Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science

6.002 – Circuits & Electronics – Fall 2007

# Problem Set #7 - SOLUTIONS P7.1 and P7.2

## Problem 7.1

(A) Circuit: Inductor is connected to the voltage source.
$i(t) = 1/L \int V dt = V/L\ t + K$ and since $i(0) = 0 \dashrightarrow K = 0$
**--> $i(t) = V/L\ t$ and $v(t) = 0$ for $0 \le t \le T_1$**

(B) Circuit: Inductor is connected to the capacitor.
$v(t) = L\ di/dt = L\ d/dt\ (-C\ dv/dt) = -LC\ d^2v/dt^2$
--> $d^2v/dt^2 + 1/LC\ v = 0$
$v(t) = A \cos[\omega(t-T_1)] + B \sin[\omega(t-T_1)]$ and $\omega = 1/\sqrt{(LC)}$
$i(t) = -C\ dv/dt = CA\omega \sin[\omega(t-T_1)] - CB\omega \cos[\omega(t-T_1)]$
We know from before at $t=T_1$:
$v(T_1) = 0 \dashrightarrow A = 0$ and
$i(T_1) = V/L\ T_1 = -CB\omega \dashrightarrow B = -V/L\ T_1/(C\omega)$

Therefore:
**$v(t) = -T_1/\sqrt{(LC)} \sin[(t-T_1)/\sqrt{(LC)}]$ and**
**$i(t) = V/L\ T_1 \cos[(t-T_1)/\sqrt{(LC)}]$ for $T_1 \le t \le T_2$**
For $T_2$ it is required that: $i(T_2) = 0$
--> $(T_2-T_1)/\sqrt{(LC)} = \pi/2 \dashrightarrow T_2 = \pi/2 \sqrt{(LC)} + T_1$

(C) Circuit: All three elements are disconnected.
$v(T_2) = -VT_1/\sqrt{(LC)}$ and $i(T_2) = 0$
Therefore:
**$v(t) = -VT_1/\sqrt{(LC)}$ and**
**$i(t) = 0$ for $T_2 \le t \le T_3$**

(D) Circuit: Inductor is connected to the voltage source. Using information from part (A):
**$i(t) = V/L(t-T_3)$ and**
**$v(t) = v(T_3) = v(T_2) = -VT_1/\sqrt{(LC)}$ for $T_3 \le t \le T_4$**

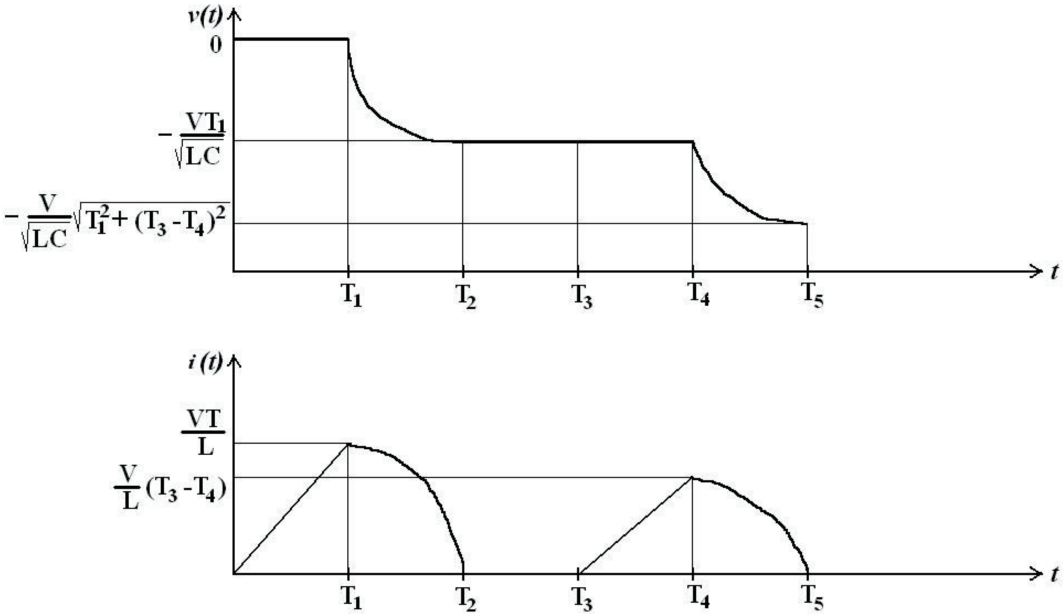
(E) Circuit: Inductor is connected to the capacitor.
Using information from part (B): $d^2v/dt^2 + 1/(LC)\ v = 0$
$v(t) = A \cos[\omega(t-T_4)] + B \sin[\omega(t-T_4)]$ and $\omega = 1/\sqrt{(LC)}$
$i(t) = CA\omega \sin[\omega(t-T_4)] - CB\omega \cos[\omega(t-T_4)]$

