Basic Electrical Engineering

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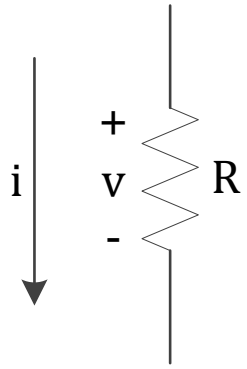
Faculty of Electrical and Computer Engineering
Department of Electrical & Electronics Engineering

Transient state

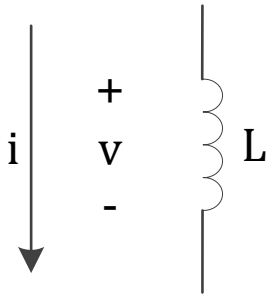
حالت گذرا

رفتار عناصر مدار



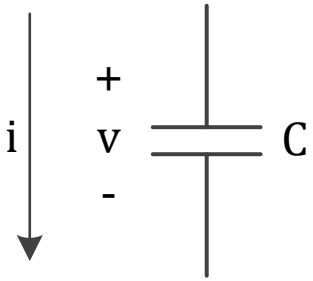
$$v = Ri$$

$$i = \frac{1}{R}v = Gv$$



$$v = L\frac{di}{dt}$$

$$i = \frac{1}{L}\int v dt + i_0$$



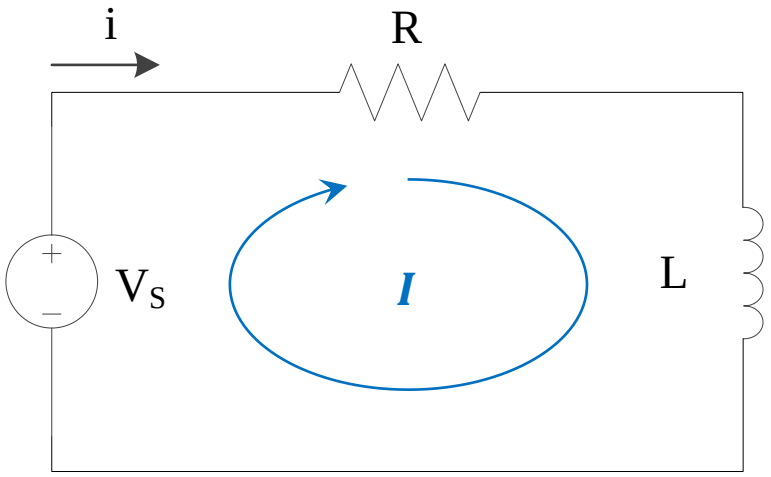
$$v = \frac{1}{C}\int i dt + v_0$$

$$i = C\frac{dv}{dt}$$

Transient state

حالت گذرا

حالت دائمی ثابت



$$-V_S + V_R + V_L = 0$$

$$V_R = RI \qquad V_L = L\frac{di}{dt}$$

حالت دائمی ثابت ← مدار مدت زمان زیادی بدون تغییر است ← تغییرات وجود ندارد

$$V_L = 0 \qquad \frac{di}{dt} = 0$$

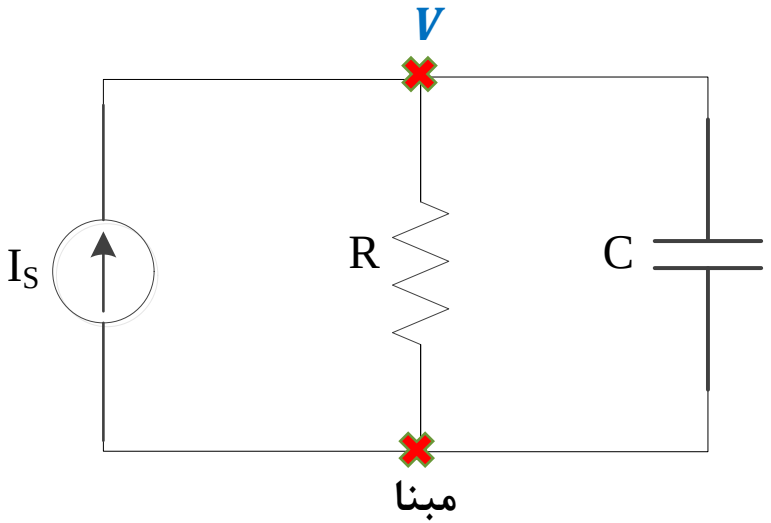
$$-V_S + RI + 0 = 0 \qquad I = \frac{V_S}{R} \qquad I_L = I_R = \frac{V_S}{R}$$

سلف در زمان بی نهایت ← اتصال کوتاه با جریان $\mathbf{I_0}$ است.

Transient state

حالت گذرا

حالت دائمی ثابت



$$-I_S + I_R + I_C = 0$$

$$I_R = \frac{V}{R} \qquad I_C = C\frac{dV}{dt}$$

حالت دائمی ثابت ← مدار مدت زمان زیادی بدون تغییر است ← تغییرات وجود ندارد

$$I_C = 0 \qquad \frac{dV}{dt} = 0$$

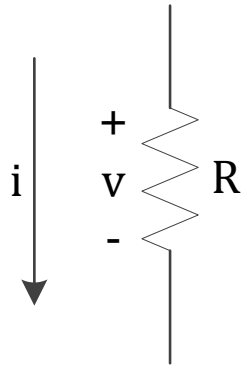
$$-I_S + \frac{V}{R} + 0 = 0 \qquad V = RI_S \qquad V_C = V_R = RI_S$$

خازن در زمان بی نهایت ← اتصال باز با ولتاژ $\mathbf{V_0}$ است.

Transient state

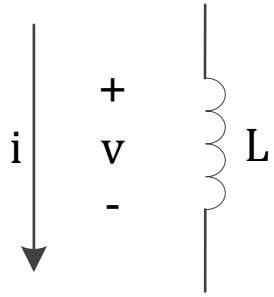
حالت گذرا

حالت دائمی ثابت (رفتار در زمان بی نهایت)



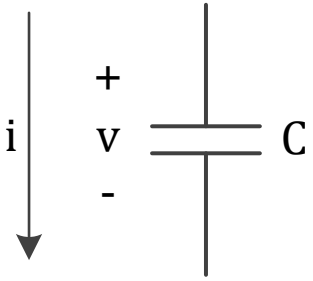
$$V_R = RI_R$$

$$I_R = \frac{1}{R}V_R$$



$$V_L = 0$$

$$I_L = cte$$



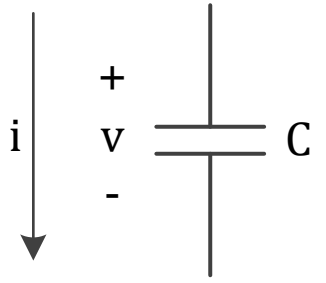
$$I_C = 0$$

$$V_C = cte$$

Transient state

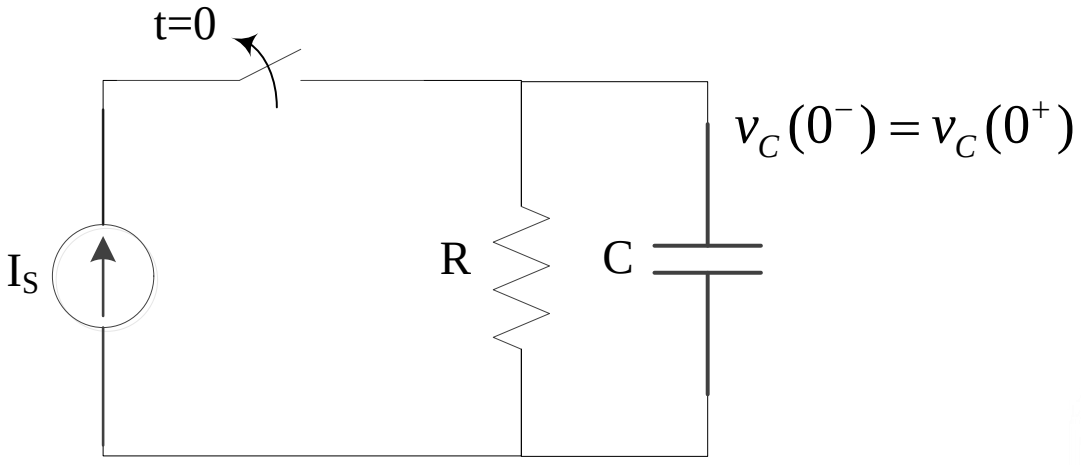
حالت گذرا

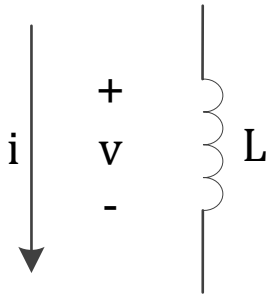
حالت گذرا



$$i_C = C\frac{dv_C}{dt}$$

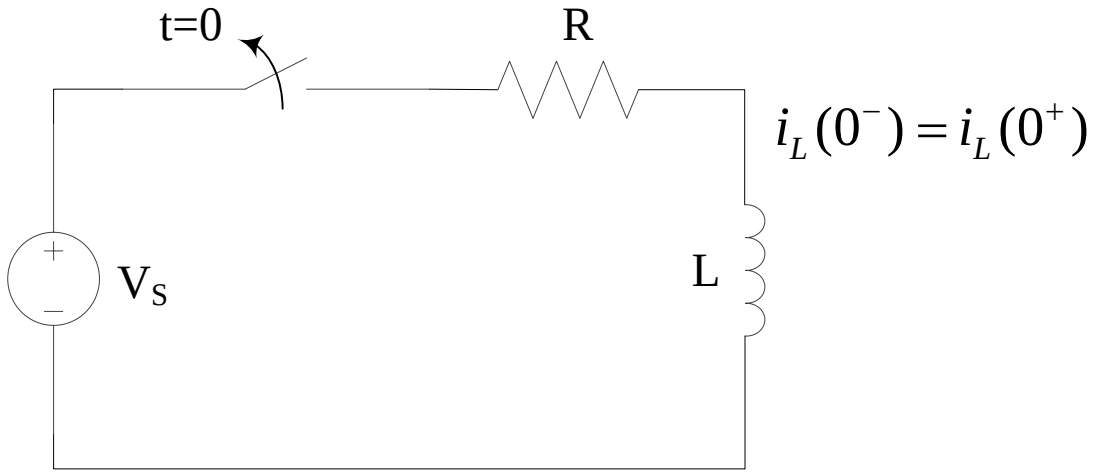
ولتاژ خازن تغییر ناگهانی ندارد $i_C \neq \infty$





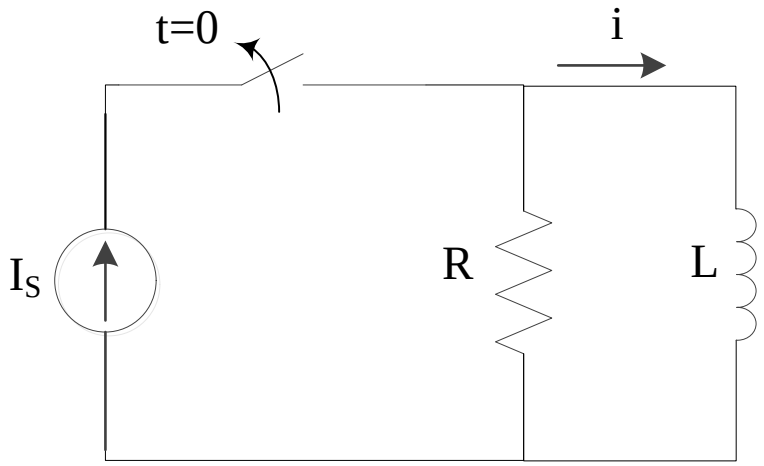
$$v_L = L\frac{di_L}{dt}$$

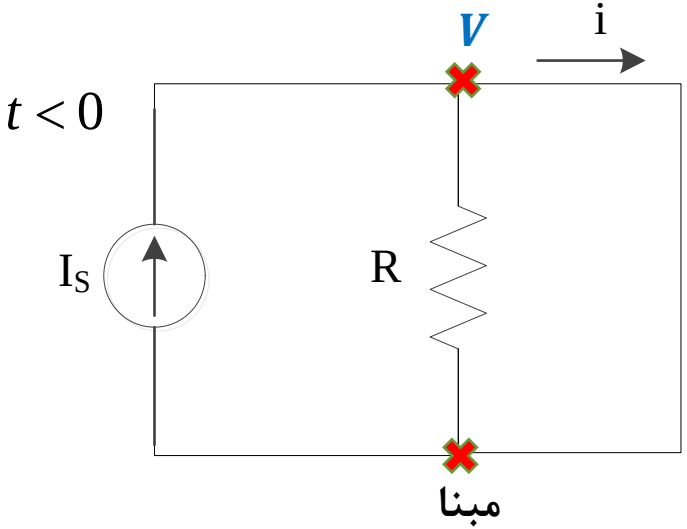
جریان سلف تغییر ناگهانی ندارد $v_L \neq \infty$



