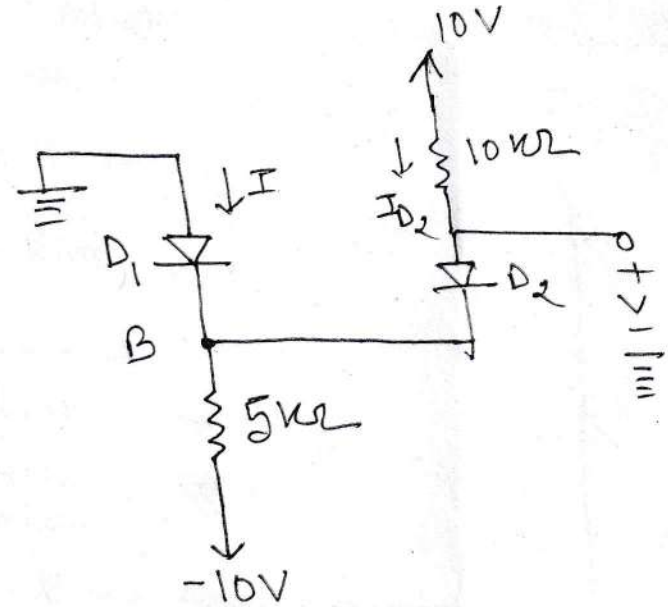
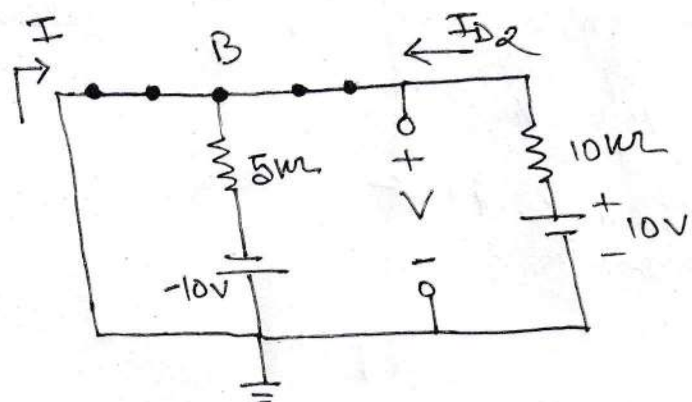
4.2 (a)



Solⁿ:

Let assume the diode D_1 & D_2 are conducting.
We can redraw the circuit as,



Therefore, $V = 0\,V$ ~~and I = 0~~ and $I_{D_2} = \frac{10-V}{10} = 1\,mA$

Applying nodal analysis at node B, we get,

$$I + I_{D_2} = \frac{V-(-10)}{5}$$

$$\Rightarrow I + \frac{10-V}{10} = \frac{V+10}{5}$$

$$\Rightarrow I + 1 = 2$$

$$\Rightarrow I = 2 - 1$$

$$\therefore I = 1\,mA \quad \text{(Ans)}$$

*) In the forward region, the i-v relationship is closely approximated by,

$$i = I_S \left(e^{v/V_T} - 1\right) \text{ ——— (i)}$$

where, i = diode current

I_S = saturation current

V_T = thermal voltage $= \frac{KT}{q} \cong 25.3 \text{ mV}$ at room temparature ($20°C$)

As $i \gg I_S$, eqn (i) can be written as

$$\boxed{i \cong I_S e^{v/V_T}} \text{ ——— (ii)}$$

Now, for the diode voltage V_1, the diode current I_1 is

$$I_1 = I_S e^{V_1/V_T} \text{ — (iii)}$$

Similarly, for a voltage V_2, the diode current I_2 is

$$I_2 = I_S e^{V_2/V_T} \text{ ——— (iv)}$$

Now, eqn $\{(iv) \div (iii)\} \Rightarrow \frac{I_2}{I_1} = e^{(V_2 - V_1)/V_T}$

$$\Rightarrow V_2 - V_1 = V_T \ln \frac{I_2}{I_1}$$

~~or~~ $\cancel{V_2 - V_1 = 2.3 \log}$

$$\text{or, } \boxed{V_2 - V_1 = 2.3\, V_T \log \frac{I_2}{I_1}}$$

Example 4.3 (Ch-4, SM)

A silicon diode said to be a 1 mA device displays a forward voltage of 0.7 V at a current of 1 mA. Evaluate the junction scaling constant I_S. What scaling constants would apply for a 1-A diode of the same manufacture that conducts 1 A at 0.7 V?

Solution: we know, $i = I_S e^{v/V_T}$

$$\Rightarrow 10^{-3} = I_S \times e^{\frac{0.7}{25 \times 10^{-3}}}$$

$$\Rightarrow I_S = 6.9 \times 10^{-16} \text{ A.} \quad \text{(Ans.)}$$

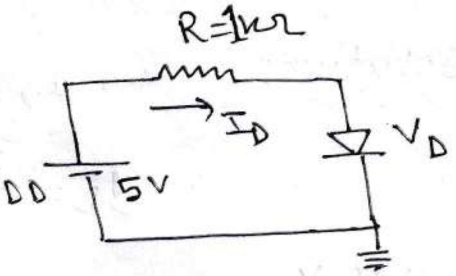
The diode conducting 1 A at 0.7 V corresponds to one-thousand 1 mA diodes in parallel with a total junction area 1000 times greater. Therefore, I_S will be 1000 times greater.

$$\therefore I_S = 1000 \times 6.9 \times 10^{-16} = 6.9 \times 10^{-13} \text{ A.} \quad \text{(Ans).}$$

**) Practise exercises 4.6 & 4.7 [Ch-4, SM, P-188]

Example 4.4 (Ch-4, SM, P-192)

Determine the current I_D and the diode voltage V_D for the circuit with $V_{DD} = 5V$ and $R = 1 k\Omega$. Assume that the diode has a current of 1 mA at a voltage of 0.7 V.



Solution: If $V_D = 0.7V$ then,

$$I_D = \frac{V_{DD} - V_D}{R}$$

$$= \frac{5 - 0.7}{1} = 4.3 \text{ mA}.$$

we know, $$V_{D2} - V_{D1} = 2.3 V_T \log \frac{I_{D2}}{I_{D1}}$$

$$\Rightarrow V_{D2} - 0.7 = 2.3 \times (25 \times 10^{-3}) \times \log \frac{4.3}{1}$$

$$\Rightarrow V_{D2} = 0.738 V$$

For $V_D = 0.738 V$,

$$\therefore I_D = \frac{V_{DD} - V_D}{R} = \frac{5 - 0.738}{1} = 4.262 \text{ mA}$$

Now, $$V_{D3} - V_{D2} = 2.3 V_T \log \frac{I_{D3}}{I_{D2}}$$

$$\Rightarrow V_{D3} - 0.738 = 2.3 \times (25 \times 10^{-3}) \log \frac{4.262}{4.3}$$

$$\therefore V_{D3} = 0.738 V.$$

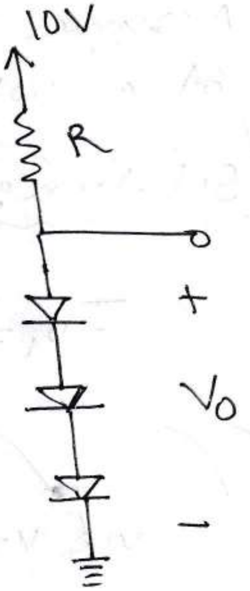
Therefore, no further iterations are necessary.

$\therefore I_D = 4.262$ mA and $V_D = 0.738 V$. (Ans.)

**) Practise Ex 4.10 [Ch-4, SM, P-194].

Exercise D4.11 [Ch-4, SM, P- 194]

Design the circuit in Fig. to provide an output voltage of 2.4 V. Assume that the diodes available have 0.7 V drop at 1 mA.



Solution: Here, $V_o = 2.4\,V$

$$\therefore V_D = \frac{V_o}{3} = 0.8\,V$$

we know,

$$V_{D2} - V_{D1} = 2.3 V_T \log \frac{I_{D2}}{I_{D1}}$$

$$\Rightarrow 0.8 - 0.7 = 2.3 \times (25 \times 10^{-3}) \times \log \frac{I_{D2}}{1}$$

$$\therefore I_{D2} = 54.84\ mA.$$

$$\therefore R = \frac{V_{DD} - V_o}{I_{D2}} = \frac{10 - 2.4}{54.84}$$

$$= 0.139\ k\Omega$$

$$= 139\ \Omega.$$

(Ans.).

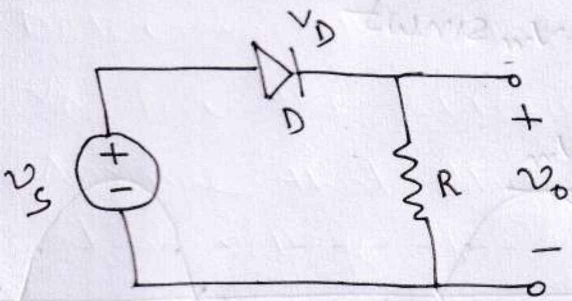
**) practise

EX: 4.9, 4.23, 4.28, 4.35, 4.58 [Ch-4, SM, at the end of the chapter].

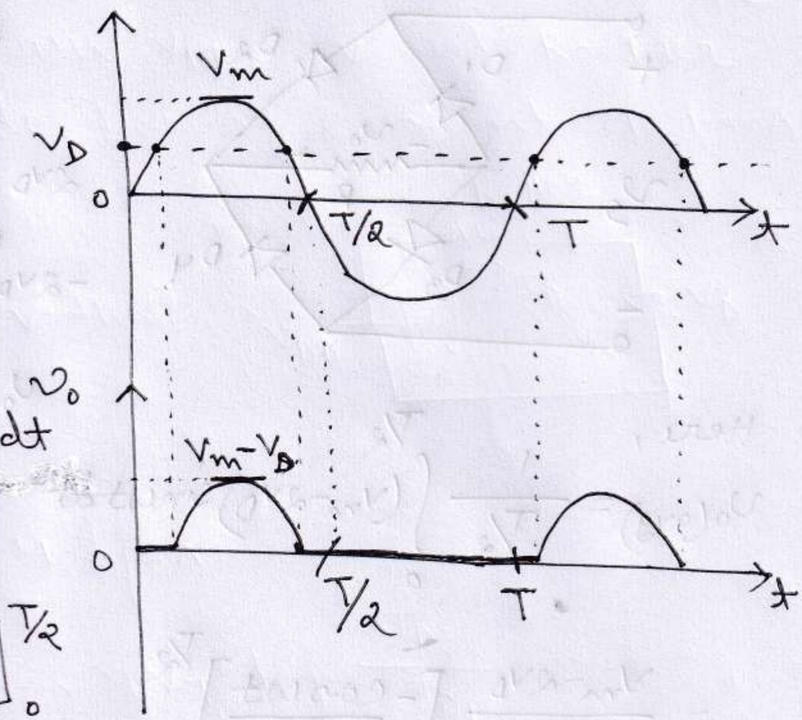
**) Practise

EX: 10, 11, 13 [Ch-2, BL, at the end of the chapter]
29, 30, 31

*) Half-wave rectifier



$v_s = V_m \sin\omega t$



Here,

$$v_0(\text{avg.}) = \frac{1}{T}\int_0^{T/2} (V_m - V_D)\sin\omega t\, dt$$

$$= \frac{V_m - V_D}{T}\left[-\frac{\cos\omega t}{\omega}\right]_0^{T/2}$$

$$= \frac{V_m - V_D}{\omega T}\left[\cos 0 - \cos\omega\frac{T}{2}\right]$$

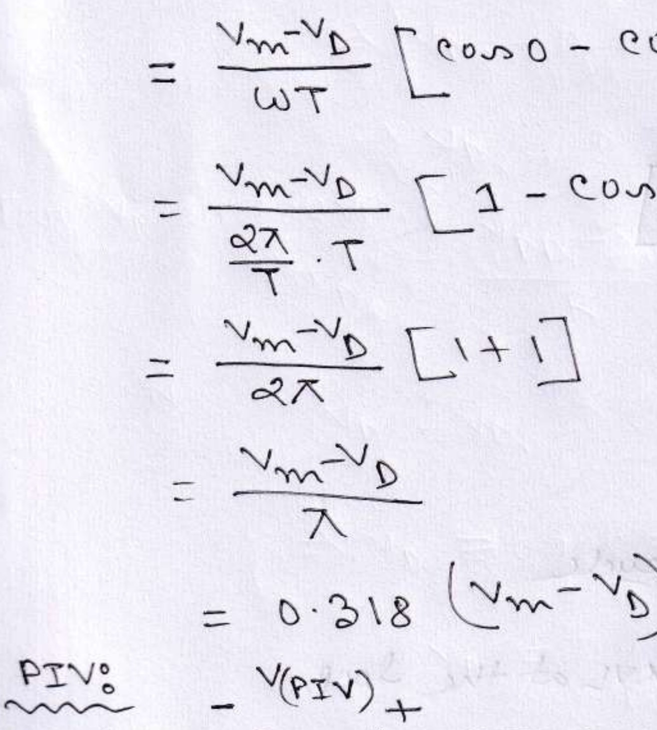
$$= \frac{V_m - V_D}{\frac{2\pi}{T}\cdot T}\left[1 - \cos\frac{2\pi}{T}\cdot\frac{T}{2}\right]$$

$$= \frac{V_m - V_D}{2\pi}[1 + 1]$$

$$= \frac{V_m - V_D}{\pi}$$

$$= 0.318\,(V_m - V_D).$$

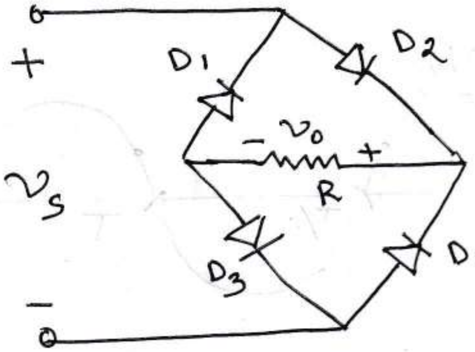
PIV:

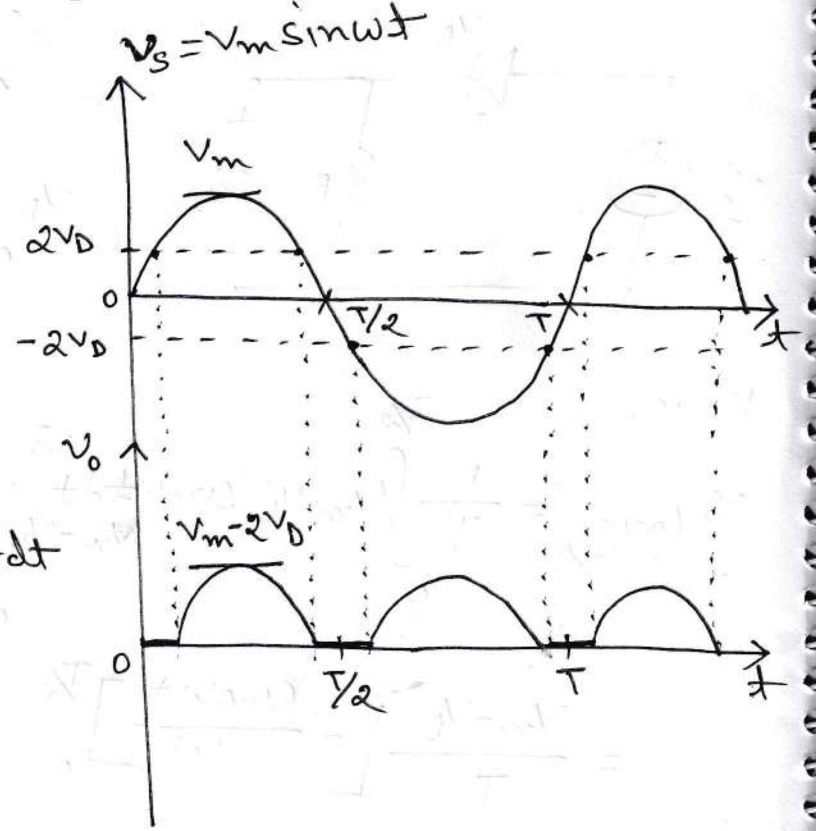


$v_o = I_D R = 0\,V$

$\therefore V_{(PIV)} = V_m.$

*) Full-wave (bridge) rectifier:





Here,

$$v_{o(avg)} = \frac{1}{T/2}\int_0^{T/2} (V_m - 2V_D)\sin\omega t\,dt$$

$$= \frac{V_m - 2V_D}{T/2}\left[-\frac{\cos\omega t}{\omega}\right]_0^{T/2}$$

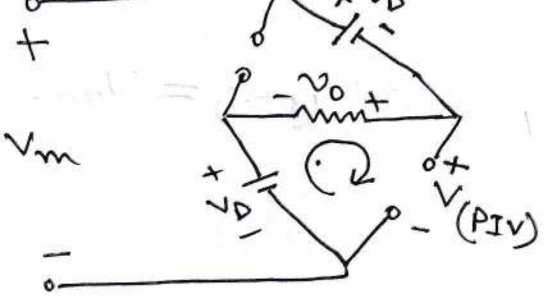
$$= \frac{V_m - 2V_D}{\omega T/2}\left[\cos 0 - \cos\omega\frac{T}{2}\right]$$

$$= \frac{(V_m - 2V_D)}{\frac{2\pi}{T}\cdot\frac{T}{2}}\left[1 - \cos\frac{2\pi}{T}\cdot\frac{T}{2}\right]$$

$$= \frac{2(V_m - 2V_D)}{\pi}$$

$$= 0.636\,(V_m - 2V_D).$$

PIV: consider the positive half cycle



Apply KVL at the loop,

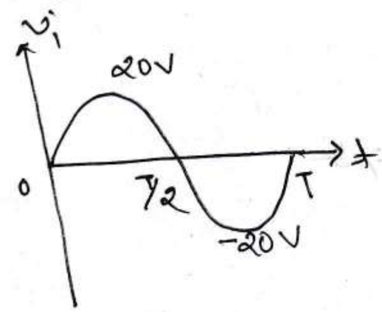
$$V_D + v_{o(peak)} - V_{(PIV)} = 0$$

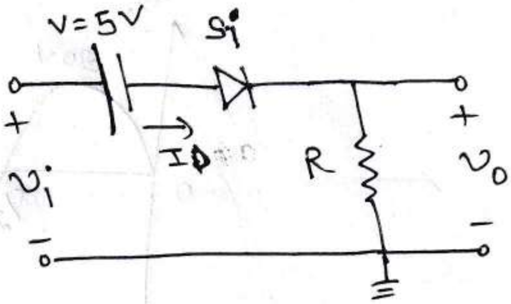
$$\Rightarrow V_{(PIV)} = V_D + V_m - 2V_D$$

$$= V_m - V_D.$$

*) Clippers

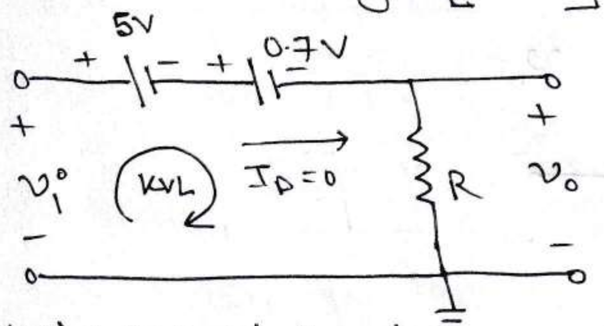
Example 1: Sketch the output waveform of the network





Solution:

Transition voltage [$I_D=0$]



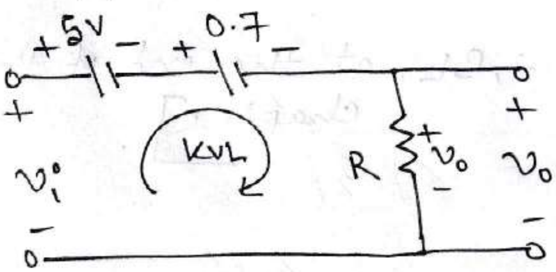
Apply KVL at the loop,

$$v_i - 5 - 0.7 - I_D R = 0$$

$$\Rightarrow V_i = 5.7\ V$$

Diode is in on-state, when

$v_i > 5.7\ V$

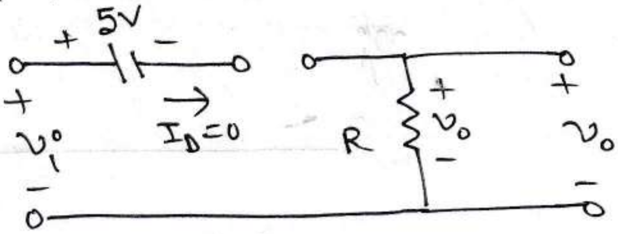


$$v_i - 5 - 0.7 - v_o = 0$$

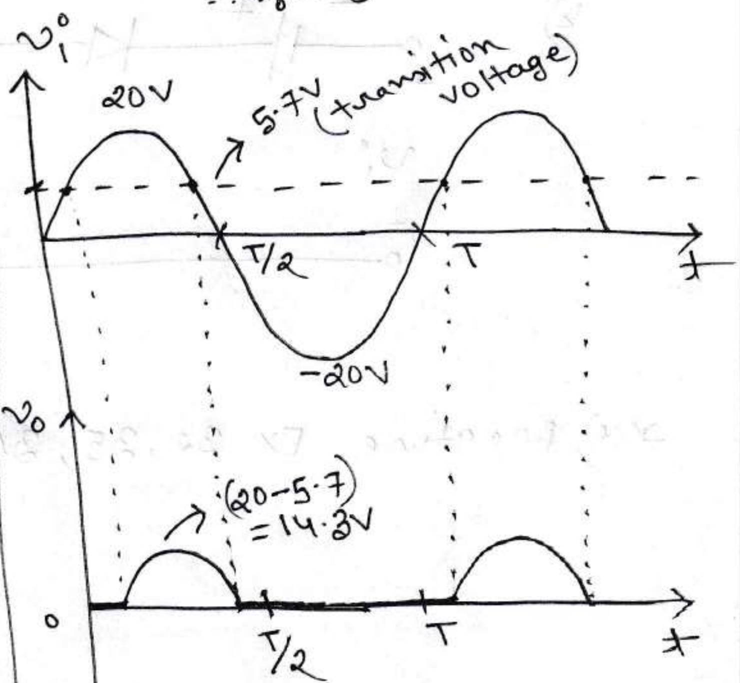
$$\Rightarrow v_o = v_i - 5.7$$

Diode is in off-state, when

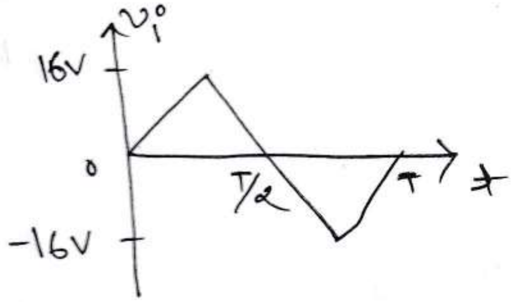
$v_i < 5.7\ V$

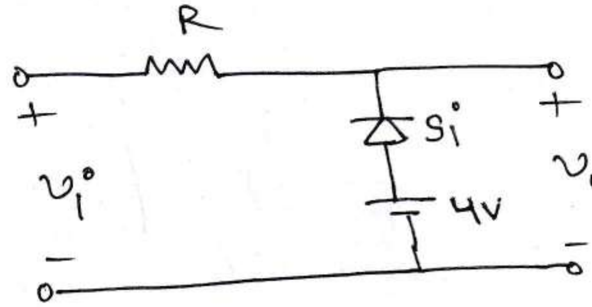


$\therefore v_o = 0$



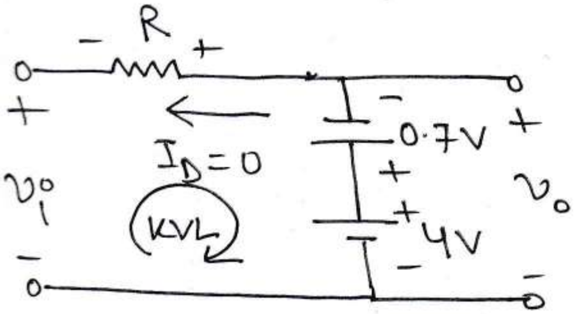
Example 2: Determine v_o for the circuit





Solution:

Transition voltage [$I_D = 0$]



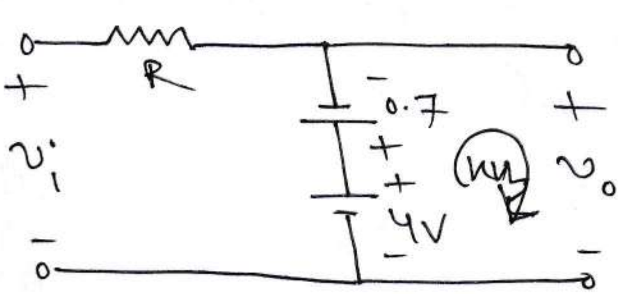
Apply KVL at the loop,

$$v_i + (0 \times R) + 0.7 - 4 = 0$$

$$\Rightarrow v_i - 3.3 = 0$$

$$\therefore v_i = 3.3V$$

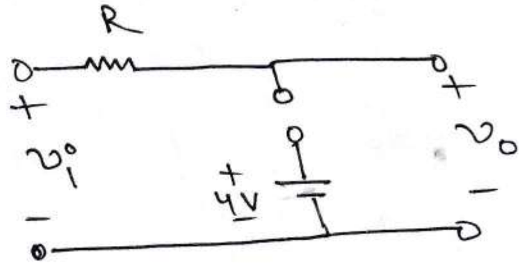
Diode is in on-state, when $v_i < 3.3V$.



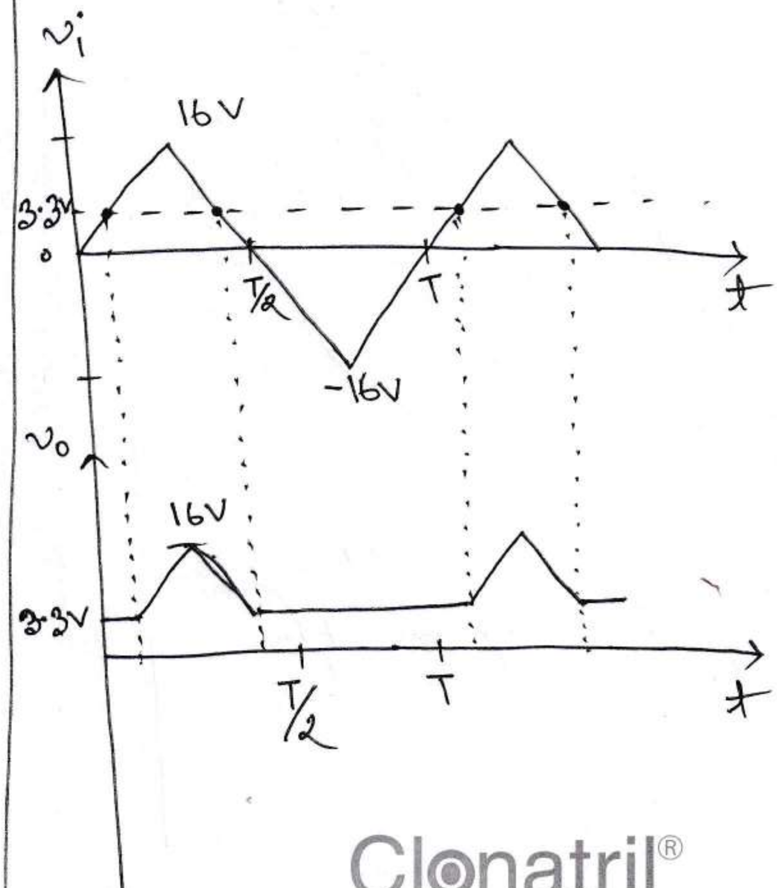
$$4 - 0.7 - v_o = 0$$

$$\Rightarrow v_o = 3.3V$$

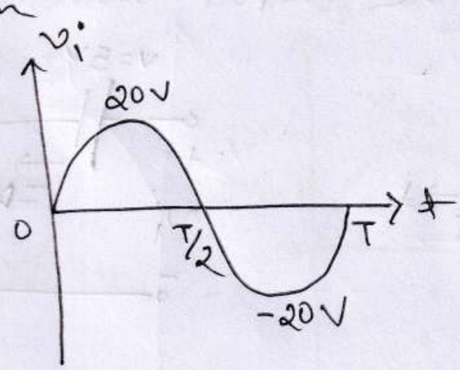
Diode is in off-state when $v_i > 3.3V$



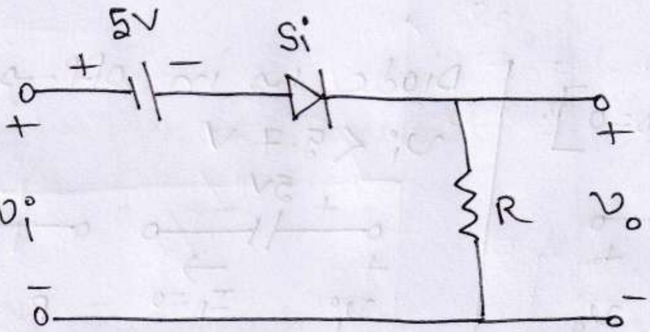
$$\therefore v_o = v_i$$



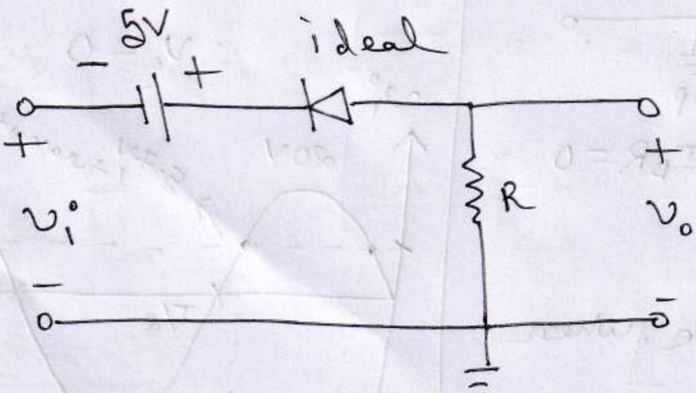
**) Practise the following Clippers circuit and sketch output waveform



a)



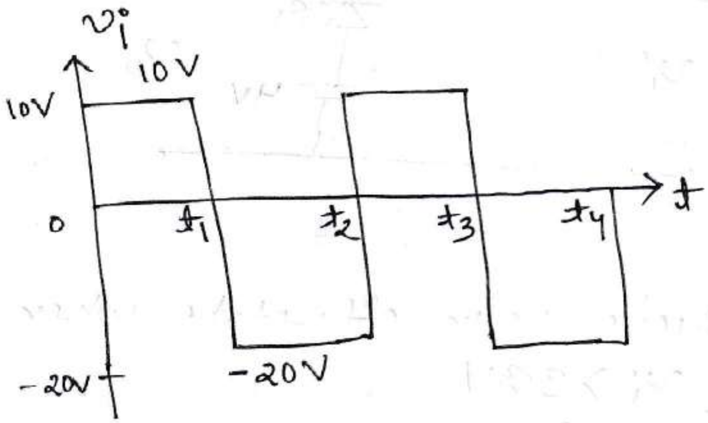
b)

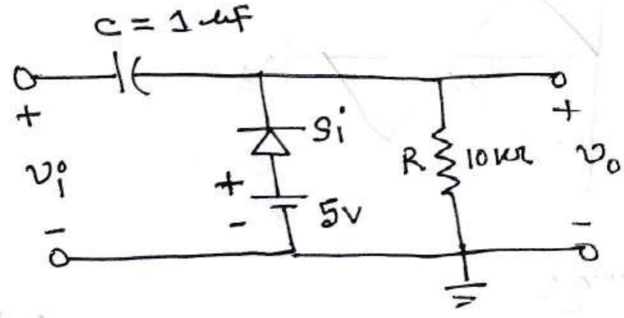


**) Practise EX 32, 35, 36 [Ch-2, BL, at the end of the chapter].

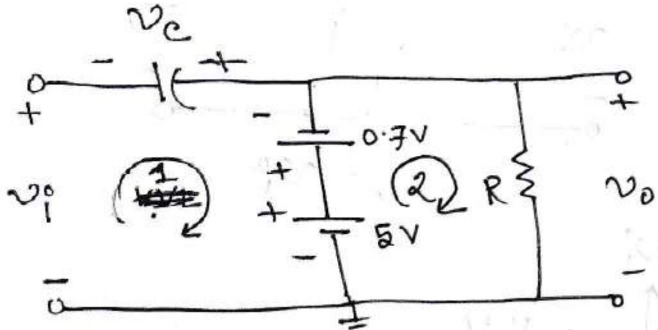
*) Clampers

Example: Determine v_o for the given network.