We know that at T4: $v(T_4) = -VT_1/\sqrt{(LC)} \dashrightarrow A = -VT_1/\sqrt{(LC)}$
$i(T_4) = V/L\ (T_4-T_3) \dashrightarrow V/L\ (T_4-T_3) = -CB\omega \dashrightarrow B = V/L\ (T_4-T_3)/(C\omega)$

Therefore:
**$v(t) = -VT_1/\sqrt{(LC)} \cos[(t-T_4)/\sqrt{(LC)}] - V(T_4-T_3)/\sqrt{(LC)} \sin[(t-T_4)/\sqrt{(LC)}]$ and**
**$i(t) = -VT_1/L \sin[(t-T_4)/\sqrt{(LC)}] + V(T_4-T_3)/L \cos[(t-T_4)/\sqrt{(LC)}]$ for $T_4 \le t \le T_5$**

We know that at $T_5$: $i(T_5) = 0$
--> $VT_1/L \sin[(T_5-T_4)/\sqrt{(LC)}] = V(T_4-T_3)/L \cos[(T_5-T_4)/\sqrt{(LC)}]$
$\tan[1/\sqrt{(LC)}(T_5-T_4)] = (T_4-T_3)/T_1$
--> $T_5 = \sqrt{(LC)}\ \tan{-1}\ [(T_4-T_3)/T_1] + T_4$
$v(T_5) = -VT_1/\sqrt{(LC)} \cos[(T_5-T_4)/\sqrt{(LC)}] - V(T_4-T_3)/\sqrt{(LC)} \sin[(T_5-T_4)/\sqrt{(LC)}]$ ...
$v(T_5) = -V \sqrt{[T_1^2 + (T_4-T_3)^2]}/\sqrt{(LC)}$

(F)




**Problem 7.2**

(A) $E_L = 1/2\ L\ i^2(t) = 1/2\ L\ i^2(T_1) = 1/2\ L\ (V/L\ T_1)^2 = 1/2\ V^2\ T_1^2\ /\ L$

(B) $E_L = E_C = 1/2\ C\ v^2(t) = 1/2\ C\ v^2(T_2)$ --> $1/2\ V^2\ T_1^2\ /\ L = 1/2\ C\ v^2(T_2)$ --> $v(T_2) = -VT_2/\sqrt{(LC)}$
Negative solution is selected because of the direction of current i.

(C) $E_L = 1/2\ L\ i^2(T_4) = 1/2\ L\ V^2/L^2\ (T_4\text{-}T_3)^2 = 1/2\ V^2\ (T_4\text{-}T_3)^2\ /\ L$

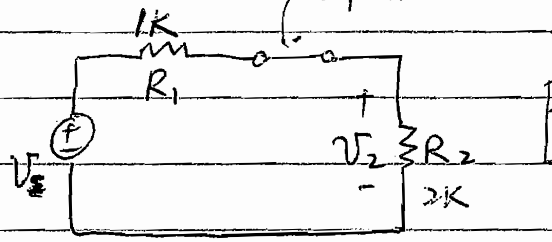
(D) $E_L + 1/2\ C\ v^2(T_2) = E_C$ --> $1/2\ V^2\ (T_4\text{-}T_3)^2\ /\ L + 1/2\ C\ v^2(T_2) = 1/2\ C\ v^2(T_5)$
$v(T_5) = -V/\sqrt{(LC)}\ \sqrt{[(T_4\text{-}T_3)^2 + T_1^2]}$

(E) From part (D), we see that if $(T_4\text{-}T_3)$ = T1 then: $v(T_5) = -V/\sqrt{(LC)}\ \sqrt{(T_1^2 + T_1^2)} = -VT_1/\sqrt{(LC)}\ \sqrt{(2)}$
Hence, after n switching cycles: $v(nT_1) = -VT_1/\sqrt{(LC)}\ s\sqrt{(n)} = -VT_1\ \sqrt{(n/(LC))}$

# Solution of PS 8 / 6.002 Fall 2007

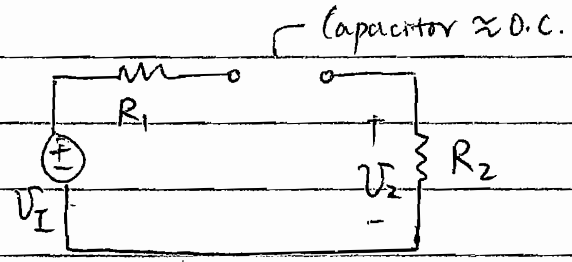
## Exercise 8.1

at time $t=0^+$




$$\boxed{V_2(t=0^+)} = \frac{R_2}{R_1+R_2} V_I = \frac{2}{3}\cdot 6 = \boxed{4\ (V)}$$