Transient state

حالت گذرا



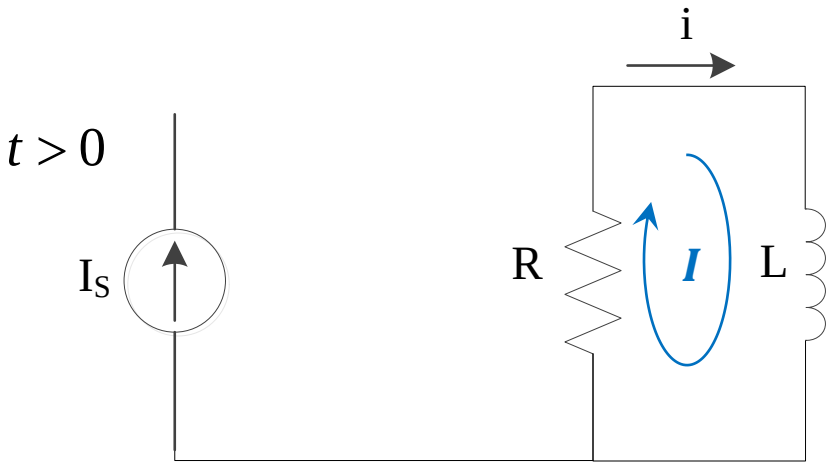


حالت گذرا

سلف اتصال کوتاه

$$-I_S+\frac{0}{R}+I=0$$

$$I=I_S \qquad i_L(0^-)=I_S$$



$$Ri+L\frac{di}{dt}=0 \qquad i_L(0^+)=i_L(0^-)=I_S$$

Transient state

حالت گذرا

حالت گذرا

$$Ri + L\frac{di}{dt} = 0 \qquad \frac{di}{i} = -\frac{R}{L}dt \qquad i_L(0^+) = I_S$$

$$\int_{i(0^+)}^{i(t)} \frac{di}{i} = -\int_{0^+}^{t} \frac{R}{L}dt \qquad Ln[i(t)] - Ln[i(0^+)] = -\frac{R}{L}[t-0] \qquad Ln\frac{i(t)}{i(0^+)} = -\frac{R}{L}t$$

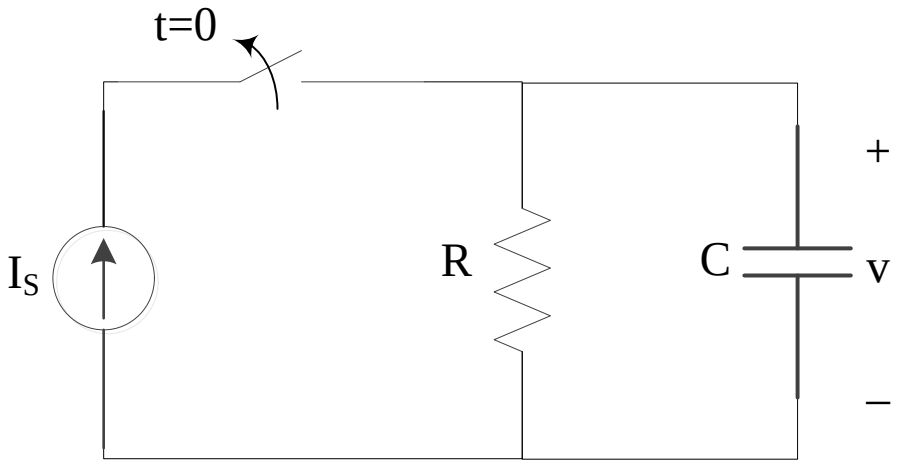
$$\frac{i(t)}{i(0^+)} = e^{-\frac{R}{L}t} \qquad i(t) = i(0^+)e^{-\frac{R}{L}t} \qquad i(t) = I_S e^{-\frac{R}{L}t}$$

$$i(t) = I_0 e^{-\frac{t}{\tau}} \qquad I_0 = I_S \qquad \tau = \frac{L}{R}$$

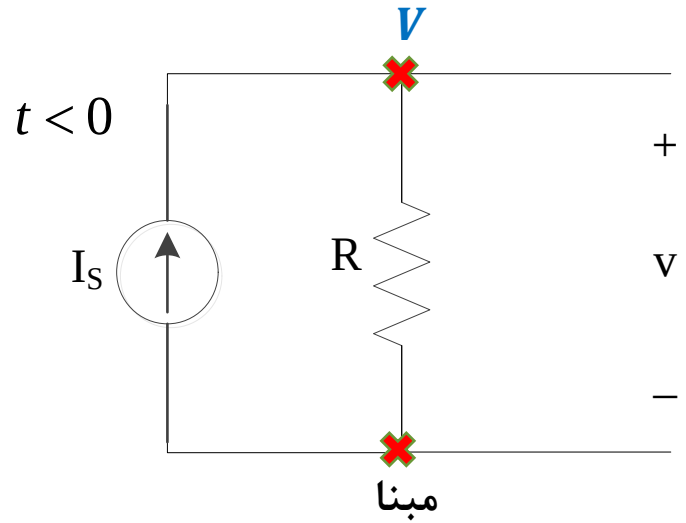
ثابت زمانی

Transient state

حالت گذرا



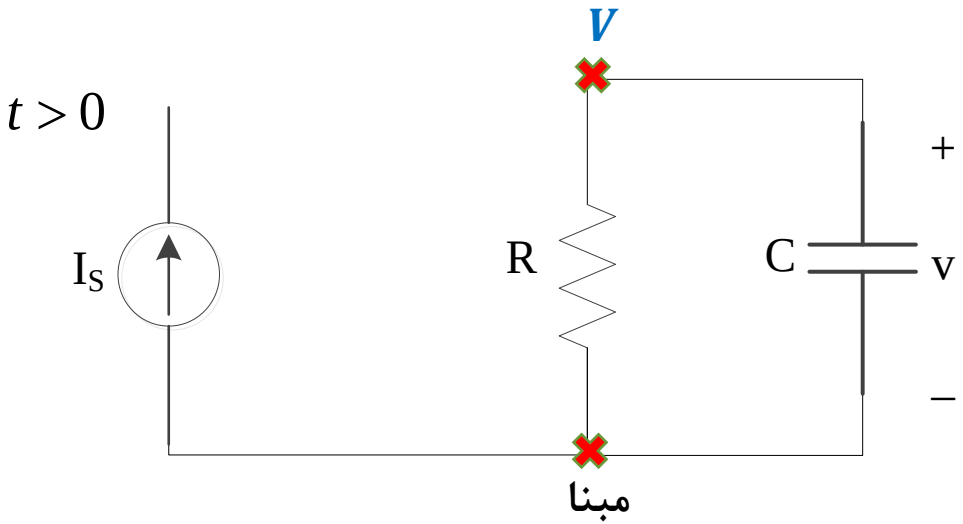
حالت گذرا



خازن اتصال باز

$$-I_S + \frac{V}{R} = 0$$

$$V = RI_S \qquad v_C(0^-) = RI_S$$



$$i_R + i_C = 0$$

$$\frac{v}{R} + C\frac{dv}{dt} = 0$$

$$v_C(0^+) = v_C(0^-) = RI_S$$

Transient state

حالت گذرا

حالت گذرا

$$\frac{v}{R}+C\frac{dv}{dt}=0 \qquad \frac{dv}{v}=-\frac{1}{RC}dt \qquad v_C(0^+)=v_C(0^-)=RI_S$$

$$\int_{v(0^+)}^{v(t)}\frac{dv}{v}=-\int_{0^+}^{t}\frac{1}{RC}dt \qquad Ln[v(t)]-Ln[v(0^+)]=-\frac{1}{RC}[t-0] \qquad Ln\frac{v(t)}{v(0^+)}=-\frac{1}{RC}t$$

$$\frac{v(t)}{v(0^+)}=e^{-\frac{1}{RC}t} \qquad v(t)=v(0^+)e^{-\frac{1}{RC}t} \qquad v(t)=RI_Se^{-\frac{1}{RC}t}$$

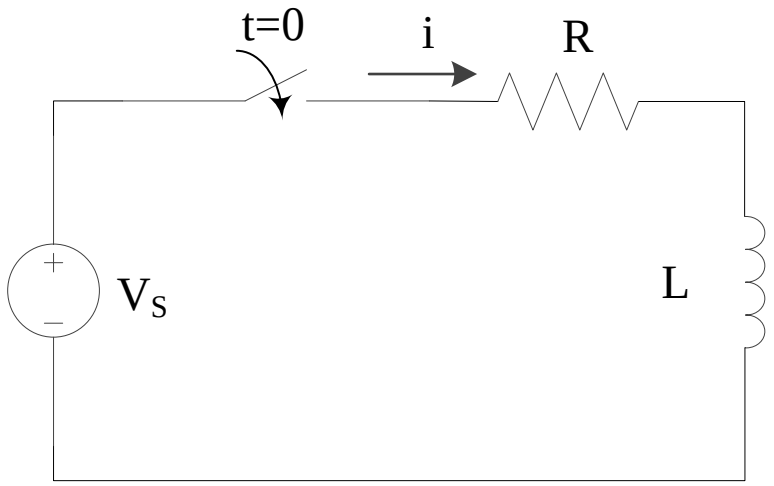
$$v(t)=V_0e^{-\frac{t}{\tau}} \qquad V_0=RI_S \qquad \tau=RC$$

