1} = 1.$$

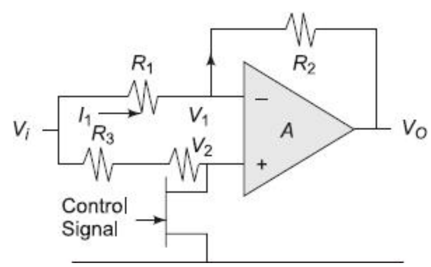
When the switch is closed, the non-inverting input terminal is pulled to ground and hence its gain

$$= -\frac{R_2}{R_1}.$$

32. Obtain voltage gain under the control of voltage applied at the gate of the JFET in **Fig. 15.128**. When control signal = 0, the JFET offers minimum drain resistance and hence non-inverting input terminal is pulled to approximately ground. Thus, $\frac{V_O}{V_i} = -\frac{R_2}{R_1}.$.

Solution:

Figure 15.128. Figure 15.128



When the control signal is high, it reduces the channel width and provides very large resistance to provide open circuit, thus $V_1 = V_2 = V_i$.

$$\text{Hence, } \frac{V_O}{V_i} = \frac{R_1}{R_1} = 1.$$

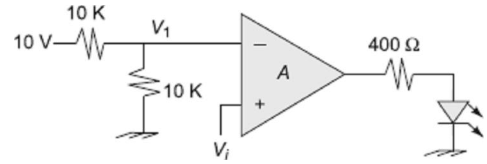
33. Find the condition of input voltage for making the LED ON in **Fig. 15.129**.

Solution:

$$V_1 = \frac{10 \times 10}{20} = 5\text{ V}.$$

Hence, LED will glow if $V_i > 5$ V.

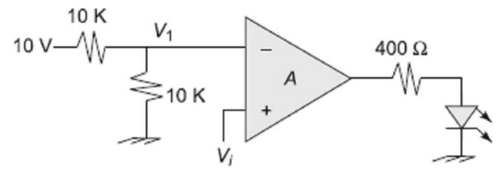
Figure 15.129. Figure 15.129



34. What will be the value of input voltage V_i such that the LED in **Fig. 15.130** starts glowing.

LED will glow if V_i > 5 V.

Figure 15.130. Figure 15.130



35. An op-amp with a slew rate of 1.5 V/ms has been used as an inverting amplifier with gain of 10. What is the maximum input signal if the frequency of input signal is 1 kHz?

$$\omega_{\max} = \frac{MSR}{V_m},\ V_m = \frac{MSR}{\omega_{\max}}$$

$$= \frac{1.5}{10^{-6} \times 2\pi \times 1\,\mathrm{K}} = \frac{0.159 \times 1.5}{10^{-3}}$$

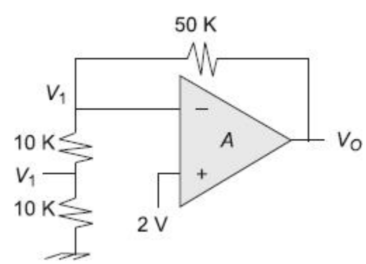
$$= 0.2385 \times 10^3.$$

36. Calculate the voltages V_1 and V_O in **Fig. 15.131**.

$$V_1 = \frac{2 \times 10}{20} = 1\ \mathrm{V}\ ,\ V_O = \left(1 + \frac{50}{20}\right) 2\ \mathrm{V}$$

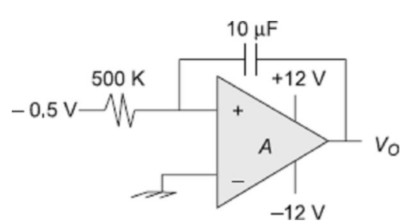
$$= 7\ \mathrm{V}$$

Figure 15.131. Figure 15.131



37. When will the output get saturated in **Fig. 15.132**?

Figure 15.132. Figure 15.132



$$V_o = -\frac{1}{RC}\int (-0.5)dt = 12 = \frac{0.5}{5}\int dt,$$

$$t = 120\ \mathrm{s}.$$

38. The switch was closed initially for 0.5 minutes and then opened. What will be the input voltage if the output in **Fig. 15.133** is initially 0 and −5.4 V after the switch is opened.