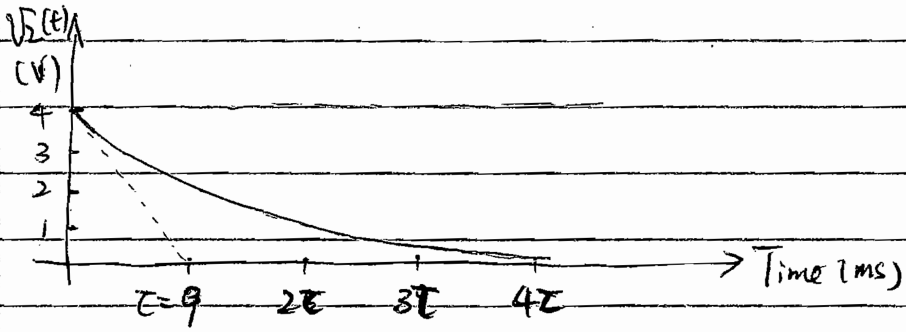
at time $t=\infty$



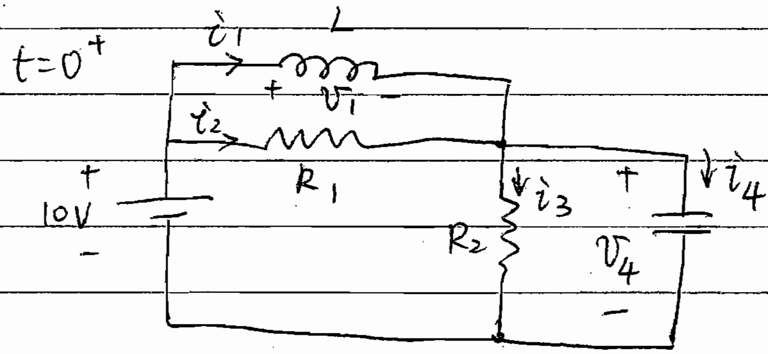

$$\boxed{V_2(t\to\infty) = 0}$$

time constant $\boxed{\tau = (R_1+R_2)\cdot C = 3k\Omega \cdot 3\mu F = 9ms}$

$$\therefore \boxed{V_2(t) = 4\cdot e^{-t/\tau}}$$



Exercise 8.2.




$R_2 = 1\Omega$

$L = 1H$

$C = 0.5F$

$R_1 = 2\Omega$

From inductor L $\quad i_1(0^+) = i_1(0^-) = 2A$

From capacitor C $\quad v_4(0^+) = v_4(0^-) = 4V \Rightarrow i_3(0^+) = \dfrac{v_4(0^+)}{R_2} = 4A$

~~From KCL $\quad i_2(0^+) = i_1(0^+)$~~

From KVL $\quad v_1(0^+) = 10 - v_4(0^+) = 6V \Rightarrow i_2(0^+) = \dfrac{v_1(0^+)}{R_1} = 3A$

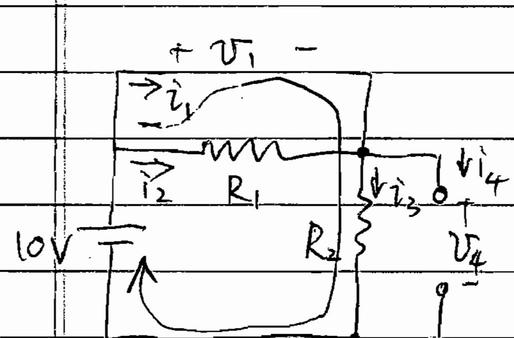
From KCL $\quad i_4(0^+) = i_1(0^+) + i_2(0^+) - i_3(0^+)$

$= 2 + 3 - 4$

$= 1A$

$$\therefore \boxed{\begin{array}{lll} v_1(0^+) = 6V & i_1(0^+) = 2A & i_2(0^+) = 3A \\ v_4(0^+) = 4V & i_3(0^+) = 4A & i_4(0^+) = 1A \end{array}}$$

$t = \infty$ $\quad$ Inductor L = S.C. $\quad$ Capacitor C = O.C.




$i_1(\infty) = i_3(\infty) = \dfrac{10V}{R_2} = 10A$

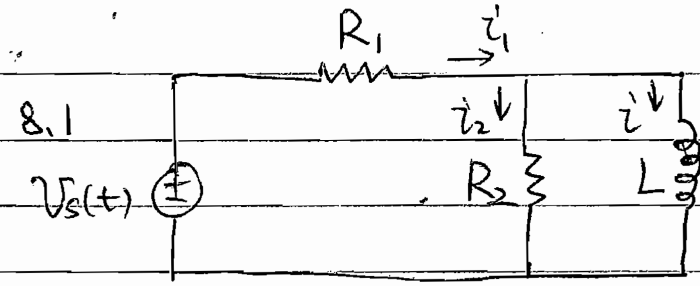
$i_2(\infty) = i_4(\infty) = 0A$

$v_1(\infty) = 0V$

$v_4(\infty) = 10V$

$$\therefore \boxed{\begin{array}{ll} v_1(\infty) = 0V & i_1(\infty) = i_3(\infty) = 10A \\ v_4(\infty) = 10V & i_2(\infty) = i_4(\infty) = 0A \end{array}}$$