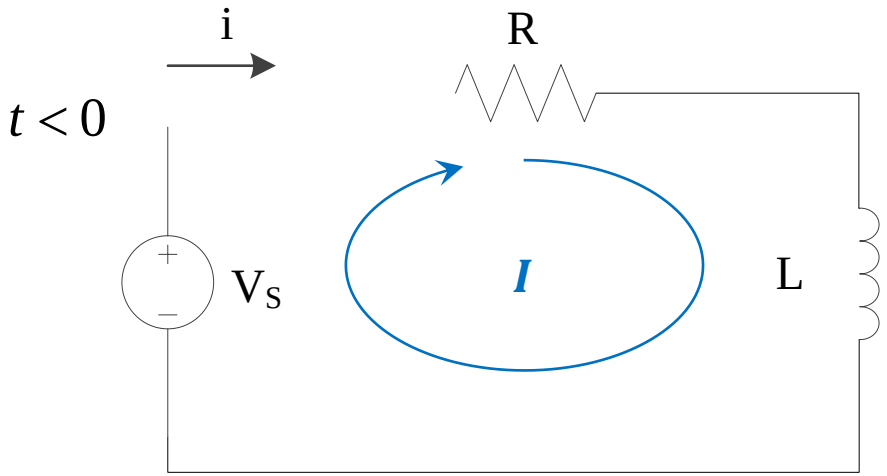
ثابت زمانی

Transient state

حالت گذرا

حالت گذرا

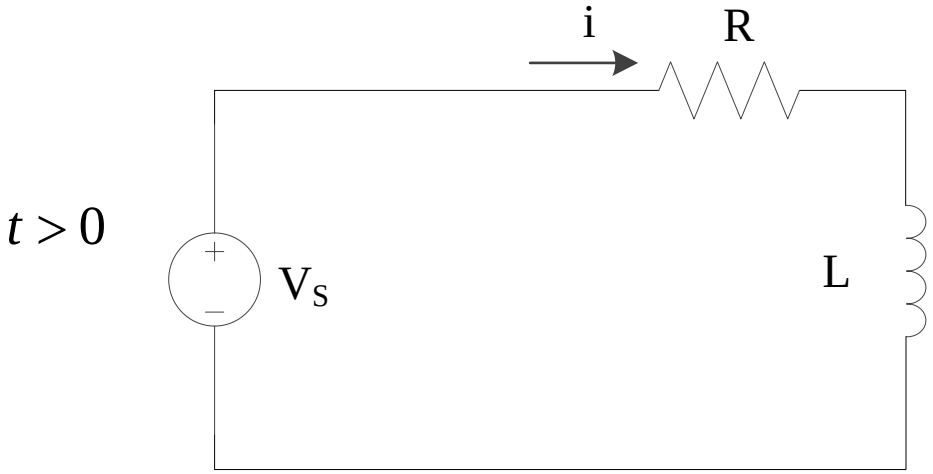




سلف اتصال کوتاه

$$I = 0$$

$$i_L(0^-) = 0$$



$$-V_S + V_R + V_L = 0$$

$$i_L(0^+) = i_L(0^-) = 0$$

$$Ri + L\frac{di}{dt} = V_S$$

Transient state

حالت گذرا

حالت گذرا

$$Ri + L\frac{di}{dt} = V_S$$

جواب عمومی

$$Ri + L\frac{di}{dt} = 0$$

$$\frac{di}{i} = -\frac{R}{L}dt$$

$$\int_{i(0^+)}^{i(t)} \frac{di}{i} = -\int_{0^+}^{t} \frac{R}{L}dt$$

$$Ln[i(t)] - Ln[i(0^+)] = -\frac{R}{L}[t-0]$$

$$Ln\frac{i(t)}{i(0^+)} = -\frac{R}{L}t$$

$$\frac{i(t)}{i(0^+)} = e^{-\frac{R}{L}t}$$

$$i(t) = i(0^+)e^{-\frac{R}{L}t}$$

$$i(t) = K_1 e^{-\frac{R}{L}t}$$

$$Ri + L\frac{di}{dt} = V_S$$

جواب خصوصی معادله

$$i = cte = K_2$$

$$i(t) = K_2 + K_1 e^{-\frac{R}{L}t}$$

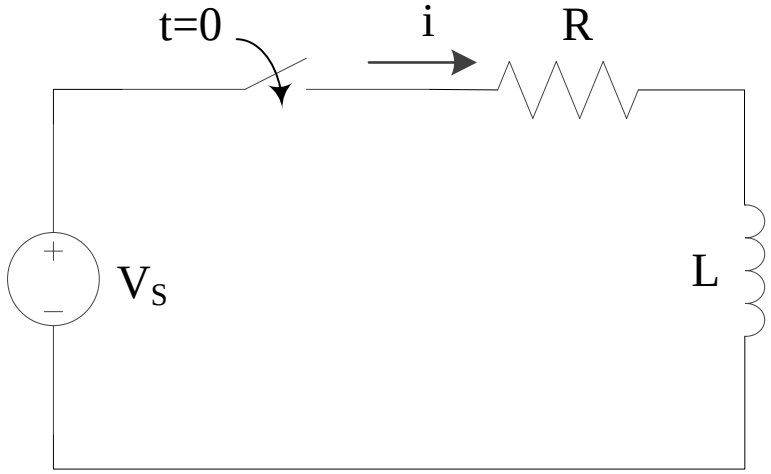
Transient state

حالت گذرا

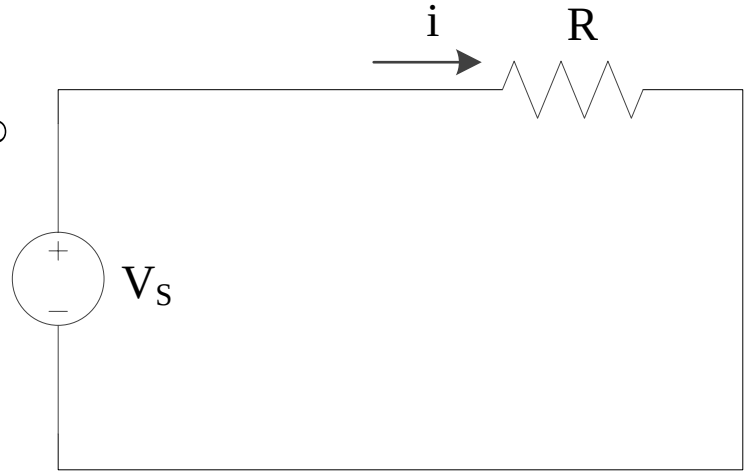
حالت گذرا

$$i(t) = K_2 + K_1 e^{-\frac{R}{L}t} \qquad i_L(0^+) = 0 \qquad i_L(\infty) = \frac{V_S}{R}$$

$$K_2 = \frac{V_S}{R} \qquad K_1 + K_2 = 0 \qquad i(t) = \frac{V_S}{R}(1 - e^{-\frac{R}{L}t})$$



$t \to \infty$



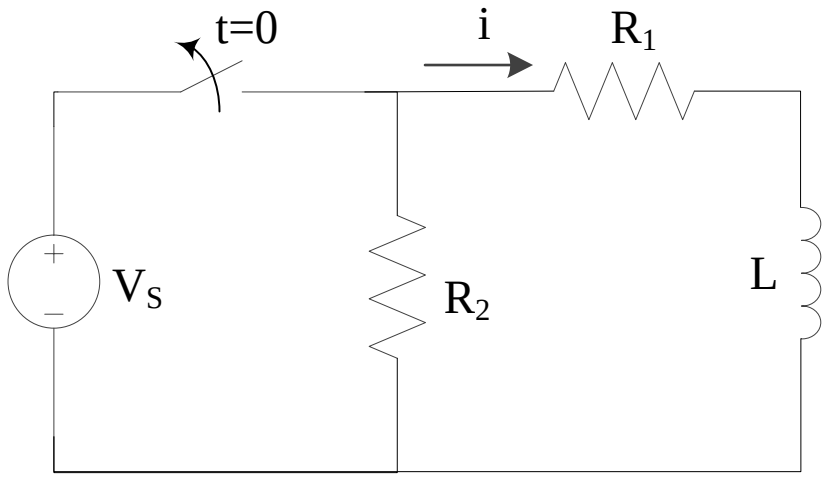
سلف اتصال کوتاه

$$I = \frac{V_S}{R}$$

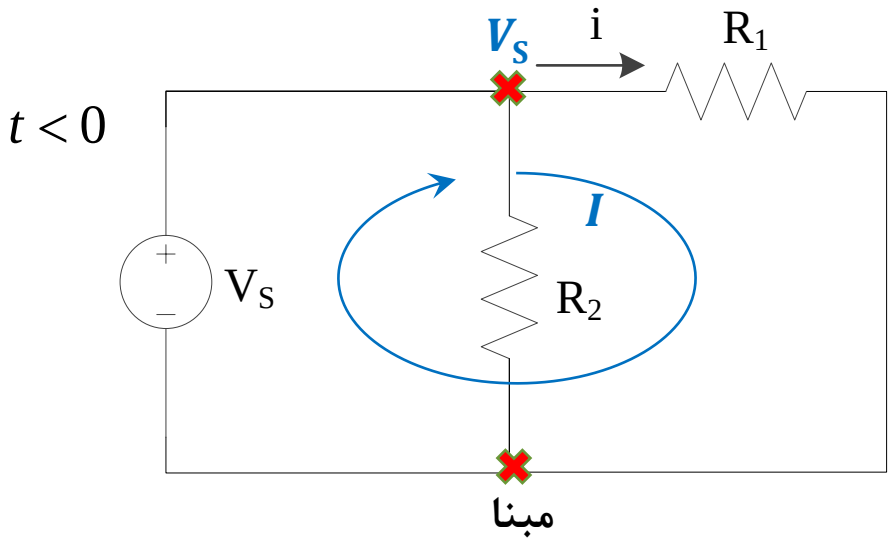
$$i_L(\infty) = \frac{V_S}{R}$$

Transient state

حالت گذرا



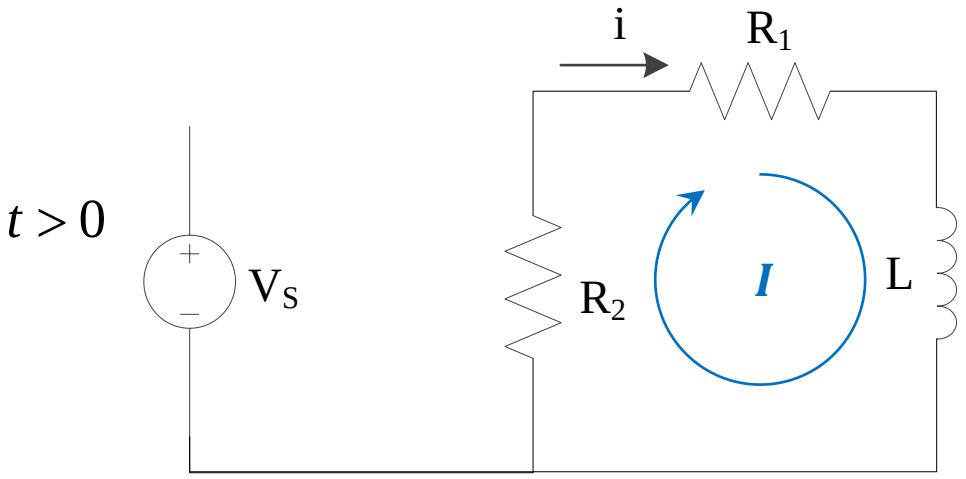
حالت گذرا



سلف اتصال کوتاه

$$I = \frac{V_S}{R_1}$$

$$i_L(0^-) = \frac{V_S}{R_1}$$



$$R_1 i + R_2 i + L\frac{di}{dt} = 0$$

$$i_L(0^+) = i_L(0^-) = \frac{V_S}{R_1}$$

Transient state

حالت گذرا

حالت گذرا

$$R_1 i + R_2 i + L\frac{di}{dt} = 0 \qquad \frac{di}{i} = -\frac{(R_1+R_2)}{L}dt \qquad i_L(0^+) = \frac{V_S}{R_1}$$

$$\int_{i(0^+)}^{i(t)} \frac{di}{i} = -\int_{0^+}^{t} \frac{(R_1+R_2)}{L}dt \qquad Ln[i(t)] - Ln[i(0^+)] = -\frac{(R_1+R_2)}{L}[t-0] \qquad Ln\frac{i(t)}{i(0^+)} = -\frac{(R_1+R_2)}{L}t$$

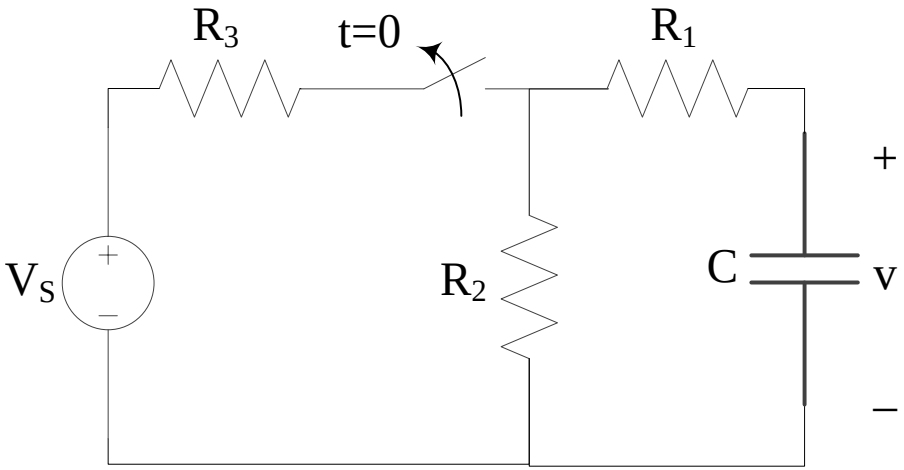
$$\frac{i(t)}{i(0^+)} = e^{-\frac{(R_1+R_2)}{L}t} \qquad i(t) = i(0^+)e^{-\frac{(R_1+R_2)}{L}t} \qquad i(t) = \frac{V_S}{R_1}e^{-\frac{(R_1+R_2)}{L}t}$$

$$i(t) = I_0 e^{-\frac{t}{\tau}} \qquad I_0 = \frac{V_S}{R_1} \qquad \tau = \frac{L}{(R_1+R_2)}$$