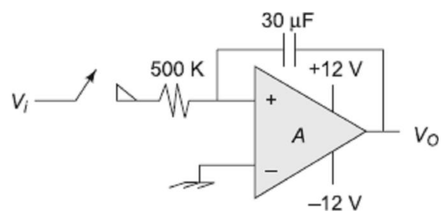
$$V_o = -\frac{1}{RC}\int V_i dt = -\frac{V_i}{RC}t = -5.4$$

$$= -\frac{V_i}{500\times 10^3\times 30\times 10^{-6}}30$$

$$= -\frac{V_i}{5\times 3}30 = -2V_i$$

$$\text{or, } V_i = \frac{5.4}{2} = 2.7 \text{ V}$$

Figure 15.133. Figure 15.133



39. A differential amplifier converted to difference amplifier has feedback and input resistor of equal values as in **Fig. 15.134**. What will be the output, if inputs to inverting and non-inverting terminals are 1.5sin *ωt* and 1.5 cos *ωt*.

Solution:

$$V_o = V_2 - V_1 = 1.5\cos\,\omega t - 1.5\sin\,\omega t$$

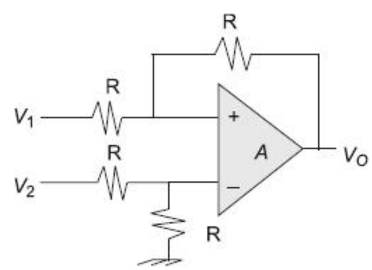
$$= 1.5(\cos\,\omega t - \sin\,\omega t)$$

$$= 1.5\times\sqrt{2}(\frac{1}{\sqrt{2}}\cos\omega t - \frac{1}{\sqrt{2}}\sin\omega t)$$

$$= 1.5\times\sqrt{2}(\cos\frac{\pi}{4}\cos\omega t - \sin\frac{\pi}{4}\sin\omega t)$$

$$= 2.12\cos\left(\omega t + \frac{\pi}{4}\right)$$

Figure 15.134. Figure 15.134

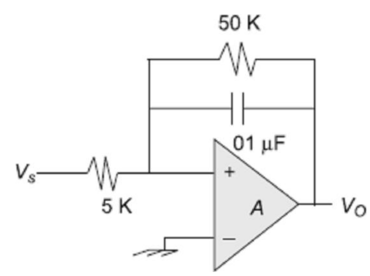


40. The integrator shown in **Fig. 15.135** produces an output voltage = $V_o = V_m \sin(100t + \varphi)$ in response to an input voltage of $V_i = 0.1\sin(100t)$. What is the maximum value of the output voltage?

$$A_{vCL} = -\frac{R_2/(SCR_2+1)}{5K}$$
$$= -\frac{50K}{5K(SCR_2+1)} = -\frac{10}{(SCR_2+1)}$$
$$= -\frac{10}{(j100\times 0.1\times 10^{-6}\times 50\times 10^3+1)}$$
$$= -\frac{10}{(j0.5+1)}$$
$$= -\frac{10}{\left(\sqrt{0.5^2+1}\right)} = -\frac{10}{\left(\sqrt{0.25+1}\right)} = -8.94$$

$$V_O = -8.94\times 0.1 = -0.894\text{ V} = V_m$$
$$\cong -0.9\text{ V}$$

Figure 15.135. Figure 15.135



41. What is the relationship between resistors *R* and R_1 and R_2 in **Fig. 15.136**.

Solution:

$$R = R_1 \| R_2.$$

Figure 15.136. Figure 15.136

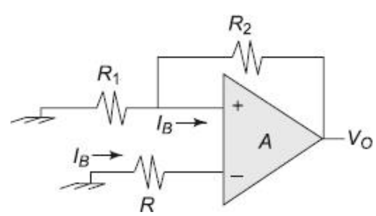
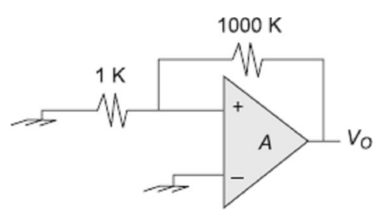


Figure 15.137. Figure 15.137



42. The offset voltage to the circuit of **Fig. 15.137** is 1 mV. How much output voltage will be displayed?

Solution:

$$\pm\frac{1000}{1}\times 1\text{ mV} = \pm 1\text{ V}.$$

43. What would be the frequency of oscillation in **Fig. 15.138**, if $C = \frac{1}{2\pi}$ μF and *R* = 1 K? What would be the minimum gain of the amplifier to sustain oscillations?