Problem 8.1




$$V_s(t) = \begin{cases} 0, & t<0 \\ V_s, & t \geq 0 \end{cases}$$

a) From KCL, we have $i_1 = i_2 + i \Rightarrow \frac{V_s - v}{R_1} = \frac{v}{R_2} + i$

From inductor L, we have $v = L\frac{di}{dt}$

Therefore we have differential equation for $v(t)$ & $i(t)$:

$$\begin{cases} \frac{V_s - v(t)}{R_1} = \frac{v(t)}{R_2} + i(t) & \cdots (1) \\ v(t) = L\frac{di(t)}{dt} & \cdots\cdots (2) \end{cases}$$

We can plug (2) into (1) and solve for $i(t)$ first.

Rearrange (1) after plugging (2) into (1), we have,

$$L\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\frac{di(t)}{dt} + i(t) = \frac{V_s}{R_1}$$

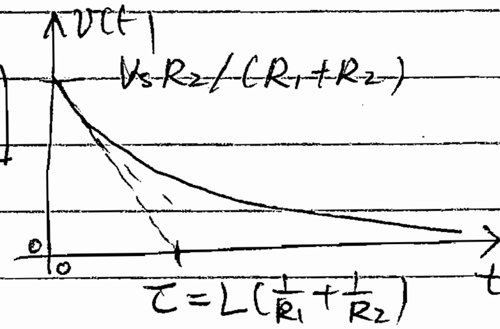
Hence the particular solution $\boxed{i_p(t) = \frac{V_s}{R_1}}$

the homogeneous solution $\boxed{i_h(t) = Ae^{-t/\tau} \quad \tau = L\left(\frac{1}{R_1}+\frac{1}{R_2}\right)}$

From the initial condition $i(0^-) = i(0^+) = 0 \Rightarrow A = -\frac{V_s}{R_1}$

$\therefore \boxed{i(t) = \frac{V_s}{R_1}(1 - e^{-t/\tau}) \quad t \geq 0}$

$\therefore \boxed{v(t) = L\frac{di(t)}{dt} = \frac{V_s R_2}{R_1 + R_2}e^{-t/\tau} \quad t \geq 0}$



b) Let's say in part a) $v_s(t) = v_{sa}(t) = V_s\, u_{-1}(t) = \begin{cases} 0, & t<0 \\ V_s, & t \geq 0 \end{cases}$

in this part, $v_s(t) = v_{sb}(t) = \Lambda\, u_0(t)$

$$\because\ v_{sb}(t) = \Lambda\, u_0(t) = \frac{\Lambda}{V_s} \frac{d(v_{sa}(t))}{dt}$$

∴ The output $v(t)$ satisfy the similiar relation shown in inputs above,

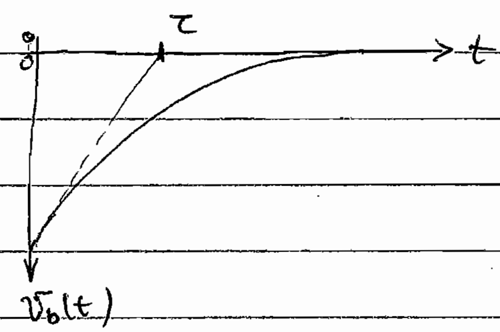
i.e., $v_b(t) = \frac{\Lambda}{V_s} \frac{d(v_a(t))}{dt}$

$v(t)$ in part b)

$v_a(t) = V_s \frac{R_2}{R_1+R_2} e^{-t/\tau}$

($v(t)$ in part a))

$$\Rightarrow \boxed{v_b(t) = -\Lambda \left(\frac{R_2}{R_1+R_2}\right)^2 \cdot \frac{R_1}{L} e^{-t/\tau} \quad t \geq 0}$$




c) Similiarly, $v_{sc}(t) = M\, u_{-2}(t)$

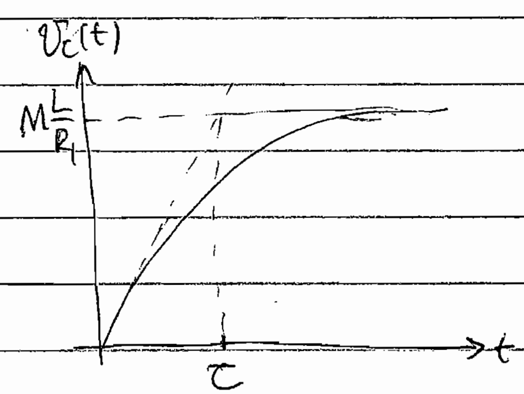
$$\therefore\ v_{sc}(t) = \frac{M}{V_s} \int V_s\, u_{-1}(t)\, dt$$