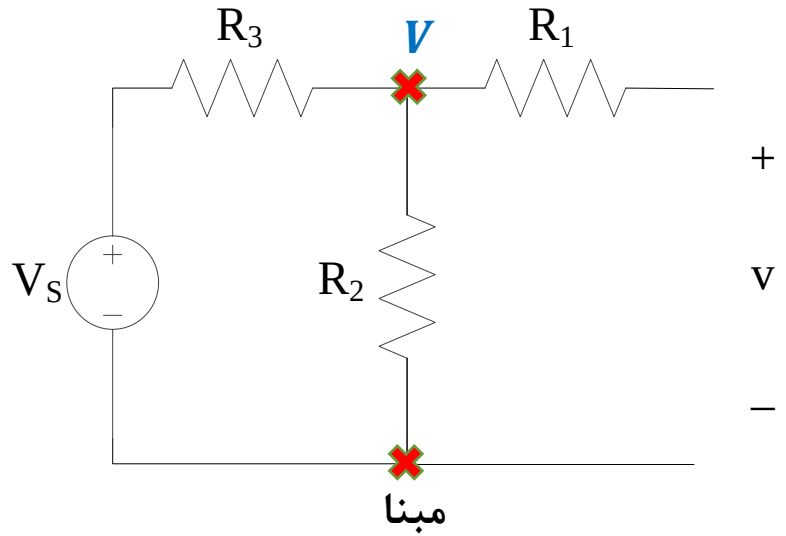
ثابت زمانی

Transient state

حالت گذرا



$t < 0$



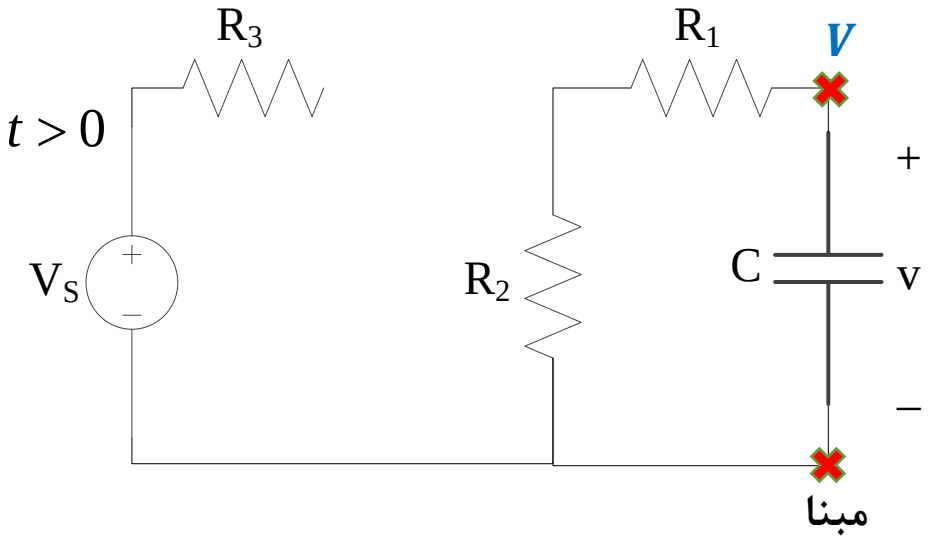
حالت گذرا

خازن اتصال باز

$$\frac{V - V_S}{R_3} + \frac{V}{R_2} = 0$$

$$V = \frac{R_2}{R_2 + R_3} V_S$$

$$v_C(0^-) = \frac{R_2}{R_2 + R_3} V_S$$



$$i_{R1} + i_C = 0$$

$$\frac{v}{R_1 + R_2} + C\frac{dv}{dt} = 0$$

$$v_C(0^+) = v_C(0^-) = \frac{R_2}{R_2 + R_3} V_S$$

Transient state

حالت گذرا

حالت گذرا

$$\frac{v}{R_1+R_2}+C\frac{dv}{dt}=0 \qquad \frac{dv}{v}=-\frac{1}{(R_1+R_2)C}dt \qquad v_C(0^+)=v_C(0^-)=\frac{R_2}{R_2+R_3}V_S$$

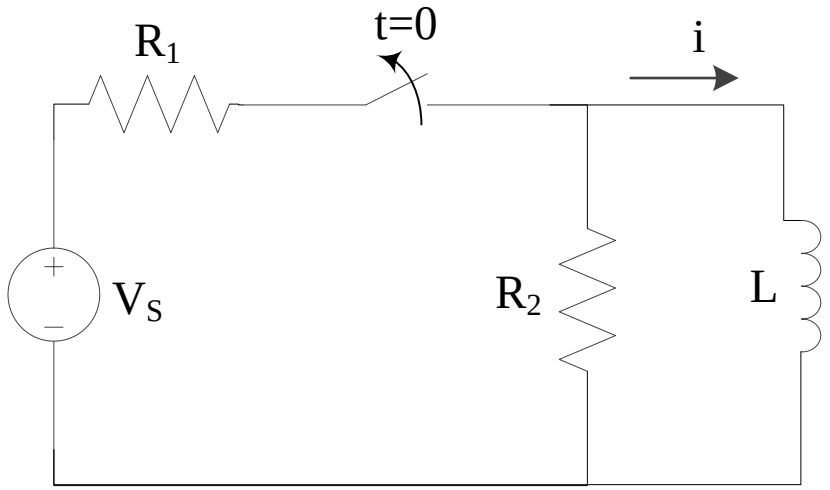
$$\int_{v(0^+)}^{v(t)}\frac{dv}{v}=-\int_{0^+}^{t}\frac{1}{(R_1+R_2)C}dt \qquad Ln[v(t)]-Ln[v(0^+)]=-\frac{1}{(R_1+R_2)C}t \qquad Ln\frac{v(t)}{v(0^+)}=-\frac{1}{(R_1+R_2)C}t$$

$$\frac{v(t)}{v(0^+)}=e^{-\frac{1}{(R_1+R_2)C}t} \qquad v(t)=v(0^+)e^{-\frac{1}{(R_1+R_2)C}t} \qquad v(t)=\frac{R_2}{R_2+R_3}V_S e^{-\frac{1}{(R_1+R_2)C}t}$$

$$v(t)=V_0 e^{-\frac{t}{\tau}} \qquad V_0=\frac{R_2}{R_2+R_3}V_S \qquad \tau=(R_1+R_2)C$$ ثابت زمانی