Solⁿ. During the period $t_1 \rightarrow t_2$.



Applying KVL at the loop 1,

$$v_i + v_C + 0.7 - 5 = 0$$

$$\Rightarrow -20 + v_C - 4.3 = 0$$

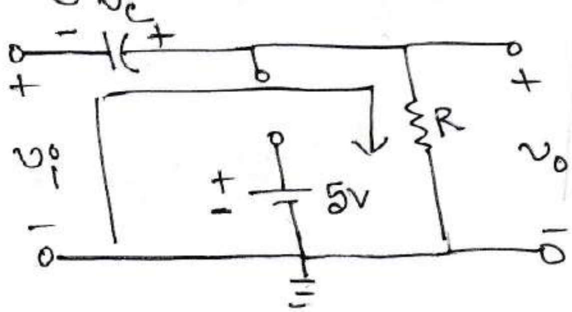
$$\therefore v_C = 24.3\text{V}$$

Apply KVL at loop 2,

$$5 - 0.7 - v_o = 0$$

$$\Rightarrow v_o = 4.3\text{V}$$

During the period $t_2 \rightarrow t_3$



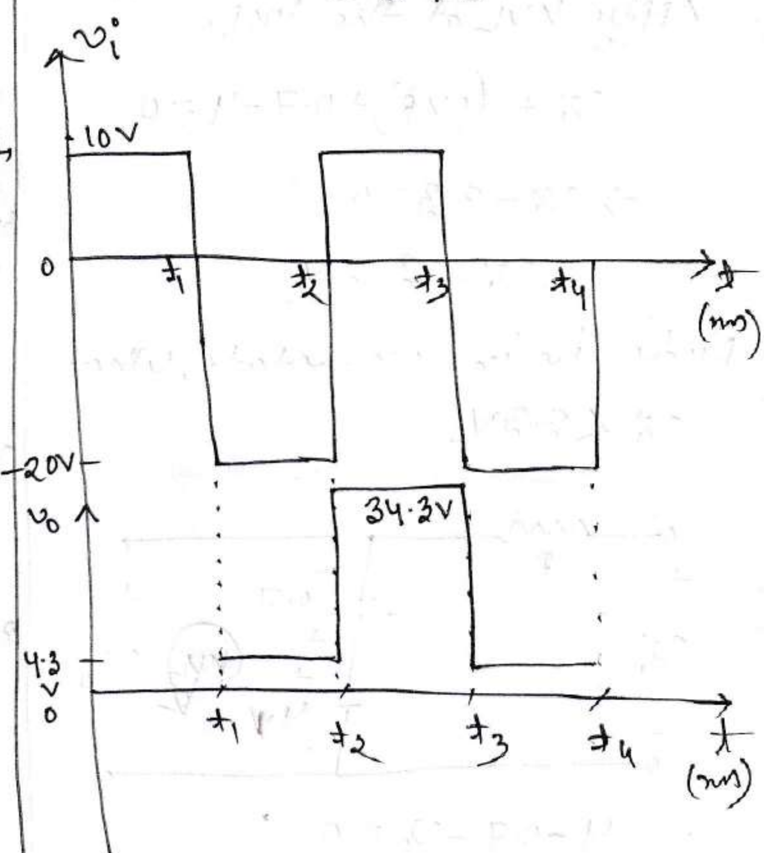
Apply KVL at the loop,

$$v_i + v_C - v_o = 0$$

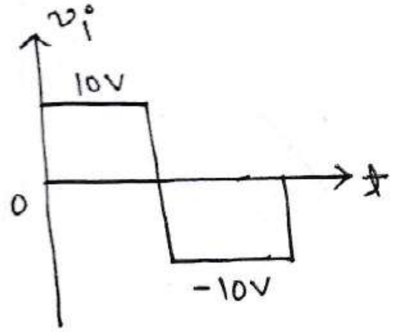
$$\Rightarrow v_o = v_i + v_C$$

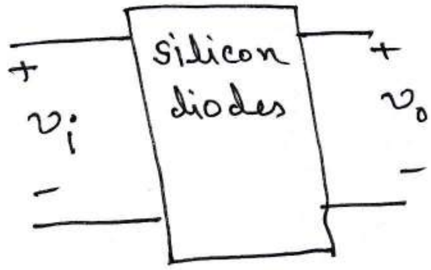
$$= 10 + 24.3$$

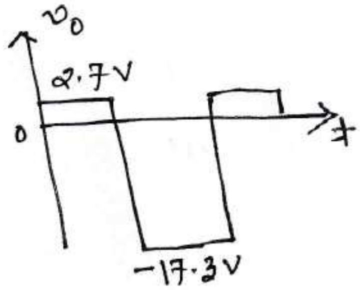
$$= 34.3\text{V}$$



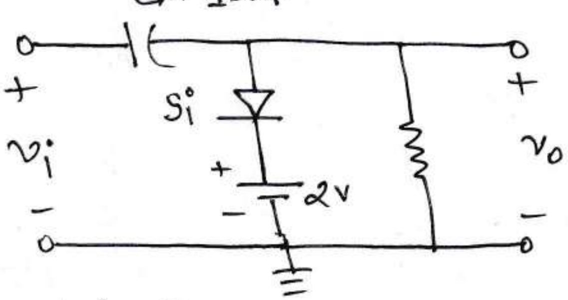
Example: Design a clamper to perform the indicated in the network.



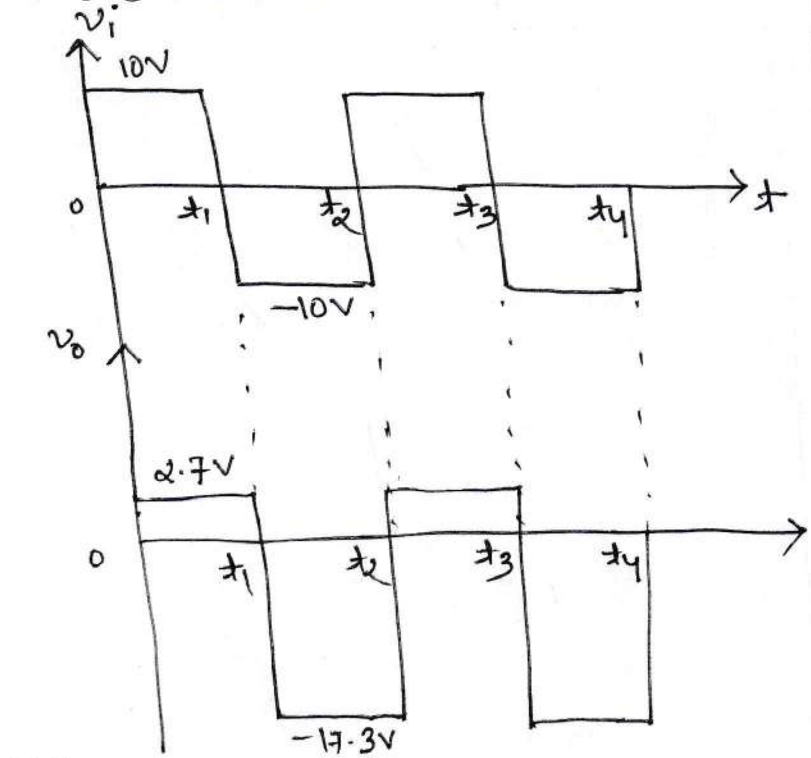




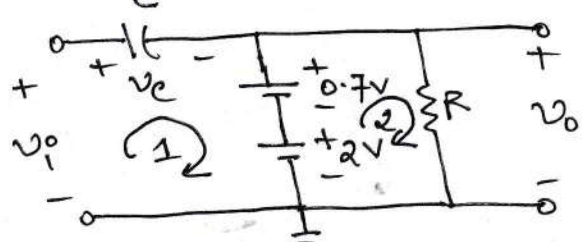
Sol^n: The required clamper circuit to generate the v_o is



Justification:



During the period $0 \rightarrow t_1$



Apply KVL at loop 1,

$$v_i - v_c - 0.7 - 2 = 0$$

$$\Rightarrow v_c = v_i - 2.7$$

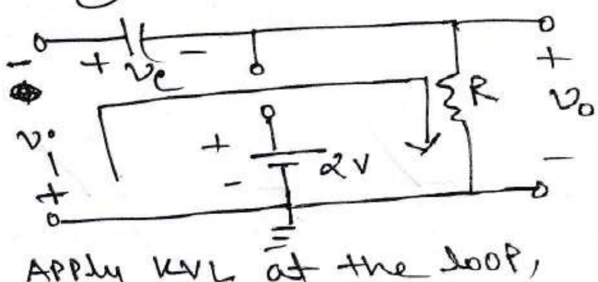
$$= 10 - 2.7 = 7.3V$$

Apply KVL at loop 2,

$$2 + 0.7 - v_o = 0$$

$$\Rightarrow v_o = 2.7V$$

During the period $t_1 \rightarrow t_2$,



Apply KVL at the loop,

$$-v_i - v_c - v_o = 0$$

$$\Rightarrow v_o = -v_i - v_c = -10 - 7.3$$

$$= -17.3V.$$

—x—

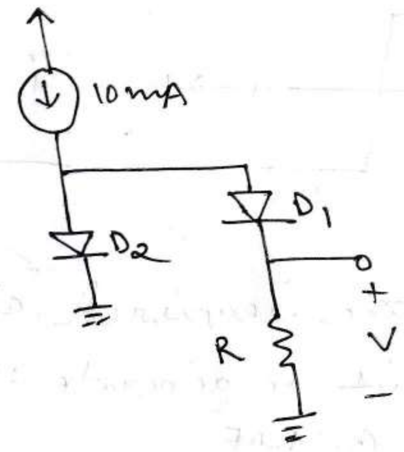
EX 4.28 (ch-4, SM)

For the circuit shown in Fig., both diodes are identical. Find the value of R for which V = 50mV

Solution:

Here, diode D_1 is in ON state

and " D_2 " " OFF " .



$\therefore R = \frac{V}{I} = \frac{50}{10} = 5\Omega$.

(Ans).

Ex: 4.58 (ch-4, SM)

Diode D_1 & D_2 are 10 mA units, that is, each has a voltage drop of 0.7 V at a current of 10mA. use ~~iterative~~ constant voltage drop model to find V_0 with the 150Ω load connected.

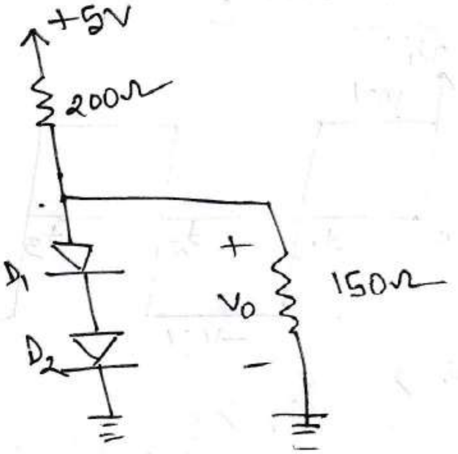
Soln:

Here,

$V_0 = 0.7 + 0.7$

$= 1.4V$.

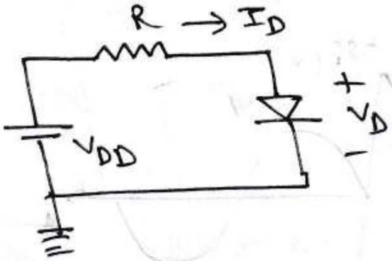
(Ans).



*) Practise: 37, 39(c), 40, 41, 42. (ch-2, BL)

4.35 (ch-4, SM)

Use the iterative analysis to determine the diode current and voltage of Fig. (4.10) for $V_{DD} = 1V$, $R = 1k\Omega$, and $I_S = 10^{-15} A$.



Soln: To begin the iteration, we assume, $V_D = 0.7V$

$$\therefore I_D = I_S e^{V_D/V_T}$$

$$= 10^{-15} \times e^{\frac{0.7}{0.025}}$$

$$= 1.44 \text{ mA}$$

From the circuit,

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{1 - 0.7}{1} = 0.3 \text{ mA}$$

We know,

$$V_{D2} - V_{D1} = 2.3 V_T \log\left(\frac{I_{D2}}{I_{D1}}\right)$$

$$\Rightarrow V_{D2} - 0.7 = 2.3 \times 0.025 \times \log\left(\frac{0.3}{1.44}\right)$$

$$\Rightarrow V_{D2} - 0.7 = -0.0392$$

$$\Rightarrow V_{D2} = 0.6608 V$$

Again from the circuit, $I_D = \frac{V_{DD} - V_D}{R} = \frac{1 - 0.6608}{1}$

$$= 0.3392 \text{ mA}$$

Again,

$$V_{D3} - V_{D2} = 2.3 V_T \log\left(\frac{I_{D3}}{I_{D2}}\right)$$

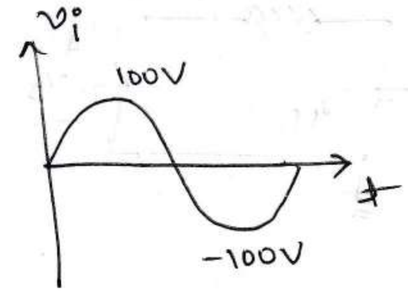
$$\Rightarrow V_{D3} - 0.6608 = 2.3 \times 0.025 \times \log\left(\frac{0.3392}{0.3}\right)$$

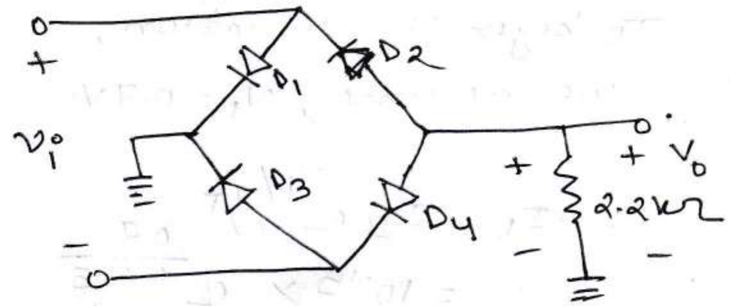
$$\Rightarrow V_{D3} - 0.6608 = 0.003$$

$$\therefore V_{D3} = 0.6638 V$$

Do another one or two more iterations and write the answers.

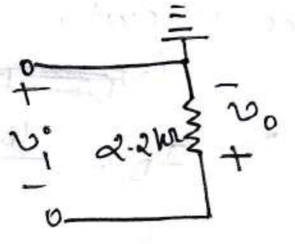
Ex 29 (Ch-2, BL) Determine v_o and PIV of the fig.





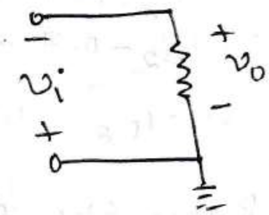
Solⁿ: During the positive half cycle, diodes D_1 & D_4 are ON.