$$= \frac{M}{V_s} \int v_{sa}(t)\, dt$$

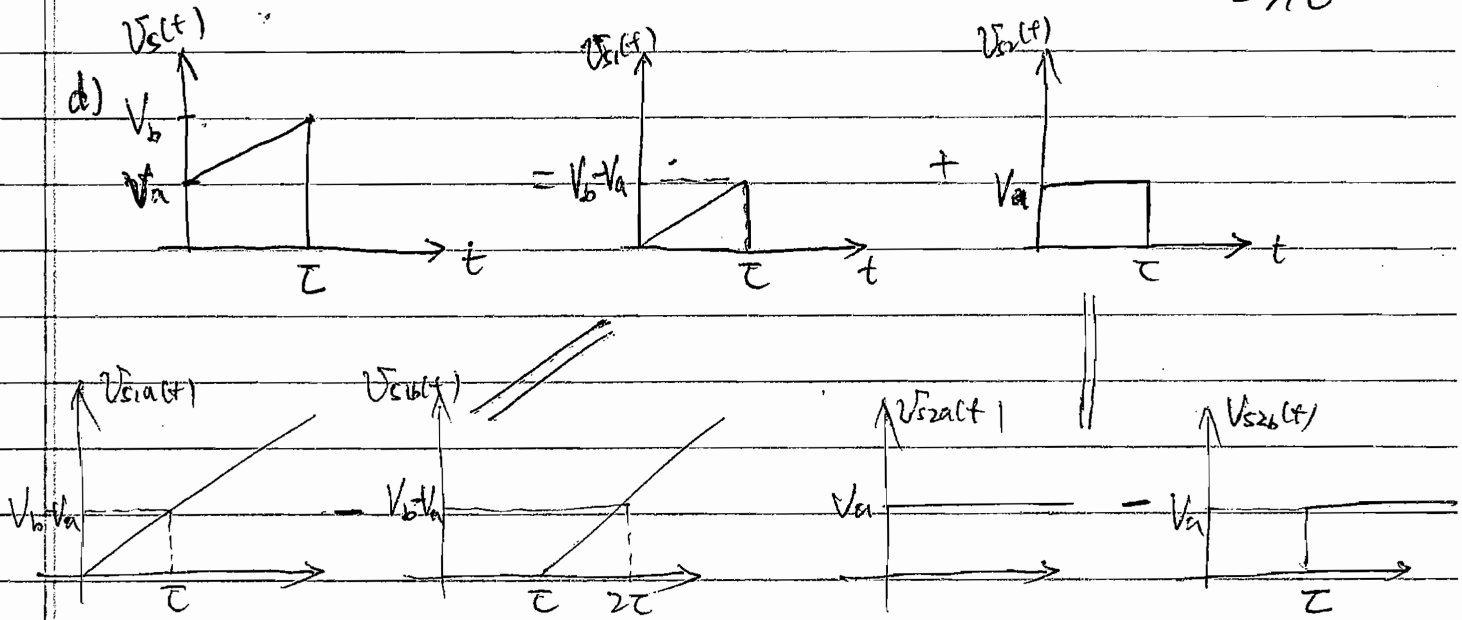
$$\therefore\ v_c(t) = \frac{M}{V_s} \int v_a(t)\, dt \quad \& \quad v_c(0^+) = v_c(0^-) = 0$$

$v(t)$ in part c)

$$\therefore\ \boxed{v_c(t) = \frac{M}{V_s} \int V_s \frac{R_2}{R_1+R_2} e^{-t/\tau} dt = M \frac{L}{R_1}(1 - e^{-t/\tau})}$$



d)




Therefore this input can be decomposed into two ramps and two steps,

$$\boxed{\begin{aligned} v_s(t) &= v_{s1}(t) + v_{s2}(t) = v_{s1a}(t) \overset{-}{\cancel{+}} v_{s1b}(t) + v_{s2a}(t) \overset{-}{\cancel{+}} v_{s2b}(t) \\ &= \frac{V_b - V_a}{\tau}\left(u_{-2}(t) - u_{-2}(t-\tau)\right) + V_a\left(u_{-1}(t) - u_{-1}(t-\tau)\right) \end{aligned}}$$

e) Using results from a) & c), by superposing response to step and ramp inputs, we can derive $v_e(t)$ ($v(t)$ - in part e)) for $t \geq 0$,

$$v_e(t) = \frac{R_2}{R_1 + R_2} \cdot V_a \cdot \left(e^{-t/\tau} - e^{-(t-\tau)/\tau}\right)$$