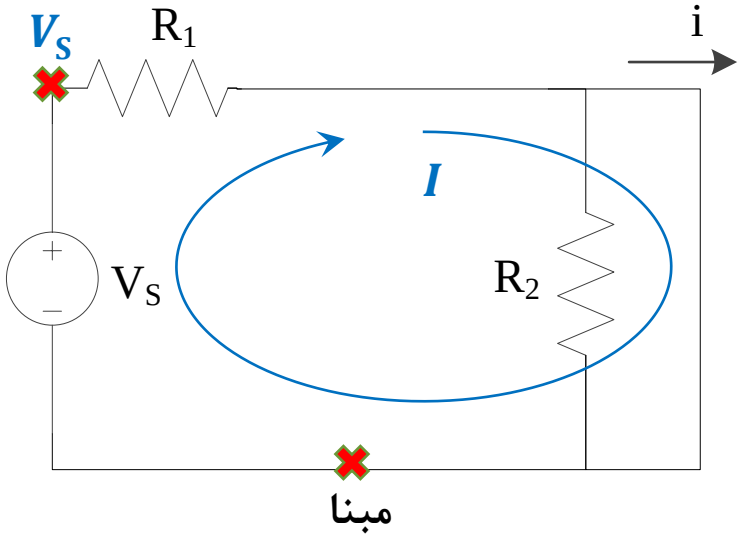
Transient state

حالت گذرا



حالت گذرا

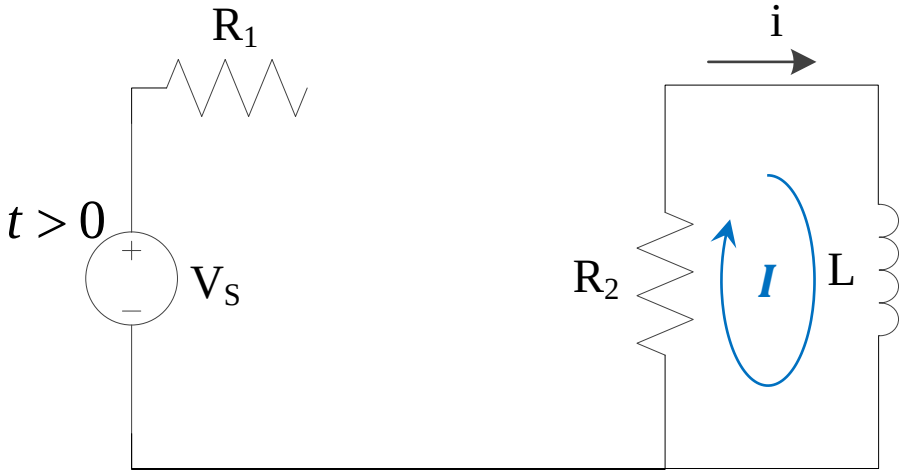
$t < 0$



سلف اتصال کوتاه

$$I = \frac{V_S}{R_1}$$

$$i_L(0^-) = \frac{V_S}{R_1}$$



$$R_2 i + L\frac{di}{dt} = 0$$

$$i_L(0^+) = i_L(0^-) = \frac{V_S}{R_1}$$

Transient state

حالت گذرا

حالت گذرا

$$R_2 i + L\frac{di}{dt} = 0$$

$$i_L(0^+) = \frac{V_S}{R_1}$$

$$i(t) = I_0 e^{-\frac{t}{\tau}}$$

$$I_0 = \frac{V_S}{R_1}$$

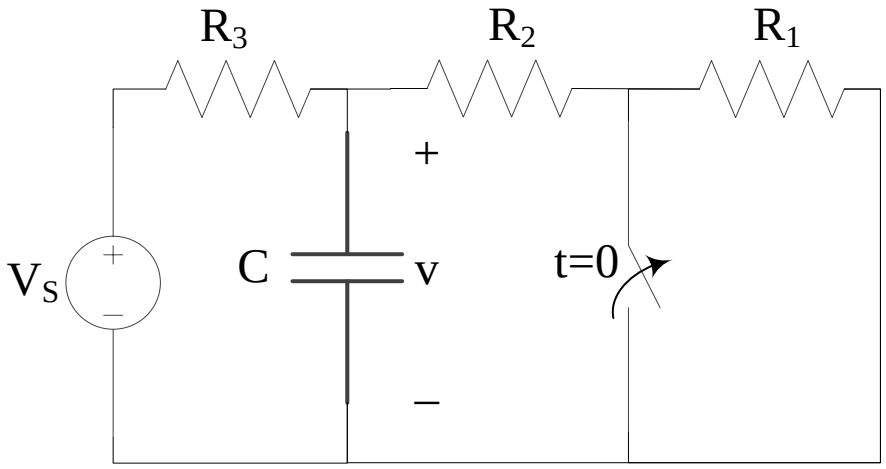
$$\tau = \frac{L}{R_2}$$

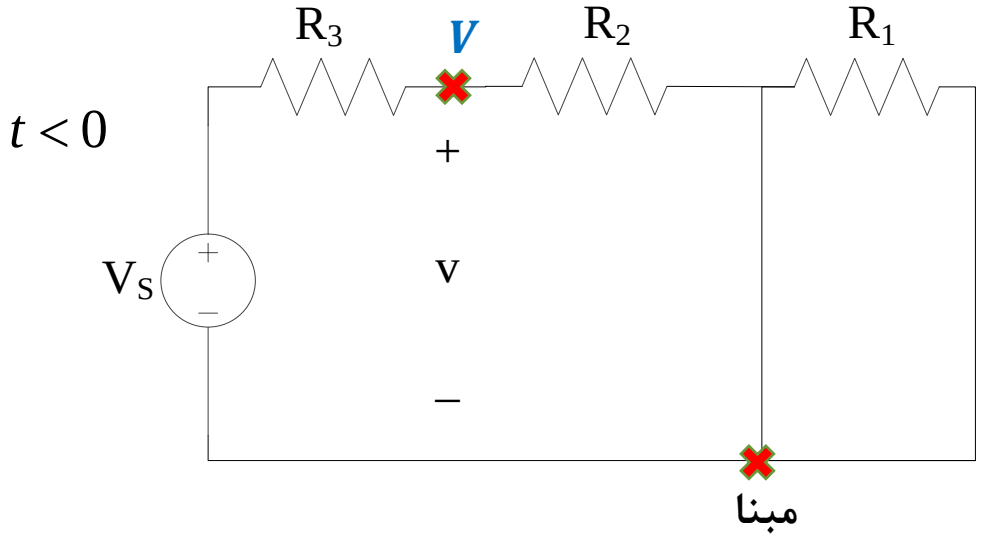
ثابت زمانی

$$i(t) = \frac{V_S}{R_1} e^{-\frac{R_2 t}{L}}$$

Transient state

حالت گذرا





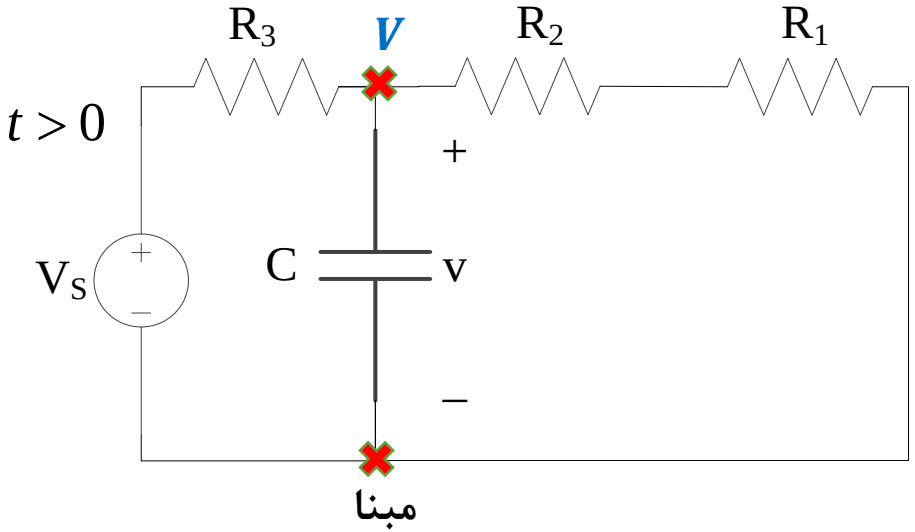
حالت گذرا

خازن اتصال باز

$$\frac{V-V_S}{R_3}+\frac{V}{R_2}=0$$

$$V=\frac{R_2}{R_2+R_3}V_S$$

$$v_C(0^-)=\frac{R_2}{R_2+R_3}V_S$$



$$\frac{v-V_S}{R_3}+\frac{v}{R_1+R_2}+C\frac{dv}{dt}=0$$

$$v_C(0^+)=v_C(0^-)=\frac{R_2}{R_2+R_3}V_S$$

Transient state

حالت گذرا

حالت گذرا

$$\frac{v-V_S}{R_3}+\frac{v}{R_1+R_2}+C\frac{dv}{dt}=0$$

$$v_C(0^+)=\frac{R_2}{R_2+R_3}V_S$$

$$\frac{v}{R_3}+\frac{v}{R_1+R_2}+C\frac{dv}{dt}=\frac{V_S}{R_3}$$

$$v(\frac{1}{R_3}+\frac{1}{R_1+R_2})+C\frac{dv}{dt}=\frac{V_S}{R_3}$$

$$\frac{1}{R_T}=(\frac{1}{R_3}+\frac{1}{R_1+R_2})$$

$$R_T=R_3\,||\,(R_1+R_2)$$

$$\frac{v}{R_T}+C\frac{dv}{dt}=\frac{V_S}{R_3}$$

$$v(t)=K_1+K_2e^{-\frac{t}{\tau}}$$

$$\tau=[(R_1+R_2)\,||\,R_3]C$$

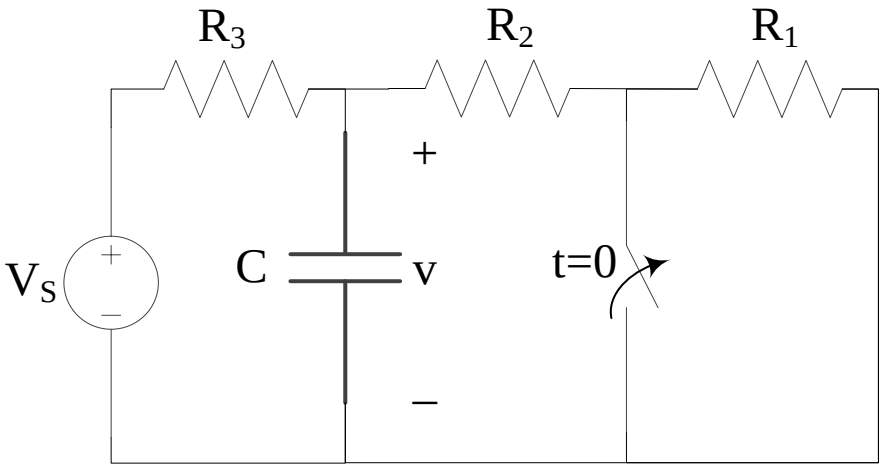
ثابت زمانی

$$v_C(0^+)=\frac{R_2}{R_2+R_3}V_S$$

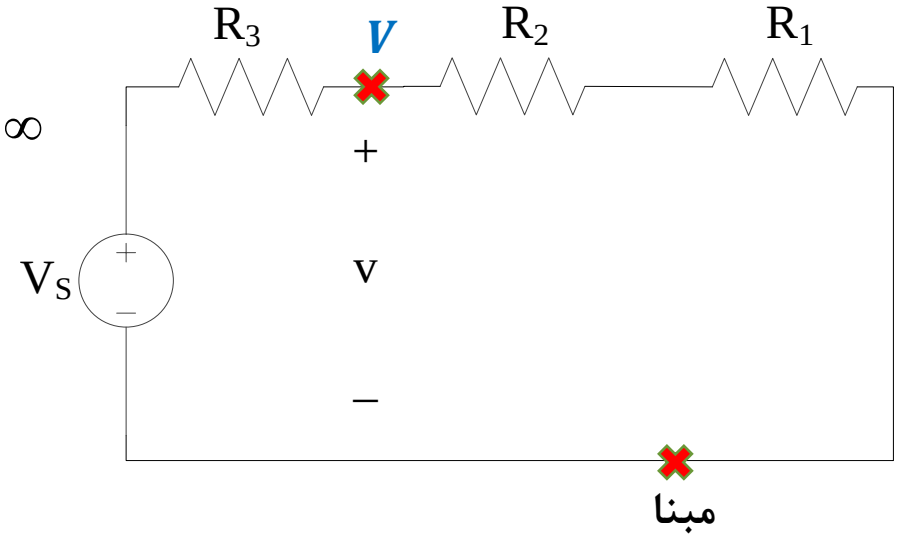
$$K_1+K_2=\frac{R_2}{R_2+R_3}V_S$$

Transient state

حالت گذرا



$t \to \infty$



حالت گذرا

خازن اتصال باز

$$\frac{V - V_S}{R_3} + \frac{V}{R_1 + R_2} = 0$$

$$V = \frac{R_1 + R_2}{R_1 + R_2 + R_3} V_S$$

$$v_C(\infty) = \frac{R_1 + R_2}{R_1 + R_2 + R_3} V_S$$

$$v(t) = K_1 + K_2 e^{-\frac{t}{\tau}}$$

$$K_1 + K_2 = \frac{R_2}{R_2 + R_3} V_S$$

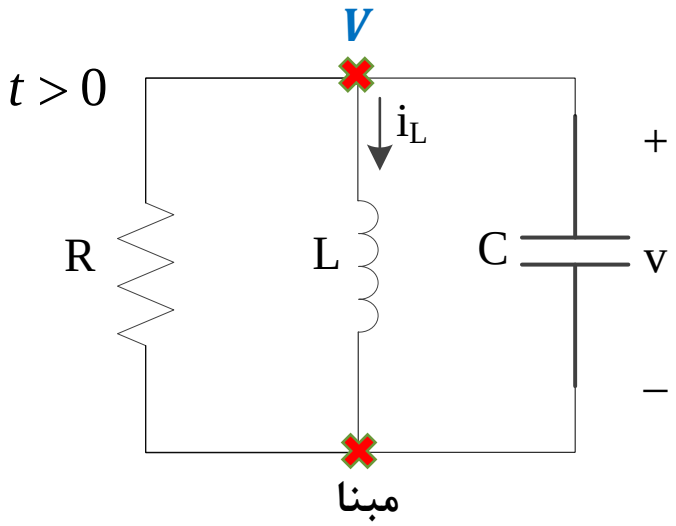
$$K_1 = \frac{R_1 + R_2}{R_1 + R_2 + R_3} V_S$$

$$K_2 = \frac{R_2}{R_2 + R_3} V_S - \frac{R_1 + R_2}{R_1 + R_2 + R_3} V_S$$

Transient state

حالت گذرا

مدارهای RLC موازی



$$i_L(0^+) = i_0$$

$$v_C(0^+) = v_0$$

$$i_R + i_L + i_C = 0$$

$$\frac{v}{R} + \frac{1}{L}\int_{0^+}^{t} v dt + i_L(0^+) + C\frac{dv}{dt} = 0$$

$$\frac{1}{R}\frac{dv}{dt} + \frac{v}{L} + C\frac{d^2v}{dt^2} = 0$$

$$\frac{d^2v}{dt^2} + \frac{1}{RC}\frac{dv}{dt} + \frac{v}{LC} = 0$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$\frac{d^2v}{dt^2}+\frac{1}{RC}\frac{dv}{dt}+\frac{v}{LC}=0 \qquad v=Ke^{st}$$

$$Ks^2e^{st}+\frac{Ks}{RC}e^{st}+\frac{Ke^{st}}{LC}=0 \qquad Ke^{st}(s^2+\frac{1}{RC}s+\frac{1}{LC})=0 \qquad s^2+\frac{1}{RC}s+\frac{1}{LC}=0$$

$$\alpha=\frac{1}{2RC} \qquad \omega_0^2=\frac{1}{LC} \qquad s^2+2\alpha s+\omega_0^2=0$$

معادله مشخصه

$$s=-\alpha\pm\sqrt{\alpha^2-\omega_0^2}$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$\omega_0^2 = \frac{1}{LC} \qquad \alpha = \frac{1}{2RC} \qquad s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$$

$$v = K_1 e^{s_1 t} + K_2 e^{s_2 t}$$

$$v = e^{-\alpha t}[K_1 e^{-\beta_n t} + K_2 e^{\beta_n t}]$$

پاسخ فوق میرا

$$s_1 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} = -\alpha - \beta_n$$

$$s_2 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} = -\alpha + \beta_n$$