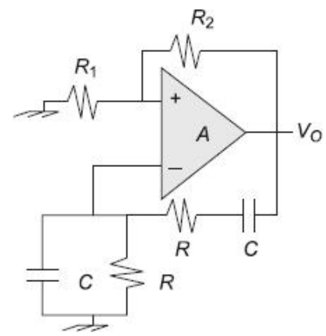
$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 10^3 \times \frac{1}{2\pi} \times 10^{-6}}$$

$= 10^3$ Hz

The minimum gain $= 1 + \frac{R_2}{R_1} = 1 + \frac{2R_1}{R_1}$

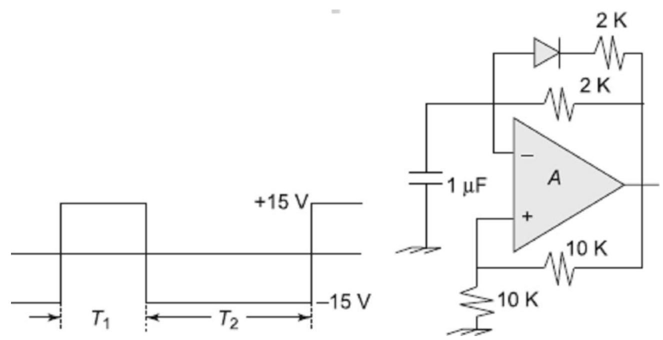
$= 3\ (R_2 = 2R_1)$

Figure 15.138. Figure 15.138



44. Calculate the ratio of ON duration to OFF duration of the output waveform of circuit in **Fig. 15.139**.

Figure 15.139. Figure 15.139



$T_1 = RC \ln\frac{1+\beta}{1-\beta}$,

$T_2 = RC \ln\frac{1+\beta}{1-\beta}$,

$\beta = \frac{10\text{ K}}{10\text{ K} + 10\text{ K}} = \frac{1}{2}$, $RC = 1\text{ K} \times 1\ \mu\text{F}$

$= 1$ ms ,

$\ln\frac{1+\beta}{1-\beta} = \ln 3 = 1.1$

For T_2 at –15 V, diode is forward biased.
$R = 2\text{ K}||2\text{ K} = 1\text{ K}$

Hence, $T_2 = RC \ln\frac{1+\beta}{1-\beta} = 1\text{ ms} \times 1.1$

$= 1.1$ ms,
For T_1 at +15 V , diode is off, $R = 2$ K, RC
$= 2\text{ K} \times 1\ \mu\text{F} = 2$ ms

$$T_1 = RC\ln\frac{1+\beta}{1-\beta} = 2\text{ ms} \times 1.1 = 2.2\text{ ms},$$

$$\text{Hence, } \frac{T_1}{T_2} = \frac{2.2\text{ ms}}{1.1\text{ ms}} = 2$$

45. Obtain CMRR for the circuit shown in **Fig. 15.140**.

$$V_+ = \frac{R_3V_2}{R_3+R_2} = V_-$$

$$= \frac{V_1R_F}{R_1+R_F} + \frac{V_OR_1}{R_1+R_F}$$

$$\text{For } V_1 = 0\text{ , } V_{o2} = \left(1+\frac{R_F}{R_1}\right)V_+$$

$$= \left(1+\frac{R_F}{R_1}\right)\frac{R_3}{R_2+R_3}V_2$$

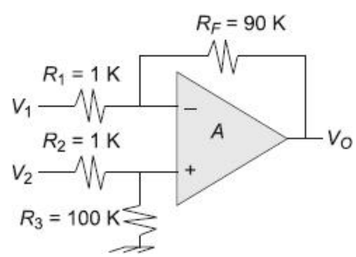
$$\text{For } V_2 = 0\text{ , } V_{o1} = -\frac{R_F}{R_1}V_1$$

$$V_o = V_{o1} + V_{o2}$$

$$= -\frac{R_F}{R_1}V_1 + \left(1+\frac{R_F}{R_1}\right)\frac{R_3}{R_2+R_3}V_2$$

$$V_2 = V_C + \frac{V_d}{2} \text{ and } V_1 = V_C - \frac{V_d}{2}$$

Figure 15.140. Figure 15.140



$$V_o = V_{o1} + V_{o2}$$

$$= -\frac{R_F}{R_1}\left(V_C - \frac{V_d}{2}\right) + \left(1 + \frac{R_F}{R_1}\right) \frac{R_3}{R_2 + R_3}\left(V_C + \frac{V_d}{2}\right)$$

$$= \left[-\frac{R_F}{R_1} + \left(\frac{R_1 + R_F}{R_1}\right)\left(\frac{R_3}{R_2 + R_3}\right)\right]V_C$$