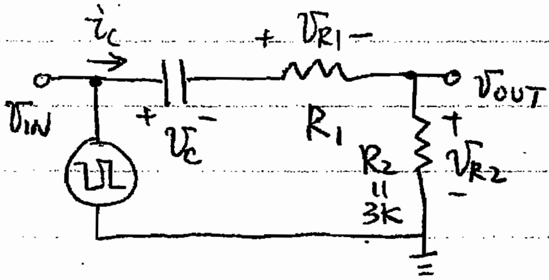
$$- \left(\frac{L}{R_1}\right) \cdot \frac{(V_b - V_a)}{\tau} \cdot \left(e^{-t/\tau} - e^{-(t-\tau)/\tau}\right)$$

$$= \left(\frac{R_2 V_a}{R_1 + R_2} - \frac{L(V_b - V_a)}{R_1 \tau}\right) \cdot \left(e^{-t/\tau} - e^{-(t-\tau)/\tau}\right)$$

$\because \tau = L \cdot \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$ from part a)

$\therefore$ we can further simply $\boxed{v_e(t) = \frac{R_2}{R_1 + R_2} \cdot (2V_a - V_b) \cdot \left(e^{-t/\tau} - e^{-(t-\tau)/\tau}\right)}$

Problem 8.2




a) when $v_{IN} = V$, from KVL, we have, $V = v_c(t) + v_{R_1}(t) + v_{R_2}(t)$

$\because v_{R1}(t) = R_1 \cdot i_c(t)$, $v_{R2}(t) = R_2 \cdot i_c(t)$, and $i_c(t) = C\dfrac{dv_c(t)}{dt}$

$\therefore V = v_c(t) + (R_1+R_2)\cdot C\dfrac{dv_c(t)}{dt}$.

$$\Rightarrow V = v_c(t) + \tau\cdot\frac{dv_c(t)}{dt} \quad \text{where } \tau = (R_1+R_2)C$$

If define $t=0$ when source $v_{IN}$ jumps from "$-V$" to "$V$", then we have

$$\tau\cdot\frac{dv_c(t)}{dt} + v_c(t) = V \quad \& \quad v_c(t=0^-) = -V$$

Similiarly, we define $t'=0$ when source $v_{IN}$ jumps from "$V$" to "$-V$", then we have $\tau\cdot\dfrac{dv_c(t)}{dt} + v_c(t) = -V$ & $v_c(t'=0^-) = V$

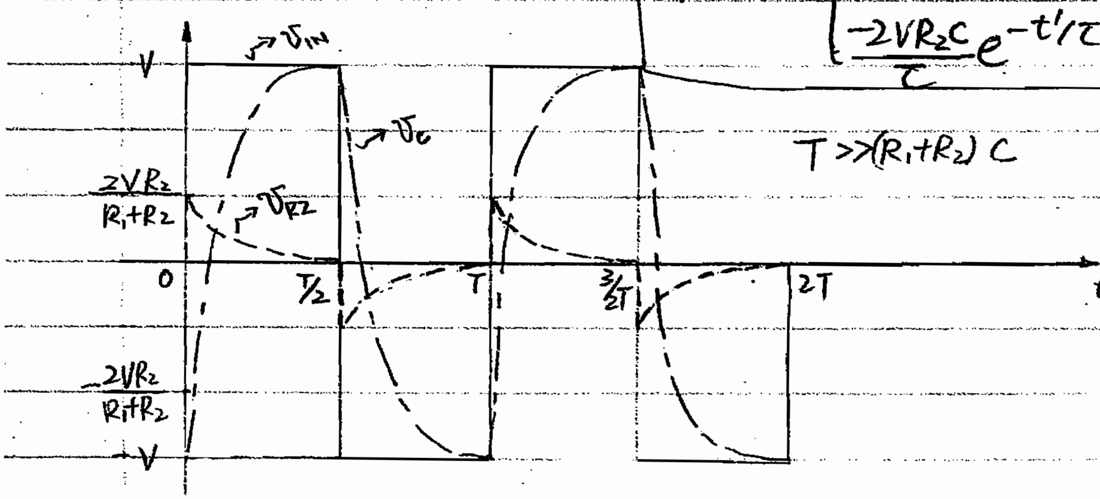
Solve equations above, we have
$$\boxed{v_c(t) = \begin{cases} V - 2Ve^{-t/\tau} & v_{IN} = V \\ -V + 2Ve^{-t'/\tau} & v_{IN} = -V \end{cases}}$$

b) $\because i_c(t) = C\dfrac{dv_c(t)}{dt}$

$$\therefore \boxed{i_c(t) = \begin{cases} \dfrac{2VC}{\tau}e^{-t/\tau} & v_{IN} = V \left(\text{or, } \dfrac{2V}{R_1+R_2}e^{-t/\tau}\right) \\ \dfrac{-2VC}{\tau}e^{-t'/\tau} & v_{IN} = -V \left(\text{or, } \dfrac{-2V}{R_1+R_2}e^{-t'/\tau}\right) \end{cases}}$$

c) $\because v_{R2}(t) = R_2 \cdot i_c(t)$

$$\therefore \boxed{v_{R2}(t) = \begin{cases} \dfrac{2VR_2C}{\tau}e^{-t/\tau} & v_{IN} = V \left(\text{or, } \dfrac{2VR_2}{R_1+R_2}e^{-t/\tau}\right) \\ \dfrac{-2VR_2C}{\tau}e^{-t'/\tau} & v_{IN} = -V \left(\text{or, } \dfrac{2VR_2}{R_1+R_2}e^{-t'/\tau}\right) \end{cases}}$$