$\alpha > \omega_0$

دو ریشه حقیقی و مجزا

$$v = e^{-\alpha t}[K_1 e^{-j\omega_n t} + K_2 e^{+j\omega_n t}]$$

پاسخ زیرمیرا

$$s_1 = -\alpha - j\sqrt{\omega_0^2 - \alpha^2} = -\alpha - j\omega_n$$

$$s_2 = -\alpha + j\sqrt{\omega_0^2 - \alpha^2} = -\alpha + j\omega_n$$

$\alpha < \omega_0$

دو ریشه مختلط مزدوج

$$v = e^{-\alpha t}[K_1 t + K_2]$$

پاسخ میرای بحرانی

$$s_1 = -\alpha$$

$$s_2 = -\alpha$$

$\alpha = \omega_0$

دو ریشه حقیقی یکسان

Transient state

حالت گذرا

مدارهای RLC موازی

$$\omega_0^2 = \frac{1}{LC} \qquad \alpha = \frac{1}{2RC} \qquad s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$$

$$v = [K_1 e^{-j\omega_0} + K_2 {}^{j\omega_0}]$$

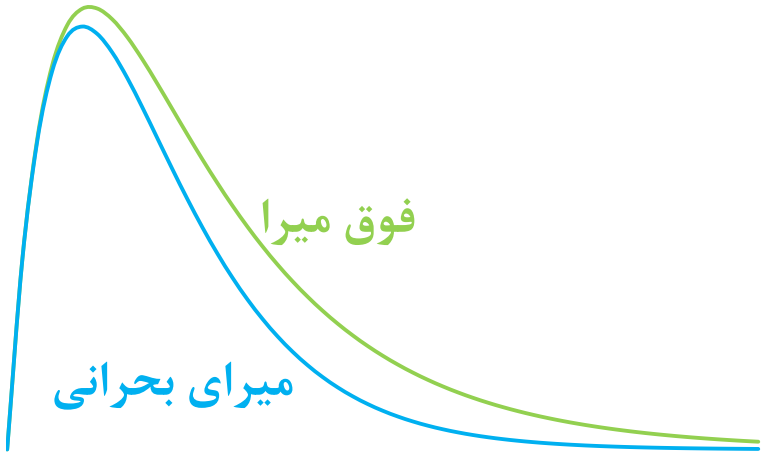
پاسخ نامیرا

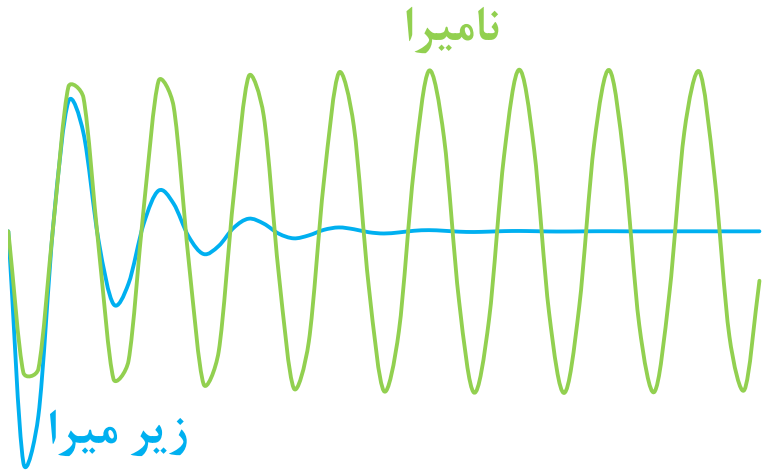
$$s_1 = -j\omega_0$$

$$s_2 = +j\omega_0$$

$$\alpha = 0$$

دو ریشه موهومی

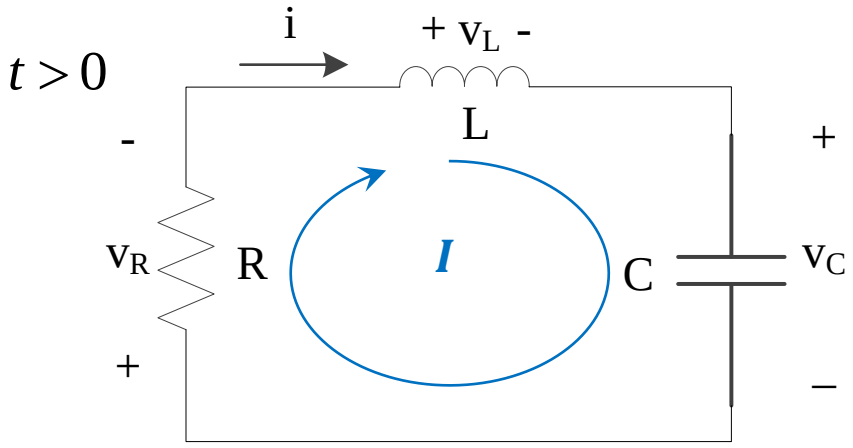




Transient state

حالت گذرا

مدارهای RLC سری



$$i_L(0^+) = i_0$$

$$v_C(0^+) = v_0$$

$$v_R + v_L + v_C = 0$$

$$Ri + L\frac{di}{dt} + + \frac{1}{C}\int_{0^+}^{t} idt + v_C(0^+) = 0$$

$$R\frac{di}{dt} + L\frac{d^2i}{dt^2} + \frac{i}{C} = 0$$

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{i}{LC} = 0$$

Transient state

حالت گذرا

مدارهای RLC سری

$$\frac{d^2i}{dt^2}+\frac{R}{L}\frac{di}{dt}+\frac{i}{LC}=0 \qquad i=Ke^{st}$$

$$Ks^2e^{st}+\frac{RKs}{L}e^{st}+\frac{Ke^{st}}{LC}=0 \qquad Ke^{st}(s^2+\frac{R}{L}s+\frac{1}{LC})=0 \qquad s^2+\frac{R}{L}s+\frac{1}{LC}=0$$

$$\alpha=\frac{R}{2L} \qquad \omega_0^2=\frac{1}{LC} \qquad s^2+2\alpha s+\omega_0^2=0$$

معادله مشخصه

$$s=-\alpha\pm\sqrt{\alpha^2-\omega_0^2}$$

Transient state

حالت گذرا

مدارهای RLC سری

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

$$i = K_1 e^{s_1 t} + K_2 e^{s_2 t}$$

$$i = e^{-\alpha t}[K_1 e^{-\beta_n t} + K_2 e^{\beta_n t}]$$

پاسخ فوق میرا

$$s_1 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} = -\alpha - \beta_n$$

$$s_2 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} = -\alpha + \beta_n$$