$\therefore v_o = -v_i$

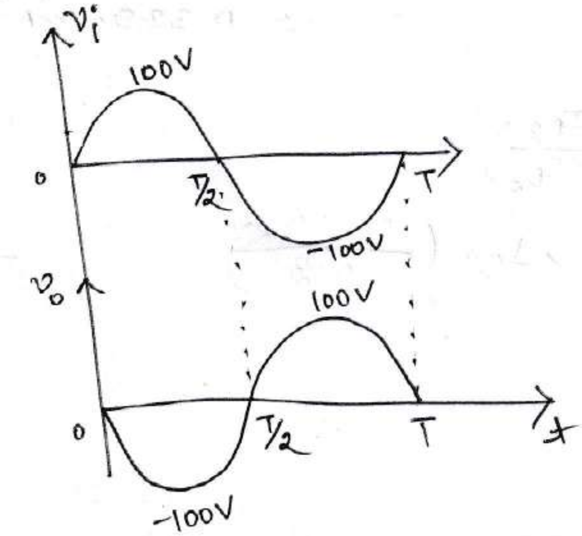


During the negative half cycle, diodes D_2 & D_3 are ON

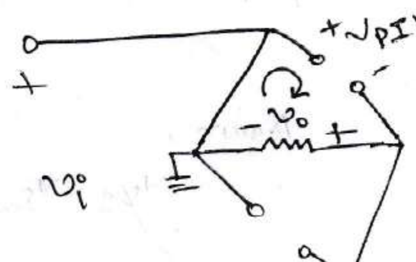
$\therefore v_o = -v_i$



Waveform:



PIV:



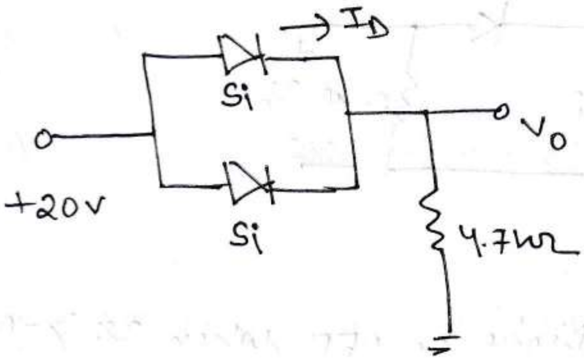
Apply KVL,

$-V_{PIV} - v_o(\text{peak}) = 0$

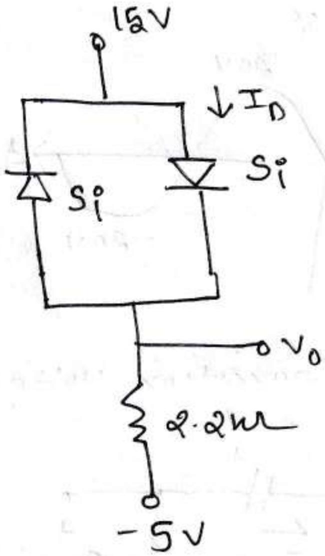
$\Rightarrow V_{PIV} = -v_o(\text{peak})$

$= -100V.$ (Ans.)

Ex 10 (ch-2, BL): Determine V_o and I_D for the networks.

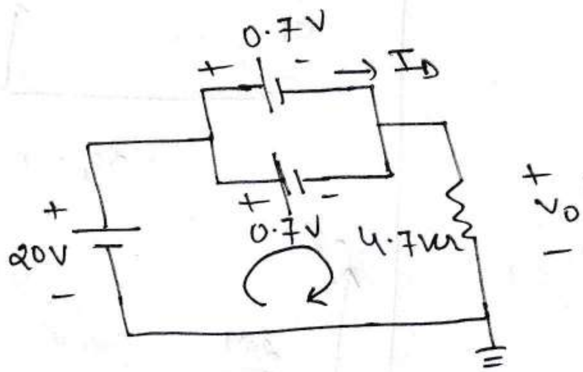


(a)



(b)

Solⁿ: (a)



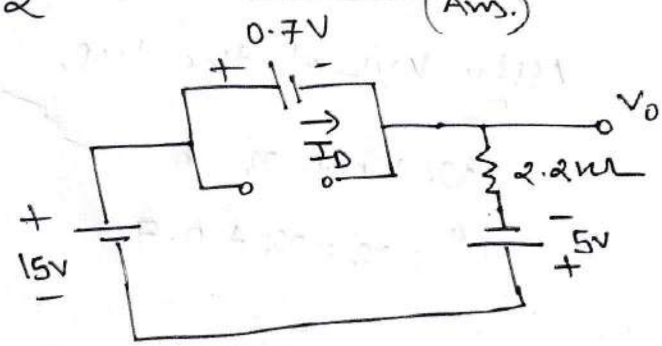
Apply KVL, $20 - 0.7 - V_o = 0$

$\Rightarrow V_o = 19.3\,V$

$\therefore I_{4.7k\Omega} = \frac{V_o}{4.7} = \frac{19.3}{4.7} = 4.11\ mA.$

$\therefore I_D = \frac{I_{4.7k\Omega}}{2} = 2.055\ mA.$ (Ans.)

b) Here,



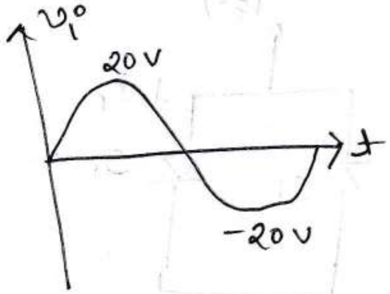
$V_o = 15 - 0.7$

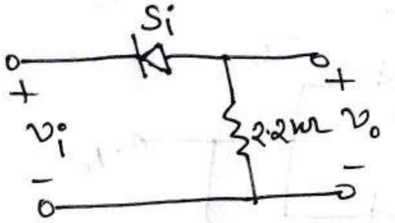
$= 14.3V$

and $I_D = \frac{15+5-0.7}{2.2}$

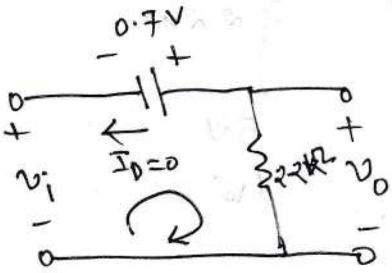
$= 8.77\ mA.$ (Ans.)

32). (ch-2, BM) Determine V_o for the network.





Soln. Transition voltage ($I_D=0$)

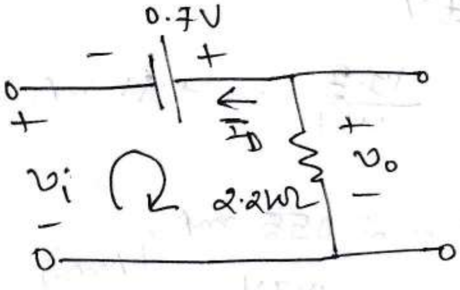


Apply KVL at the loop,

$$v_i + 0.7 - (2.2 \times I_D) = 0$$

$$\Rightarrow v_i = -0.7$$

Diode is ON when $v_i < -0.7\,V$

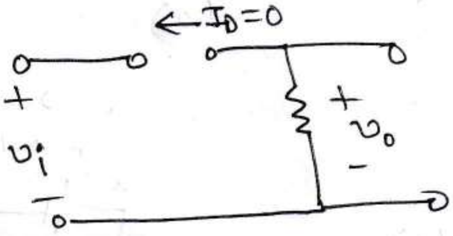


Apply KVL at the loop,

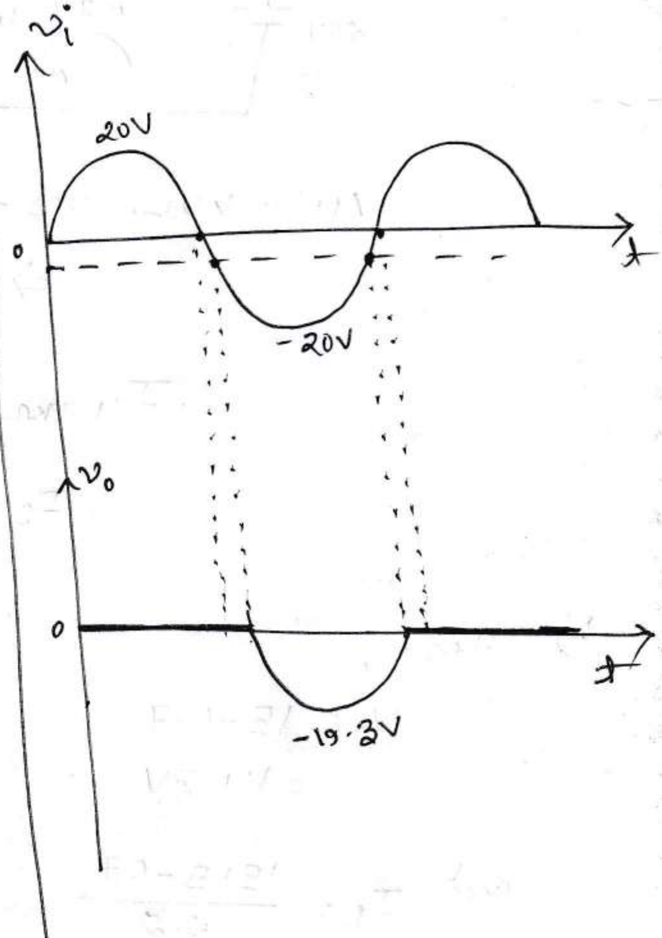
$$v_i + 0.7 - v_o = 0$$

$$\therefore v_o = v_i + 0.7$$

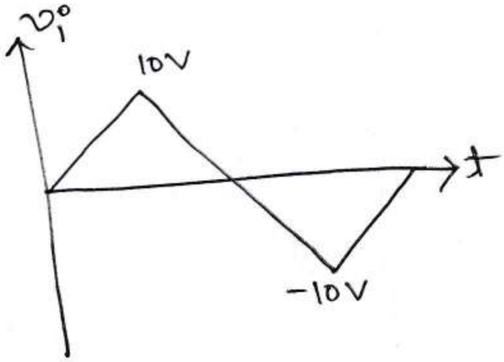
Diode is OFF when $v_i > -0.7\,V$

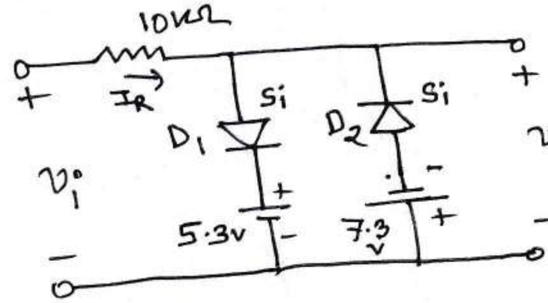


$$\therefore v_o = 0$$

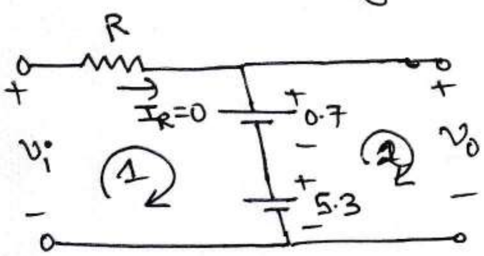


36 (Ch-2, BL) : Sketch v_o for the network





Sol^n: For the diode D_1, the transition voltage is,

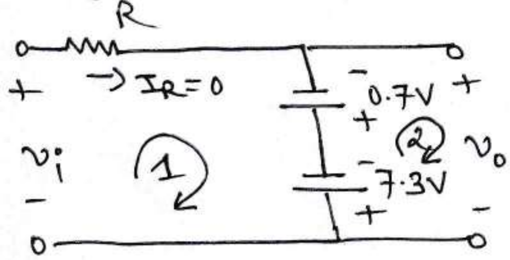


Fig(a)

$$v_i-(0\times R)-0.7-5.3=0$$

$$\Rightarrow v_i=6V$$

For the diode D_2, the transition voltage is,



Fig(b)

$$v_i+0.7+7.3=0$$

$$\Rightarrow v_i=-8V$$

When $v_i>6V$, diode D_1 is ON and D_2 is off. Apply KVL at the loop 2 in Fig(a),

$$5.3+0.7-v_o=0$$

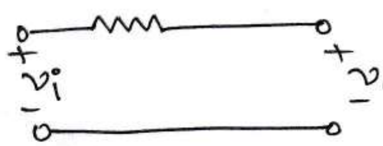
$$\Rightarrow v_o=6V$$

When $v_i<-8V$, the diode D_1 is off and D_2 is ON. Apply KVL at the loop 2 in Fig(b),

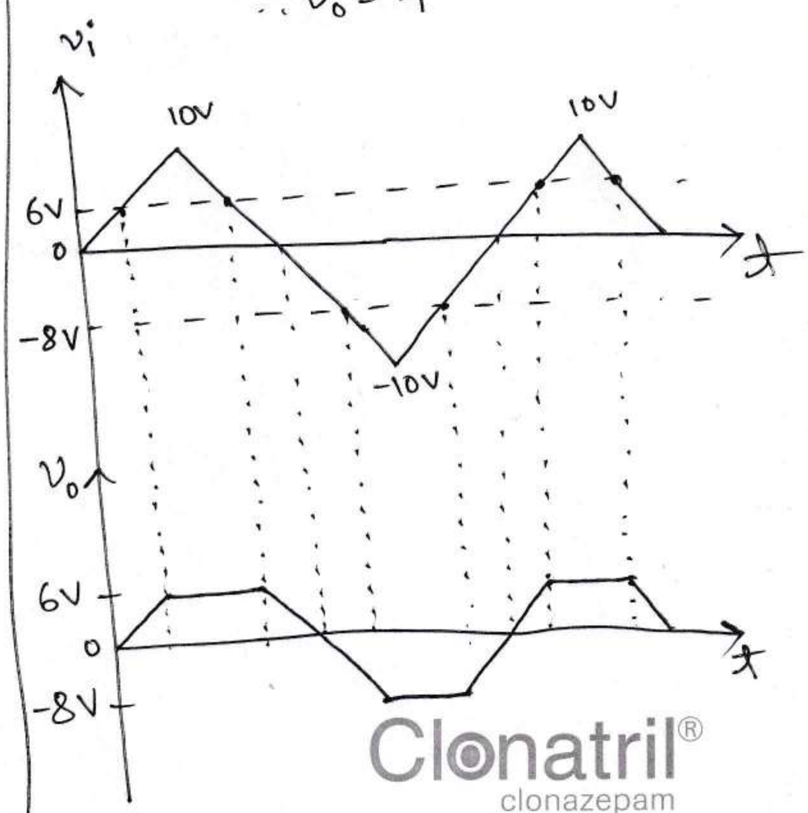
$$-7.3-0.7-v_o=0$$

$$\Rightarrow v_o=-8V$$

When $-8V<v_i<6V$, both D_1 & D_2 are off.



$$\therefore v_o=v_i$$



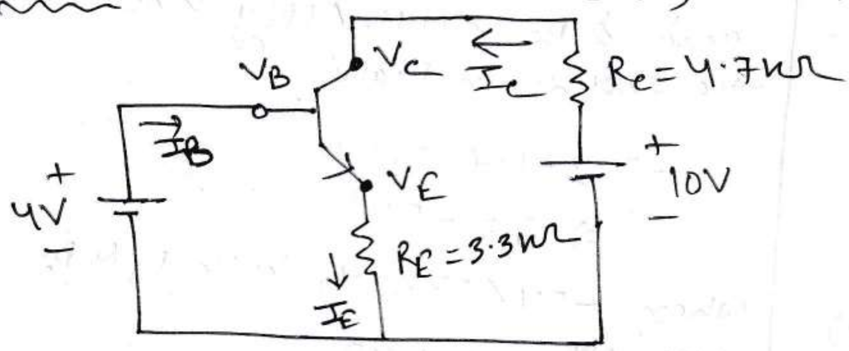
BJT

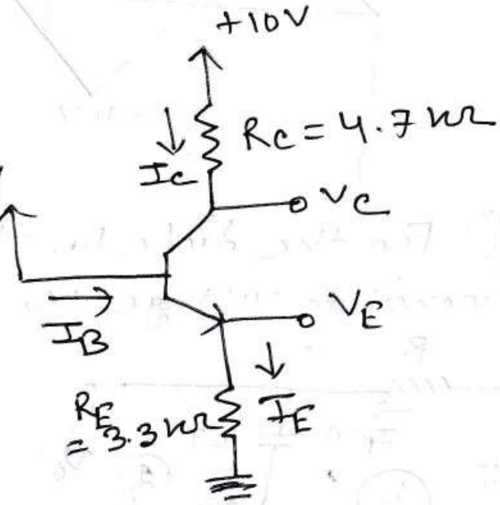
Example 6.4 (P-335)

Analyse this circuit to determine all node voltages and branch currents. $\beta = 100$.

