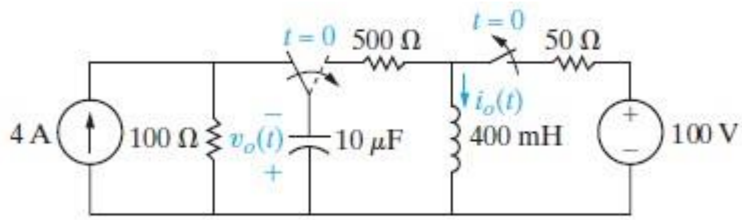
END_SEM_EXAM_QUESTION_BANK_2020

1. The circuit shown in Fig. below has been in operation for a long time. At $t = 0$ the two switches move to the new positions shown in the figure. Find a) $i_o(t)$for $t \geq 0$,

b) $v_o(t)$ for $t \geq 0$.



==

Soln:

[a] $t < 0$:

$$i_o = \frac{100}{50} = 2\,\text{A}; \qquad v_o = -4(100) = -400\,\text{V}$$

$t > 0$:

$$\alpha = \frac{R}{2L} = \frac{500}{2(0.4)} = 625 \text{ rad/s}$$

$$\omega_o = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{(0.4)(10 \times 10^{-6})}} = 500 \text{ rad/s}$$

$$\alpha^2 < \omega_o^2 \quad \therefore \quad \text{overdamped}$$

$$s_{1,2} = -625 \pm \sqrt{625^2 - 500^2} = -250, -1000 \text{ rad/s}$$

$$i_o = A_1 e^{-250t} + A_2 e^{-1000t}$$

$$i_o(0) = A_1 + A_2 = 2$$

$$\frac{di_o}{dt}(0) = -250A_1 - 1000A_2 = \frac{1}{L}(-V_0 - RI_0) = -1500$$

$$\text{Solving,} \qquad A_1 = \frac{2}{3}; \qquad A_2 = \frac{4}{3}$$

$$\therefore \qquad i_o(t) = \frac{2}{3}e^{-250t} + \frac{4}{3}e^{-1000t}\,\text{A}, \quad t \geq 0$$

[b] $$v_o(t) = \frac{1}{10 \times 10^{-6}} \int_0^t i_o(x)\,dx - 400$$

$$= 10^5 \left(\int_0^t \frac{2}{3} e^{-250x}\,dx + \int_0^t \frac{4}{3} e^{-1000x}\,dx \right) - 400$$

$$= 10^5 \left(\frac{(2/3)e^{-250x}}{-250} \Big|_0^t + \frac{(4/3)e^{-1000x}}{-1000} \Big|_0^t \right) - 400$$

$$= -266.67 e^{-250t} - 133.33 e^{-1000t}\ \mathrm{V}, \quad t \geq 0$$

RUBRIC :

1.5 marks for $i_o(t)$ calculation. Step marking to be done which should not exceed 1 mark in case of incorrect final answer.

1.5 marks for $v_o(t)$ calculation. Step marking to be done which should not exceed 1 mark in case of incorrect final answer.

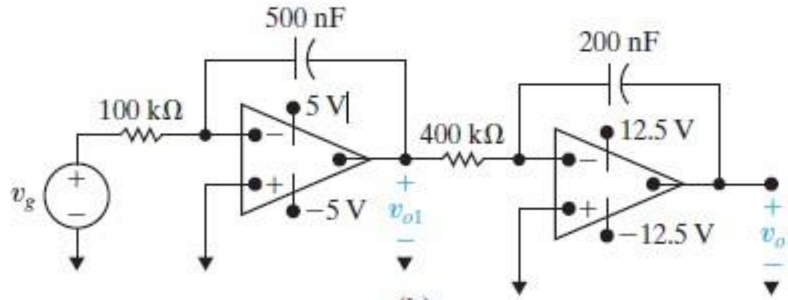
---

2. The voltage signal of Fig.(a) shown below is applied to the cascaded integrating amplifiers shown in Fig.(b). There is no energy stored in the capacitors at the instant the signal is applied.

a) Derive the numerical expressions for $v_o(t)$ and $v_{o1}(t)$ for the time intervals $0 \leq t \leq 0.5\ s$ and $0.5\ s \leq t \leq t_{sat}$

b) Compute the value of t_{sat}.

(a)



(b)

==

Soln:

3 .

[a] $\frac{d^2v_o}{dt^2} = \frac{1}{R_1C_1R_2C_2}v_g$

$$\frac{1}{R_1C_1R_2C_2} = \frac{10^{-6}}{(100)(400)(0.5)(0.2)\times 10^{-6}\times 10^{-6}} = 250$$

$$\therefore \quad \frac{d^2v_o}{dt^2} = 250v_g$$

$0 \leq t \leq 0.5^-$:

$v_g = 80\,\text{mV}$

$$\frac{d^2v_o}{dt^2} = 20$$

Let $g(t) = \frac{dv_o}{dt}$, then $\frac{dg}{dt} = 20$ or $dg = 20\,dt$

$$\int_{g(0)}^{g(t)} dx = 20\int_0^t dy$$

$$g(t) - g(0) = 20t, \quad g(0) = \frac{dv_o}{dt}(0) = 0$$

$$g(t) = \frac{dv_o}{dt} = 20t$$

$$dv_o = 20t\,dt$$

$$\int_{v_o(0)}^{v_o(t)} dx = 20\int_0^t x\,dx; \qquad v_o(t) - v_o(0) = 10t^2, \quad v_o(0) = 0$$

$$v_o(t) = 10t^2\,\text{V}, \quad 0 \leq t \leq 0.5^-$$

$$\frac{dv_{o1}}{dt} = -\frac{1}{R_1C_1}v_g = -20v_g = -1.6$$

$$dv_{o1} = -1.6\,dt$$

$$\int_{v_{o1}(0)}^{v_{o1}(t)} dx = -1.6\int_0^t dy$$

$$v_{o1}(t) - v_{o1}(0) = -1.6t, \qquad v_{o1}(0) = 0$$

$$v_{o1}(t) = -1.6t\,\text{V}, \qquad 0 \leq t \leq 0.5^-$$

$0.5^+ \leq t \leq t_{\text{sat}}$:

$$\frac{d^2v_o}{dt^2} = -10, \qquad \text{let} \quad g(t) = \frac{dv_o}{dt}$$

$$\frac{dg(t)}{dt} = -10; \qquad dg(t) = -10\,dt$$

$$\int_{g(0.5^+)}^{g(t)} dx = -10\int_{0.5}^{t} dy$$

$$g(t) - g(0.5^+) = -10(t-0.5) = -10t + 5$$

$$g(0.5^+) = \frac{dv_o(0.5^+)}{dt}$$

$$C\frac{dv_o}{dt}(0.5^+) = \frac{0 - v_{o1}(0.5^+)}{400 \times 10^3}$$

$$v_{o1}(0.5^+) = v_o(0.5^-) = -1.6(0.5) = -0.80\,\text{V}$$

$$\therefore \quad C\frac{dv_{o1}(0.5^+)}{dt} = \frac{0.80}{0.4 \times 10^3} = 2\,\mu\text{A}$$

$$\frac{dv_{o1}}{dt}(0.5^+) = \frac{2 \times 10^{-6}}{0.2 \times 10^{-6}} = 10\,\text{V/s}$$

$$\therefore \quad g(t) = -10t + 5 + 10 = -10t + 15 = \frac{dv_o}{dt}$$

$$\therefore \quad dv_o = -10t\,dt + 15\,dt$$

$$\int_{v_o(0.5^+)}^{v_o(t)} dx = \int_{0.5^+}^{t} -10y\,dy + \int_{0.5^+}^{t} 15\,dy$$

$$v_o(t) - v_o(0.5^+) = -5y^2 \Big|_{0.5}^{t} + 15y \Big|_{0.5}^{t}$$

$$v_o(t) = v_o(0.5^+) - 5t^2 + 1.25 + 15t - 7.5$$

$$v_o(0.5^+) = v_o(0.5^-) = 2.5\,\text{V}$$

$$\therefore \quad v_o(t) = -5t^2 + 15t - 3.75\,\text{V}, \qquad 0.5^+ \le t \le t_{\text{sat}}$$

$$\frac{dv_{o1}}{dt} = -20(-0.04) = 0.8, \qquad 0.5^+ \le t \le t_{\text{sat}}$$

$$dv_{o1} = 0.8\,dt; \qquad \int_{v_{o1}(0.5+)}^{v_{o1}(t)} dx = 0.8 \int_{0.5+}^{t} dy$$

$$v_{o1}(t) - v_{o1}(0.5^+) = 0.8t - 0.4; \qquad v_{o1}(0.5^+) = v_{o1}(0.5^-) = -0.8\,\text{V}$$

$$\therefore \quad v_{o1}(t) = 0.8t - 1.2\,\text{V}, \qquad 0.5^+ \le t \le t_{\text{sat}}$$

Summary:

$0 \le t \le 0.5^-\text{s}: \qquad v_{o1} = -1.6t\,\text{V}, \quad v_o = 10t^2\,\text{V}$

$0.5^+\text{s} \le t \le t_{\text{sat}}: \qquad v_{o1} = 0.8t - 1.2\,\text{V}, \quad v_o = -5t^2 + 15t - 3.75\,\text{V}$

[b] $-12.5 = -5t_{\text{sat}}^2 + 15t_{\text{sat}} - 3.75$

$$\therefore \quad 5t_{\text{sat}}^2 - 15t_{\text{sat}} - 8.75 = 0$$

Solving, $\qquad t_{\text{sat}} = 3.5\,\text{sec}$

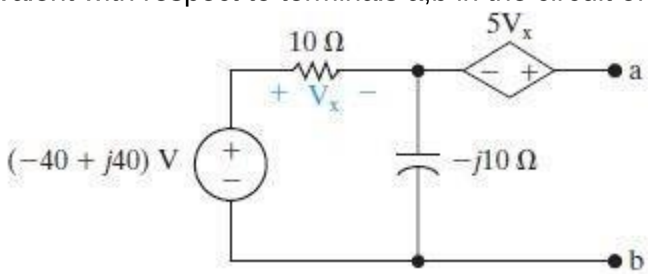
$$v_{o1}(t_{\text{sat}}) = 0.8(3.5) - 1.2 = 1.6\,\text{V}$$

RUBRIC :

1 mark each for expressions of $v_o(t)$ and $v_{o1}(t)$.
1 mark for calculating t_{sat}
*Step marking to be done for each part.
Do check for plag cases.
Notations for resistances and capacitors, may be there in solution but not mentioned on the circuit used

7 .