$\alpha > \omega_0$

دو ریشه حقیقی و مجزا

$$i = e^{-\alpha t}[K_1 e^{-j\omega_n t} + K_2 e^{j\omega_n t}]$$

پاسخ زیرمیرا

$$s_1 = -\alpha - j\sqrt{\omega_0^2 - \alpha^2} = -\alpha - j\omega_n$$

$$s_2 = -\alpha + j\sqrt{\omega_0^2 - \alpha^2} = -\alpha + j\omega_n$$

$\alpha < \omega_0$

دو ریشه مختلط مزدوج

$$i = e^{-\alpha t}[K_1 t + K_2]$$

پاسخ میرای بحرانی

$$s_1 = -\alpha$$

$$s_2 = -\alpha$$

$\alpha = \omega_0$

دو ریشه حقیقی یکسان

Transient state

حالت گذرا

مدارهای RLC سری

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

$$i = [K_1 e^{-j\omega_0} + K_2 {}^{j\omega_0}]$$

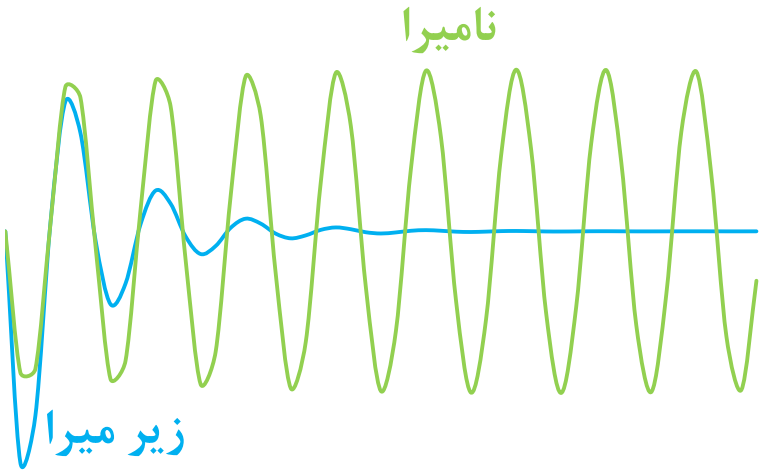
پاسخ نامیرا

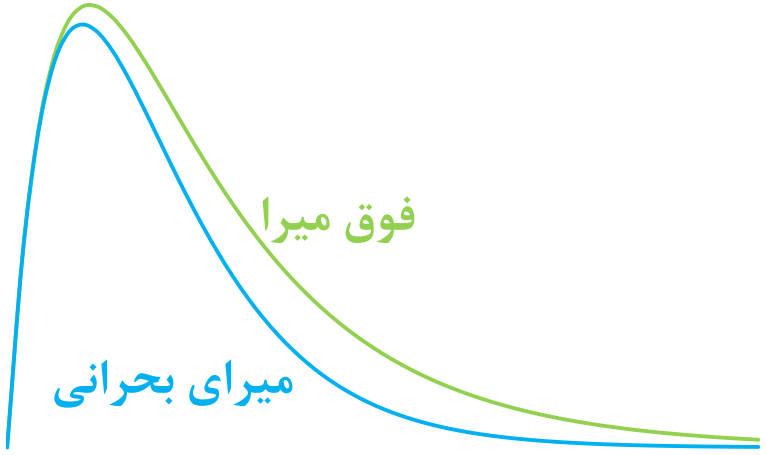
$$s_1 = -j\omega_0$$

$$s_2 = +j\omega_0$$

$$\alpha = 0$$

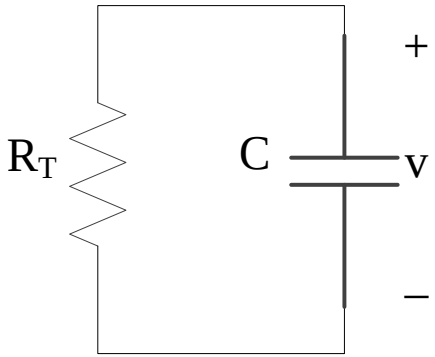
دو ریشه موهومی





Transient state

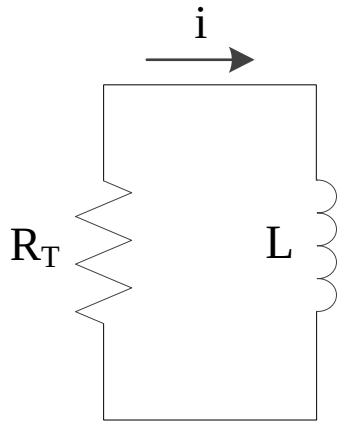
حالت گذرا



$$v(t) = K_1 + K_2 e^{-\frac{t}{\tau}}$$

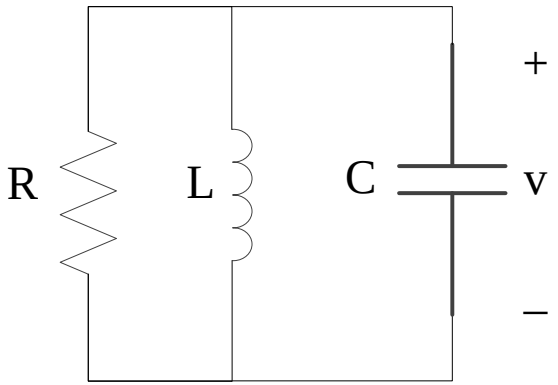
$$\tau = R_T C$$

حالت گذرا



$$i(t) = K_1 + K_2 e^{-\frac{t}{\tau}}$$

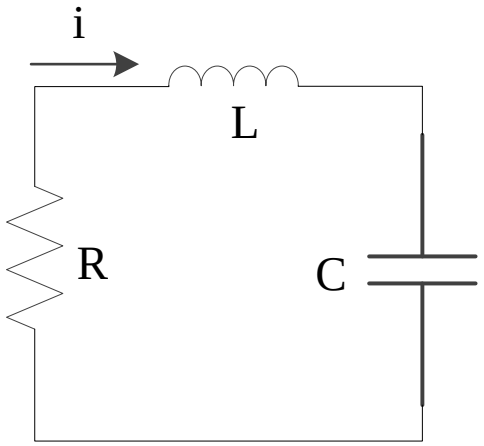
$$\tau = \frac{L}{R_T}$$



$$s^2 + 2\alpha s + \omega_0^2 = 0$$

$$\alpha = \frac{1}{2RC}$$

$$\omega_0^2 = \frac{1}{LC}$$



$$s^2 + 2\alpha s + \omega_0^2 = 0$$

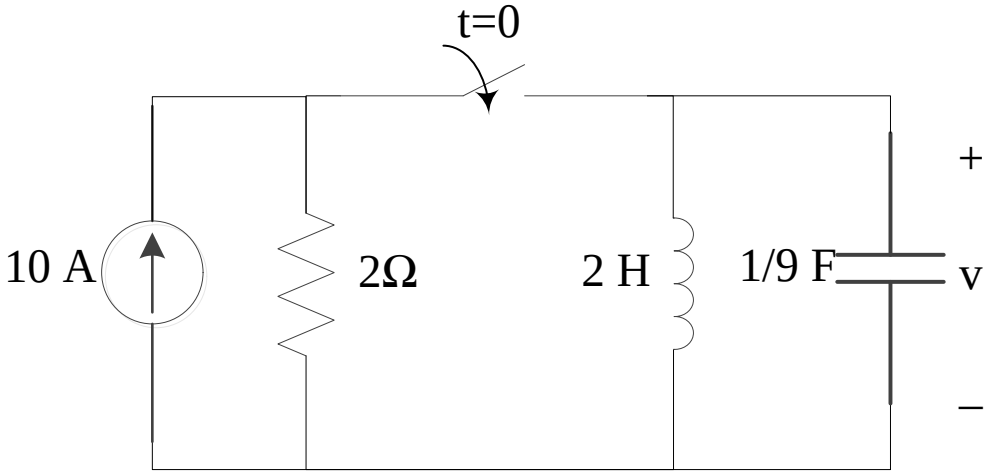
$$\alpha = \frac{R}{2L}$$

$$\omega_0^2 = \frac{1}{LC}$$

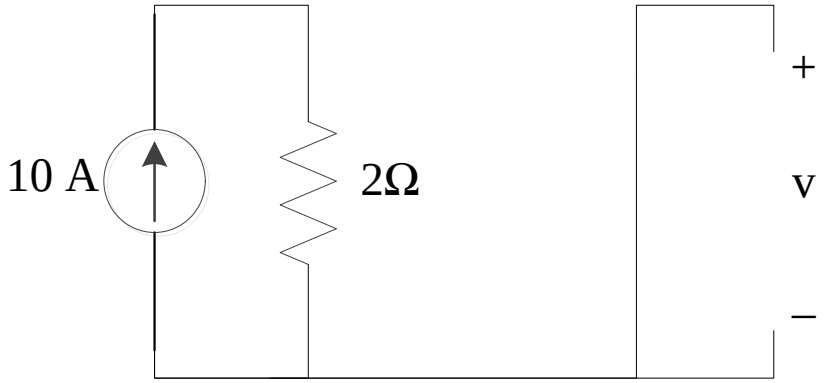
Transient state

حالت گذرا

مدارهای RLC موازی



$t < 0$



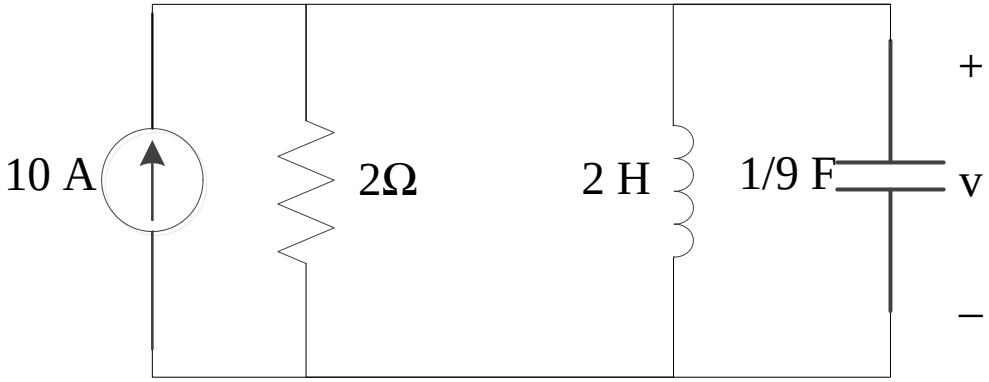
خازن اتصال باز،
سلف اتصال کوتاه

$$i_L(0^+) = 0$$

$$v_C(0^+) = 0$$

جواب کلی = جواب عمومی + جواب خصوصی

$t > 0$



$$s^2 + 2\alpha s + \omega_0^2 = 0$$

$$\alpha = \frac{1}{2RC} = \frac{1}{2 \times 2 \times \frac{1}{9}} = \frac{9}{4}$$

$$\alpha > \omega_0$$

$$\omega_0^2 = \frac{1}{LC} = \frac{1}{2 \times \frac{1}{9}} = \frac{9}{2}$$

$$\omega_0 = \sqrt{\frac{9}{2}}$$

Transient state

حالت گذرا

مدارهای RLC موازی

$\alpha = 9/4$ $\omega_0 = \sqrt{9/2}$ $\boxed{\alpha > \omega_0}$ $s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$s_1 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} = -\alpha - \beta_n$ $s_1 = -\frac{9}{4} - \sqrt{\frac{81}{16} - \frac{9}{2}}$ $s_1 = -3$

$s_2 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} = -\alpha + \beta_n$ $s_2 = -\frac{9}{4} + \sqrt{\frac{81}{16} - \frac{9}{2}}$ $s_2 = -1.5$

جواب عمومی $v = K_1 e^{s_1 t} + K_2 e^{s_2 t}$ $v = K_1 e^{-3t} + K_2 e^{-1.5t}$

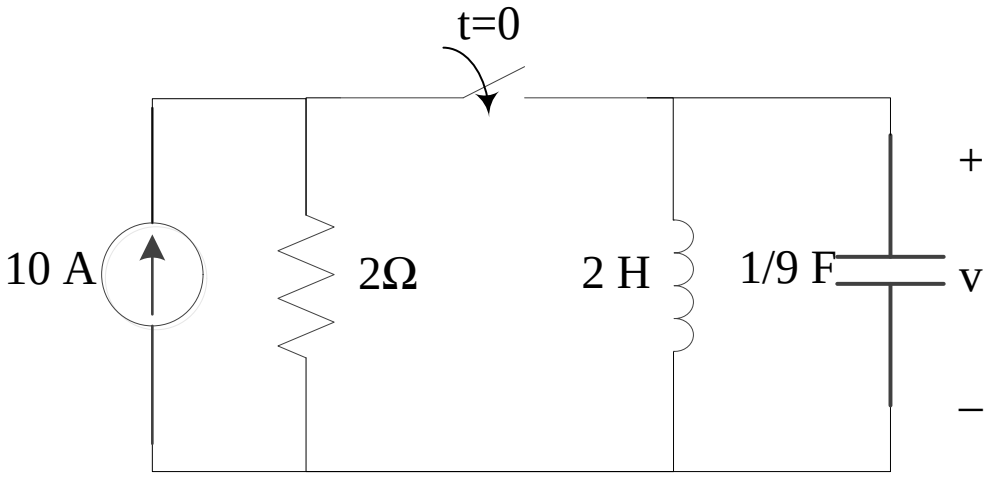
جواب کلی $v = K_1 e^{-3t} + K_2 e^{-1.5t} + K_3$

شرایط مرزی $i_L(0^+) = i_0$ $v_C(0^+) = v_0$ $v_C(\infty) = ?$

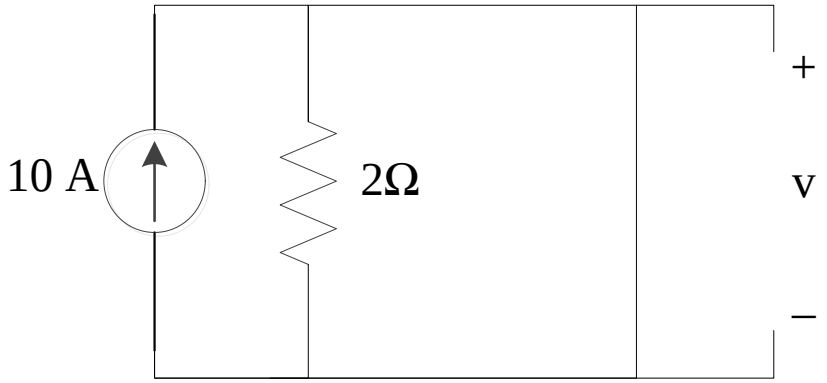
Transient state

حالت گذرا

مدارهای RLC موازی



$t \to \infty$



خازن اتصال باز،
سلف اتصال کوتاه

$$v(\infty) = 0$$

$$v = K_1 e^{-3t} + K_2 e^{-1.5t} + K_3 \qquad i_L(0^+) = 0 \qquad v(0^+) = 0 \qquad v(\infty) = 0$$

$$v(\infty) = 0 \longrightarrow K_3 = 0$$

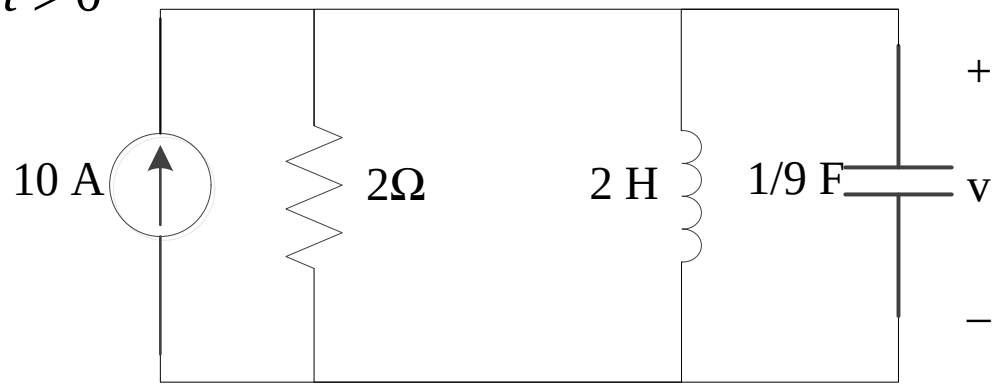
$$v = K_1 e^{-3t} + K_2 e^{-1.5t}$$

Transient state

حالت گذرا

مدارهای RLC موازی

$t > 0$



$$v = K_1 e^{-3t} + K_2 e^{-1.5t}$$

$$i_L(0^+) = 0 \qquad v(0^+) = 0 \qquad \frac{dv}{dt} = -3K_1 e^{-3t} - 1.5K_2 e^{-1.5t}$$