$T \gg (R_1+R_2)C$

Notice that

$t' = t - T/2$

where $T = \dfrac{1}{f}$

See P9&10 for experimental data used in part d & e

d) For $V_{R2}$, we have $V_{R2}(0^+) = 206\,mV$, $V_{R2}(1.1ms) = 10.3\,mV = 0.05 \times V_{R2}(0^+)$

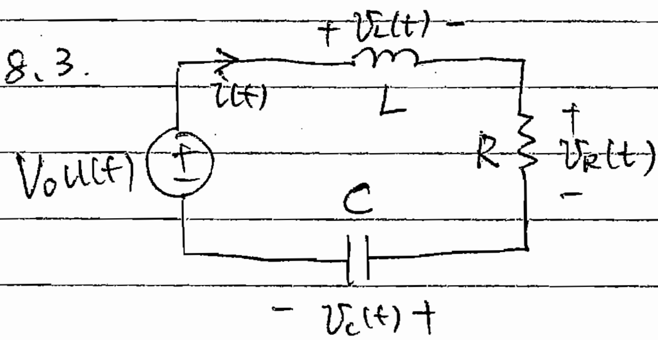
$\therefore\ 3\tau = 1.1\,ms \Rightarrow \boxed{\tau \approx 0.367\,ms}$ (Don't need to be so accurate actually. 0.37ms is fine.) right

e) Before the input switches from positive to negtive, $V_C = 1.19\,V = V_{IN}$. after the input switches to negtive, $V_C$ keeps the same as 1.19 V while $V_{IN} = -1.14\,V$,

So we have, $\dfrac{-1.19 - 1.14}{R_1 + R_2} = \dfrac{-190 \times 10^{-3}}{R_2} \Rightarrow \boxed{R_1 \approx 34K}$ (given $R_2 = 3k$)

f) $\tau = (R_1 + R_2) \cdot C \Rightarrow \boxed{C = \dfrac{\tau}{R_1 + R_2} = \dfrac{0.367\,ms}{34K + 3K} \approx 9.9\,nF = 9.9 \times 10^{-9}\,F}$

problem 8.3.




a) $\boxed{V_C(t) = 0}$, because capacitor behaves like short circuit @ t=0

$\boxed{i(0) = 0}$, because inductor behaves like open circuit @ t=0

$\therefore\ \boxed{V_R(0) = i(0) \cdot R = 0}$

$\boxed{V_L(0) = V_0 u(0) - V_R(0) - V_C(0) = V_0}$

$\because\ V_L = L \dfrac{di}{dt}$

$\therefore\ \boxed{\left.\dfrac{di}{dt}\right|_{t=0} = \dfrac{V_L(0)}{L} = \dfrac{V_0}{L}}$

c) Because capacitor behaves like open circuit @ $t = \infty$, $\therefore\ \boxed{i(t = \infty) = 0}$

b) $V_C(t) = V_0(1 - \cos(\omega_0 t))$ $\quad \omega_0 = \dfrac{1}{\sqrt{LC}}$, $t > 0$

$i(t) = \sqrt{\dfrac{C}{L}}\, V_0 \sin(\omega_0 t)$

d) From KVL, we have, $V_0 = v_L(t) + v_R(t) + v_C(t)$

$$= L\frac{di(t)}{dt} + i(t)\cdot R + \frac{1}{C}\int i(t)\,dt$$

$$\Rightarrow 0 = L\frac{d^2 i(t)}{dt^2} + R\frac{di(t)}{dt} + \frac{1}{C}i(t)$$

$$\Rightarrow \boxed{\frac{d^2 i(t)}{dt^2} + \frac{R}{L}\frac{di(t)}{dt} + \frac{1}{LC}i(t) = 0}$$

e) $\frac{d^2 i(t)}{dt^2} + \frac{R}{L}\frac{di(t)}{dt} + \frac{1}{LC}i(t) = 0 \Rightarrow s^2 + \frac{R}{L}s + \frac{1}{LC} = 0$

$$\therefore s = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

$$= -\alpha \pm \sqrt{\alpha^2 - \omega_0^2} \qquad \therefore \alpha = \frac{R}{2L},\ \omega_0 = \frac{1}{\sqrt{LC}}$$

$$= -\alpha \pm j\omega_d \qquad \therefore \omega_d = \sqrt{\omega_0^2 - \alpha^2} \quad (\omega_0 > \alpha)$$

$$i(t) = e^{-\alpha t}(A\cos(\omega_d t) + B\sin(\omega_d t))$$

$\because i(0) = 0 \quad \therefore A = 0$

$\therefore i(t) = Be^{-\alpha t}\sin(\omega_d t)$

$$\frac{di(t)}{dt} = -\alpha Be^{-\alpha t}\sin(\omega_d t) + Be^{-\alpha t}\cdot\omega_d\cos(\omega_d t)$$