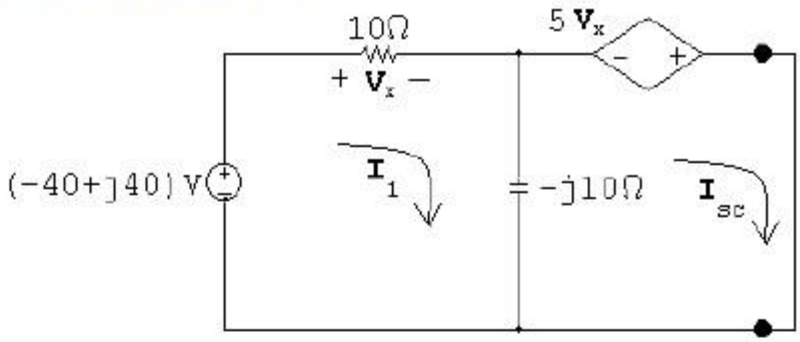
3.Find the Norton equivalent with respect to terminals a,b in the circuit of Fig. shown below.



==

Soln:

Short circuit current



$$\mathbf{V}_x - j10(\mathbf{I}_1 - \mathbf{I}_{sc}) = -40 + j40$$

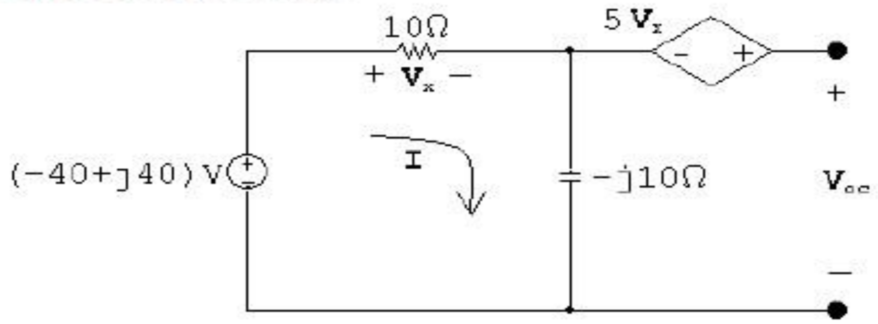
$$-5\mathbf{V}_x - j10(\mathbf{I}_{sc} - \mathbf{I}_1) = 0$$

$$\mathbf{V}_x = 10\mathbf{I}_1$$

Solving,

$$\mathbf{I}_N = \mathbf{I}_{sc} = 6 + j4\,\text{A}$$

Open circuit voltage



$$\mathbf{I} = \frac{-40 + j40}{10 - j10} = -4\,\text{A}$$

$$\mathbf{V}_x = 10\mathbf{I} = -40\,\text{V}$$

$$\mathbf{V}_{oc} = 5\mathbf{V}_x - j10\mathbf{I} = -200 + j40\,\text{V}$$

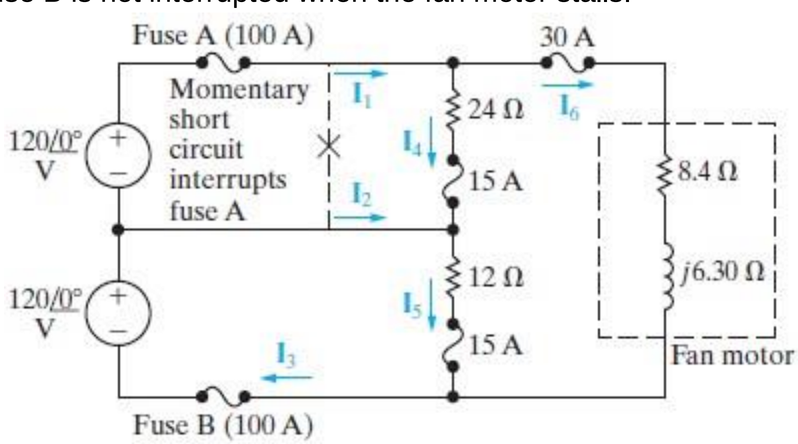
$$Z_N = \frac{-200 + j40}{6 + j4} = -20 + j20\,\Omega$$

RUBRIC :

1.5 marks for Z_N calculations
1.5 marks for I_N calculations

4.You may have the opportunity as an engineering graduate to serve as an expert witness in lawsuits involving either personal injury or property damage. As an example of the type of problem on which you may be asked to give an opinion, consider the following event. At the end of a day of fieldwork, a farmer returns to his farmstead, checks his hog confinement building, and finds to his dismay that the hogs are dead. The problem is traced to a blown fuse that caused a 240 V fan motor to stop.The loss of ventilation led to the suffocation of the livestock.The interrupted fuse is located in the main switch that connects the farmstead to the electrical service. Before the insurance company settles the claim, it wants to know if the electric circuit supplying the farmstead functioned properly. The lawyers for the insurance company are puzzled because the farmer's wife, who was in the house on the day of the accident convalescing from minor surgery, was able to watch TV during the afternoon. Furthermore, when she went to the kitchen to start preparing the evening meal, the electric clock indicated the correct time.The lawyers have hired you to explain (1) why the electric clock in the kitchen and the television set in the living room continued to operate after the fuse in the main switch blew and (2) why the second fuse in the main switch didn't blow after the fan motor stalled.After ascertaining the loads on the three-wire distribution circuit prior to the interruption of fuse A, you are able to construct the circuit model shown in Fig. shown below . The impedances of the line conductors and the neutral conductor are assumed negligible. Both TV and clock are represented by a combined resistance of 12 ohms and 15 A fuse.

a) Calculate the branch currents I_1, I_2,I_3,I_4,I_5,$I_6$and prior to the interruption of fuse A.
b) Calculate the branch currents after the interruption of fuse A. Assume the stalled fan motor behaves as a short circuit.
c) Explain why the clock and television set were not affected by the momentary short circuit that interrupted fuse A.
d) Assume the fan motor is equipped with a thermal cutout designed to interrupt the motor circuit if the motor current becomes excessive. Would you expect the thermal cutout to operate? Explain.
e) Explain why fuse B is not interrupted when the fan motor stalls.