~~Solⁿ~~

Solⁿ: Redraw the circuit,





Here, $\boxed{V_B = 4V}$.

we know, $V_{BE} = 0.7\,V$

$$\Rightarrow V_B - V_E = 0.7$$

$$\Rightarrow V_E = V_B - 0.7 = 4 - 0.7 = \boxed{3.3V}$$

$$\therefore I_E = \frac{V_E}{R_E} = \frac{3.3}{3.3} = \boxed{1\,mA}.$$

we know,

$$I_E = I_B + I_C$$

$$\Rightarrow I_E = I_B + \beta I_B \quad \left[\because \beta = \frac{I_C}{I_B}\right]$$

$$\Rightarrow I_B = \frac{I_E}{\beta + 1} = \frac{1}{101} = \cancel{0.01\,mA}\ \boxed{0.0099\,mA}$$

$$\therefore I_C = \beta I_B = 100 \times 0.0099 = 0.99\,mA.$$

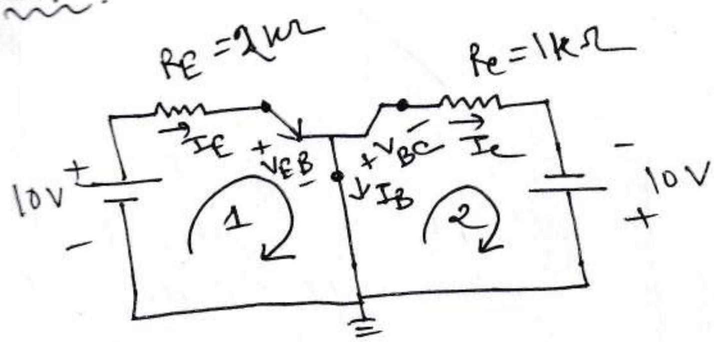
$$\therefore V_C = 10 - I_C R_C = 10 - (0.99 \times 4.7) = \boxed{5.3\,V}.$$

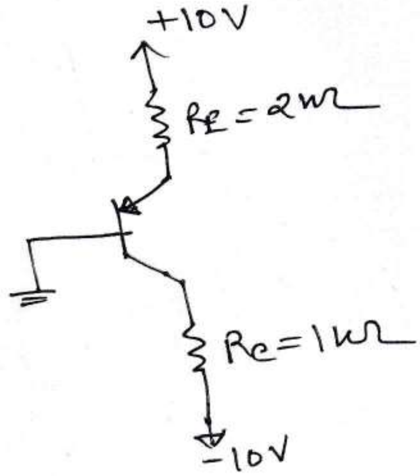
——— X ———

Example 6.7 (P-339)

Determine the voltages at all nodes and the currents through all branches. Assume, $\beta = 100$.

Soln:





Apply KVL at loop 1,

$$10 - I_E R_E - V_{EB} = 0$$

$$\Rightarrow I_E = \frac{10 - 0.7}{2} = \boxed{4.65\ mA}$$

$$\therefore I_B = \frac{I_E}{\beta + 1} = \frac{4.65}{101} \cong \boxed{0.046\ mA}$$

$$\therefore I_C = \beta I_B = 100 \times \cancel{0.05}\ 0.046 = \boxed{4.6\ mA}$$

$$V_B = \boxed{0\ V}$$

$$\therefore V_E = V_{EB} + V_B = 0.7 + 0 = \boxed{0.7V}$$

Apply KVL at loop 2,

$$-V_{BC} - I_C R_C + 10 = 0$$

$$\Rightarrow V_{BC} = 10 - (4.6 \times 1) = 5.4$$

$$\Rightarrow V_B - V_C = 5.4$$

$$\Rightarrow V_C = \boxed{-5.4\ V}$$

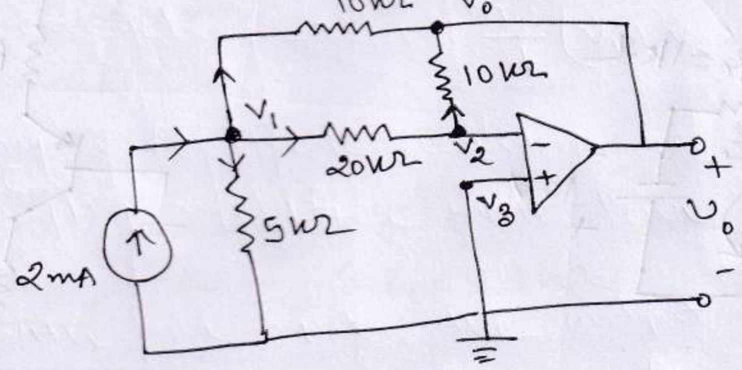
(Ans.)

Practice: Example 6.4, 6.8
Exercise 6.29, 6.32, 6.34, 6.51, 6.56

Op amp

Exercise 5.14 (P-203)

Determine the output voltage v_o in the circuit.



Soln. Apply nodal analysis at node 2,

$$\frac{V_1 - V_2}{20} = \frac{V_2 - V_o}{10}$$

$$\Rightarrow \frac{V_1}{20} = -\frac{V_o}{10} \quad [\because V_2 = V_3 = 0]$$

$$\Rightarrow V_1 = -2V_o \quad \text{——— (i)}$$

Apply nodal analysis at node 1,

$$2 = \frac{V_1}{5} + \frac{V_1 - V_2}{20} + \frac{V_1 - V_o}{10}$$

$$\Rightarrow 2 = \frac{-2V_o}{5} - \frac{2V_o}{20} - \frac{3V_o}{10} \quad [\text{from (i)}]$$

$$\Rightarrow 2 = \frac{-8V_o - 2V_o - 6V_o}{20}$$

$$\Rightarrow -16V_o = 40$$

$$\Rightarrow V_o = -\frac{40}{16}$$

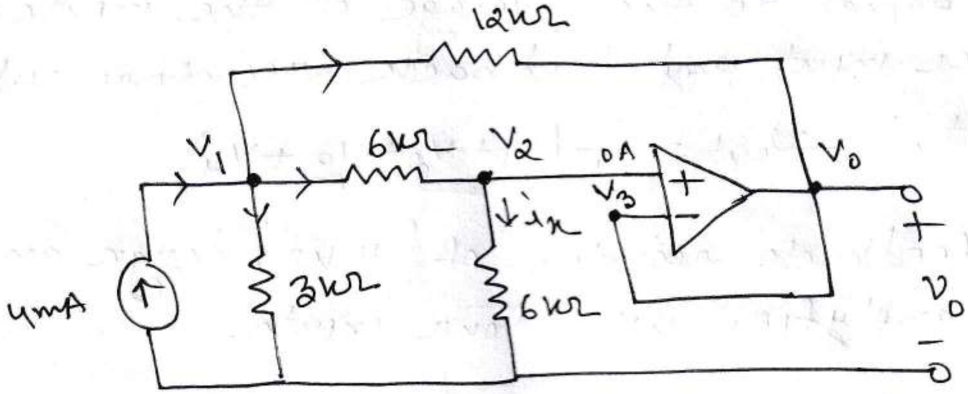
$$\therefore V_o = -\frac{5}{2}\ \text{V.}$$

(Ans.)

Practice: 5.19, 5.20.

Ex 5.31 (P-205)

For the circuit, determine i_x.



Soln. Apply nodal analysis at node 2,

$$\frac{V_1 - V_2}{6} = \frac{V_2}{6}$$

$$\Rightarrow \frac{V_1 - V_0}{6} = \frac{V_0}{6} \quad [\because V_2 = V_3 = V_0]$$

$$\Rightarrow \frac{V_1}{6} = \frac{2V_0}{6}$$

$$\therefore V_1 = 2V_0 \text{ — (i)}$$

Apply nodal analysis at node 1,

$$4 = \frac{V_1}{3} + \frac{V_1 - V_2}{6} + \frac{V_1 - V_0}{12}$$

$$\Rightarrow 4 = \frac{2V_0}{3} + \frac{2V_0 - V_0}{6} + \frac{2V_0 - V_0}{12}$$

$$\Rightarrow 4 = \frac{2V_0}{3} + \frac{V_0}{6} + \frac{V_0}{12}$$

$$\Rightarrow 4 = \frac{8V_0 + 2V_0 + V_0}{12}$$

$$\Rightarrow 11V_0 = 48$$

$$\Rightarrow V_0 = \frac{48}{11}$$

$$\therefore i_x = \frac{V_2}{6} = \frac{V_0}{6} = \frac{48}{11 \times 6} = \frac{8}{11} \text{ mA. (Ans.)}$$

Practice: 5.30, 5.27, 5.32.

Ex 5.41 (P-207)

An averaging amplifier is a summer that provides an output equal to the average of the inputs. By using proper input and feedback resistors values, one can get, $-v_{out} = \frac{1}{4}(v_1+v_2+v_3+v_4)$

Using a feedback resistor of $10\,k\Omega$, design an averaging amplifier with four inputs.

Solⁿ: With four inputs, the output of a summer is,

$$v_{out} = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3 + \frac{R_f}{R_4}v_4\right) \quad \text{--- (i)}$$

Given,

$$-v_{out} = \frac{1}{4}(v_1+v_2+v_3+v_4)$$

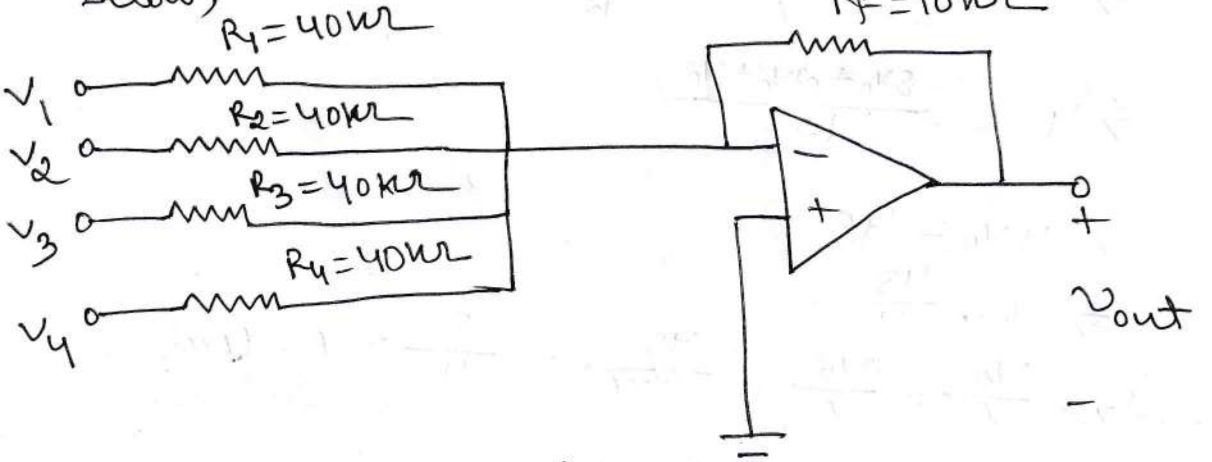
$$\Rightarrow v_{out} = -\left(\frac{1}{4}v_1 + \frac{1}{4}v_2 + \frac{1}{4}v_3 + \frac{1}{4}v_4\right) \quad \text{--- (ii)}$$

Comparing eqⁿ (i) & (ii) we get,

$$\frac{R_f}{R_1} = \frac{R_f}{R_2} = \frac{R_f}{R_3} = \frac{R_f}{R_4} = \frac{1}{4}$$

If $R_f = 10\,k\Omega$, then, $R_1 = R_2 = R_3 = R_4 = 4 \times R_f = 40\,k\Omega$

The designed circuit of the averaging amplifier is given below,



— X —

Practice: 5.42, 5.43

Ex 5.46 (P-207)

Using only two op amps, design a circuit to solve

$$-v_{out} = \frac{v_1 - v_2}{3} + \frac{v_3}{2}$$

Sol^n: Given,

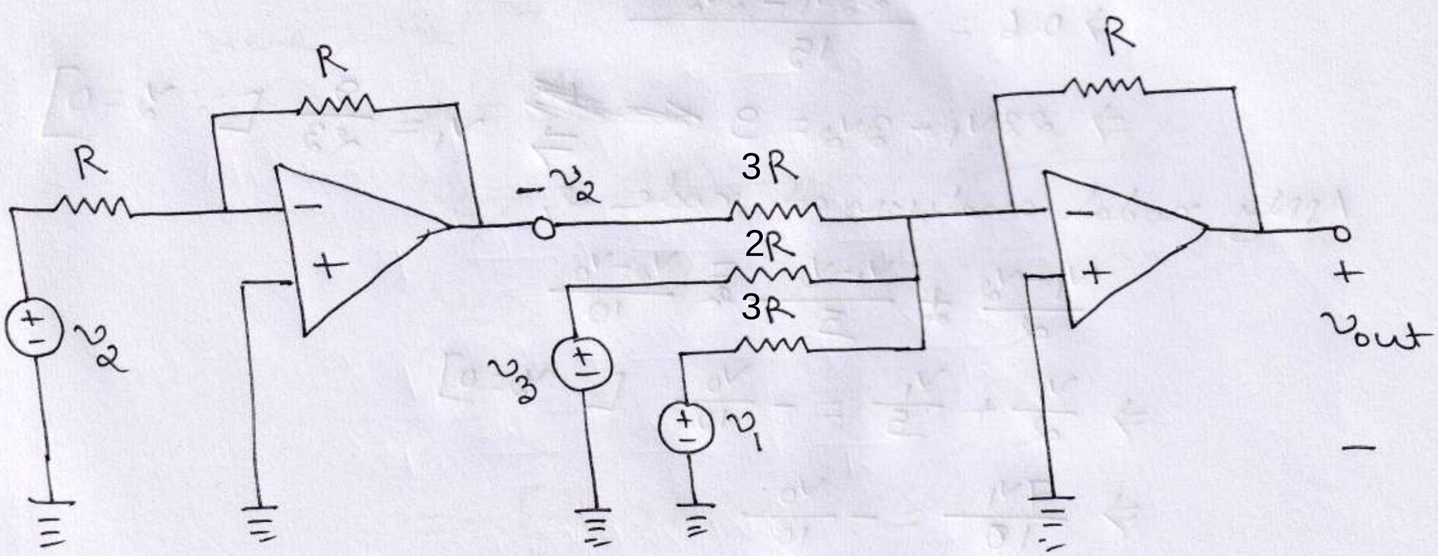
$$-v_{out} = \frac{v_1 - v_2}{3} + \frac{v_3}{2}$$

$$\Rightarrow v_{out} = -\left(\frac{1}{3}v_1 - \frac{1}{3}v_2 + \frac{1}{2}v_3\right)$$

$$\Rightarrow v_{out} = -\left[\frac{1}{3}v_1 + \frac{1}{3}(-v_2) + \frac{1}{2}v_3\right]$$

$$\Rightarrow v_{out} = -\left[\frac{R}{3R}v_1 + \frac{R}{3R}\left(-\frac{R}{R}\right)v_2 + \frac{R}{2R}v_3\right]$$

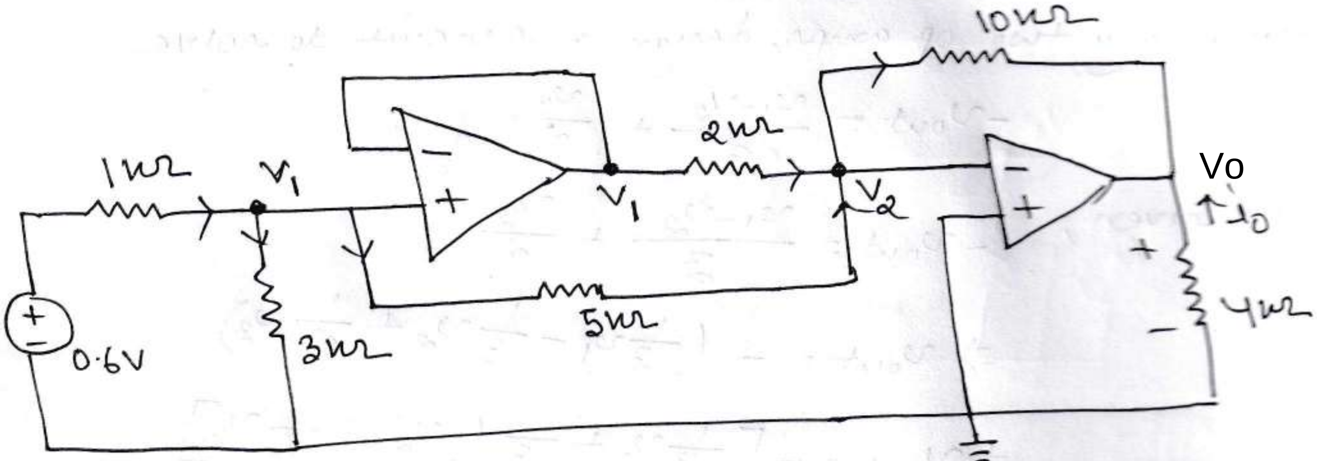
Therefore, the designed circuit is,



Practice: 5.45, 5.49, 5.50

Ex 5.58 (P-209)

Calculate i_o in the op amp circuit.