$$+ \left[\frac{R_F}{R_1} + \left(\frac{R_1 + R_F}{R_1}\right)\left(\frac{R_3}{R_2 + R_3}\right)\right]\frac{V_d}{2}$$

$$= \frac{(R_1 + R_F)R_3 - R_F(R_2 + R_3)}{R_1(R_2 + R_3)} V_C$$

$$+ \frac{(R_1 + R_F)R_3 + R_F(R_2 + R_3)}{R_1(R_2 + R_3)} \frac{V_d}{2}$$

$$A_{DM} = \left.\frac{V_o}{V_d}\right|_{V_C = 0} = \frac{V_O}{V_d}$$

$$= \frac{(R_1 + R_F)R_3 + R_F(R_2 + R_3)}{2R_1(R_2 + R_3)}$$

$$A_{CM} = \left.\frac{V_O}{V_C}\right|_{V_d = 0} = \frac{V_O}{V_C}$$

$$= \frac{(R_1 + R_F)R_3 - R_F(R_2 + R_3)}{R_1(R_2 + R_3)}$$

$$\text{Hence, CMRR} = \frac{A_{DM}}{A_{CM}}$$

$$= \frac{(R_1 + R_F)R_3 + R_F(R_2 + R_3)}{2\{(R_1 + R_F)R_3 - R_F(R_2 + R_3)\}}$$

$$= \frac{(91)100 + 90(101)}{2\{(91 \times 100 - 90(101)\}}$$

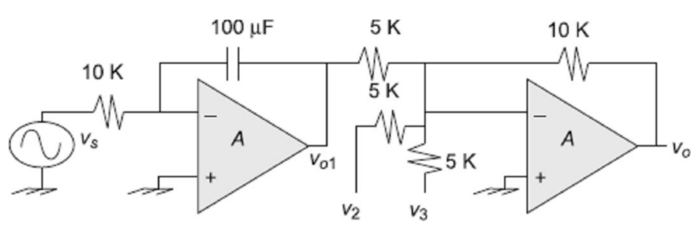
$$= \frac{(9100 + 9090)}{2(9100 - 9090)} = \frac{18190}{10 \times 2} = 909.5$$

46. Obtain the output voltage of the amplifier shown in **Fig. 15.141**

$$v_{o1} = -\frac{1}{RC}\int v_s dt = -\int v_s dt$$

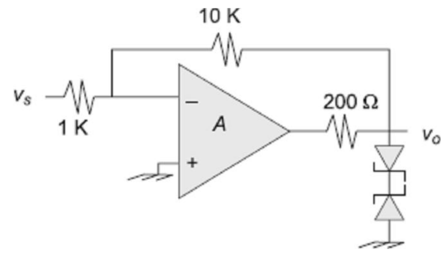
$$v_{o1} = 2\int v_s dt - 2v_2 - 2v_3$$

Figure 15.141. Figure 15.141



47. The output voltage of Schmitt trigger drawn in **Fig. 15.142** is limited to 10 V and −5 V connecting suitably chosen Zener diodes across the output. What are the upper trip and lower trip voltages of the circuit?

Figure 15.142. Figure 15.142



$$V_{UT} = -(-V_{SAT})\frac{R}{dR}$$

$$= -(-5)\frac{1}{10} = 0.5\ \text{V}$$

$$V_{LT} = -V_{SAT}\frac{R}{dR} = -10\frac{1}{10} = -1\ \text{V}$$

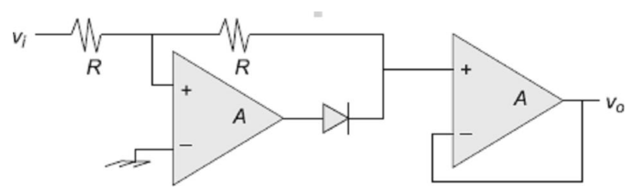
48. Obtain the output voltage for input voltage v_i = sinωt applied to the circuit in **Fig. 15.143**.

Solution:

For v_i > 0 V, diode is reverse biased, no loop closes. $v_o = v_i$

For v_i < 0 V, diode is forward biased, loop closes. $v_o = -v_i$

Figure 15.143. Figure 15.143



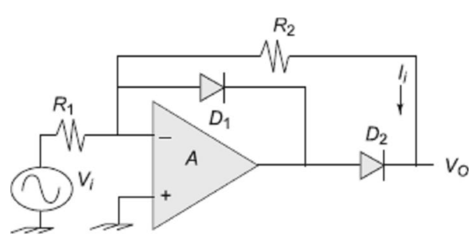
49. Obtain the output voltage of **Fig. 15.144**. What is the name of this circuit?