==

Soln:

[a] $\mathbf{I}_1 = \frac{120}{24} + \frac{240}{8.4 + j6.3} = 23.29 - j13.71 = 27.02\underline{/-30.5^\circ}\ \text{A}$

$$\mathbf{I}_2 = \frac{120}{12} - \frac{120}{24} = 5\underline{/0^\circ}\ \text{A}$$

$$\mathbf{I}_3 = \frac{120}{12} + \frac{240}{8.4 + j6.3} = 28.29 - j13.71 = 31.44\underline{/-25.87^\circ}\ \text{A}$$

$$\mathbf{I}_4 = \frac{120}{24} = 5\underline{/0^\circ}\ \text{A}; \qquad \mathbf{I}_5 = \frac{120}{12} = 10\underline{/0^\circ}\ \text{A}$$

$$\mathbf{I}_6 = \frac{240}{8.4 + j6.3} = 18.29 - j13.71 = 22.86\underline{/-36.87^\circ}\ \text{A}$$

[b] When fuse A is interrupted,

$\mathbf{I}_1 = 0$ $\qquad \mathbf{I}_3 = 15\,\text{A}$ $\qquad \mathbf{I}_5 = 10\,\text{A}$

$\mathbf{I}_2 = 10 + 5 = 15\,\text{A}$ $\qquad \mathbf{I}_4 = -5\,\text{A}$ $\qquad \mathbf{I}_6 = 5\,\text{A}$

[c] The clock and television set were fed from the uninterrupted side of the circuit, that is, the $12\,\Omega$ load includes the clock and the TV set.

[d] No, the motor current drops to $5\,\text{A}$, well below its normal running value of $22.86\,\text{A}$.

[e] After fuse A opens, the current in fuse B is only 15 A.

RUBRIC :

0.5 marks for part (a) calculations.

0.5 marks for part (b) calculations.

1 mark for part (c). Correct explanation will fetch 1 mark otherwise 0.

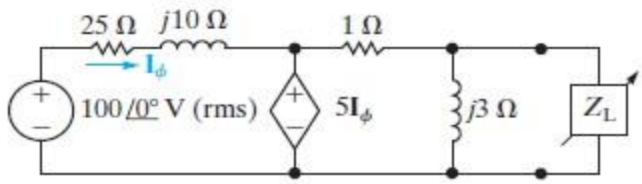
0.5 marks for part (d) calculations.

0.5 marks for part (e) calculations.

5. The load impedance Z_L for the circuit shown in Fig. below is adjusted until maximum average power is delivered to Z_L.

a) Find the maximum average power delivered to Z_L.

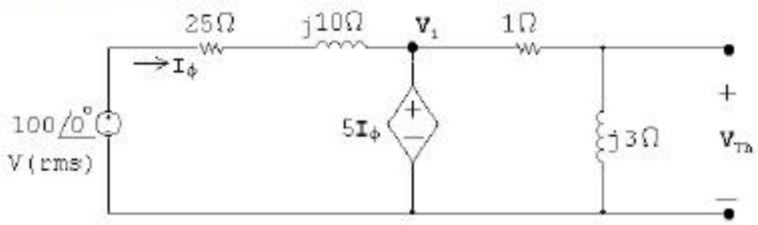
b) What percentage of the total power developed in the circuit is delivered to Z_L ?



==

Soln:

[a] Open circuit voltage:



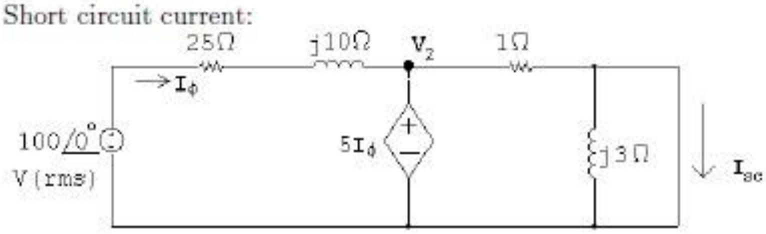
$$\mathbf{V}_1 = 5\mathbf{I}\phi = 5\frac{100 - 5\mathbf{I}_\phi}{25 + j10}$$

$$(25 + j10)\mathbf{I}_\phi = 100 - 5\mathbf{I}\phi$$

$$\mathbf{I}_\phi = \frac{100}{30 + j10} = 3 - j\ \text{A}$$

$$\mathbf{V}_{\text{Th}} = \frac{j3}{1 + j3}(5\mathbf{I}_\phi) = 15\ \text{V}$$

Short circuit current:



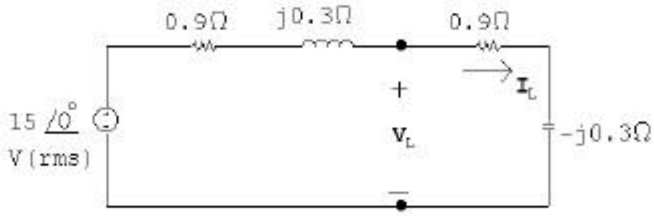
$$\mathbf{V}_2 = 5\mathbf{I}_\phi = \frac{100 - 5\mathbf{I}_\phi}{25 + j10}$$