Soln. Apply nodal analysis at node 1,

$$\frac{0.6-v_1}{1} = \frac{v_1}{3} + \frac{v_1-v_2}{5}$$

$$\Rightarrow 0.6 = v_1 + \frac{v_1}{3} + \frac{v_1}{5} - \frac{v_2}{5}$$

$$\Rightarrow 0.6 = \frac{23v_1 - 3v_2}{15}$$

$$\Rightarrow 23v_1 - 3v_2 = 9 \Rightarrow v_1 = \frac{9}{23} \quad [\because v_2 = 0]$$

Apply nodal analysis at node 2,

$$\frac{v_1-v_2}{2} + \frac{v_1-v_2}{5} = \frac{v_2-v_0}{10}$$

$$\Rightarrow \frac{v_1}{2} + \frac{v_1}{5} = -\frac{v_0}{10} \quad [\because v_2=0]$$

$$\Rightarrow \frac{7v_1}{10} = -\frac{v_0}{10}$$

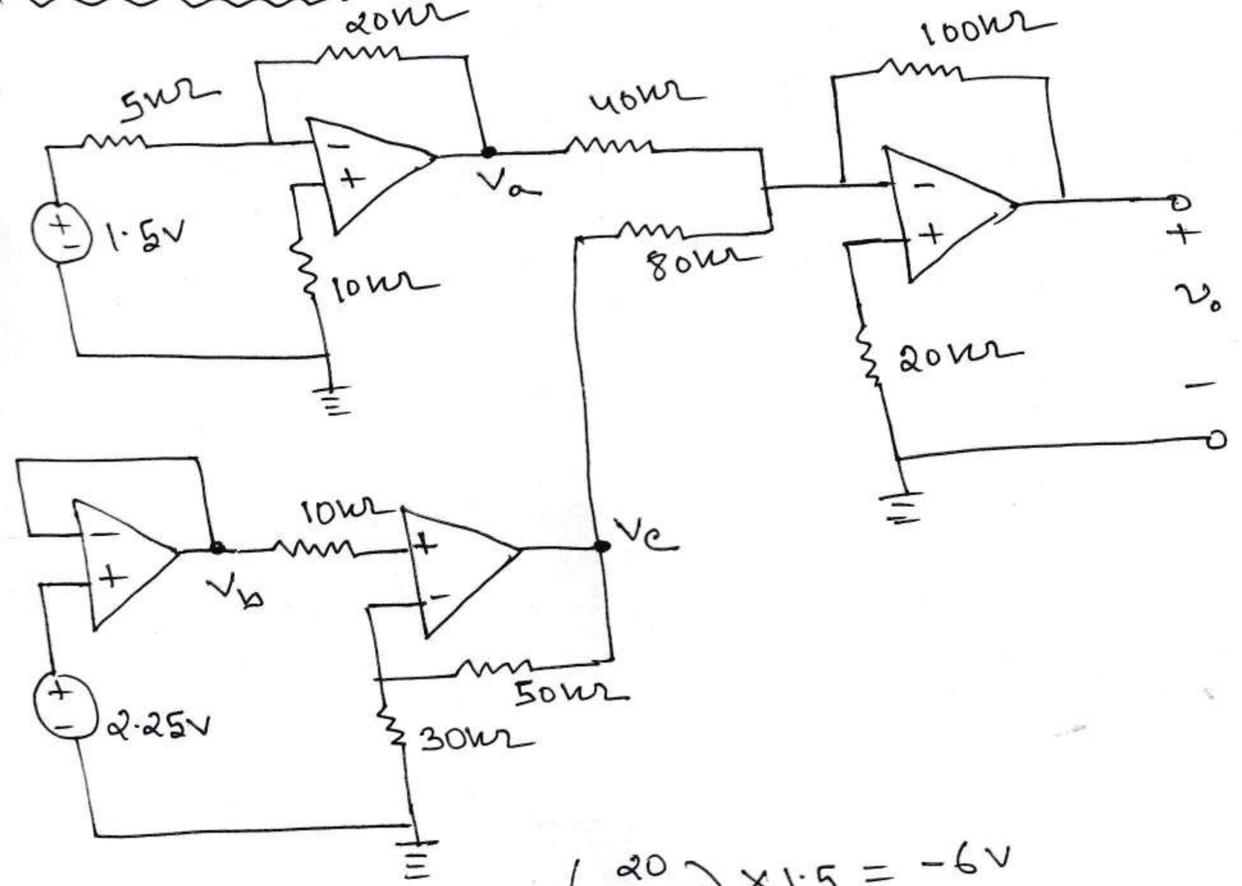
$$\Rightarrow v_0 = -7v_1$$

$$\Rightarrow v_0 = -7 \times \frac{9}{23} = -\frac{63}{23}$$

$$\therefore i_o = -\frac{v_0}{4} = \frac{63}{4 \times 23} = \frac{63}{92} = 0.685 \text{ mA.}$$

(Ans.)

Ex 5.71 (P-211) Determine v_o in the op amp circuit.



Solⁿ: Here, $v_a = -\left(\frac{20}{5}\right) \times 1.5 = -6V$

$v_b = 2.25\,V$

$\cancel{v_c = -\left(\frac{50}{30}\right) \times v_b = -\frac{5}{3} \times 2.25 =}$

$v_c = \left(1 + \frac{50}{30}\right) v_b = \left(1 + \frac{5}{3}\right) \times 2.25 = 6V$

$\therefore v_o = -\left(\frac{100}{40} v_a + \frac{100}{80} v_c\right)$

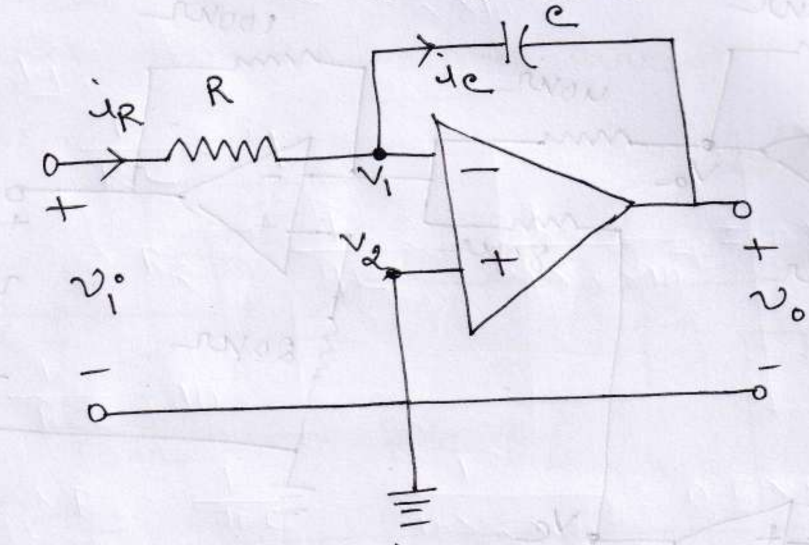
$= -\left[\frac{10}{4} \times (-6) + \frac{10}{8} \times 6\right]$

$= 15 - 7.5$

$= 7.5V$. (Ans).

Practice: 5.65, 5.68, 5.67, 5.74

Integrator



Here, $i_R = i_C$

$$\Rightarrow \frac{v_i - V_1}{R} = C\frac{dv_c}{dt}$$

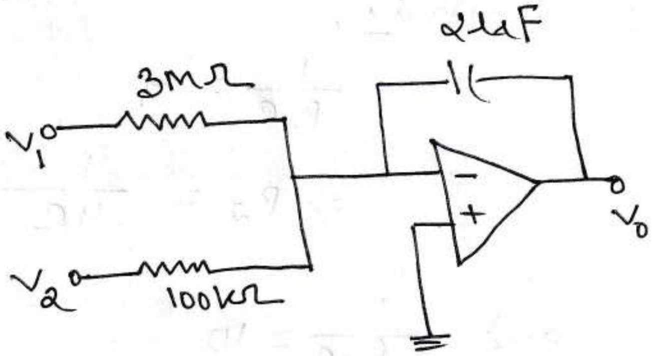
$$\Rightarrow \frac{V_i - V_1}{R} = C\frac{d}{dt}(V_1 - V_o)$$

$$\Rightarrow \frac{V_i}{R} = -C\frac{dV_o}{dt} \quad [\because V_1 = V_2 = 0]$$

$$\Rightarrow \frac{dV_o}{dt} = -\frac{1}{RC}V_i$$

$$\therefore V_o = -\frac{1}{RC}\int V_i\,dt$$

Example 6.13 (P-235) If $v_1 = 10\cos 2t$ mV and $v_2 = 0.5t$ mV find v_o in the op amp circuit.



Solⁿ: $v_o = -\left[\frac{1}{R_1C}\int v_1 dt + \frac{1}{R_2C}\int v_2 dt\right]$

$$= -\left[\frac{1}{3\times10^6\times2\times10^{-6}}\int 10\cos 2t + \frac{1}{100\times10^3\times2\times10^{-6}}\int 0.5t\right]$$

$$= -\frac{10}{6}\left[\frac{\sin 2t}{2}\right] - \frac{0.5}{0.2}\left[\frac{t^2}{2}\right]$$

$$= \left[-0.833\sin 2t - 1.25t^2\right] \text{ mV. (Ans.)}$$

Ex 6.71 (P-250): Show how you would use a single op amp to generate $v_o = -\int_0^t (v_1 + 4v_2 + 10v_3)\, dt$. If the integrating capacitor is $C = 2\mu F$, obtain the other component values.

Solⁿ: using a single op amp, the integrator circuit's output with three input signals is,

$$v_o = -\left[\frac{1}{R_1C}\int v_1 dt + \frac{1}{R_2C}\int v_2 dt + \frac{1}{R_3C}\int v_3 dt\right] \quad \text{— (i)}$$

Given, $v_o = -\int_0^t [v_1 + 4v_2 + 10v_3]\, dt$ — (ii)

comparing (i) with (ii) we have,

$$\frac{1}{R_1C} = 1$$

$$\Rightarrow R_1 = \frac{1}{C} = \frac{1}{2\times10^{-6}} = 0.5\times10^{6}\ \Omega = 500\,k\Omega$$

Similarly,

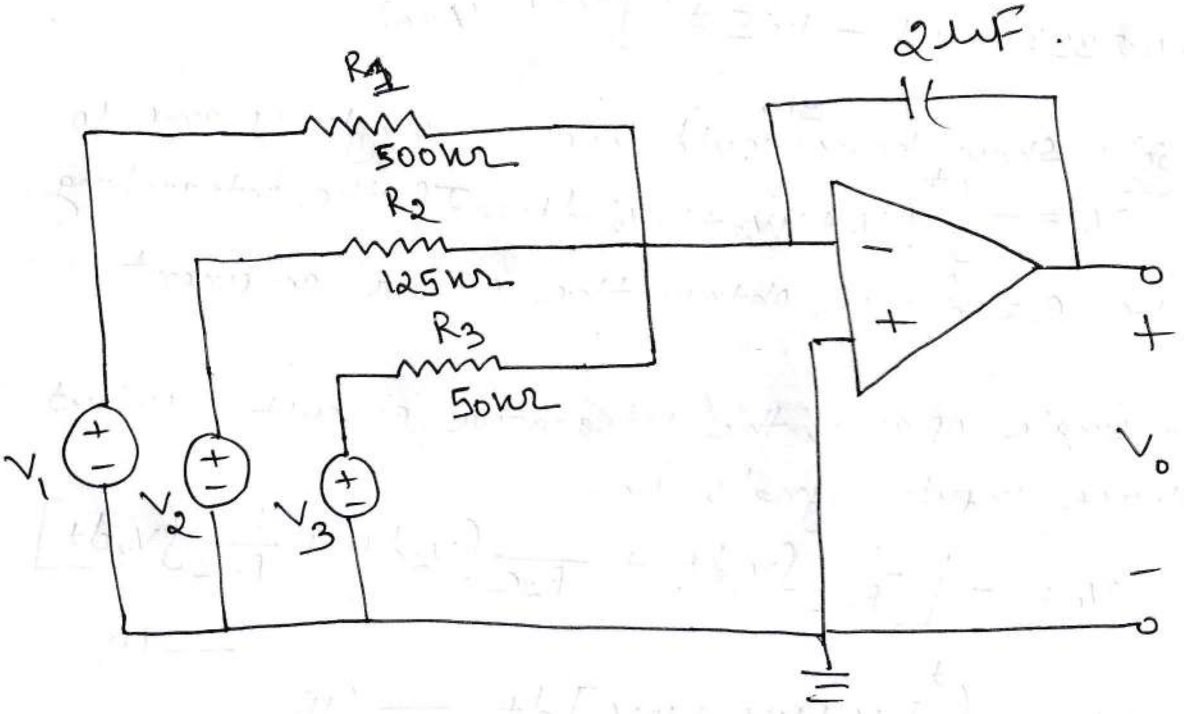
$$\frac{1}{R_2 C} = 4$$

$$\Rightarrow R_2 = \frac{1}{4C} = \frac{1}{4\times2\times10^{-6}} = 0.125\times10^{6}\,\Omega = 125\,k\Omega$$

and $\frac{1}{R_3 C} = 10$

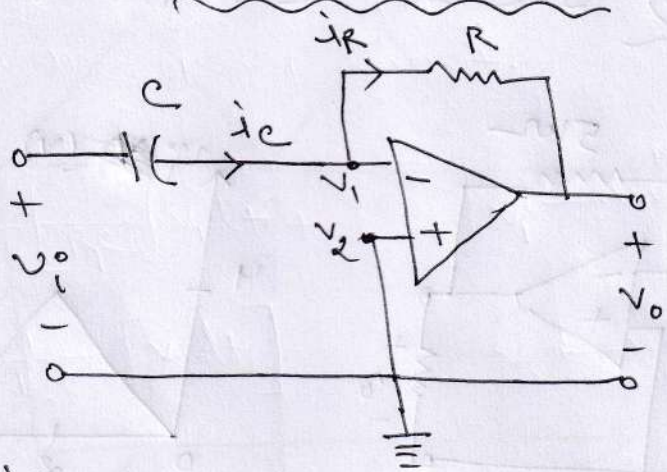
$$\Rightarrow R_3 = \frac{1}{10C} = \frac{1}{10\times2\times10^{-6}} = 0.5\times10^{5}\ \Omega = 50\,k\Omega.$$

Therefore, the designed circuit is,



practise: 6.67, 6.70, 6.72

Differentiator



Here,

$$i_C = i_R$$

$$\boxed{\cancel{C\frac{dV_c}{dt}}}$$

$$\Rightarrow C\frac{dv_c}{dt} = \frac{V_1 - V_o}{R}$$

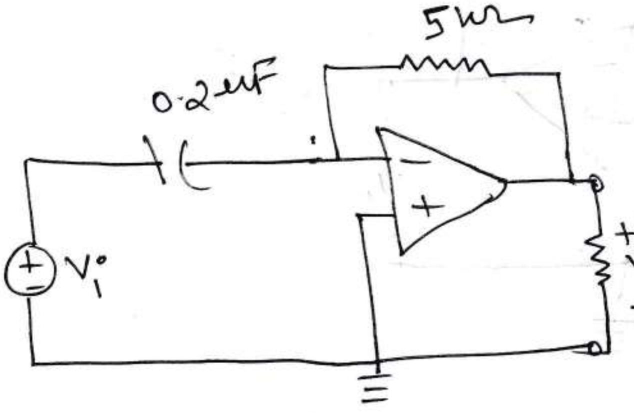
$$\Rightarrow C\frac{d}{dt}(V_i - V_1) = \frac{V_1 - V_o}{R}$$

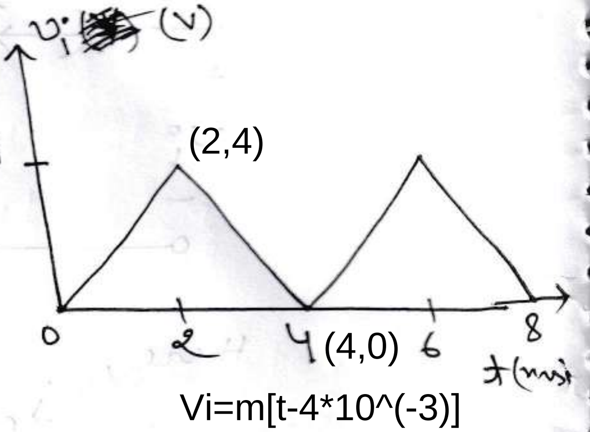
$$\Rightarrow C\frac{dv_i}{dt} = -\frac{V_o}{R} \quad [\because V_1 = V_2 = 0]$$

$$\therefore V_o = -RC\frac{dv_i}{dt}.$$

— X —

Example 6.14 (P-236) Sketch the output voltage for the circuit.