Solution:

For V_i > 0, D_1 is forward biased and D_2 is reverse biased, V_o = 0.

For V_i < 0, D_1 is reverse biased and D_2 is forward biased, $V_o = -\frac{R_2}{R_1}V_i$. The circuit is a half wave rectifier and conducts for negative half cycle only.

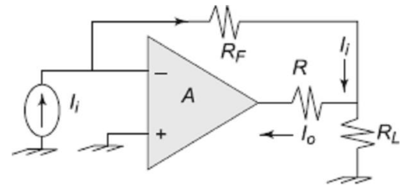
Figure 15.144. Figure 15.144



50. What is the ratio of current $\frac{I_O}{I_i}$ in **Fig. 15.145**.

$$I_O = I_i\frac{R_L}{R_L + R}$$

Figure 15.145. Figure 15.145



51. Obtain the value of R_A such that $V_O = \frac{V_2}{3} - 2V_1$ in **Fig. 15.146**.

$$V_+ = \frac{10KV_2}{10K + R_A} = V_- = \frac{V_1 10}{15} + \frac{V_0 5}{15}$$

$$= \frac{2V_1}{3} + \frac{V_0}{3}$$

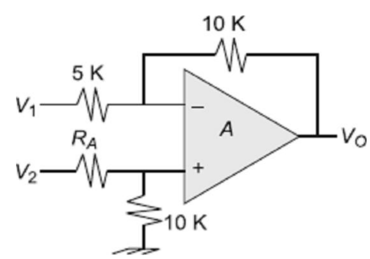
$$\text{or, } \frac{30V_2}{10 + R_A} = 2\text{V}_1 + V_O,$$

$$V_O = \frac{30V_2}{10 + R_A} - 2V_1$$

$$V_o = \frac{V_2}{3} - 2V_1 = \frac{30V_2}{10 + R_A} - 2V_1$$

$$\text{or, } \frac{1}{3} = \frac{30}{10 + R_A},\ R_A = 90 - 10 = 80\ \text{K}\Omega$$

Figure 15.146. Figure 15.146



52. What is the value of the output voltage in **Fig. 15.147**.

$$\frac{V_1}{2} + \frac{V_1 - V_{01}}{2} + \frac{V_1 - V_2}{1} = 0$$

$$2V_1 = \frac{V_{01}}{2} + \frac{V_2}{1} = 0.5\ \text{V}_{01} + V_2$$

$$V_1 = 0.25V_{01} + 0.5 \times 2\ \text{V} = 1\ \text{V}$$

$$\text{or, } V_{01} = 0$$

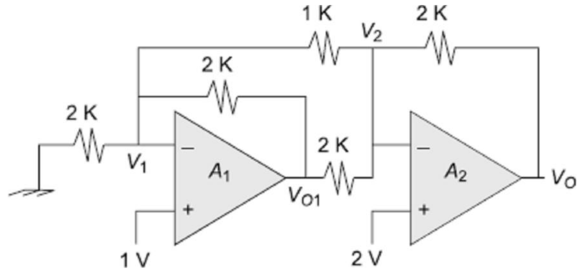
$$\text{At node 2, } \left(\frac{1}{1} + \frac{1}{2} + \frac{1}{2}\right)V_2$$

$$= \frac{V_0}{2} + \frac{V_1}{1} + \frac{V_1}{2}$$

$$\text{or, } 2V_2 = 0.5\text{V}_0 + 1$$

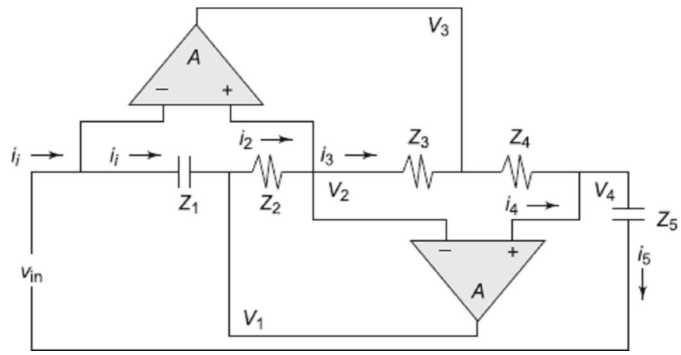
$$\text{or, } V_O = \frac{4 - 1}{0.5} = 6\ \text{V}$$

Figure 15.147. Figure 15.147



53. Show that $i_i = D\dfrac{d^2 v_{in}}{dt^2}$ in **Fig. 15.148** assuming all op-amps are ideal. Also show that *D* represents *a* frequency dependent negative resistance.