$$\mathbf{I}_\phi = 3 - j1\,\text{A}$$

$$\mathbf{I}_{sc} = \frac{5\mathbf{I}_\phi}{1} = 15 - j5\,\text{A}$$

$$Z_{\text{Th}} = \frac{15}{15 - j5} = 0.9 + j0.3\,\Omega$$

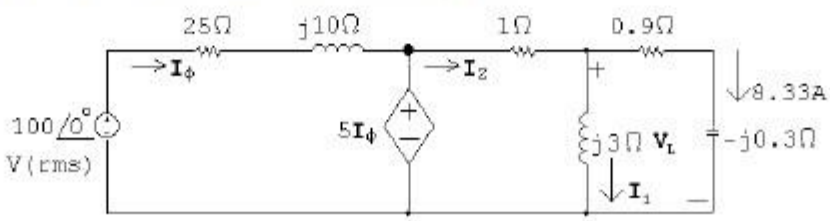
$$Z_L = Z_{\text{Th}}^* = 0.9 - j0.3\,\Omega$$



$$\mathbf{I}_L = \frac{0.3}{1.8} = 8.33\,\text{A(rms)}$$

$$P = |\mathbf{I}_L|^2(0.9) = 62.5\,\text{W}$$

[b] $\mathbf{V}_L = (0.9 - j0.3)(8.33) = 7.5 - j2.5\,\text{V(rms)}$



$$\mathbf{I}_1 = \frac{\mathbf{V}_L}{j3} = -0.833 - j2.5\,\text{A(rms)}$$

$$\mathbf{I}_2 = \mathbf{I}_1 + \mathbf{I}_L = 7.5 - j2.5\,\text{A(rms)}$$

$$5\mathbf{I}_\phi = \mathbf{I}_2 + \mathbf{V}_L \quad \therefore \quad \mathbf{I}_\phi = 3 - j1\,\text{A}$$

$$\mathbf{I}_{\text{d.s.}} = \mathbf{I}_\phi - \mathbf{I}_2 = -4.5 + j1.5\,\text{A}$$

$$S_g = -100(3 + j1) = -300 - j100\,\text{VA}$$

$$S_{\text{d.s.}} = 5(3 - j1)(-4.5 - j1.5) = -75 + j0\,\text{VA}$$

$$P_{\text{dev}} = 300 + 75 = 375\,\text{W}$$

$$\%\text{ developed} = \frac{62.5}{375}(100) = 16.67\%$$

RUBRIC :

1.5 marks for part (a) calculations

1.5 marks for part (b) calculations.

No step marking to be done.

14 .

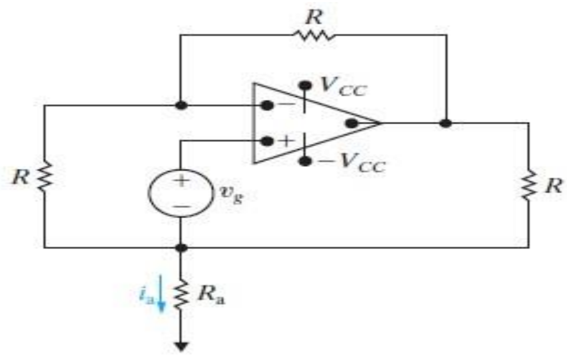
---

6. a) Show that when the ideal op amp in Fig. shown below is operating in its linear region,

$$i_a = \frac{3v_g}{R}$$

b) Show that the ideal op amp will saturate when

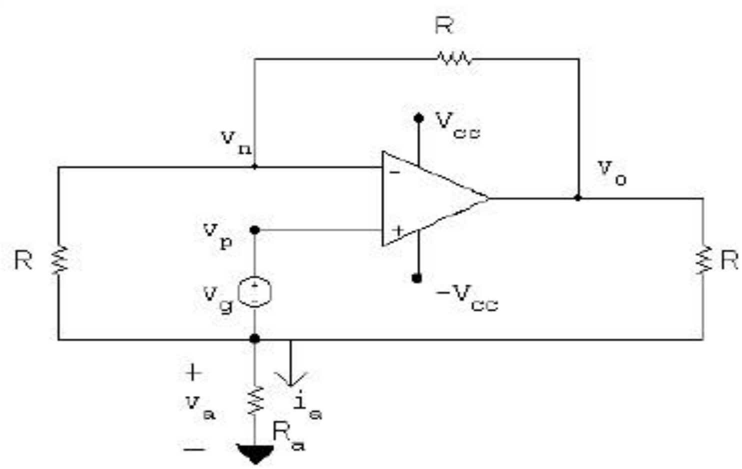
$$R_a = \frac{R(\pm V_{CC} - 2v_g)}{3v_g}.$$



==

Soln:

[a]



$$\frac{v_n - v_a}{R} + \frac{v_n - v_o}{R} = 0$$

$$2v_n - v_a = v_o$$

$$\frac{v_a}{R_a} + \frac{v_a - v_n}{R} + \frac{v_a - v_o}{R} = 0$$

$$v_a\left[\frac{1}{R_a} + \frac{2}{R}\right] - \frac{v_n}{R} = \frac{v_o}{R}$$

$$v_a\left(2 + \frac{R}{R_a}\right) - v_n = v_o$$

$v_n = v_p = v_a + v_g$

$\therefore \quad 2v_n - v_a = 2v_a + 2v_g - v_a = v_a + 2v_g$

$\therefore \quad v_a - v_o = -2v_g \qquad (1)$

$2v_a + v_a\left(\frac{R}{R_a}\right) - v_a - v_g = v_o$

$\therefore \quad v_a\left(1 + \frac{R}{R_a}\right) - v_o = v_g \qquad (2)$

Now combining equations (1) and (2) yields

$-v_a\frac{R}{R_a} = -3v_g$

or $\quad v_a = 3v_g\frac{R_a}{R}$

Hence $\quad i_a = \frac{v_a}{R_a} = \frac{3v_g}{R} \qquad$ Q.E.D.