Vi=m[t-4*10^(-3)]

Soln: Here,

$$RC = 5\times10^{3}\times0.2\times10^{-6} = 10^{-3}\,s.$$

$$v_i = \begin{cases} 2000t, & 0<t<2ms \\ 8-2000t, & 2<t<4ms \end{cases}$$

Now, for $0<t<2ms$,

$$V_o = -RC\frac{dv_i}{dt} = -10^{-3}\frac{d}{dt}(2000t)$$
$$= -2V$$

For $2<t<4ms$, $V_o = -RC\frac{dv_i}{dt}$
$$= -10^{-3}\frac{d}{dt}(8-2000t)$$
$$= 2V$$

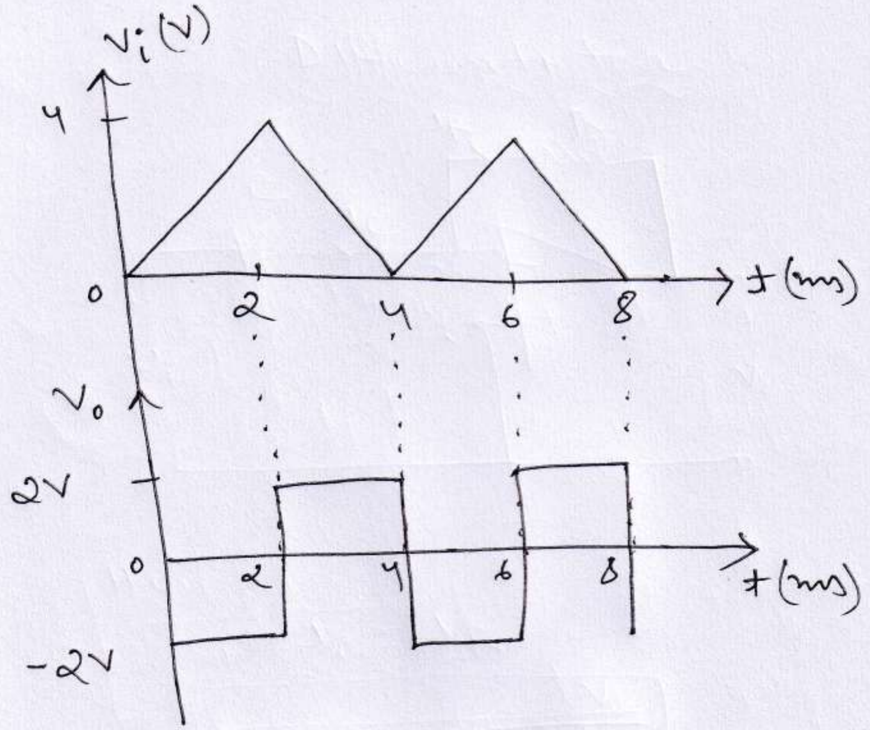
Note: use the concept of CSE 248 to get the signal value.

For $0<t<2ms$,

$$v_i = \frac{4-0}{(2-0)\times10^{-3}}t$$
$$= 2000t$$

For $2<t<4ms$.

$$v_i = \frac{0-4}{(4-2)\times10^{-3}}(t-4\times10^{-3})$$
$$= -2000(t-4\times10^{-3})$$
$$= 8-2000t$$



practise: 6.74, 6.75, 6.77 (P-250, 251).

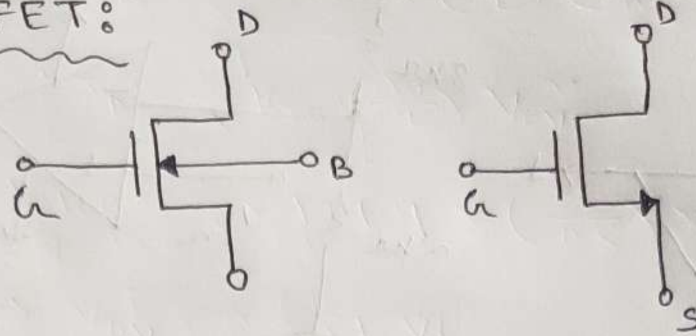
——— X ———

Chapter 5

MOSFET

n-channel MOSFET:

Symbol →



Region of operations of the NMOS transistor

Cut-off	Induced channel	Triode	Saturation
$v_{GS} < V_t$ no channel $i_D = 0$	$v_{GS} \geq V_t$ overdrive voltage, $V_{OV} = v_{GS} - V_t$	$v_{GS} \geq V_t$ and $v_{GD} > V_t$ $\Rightarrow v_{GS} - v_{DS} > V_t$ $\Rightarrow v_{DS} < v_{GS} - V_t$ $\Rightarrow v_{DS} < V_{OV}$ Drain current, $i_D = \mu_n C_{ox}\left(\frac{W}{L}\right)\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right]$ —— (i)	$v_{GS} \geq V_t$ and $v_{GD} \leq V_t$ $\Rightarrow v_{GS} - v_{DS} \leq V_t$ $\Rightarrow v_{DS} \geq v_{GS} - V_t$ $\Rightarrow v_{DS} \geq V_{OV}$ Drain current, $i_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(v_{GS} - V_t)^2$. —— (ii)

For small v_{DS} eqn (ii) becomes,

$$i_D = \mu_n C_{ox}\left(\frac{W}{L}\right)(v_{GS} - V_t)\, v_{DS}$$

$$\Rightarrow \frac{i_D}{v_{DS}} = k_n'\left(\frac{W}{L}\right)V_{OV}$$

$$\Rightarrow g_{DS} = k_n'\left(\frac{W}{L}\right)V_{OV}$$

$$\Rightarrow r_{DS} = \frac{1}{k_n'\left(\frac{W}{L}\right)V_{OV}}.$$

Example 5.1 Consider a process technology for which $L_{min} = 0.4\ \mu m$, $t_{ox} = 8\ nm$, $\mu_n = 450\ cm^2/V.s$ and $V_t = 0.7V$.

(a) Find C_{ox} and k_n'.

(b) For a MOSFET with $W/L = 8\ \mu m / 0.8\ \mu m$, calculate the values of V_{OV}, V_{GS} and $V_{DS\,min}$ needed to operate the transistor in the saturation region with a DC current $I_D = 100\ \mu A$.

(c) For the device in (b), find the values of V_{OV} and V_{GS} required to cause the device to operate as a $1000\ \Omega$ resistor for very small V_{DS}.

Solⁿ: (a)

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9\,\varepsilon_0}{t_{ox}}$$

$$= \frac{3.9 \times 8.854 \times 10^{-12}}{8 \times 10^{-9}}\ F/m^2$$

$$= 4.32 \times 10^{-3}\ F/m^2$$

$$\boxed{= 4.32\ fF/\mu m^2}$$

$$k_n' = \mu_n C_{ox} = 450\ (cm^2/V.s) \times 4.32 \times 10^{-3}\ (F/m^2)$$

$$= 450 \times 10^{-4} \times 4.32 \times 10^{-3}\ A/V^2$$

$$= 1.944 \times 10^{-4}\ A/V^2$$

$$\boxed{= 194.4\ \mu A/V^2}$$

(b) For operation in the saturation region,

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS}-V_t)^2$$

$$\Rightarrow I_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)V_{OV}^2$$

$$\Rightarrow 100 = \frac{1}{2}\times 194.4\times\left(\frac{8}{0.8}\right)\times V_{OV}^2$$

$$\Rightarrow V_{OV} = \boxed{0.321\ V.}$$

Again,

$$V_{OV} = V_{GS} - V_t$$

$$\Rightarrow V_{GS} = V_{OV} + V_t = 0.321 + 0.7$$

$$\boxed{= 1.021V.}$$

and $V_{DS\,min} = V_{GS} - V_t = V_{OV} = \boxed{0.321\ V.}$

(c) we know,

$$r_{DS} = \frac{1}{k_n'\left(\frac{W}{L}\right)V_{OV}}$$

$$\Rightarrow 1000 = \frac{1}{194.4\times10^{-6}\times\frac{8}{0.8}\times V_{OV}}$$

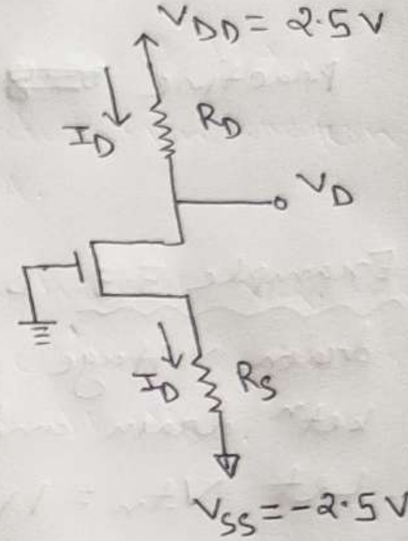
$$\Rightarrow \boxed{V_{OV} = 0.52\ V}$$

Thus, $V_{GS} = V_{OV} + V_t = 0.52 + 0.7$

$$\boxed{= 1.22V.}$$

Practise 5.2 (P-261).

Example 5.3: Design the circuit below: that is determine the values of R_D and R_S so that the transistor operates at $I_D = 0.4$ mA and $V_D = +0.5$ V. The NMOS transistor has $V_t = 0.7$ V, $\mu_n C_{ox} = 100\ \mu A/V^2$, $L = 1\ \mu m$ and $W = 32\ \mu m$.



Sol^n: Here,

$$R_D = \frac{V_{DD} - V_D}{I_D}$$

$$= \frac{2.5 - 0.5}{0.4}$$

$$\boxed{= 5\ k\Omega.}$$

Now, $V_{GD} = V_G - V_D$

$$= 0 - 0.5$$

$$= -0.5\ V$$

which is less than V_t. Therefore, the NMOS transistor is operating in the saturation region.

$$\therefore I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right)(V_{GS} - V_t)^2$$

$$\Rightarrow 0.4 = \frac{1}{2} \times (100 \times 10^{-3}) \times \left(\frac{32}{1}\right)(V_{GS} - 0.7)^2$$

$$\Rightarrow 0.25 = (V_{GS} - 0.7)^2$$

$$\Rightarrow V_{GS} = 0.5 + 0.7$$

$$\Rightarrow V_G - V_S = 1.2$$

$$\Rightarrow V_S = -1.2V.$$

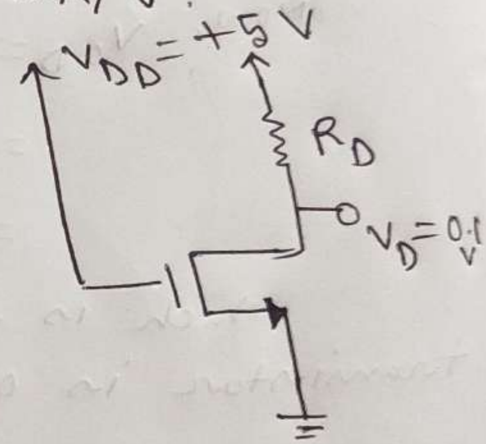
$\therefore R_S = \dfrac{V_S - V_{SS}}{I_D}$

$= \dfrac{-1.2-(-2.5)}{0.4}$

$\boxed{= 3.25\ K\Omega.}$

Practise ~~D5.8~~ D5.8 (P-278).
D5.9 (P-279)

Example 5.5 Design the circuit to establish a drain voltage of 0.1 V. What is the effective resistance betn drain and source at this operating point? Let $V_{tn} = 1V$ and $K_n'\left(\frac{W}{L}\right) = 1\ mA/V^2$.



Soln: Here,

$V_G = V_{DD} = 5V$

$V_D = 0.1V,\ V_S = 0V$

$\therefore V_{GS} = V_G - V_S = 5V$

$\therefore V_{GD} = V_G - V_D = 5 - 0.1$

$= 4.9V$

which is higher than V_t. Therefore, the NMOS transistor is operating in triode region.

$\therefore I_D = K_n'\left(\frac{W}{L}\right)\left[(V_{GS}-V_t)V_{DS} - \frac{1}{2}V_{DS}^2\right]$

$= 1 \times \left[(5-1)\times 0.1 - \frac{1}{2}(0.1)^2\right]$

$= 0.395\ mA.$

$$\therefore R_D = \frac{V_{DD} - V_D}{I_D}$$

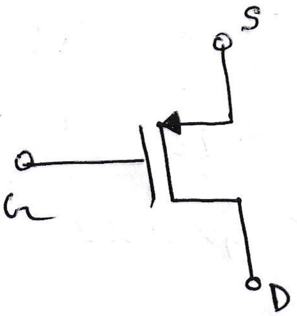
$$= \frac{5 - 0.1}{0.395}$$

$$\boxed{= 12.4\ k\Omega}.$$

The effective drain to source resistance is,

$$r_{DS} = \frac{V_{DS}}{I_{DS}} = \frac{0.1}{0.395} = \boxed{253\ \Omega}.$$

P-mos

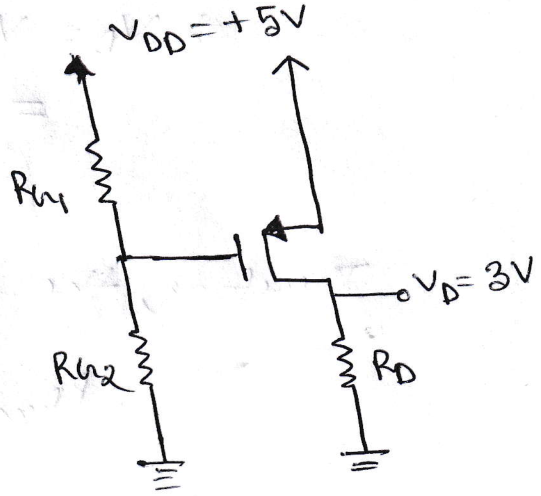


Region of operation of the PMOS transistor

Cut-off	Induced channel	Triode	Saturation
$V_{SG} < \lvert V_{tp} \rvert$ no channel $i_D = 0$	$V_{SG} \geq \lvert V_{tp} \rvert$ Overdrive voltage, $\lvert V_{ov} \rvert = V_{SG} - \lvert V_{tp} \rvert$	$V_{SG} \geq \lvert V_{tp} \rvert$ and $V_{DG} > \lvert V_{tp} \rvert$ $\Rightarrow V_{SD} < V_{SG} - \lvert V_{tp} \rvert$ $\Rightarrow V_{SD} < \lvert V_{ov} \rvert$ Drain current, $i_D = \mu_p C_{ox} \left(\frac{W}{L}\right) \left[(V_{SG} - \lvert V_{tp} \rvert) V_{SD} - \frac{1}{2} V_{SD}^2 \right]$	$V_{SG} \geq \lvert V_{tp} \rvert$ and $V_{DG} \leq \lvert V_{tp} \rvert$ $\Rightarrow V_{SD} \geq V_{SG} - \lvert V_{tp} \rvert$ $\Rightarrow V_{SD} \geq \lvert V_{ov} \rvert$ Drain current, $i_D = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L}\right) (V_{SG} - \lvert V_{tp} \rvert)^2$

Example 5.7 (P-283)

Design the circuit so that the transistor operates in saturation with $I_D = 0.5$ mA and $V_D = +3V$. Let the PMOS transistor have $V_{tp} = -1V$ and $k_p'\left(\frac{W}{L}\right) = 1\ mA/V^2$. What is the largest value of R_D can have while maintaining saturation-region operation?