Figure 15.148. Riordan circuit



The circuit of **Fig. 15.148** can now be analyzed for its input impedance as

$$v_i = v_2 = v_4$$
$$(v_i - v_1) = Z_1 i_1 = Z_1 i_i$$
$$(v_2 - v_1) = -Z_2 i_2 = -Z_2 i_3 = (v_i - v_1)$$
$$= Z_1 i_i,\ i_3 = -\frac{Z_1}{Z_2} i_i$$
$$(v_2 - v_3) = Z_3 i_3 = (v_4 - v_3) = -Z_4 i_4\ ,$$
$$i_4 = -\frac{Z_3}{Z_4} i_3$$
$$v_4 = v_i = Z_5 i_5 = Z_5 i_4$$
$$= Z_5 \frac{Z_3}{Z_4} \times \frac{Z_1}{Z_2} i_i,$$
$$i_i = \frac{Z_2 Z_4}{Z_1 Z_3 Z_5} v_{in}$$

If $Z_1 = \dfrac{1}{SC_1}$,

$Z_2 = R = Z_4 = Z_3$, and $Z_5 = \dfrac{1}{SC_2}$ are substituted in above, then

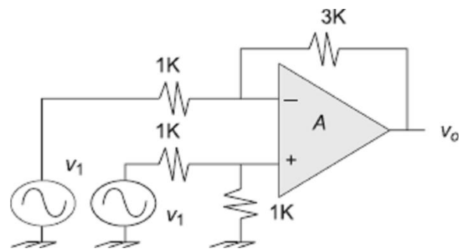
$$i_i = \frac{S^2 C_1 C_2 R_2 R_4}{R_3} v_{in}$$
$$= D\frac{d^2 v_{in}}{dt^2},$$
$$D = \frac{C_1 C_2 R_2 R_4}{R_3}.$$
$$\frac{i_i}{v_{in}} = \frac{S^2 C_1 C_2 R_2 R_4}{R_3}$$
$$= \frac{-\omega^2 C_1 C_2 R_2 R_4}{R_3}$$

= negative conductance.

54. Find out the output voltage v_o for the circuit in **Fig. 15.149**.

$$V_+ = \frac{V_2}{2}\ ,\ V_- = V_1\frac{3}{4} + V_o\frac{1}{4}$$
$$= 0.75V_1 + 0.25V_o$$
$$V_o = \frac{0.5}{0.25}V_2 - \frac{0.75}{0.25}V_1$$
$$= 2V_2 - 3V_1$$

Figure 15.149. Figure 15.149

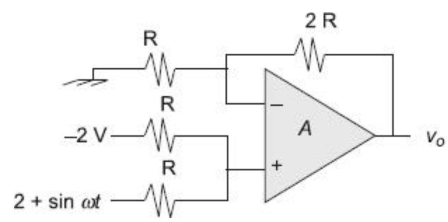


55. Obtain the output voltage of an op-amp summer shown in **Fig. 15.150**.

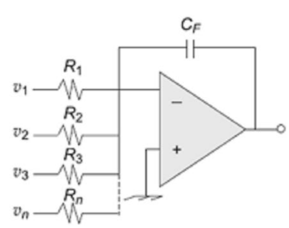
$$A_v = 1 + \frac{2R}{R} = 3$$

$$V_o = \left(1 + \frac{2R}{R}\right)(-2 + 2 + \sin\omega t) = 3\ \sin\omega t$$

Figure 15.150. Figure 15.150

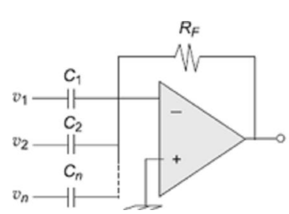


56. Circuit of summing integrator



$$v_o = -\frac{1}{C_F}\left[\frac{1}{R_1}\int v_1 dt + \frac{1}{R_2}\int v_2 dt + \cdots + \frac{1}{R_n}\int v_n dt\right] \qquad (15.12a)$$

57. Circuit of summing differentiator



$$v_o = -R_F\left[C_1\frac{dv_1}{dt} + C_2\frac{dv_2}{dt} + \cdots + C_n\frac{dv_n}{dt}\right] \qquad (15.12aa)$$