[b] At saturation $\quad v_o = \pm\, V_{cc}$

$\therefore \quad v_a = \pm\, V_{cc} - 2v_g \qquad (3)$

and

$\therefore \quad v_a\left(1 + \frac{R}{R_a}\right) = \pm\, V_{cc} + v_g \qquad (4)$

Dividing Eq (4) by Eq (3) gives

$1 + \frac{R}{R_a} = \frac{\pm\, V_{cc} + v_g}{\pm\, V_{cc} - 2v_g}$

$\therefore \quad \frac{R}{R_a} = \frac{\pm\, V_{cc} + v_g}{\pm\, V_{cc} - 2v_g} - 1 = \frac{3v_g}{\pm\, V_{cc} - 2v_g}$

or $\quad R_a = \frac{(\pm\, V_{cc} - 2v_g)}{3v_g}R \qquad$ Q.E.D.

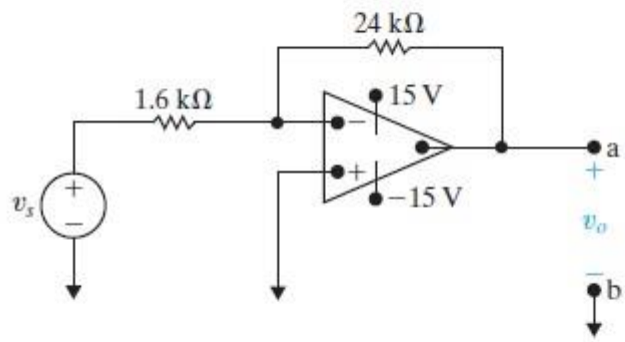
RUBRIC:

1.5 marks for part (a).

1.5 marks for part (b)

Step marking to be done, only if concepts of virtual ground/ virtual short are presented correctly, otherwise no step marks only for applying KCL/KVL at nodes.

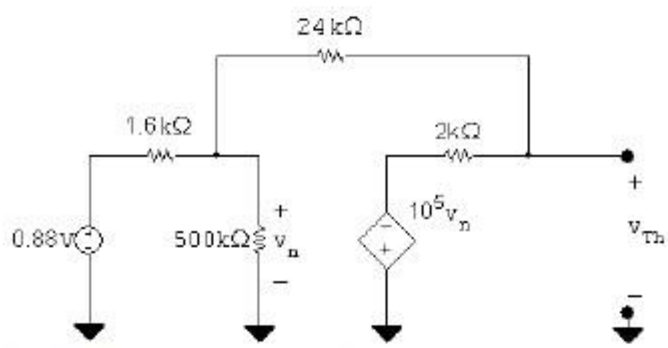
7.a) Find the Thévenin equivalent circuit with respect to the output terminals a, b for the inverting amplifier of Fig. shown below. The dc signal source has a value of 880 mV. The op amp has an input resistance of 500KΩ, an output resistance of 2kΩ and an open-loop gain of 100,000.
b) What is the output resistance of the inverting amplifier?
c) What is the resistance (in ohms) seen by the signal source v_s when the load at the terminals a, b is 300 Ω?



==

Soln:

[a]

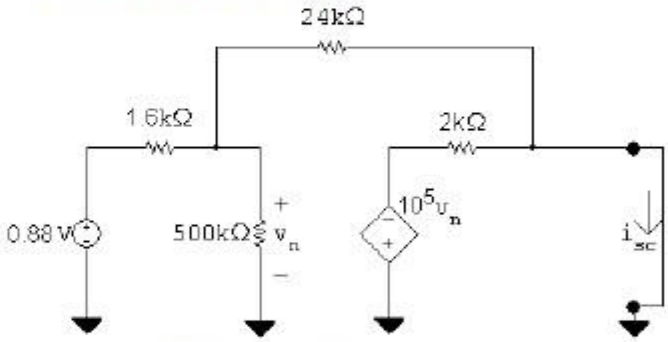


$$\frac{v_n - 0.88}{1600} + \frac{v_n}{500{,}000} + \frac{v_n - v_{Th}}{24{,}000} = 0$$

$$\frac{v_{Th} + 10^5 v_n}{2000} + \frac{v_{Th} - v_n}{24{,}000} = 0$$

Solving, $v_{Th} = -13.198$ V

Short-circuit current calculation:

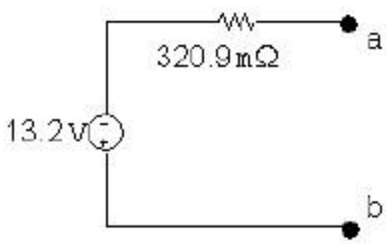


$$\frac{v_n}{500{,}000} + \frac{v_n - 0.88}{1600} + \frac{v_n - 0}{24{,}000} = 0$$

$\therefore \quad v_n = 0.8225$ V

$$i_{sc} = \frac{v_n}{24{,}000} - \frac{10^5}{2000}v_n = -41.13 \text{ A}$$

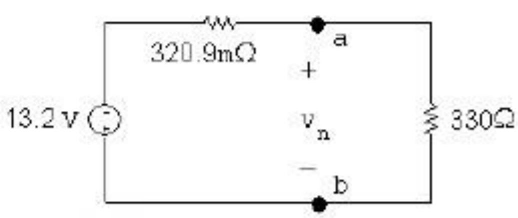
$$R_{Th} = \frac{v_{Th}}{i_{sc}} = 320.9\,\text{m}\Omega$$