Solution: The drain current at saturation,

$$I_D = \frac{1}{2} k_p'\left(\frac{W}{L}\right)\left(V_{SG} - |V_{tp}|\right)^2$$

$$\Rightarrow 0.5 = \frac{1}{2} \times 1 \left(V_{SG} - 1\right)^2$$

$$\Rightarrow V_{SG} = 2$$

$$\Rightarrow V_S - V_G = 2$$

$$\Rightarrow 5 - V_G = 2$$

$$\therefore V_G = 3V.$$

Now, $$V_G = \frac{R_{G2}}{R_{G1} + R_{G2}} \times V_{DD}$$

$$\Rightarrow 3 = \frac{R_{G2}}{R_{G1} + R_{G2}} \times 5$$

$$\Rightarrow \cancel{5R_{G1} = 2R_{G2}}$$

$$\Rightarrow 3R_{G1} = 2R_{G2}$$

$$\therefore \frac{R_{G1}}{R_{G2}} = \frac{2}{3}$$

Therefore, a possible selection is $R_{G1} = 2\ M\Omega$ and $R_{G2} = 3\ M\Omega$.

$$\therefore R_D = \frac{V_D}{I_D} = \frac{3}{0.5} = 6\ k\Omega.$$

The minimum condition to maintain saturation mode operation,

$$V_{SD} = V_{SG} - |V_{tp}|$$

$$\Rightarrow V_S - V_D = V_S - V_G - |V_{tp}|$$

$$\Rightarrow V_D = V_G + |V_{tp}|$$

$$= 3 + 1$$

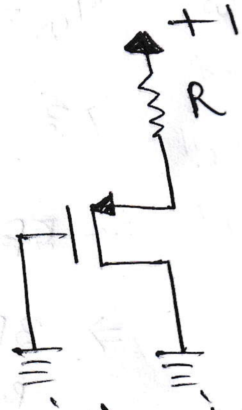
$$= 4V$$

Therefore, the max^{m} value of R_D

$$\therefore R_{D\,max} = \frac{V_D}{I_D} = \frac{4}{0.5} = 8\,k\Omega.$$

Exercise D5.14 (P-285)

Find the value of R that results in pmos transistor operating with an overdrive voltage $|V_{ov}| = 0.6\,V$. The threshold voltage is $V_{tp} = -0.4\,V$, $k_p' = 0.1\,mA/V^2$ and $W/L = \frac{10\,\mu m}{0.18\,\mu m}$



Solution:

Here,

$$V_{DG} = V_D - V_G$$

$$= 0V$$

~~V_{SG} [illegible] V~~

As $V_{DG} < |V_{tp}| = 0.4V$, the PMOS transistor is operating in ~~triode region~~ saturation region

$$\therefore I_D = k_p'\left(\frac{W}{L}\right)\left[(V_{SG} - |V_{tp}|)V_{SD} - \frac{1}{2}V_{SD}^2\right]$$

$$\cancel{= 1 \times \frac{10}{0.18}\left[(1.8 - 0.4)1.8 - \frac{1}{2}(1.8)^2\right]}$$

$\therefore I_D = \frac{1}{2} k_p' \left(\frac{W}{L}\right) |V_{OV}|^2$

$= \frac{1}{2} \times 0.1 \times \left(\frac{10}{0.18}\right) (0.6)^2$

$= 1 \text{ mA}.$

$\therefore R = \frac{1.8 - V_S}{I_D} = \frac{1.8 - 1}{1}$

$= 0.8 \text{ k}\Omega$

$= 800\Omega.$

(Ans.)

$\because |V_{OV}| = 0.6$

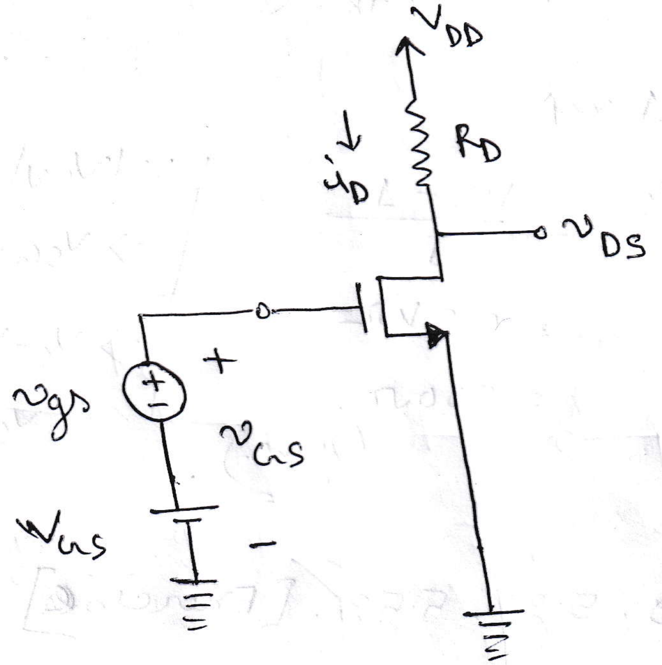
$\Rightarrow V_{SG} - |V_{tp}| = 0.6$

$\Rightarrow V_S - V_G - 0.4 = 0.6$

$\therefore V_S = 1 \text{ V}.$

Practice: 5.49, 5.38, 5.53. [Exercise]

*) MOSFET amplifier with a small time-varying signal $v_{gs}(t)$ superimposed on the dc bias voltage V_{GS}.



Small-signal condition is,

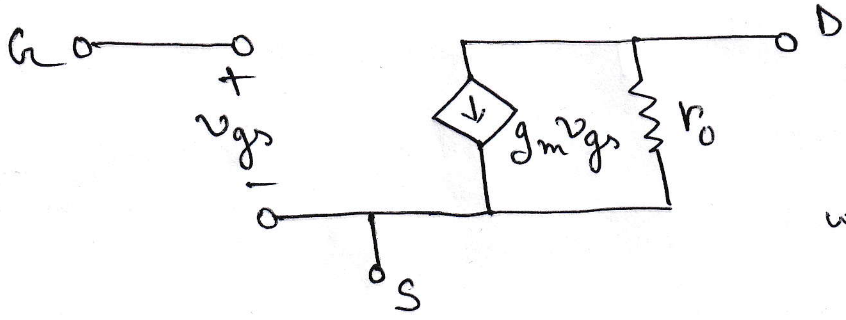
$$v_{gs} \ll 2(V_{GS} - V_t)$$

or $v_{gs} \ll 2V_{OV}$.

MOSFET transconductance $g_m \equiv \dfrac{i_d}{v_{gs}} = \cancel{k_n(V_{GS}-V_t)}$
$= k_n'\left(\frac{W}{L}\right)(V_{GS} - V_t)$

Voltage gain, $A_v \equiv \dfrac{v_{ds}}{v_{gs}} = -g_m R_D$.

Small-signal model including the effect of channel-length modulation



Here,

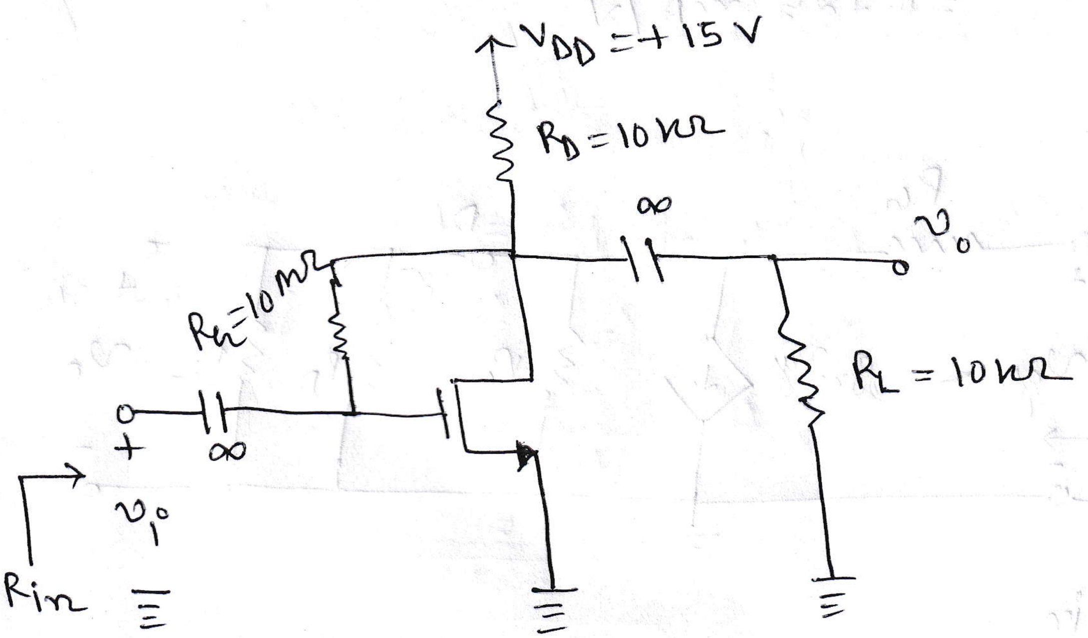
$$r_o = \frac{1}{\lambda I_D} = \frac{V_A}{I_D}$$

where,

$$V_A = \frac{1}{\lambda}.$$

Example 7.3 (Page 389)

Analyze this amplifier circuit to determine its small signal voltage gain, its input resistance, and the largest allowable input signal. The transistor has $V_t = 1.5\,V$, $K_n'\left(\frac{W}{L}\right) = 0.25\ mA/V^2$, and $V_A = 50V$.



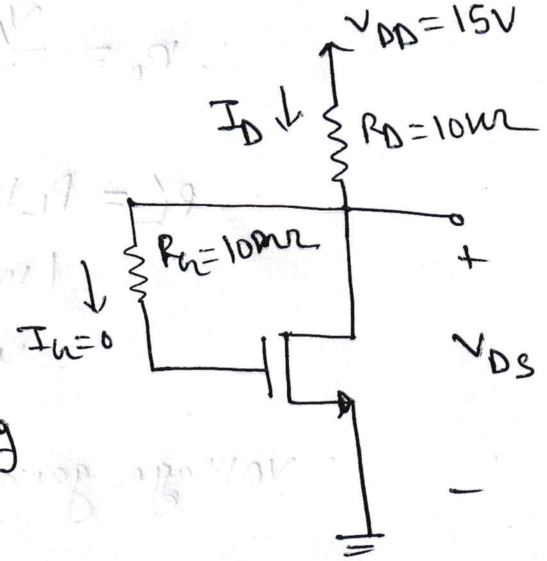
Soln:

As $I_G = 0$, here,

$V_{GD} = 0$

$\therefore V_{GS} = V_{DS} = V_{DD} - I_D R_D$

$= 15 - 10\,I_D$



Circuit for determining dc operating point.

NMOS transistor will be operating in the saturation. Thus,

$$I_D = \frac{1}{2} K_n'\left(\frac{W}{L}\right)(V_{GS} - V_t)^2$$

$$\Rightarrow 2 I_D = 0.25\,(15 - 10 I_D - 1.5)^2$$

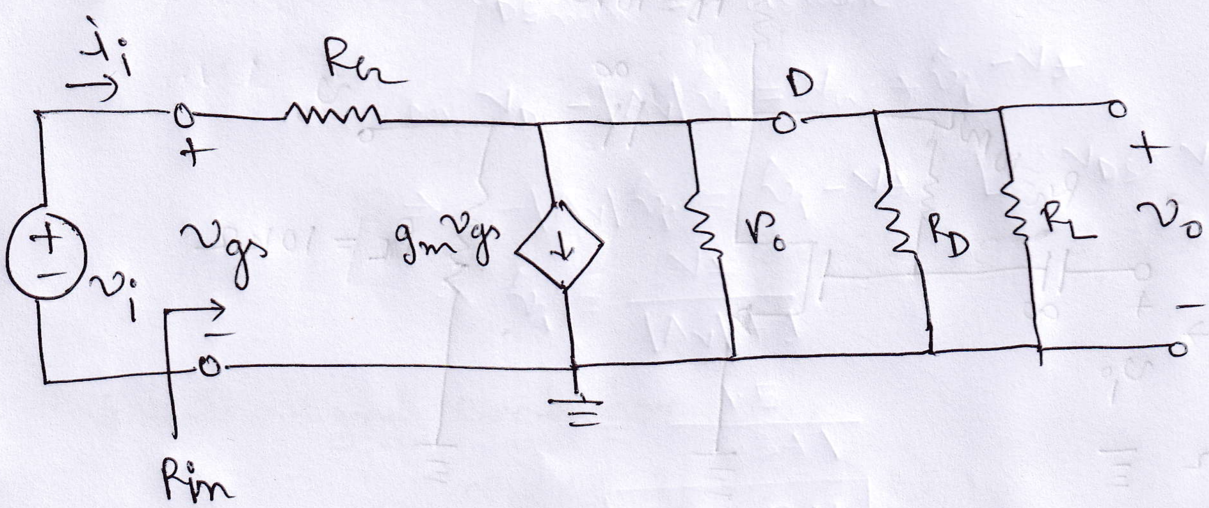
$$\Rightarrow I_D = 1.06\ mA.$$

$\therefore V_{GS} = 15 - (10 \times 1.06) = 4.4\,V.$

$\therefore g_m = k_n'\left(\frac{W}{L}\right)(V_{GS} - V_t)$

$= 0.25 \times (4.4 - 1.5)$

$= 0.725\ mA/V$



$\therefore r_o = \frac{V_A}{I_D} = \frac{50}{1.06} = 47\ k\Omega$

$\therefore R_L' = R_L \| R_D \| r_o$

$= (10 \| 10 \| 47)\ k\Omega$

$= 4.52\ k\Omega$

$\therefore$ voltage gain, $A_v \cong -g_m R_L'$

$= -0.725 \times 4.52$

$\boxed{= -3.3}$

We know, $A_v = \frac{v_o}{v_{gs}}$

$$\Rightarrow v_o = A_v v_{gs}$$

$$\Rightarrow v_o = -g_m R_L' v_{gs}$$

$$\therefore R_{in} = \frac{v_i}{i_i} = \frac{v_{gs}}{i_i}$$

$$\Rightarrow R_{in} = \frac{v_{gs}}{\frac{v_i - v_o}{R_G}}$$

$$\Rightarrow R_{in} = \frac{v_{gs} \times R_G}{v_{gs} - v_o}$$

$$= \frac{v_{gs} R_G}{v_{gs} + g_m R_L' v_{gs}}$$

$$= \frac{R_G}{1 + g_m R_L'}$$

$$= \frac{10 \times 10^3}{1 + 3.3}$$

$$= 2.33 \times 10^3 \ k\Omega$$

$$\boxed{= 2.33 \ M\Omega}$$

The largest allowable input signal $\hat{v}_i$ is constrained by the need to keep the transistor in saturation at all times; that is,

$$v_{DS} \geq v_{GS} - V_t$$

Enforcing the condition with equality,

$$v_{DS\,min} = v_{GS\,max} - V_t$$

or $v_{DS} - |A_v|\hat{v}_i = V_{GS} + \hat{v}_i - V_t$

$\Rightarrow -|A_v|\hat{v}_i = \hat{v}_i - V_t \quad [\because V_{DS} = V_{GS}]$

$$\Rightarrow \hat{v}_i = \frac{V_t}{|A_v|+1}$$

$$= \frac{1.5}{3.3+1}$$

$$\boxed{= 0.35\ V}$$

practice: 7.29, 7.31, 7.32 (P-485)