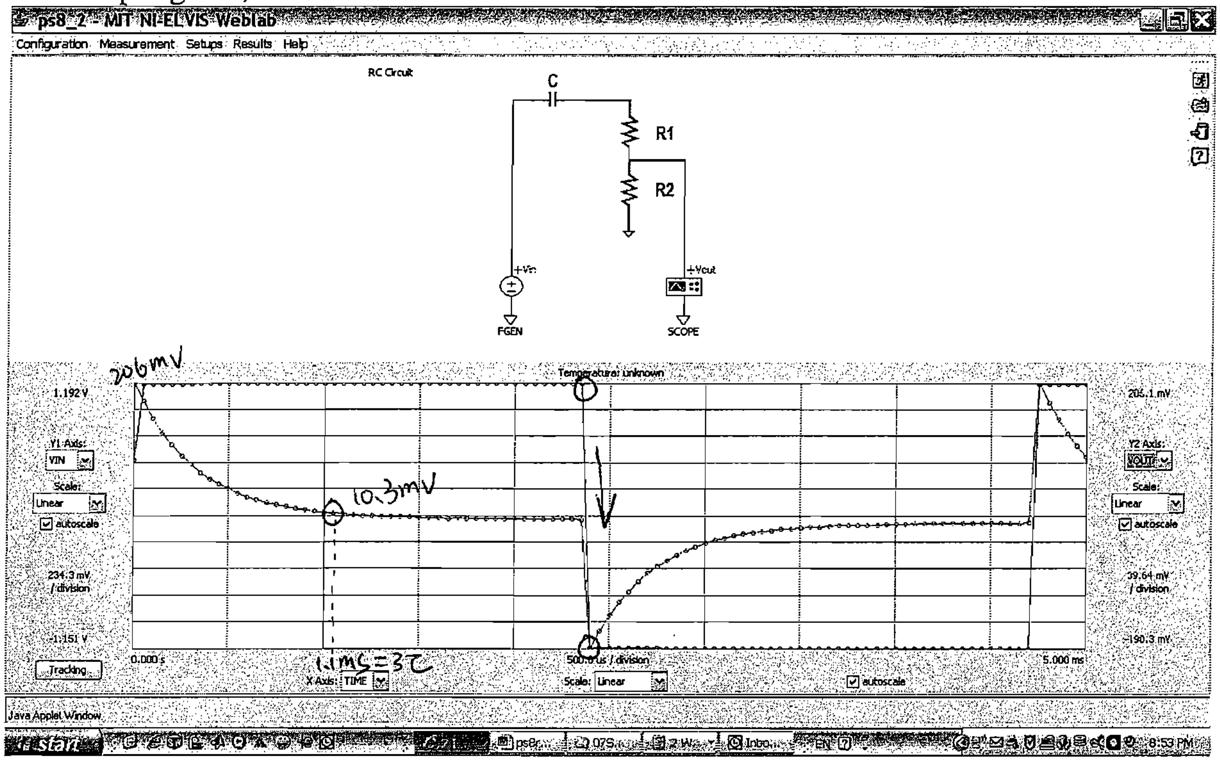
$\because \left.\frac{di(t)}{dt}\right|_{t=0} = \frac{V_0}{L} \Rightarrow B\omega_d = \frac{V_0}{L} \Rightarrow B = \frac{V_0}{\omega_d L}$

$$\therefore i(t) = \frac{V_0}{\omega_d L}e^{-\alpha t}\sin(\omega_d t) = Ie^{-\alpha t}\sin(\omega t + \phi)$$

where $I = \frac{V_0}{L\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}}$, $\omega = \omega_d = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$, $\phi = 0$, $\alpha = \frac{R}{2L}$

9/10

20k sampling rate, 5ms duration




time constant is about 0.367 ms

R1 is about 34 Kohm

C is about 9.9 nF $= 9.9 \times 10^{-9}$ F

| TIME, VIN, VOUT |
|---|
| s, V, V |
| 0, 512.032192234953e-3, 206.099181203987e-3 |
| 50e-6, 1.182187934163, 179.048278663754e-3 |
| 100e-6, 1.18379811410142, 153.607551136429e-3 |
| 150e-6, 1.18476422207144, 132.353274082149e-3 |
| 200e-6, 1.18605236603962, 113.67527424834e-3 |
| 250e-6, 1.18701847402186, 97.8955856072151e-3 |
| 300e-6, 1.18766254601292, 84.6921732706709e-3 |
| 350e-6, 1.18830661800632, 72.7768991940769e-3 |
| 400e-6, 1.18862865400389, 62.7938320656817e-3 |
| 450e-6, 1.18895069000205, 54.7429717032384e-3 |
| 500e-6, 1.1895947620001, 47.9802491530912e-3 |
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