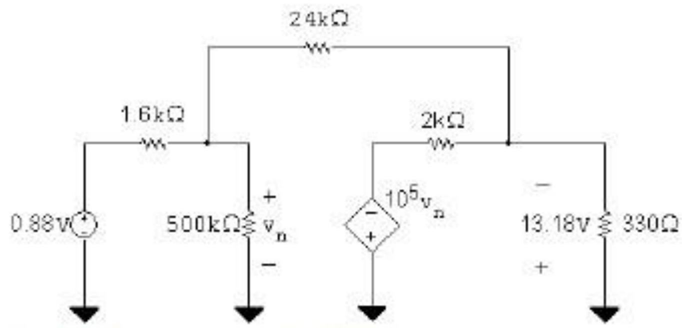
[b] The output resistance of the inverting amplifier is the same as the Thévenin resistance, i.e.,

$R_o = R_{Th} = 320.9\,\text{m}\Omega$

[c]



$$v_o = \left(\frac{330}{330.3209}\right)(-13.2) = -13.18 \text{ V}$$



$$\frac{v_n - 0.88}{1600} + \frac{v_n}{500{,}000} + \frac{v_n + 13.18}{24{,}000} = 0$$

$$\therefore \quad v_n = 942\,\mu\text{V}$$

$$i_g = \frac{0.88 - 942 \times 10^{-6}}{1600} = 549.41\,\mu\text{A}$$

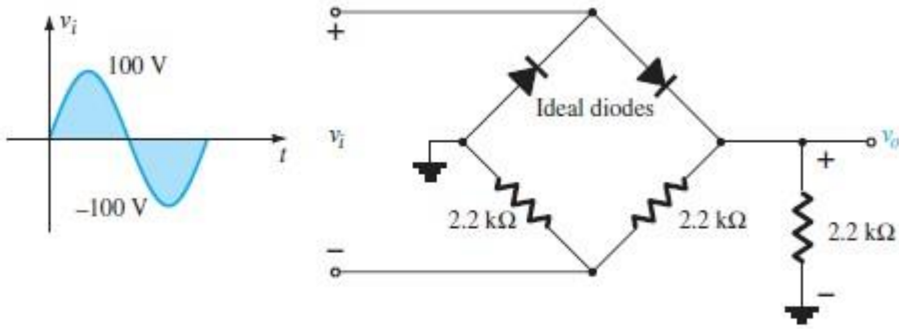
$$R_g = \frac{0.88}{i_g} = 1601.71\,\Omega$$

RUBRIC :

1 mark for each part.

Step marking to be done, only if replacement of op amp is done correctly.

8.Sketch v_o for the network of Fig.shown below and determine the dc voltage available.

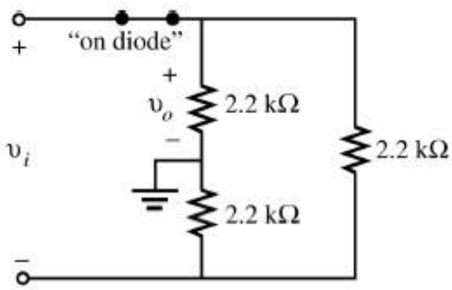


===

Soln:

Positive half-cycle of v_i:

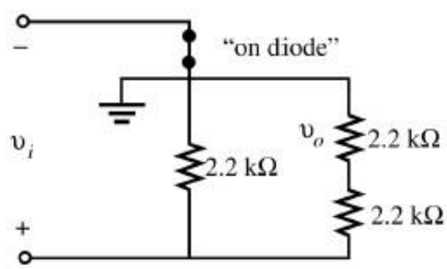
Network redrawn:



Voltage-divider rule:

$$V_{o_{max}} = \frac{2.2\ \text{k}\Omega(V_{i_{max}})}{2.2\ \text{k}\Omega + 2.2\ \text{k}\Omega} = \frac{1}{2}(V_{i_{max}}) = \frac{1}{2}(100\ \text{V}) = \mathbf{50\ V}$$

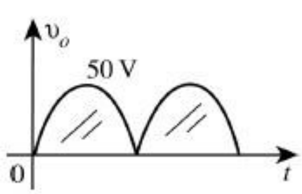
Negative half-cycle of v_i:



Polarity of v_o across the 2.2 kΩ resistor acting as a load is the same.

Voltage-divider rule:

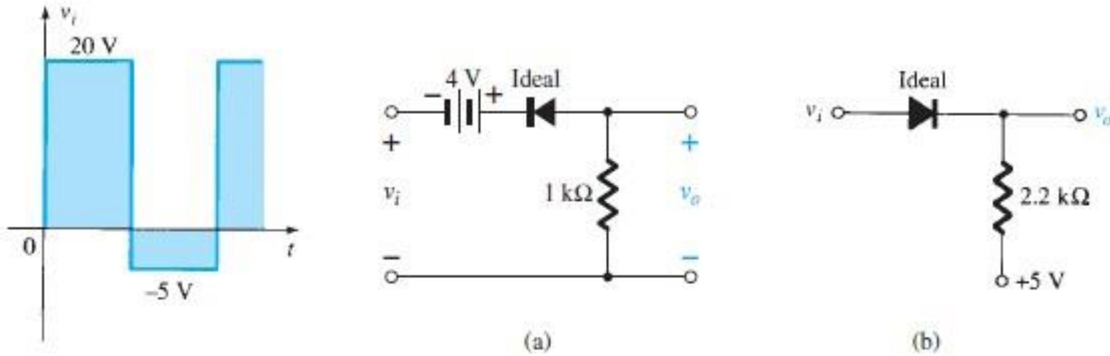
$$V_{o_{max}} = \frac{2.2\ \text{k}\Omega(V_{i_{max}})}{2.2\ \text{k}\Omega + 2.2\ \text{k}\Omega} = \frac{1}{2}(V_{i_{max}}) = \frac{1}{2}(100\ \text{V}) = \mathbf{50\ V}$$



$$V_{dc} = 0.636V_m = 0.636\ (50\ \text{V}) = \mathbf{31.8\ V}$$

1 mark for calculations in each cycle (positive and negative).
1 mark for correct waveform.
1mark calculating correct DC value.
No step marking to be done.

9. Determine v_o for each network of Fig. shown below for the input shown.



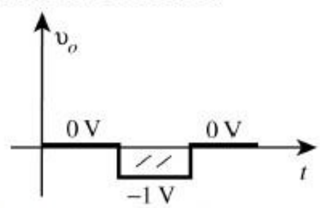
==

Soln:

(a) For $v_i = 20$ V the diode is reverse-biased and $v_o = \mathbf{0\ V}$.
For $v_i = -5$ V, v_i overpowers the 4 V battery and the diode is "on".

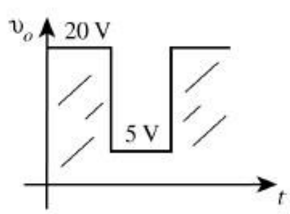
Applying Kirchhoff's voltage law in the clockwise direction:

$$-5\text{ V} + 4\text{ V} - v_o = 0$$
$$v_o = \mathbf{-1\ V}$$



(b) For $v_i = 20$ V the 20 V level overpowers the 5 V supply and the diode is "on". Using the short-circuit equivalent for the diode we find $v_o = v_i = \mathbf{20\ V}$.

For $v_i = -5$ V, both v_i and the 5 V supply reverse-bias the diode and separate v_i from v_o. However, v_o is connected directly through the 2.2 kΩ resistor to the 5 V supply and $v_o = \mathbf{5\ V}$.



RUBRIC :

1.5 marks for calculation in part (a) circuit.

1.5 marks for calculation in part (b) circuit.

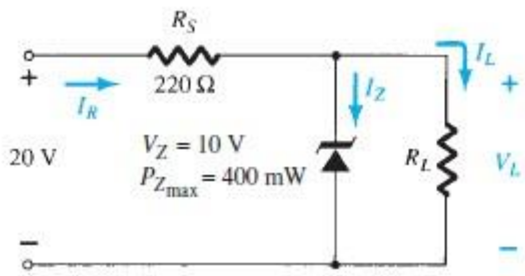
Step marking to be done for each part.

10. a. Determine V_L, I_L , I_Z , and I_R for the network of Fig. below if R_L =180Ω .

b. Repeat part (a) if R_L=470Ω .

c. Determine the value of R_L that will establish maximum power conditions for the Zener diode.

d. Determine the minimum value of R_L to ensure that the Zener diode is in the “on” state.



==

Soln:

(a) In the absence of the Zener diode

$$V_L = \frac{180\ \Omega(20\ \text{V})}{180\ \Omega + 220\ \Omega} = 9\ \text{V}$$

$V_L = 9\ \text{V} < V_Z = 10\ \text{V}$ and diode non-conducting

$$\text{Therefore, } I_L = I_R = \frac{20\ \text{V}}{220\ \Omega + 180\ \Omega} = \mathbf{50\ mA}$$

with $I_Z = \mathbf{0\ mA}$
and $V_L = \mathbf{9\ V}$

(b) In the absence of the Zener diode

$$V_L = \frac{470\ \Omega(20\ \text{V})}{470\ \Omega + 220\ \Omega} = 13.62\ \text{V}$$

$V_L = 13.62\ \text{V} > V_Z = 10\ \text{V}$ and Zener diode "on"

Therefore, $V_L = \mathbf{10\ V}$ and $V_{R_s} = 10\ \text{V}$

$$I_{R_s} = V_{R_s} / R_s = 10\ \text{V}/220\ \Omega = \mathbf{45.45\ mA}$$

$$I_L = V_L/R_L = 10\ \text{V}/470\ \Omega = \mathbf{21.28\ mA}$$

and $I_Z = I_{R_s} - I_L = 45.45\ \text{mA} - 21.28\ \text{mA} = \mathbf{24.17\ mA}$

(c) $P_{Z_{\max}} = 400\ \text{mW} = V_Z I_Z = (10\ \text{V})(I_Z)$

$$I_Z = \frac{400\ \text{mW}}{10\ \text{V}} = 40\ \text{mA}$$

$$I_{L_{\min}} = I_{R_s} - I_{Z_{\max}} = 45.45\ \text{mA} - 40\ \text{mA} = 5.45\ \text{mA}$$

$$R_L = \frac{V_L}{I_{L_{\min}}} = \frac{10\ \text{V}}{5.45\ \text{mA}} = \mathbf{1{,}834.86\ \Omega}$$

Large R_L reduces I_L and forces more of I_{R_s} to pass through Zener diode.

(d) In the absence of the Zener diode

$$V_L = 10\ \text{V} = \frac{R_L(20\ \text{V})}{R_L + 220\ \Omega}$$

$$10R_L + 2200 = 20R_L$$

$$10R_L = 2200$$

$$R_L = \mathbf{220\ \Omega}$$

RUBRIC :

0.5 marks for part (a)

0.5 marks for part (b)

1 mark for part (c)

1 mark for part (d)

Step marking to be done for parts (c) and (d) only.