$v(0^+) = 0$

$$\downarrow$$

$$K_1 + K_2 = 0$$

$i_C(0^+) = ?$ $\quad v(0^+) = 0 \longrightarrow i_R(0^+) = \frac{v(0^+)}{R} = 0 \quad i_L(0^+) = 0$

$$i_C(0^+) = 10\,A \qquad i_C(0^+) = C\frac{dv(0^+)}{dt} \longrightarrow \frac{dv(0^+)}{dt} = \frac{i_C(0^+)}{C} = \frac{10}{1/9} = 90$$

$$\frac{dv(0^+)}{dt} = -3K_1 - 1.5K_2 \longrightarrow -3K_1 - 1.5K_2 = 90$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$v = K_1 e^{-3t} + K_2 e^{-1.5t}$$

$$K_1 + K_2 = 0 \qquad K_1 = -K_2 \qquad K_1 = -60$$

$$-3K_1 - 1.5K_2 = 90 \qquad 3K_2 - 1.5K_2 = 90 \qquad 1.5K_2 = 90 \qquad K_2 = 60$$

$$v = -60e^{-3t} + 60e^{-1.5t}$$

$$v = K_1 e^{s_1 t} + K_2 e^{s_2 t}$$

$$i_L = \frac{1}{L}\int_0^t v\,dt + i_L(0^+) = \frac{1}{L}\int_0^t K_1 e^{s_1 t} + K_2 e^{s_2 t} + i_L(0^+)$$

$$i_L = \frac{K_1}{Ls_1}[e^{s_1 t} - 1] + \frac{K_2}{Ls_2}[e^{s_2 t} - 1] + i_L(0^+)$$

$$i_L = 10e^{-3t} - 20e^{-1.5t} + 10$$

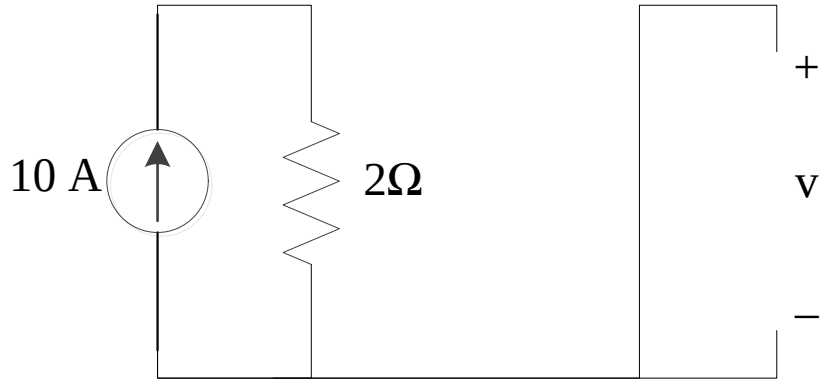
Transient state

حالت گذرا

مدارهای RLC موازی

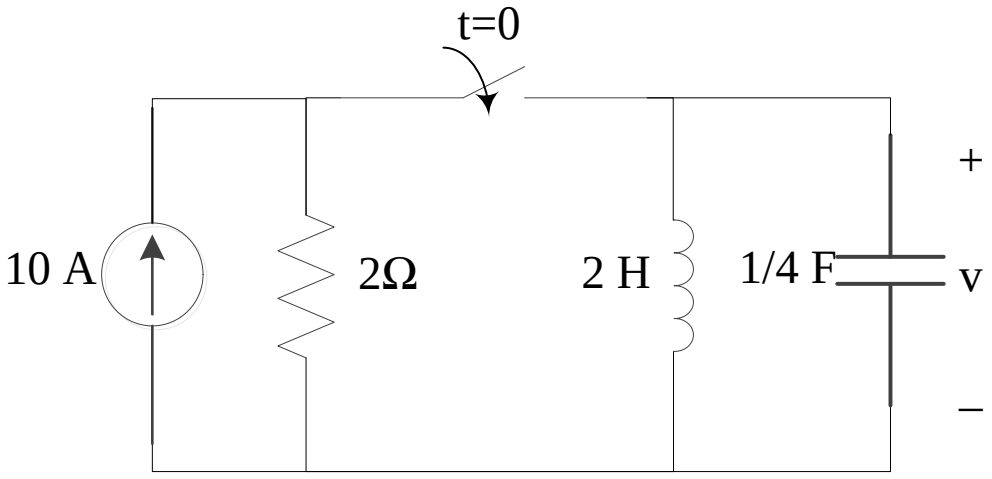
خازن اتصال باز،
سلف اتصال کوتاه

$t < 0$



$$i_L(0^+) = 0$$

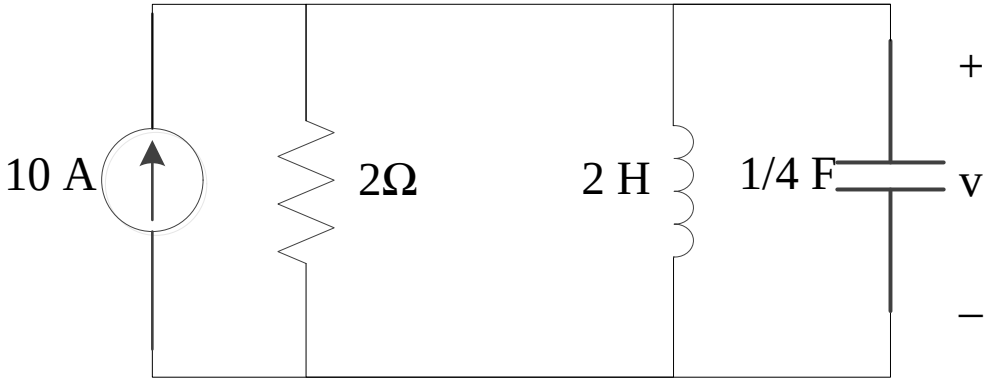
$$v_C(0^+) = 0$$



جواب کلی = جواب عمومی + جواب خصوصی

$t > 0$

$$s^2 + 2\alpha s + \omega_0^2 = 0$$



$$\alpha = \frac{1}{2RC} = \frac{1}{2 \times 2 \times 1/4} = 1$$

$$\omega_0^2 = \frac{1}{LC} = \frac{1}{2 \times 1/4} = 2 \qquad \omega_0 = \sqrt{2}$$

$$\boxed{\alpha < \omega_0}$$

Transient state

حالت گذرا

مدارهای RLC موازی

$\alpha = 1$ $\omega_0 = \sqrt{2}$ $\alpha < \omega_0$ $s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$s_1 = -\alpha - j\sqrt{\omega_0^2 - \alpha^2} = -\alpha - j\omega_n$ $s_1 = -1 - j\sqrt{2-1}$ $s_1 = -1 - j1$

$s_2 = -\alpha + j\sqrt{\omega_0^2 - \alpha^2} = -\alpha + j\omega_n$ $s_2 = -1 + j\sqrt{2-1}$ $s_2 = -1 + j1$

جواب عمومی

$v = e^{-\alpha t}[K_1 e^{-j\omega_n t} + K_2 e^{+j\omega_n t}]$ $v = Ke^{-t}\cos(t+\theta)$

جواب کلی

$v = Ke^{-\alpha t}\cos(\omega_n t + \theta)$ $v = Ke^{-t}\cos(t+\theta) + K_3$

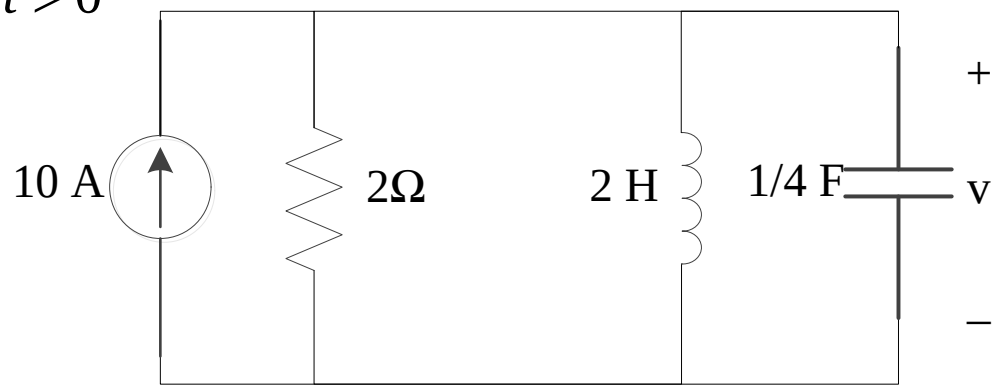
$v_C(\infty) = 0 \longrightarrow K_3 = 0$

Transient state

حالت گذرا

مدارهای RLC موازی

$t > 0$



$$v = Ke^{-t}\cos(t+\theta)$$

$$i_L(0^+) = 0 \qquad v(0^+) = 0 \qquad \frac{dv}{dt} = -Ke^{-t}\cos(t+\theta) - Ke^{-t}\sin(t+\theta)$$

$$v(0^+) = 0$$

$$\downarrow$$

$$K\cos(\theta) = 0$$

$$i_C(0^+) = ? \qquad v(0^+) = 0 \longrightarrow i_R(0^+) = \frac{v(0^+)}{R} = 0 \qquad i_L(0^+) = 0$$

$$i_C(0^+) = 10\,A \qquad i_C(0^+) = C\frac{dv(0^+)}{dt} \longrightarrow \frac{dv(0^+)}{dt} = \frac{i_C(0^+)}{C} = \frac{10}{1/4} = 40$$

$$\frac{dv(0^+)}{dt} = -K\cos(\theta) - K\sin(\theta) \longrightarrow -K\cos(\theta) - K\sin(\theta) = 40$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$v = Ke^{-t}\cos(t+\theta)$$

$$K\cos(\theta) = 0 \longrightarrow \cos(\theta) = 0 \longrightarrow \theta = \frac{\pi}{2}$$

$$-K\cos(\theta) - K\sin(\theta) = 40 \longrightarrow K\sin(\theta) = -40 \longrightarrow K = -40$$

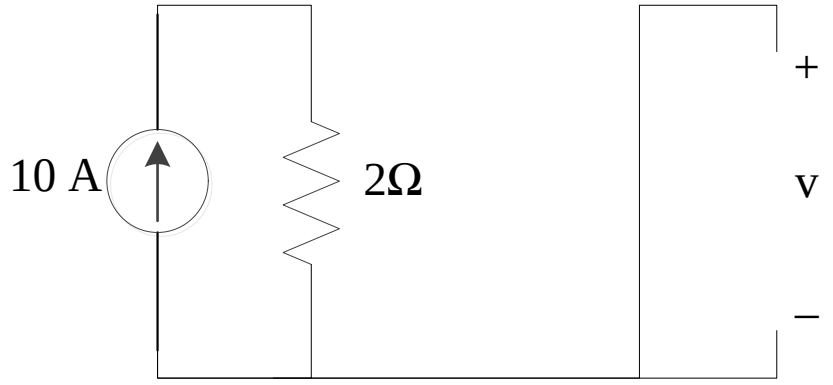
$$\boxed{v = -40e^{-t}\cos(t+\frac{\pi}{2})}$$

Transient state

حالت گذرا

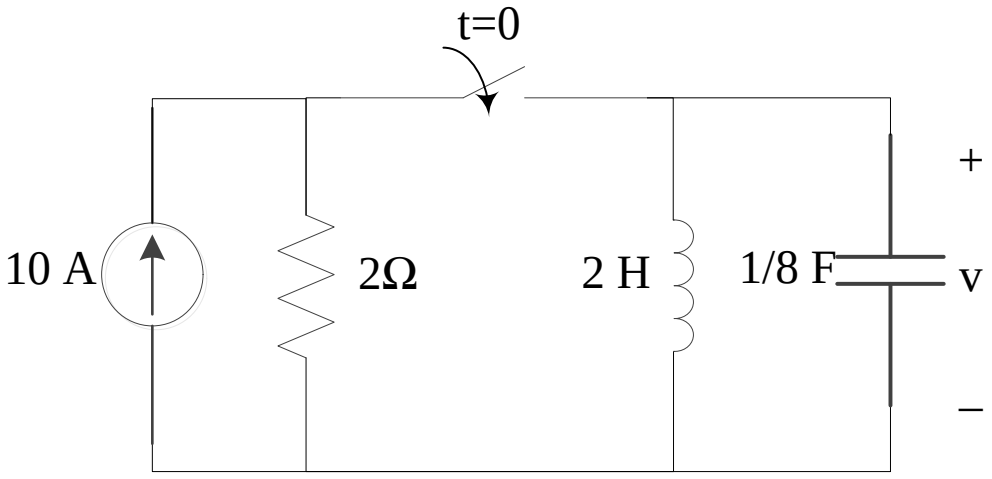
مدارهای RLC موازی

خازن اتصال باز،
سلف اتصال کوتاه



$$i_L(0^+)=0$$

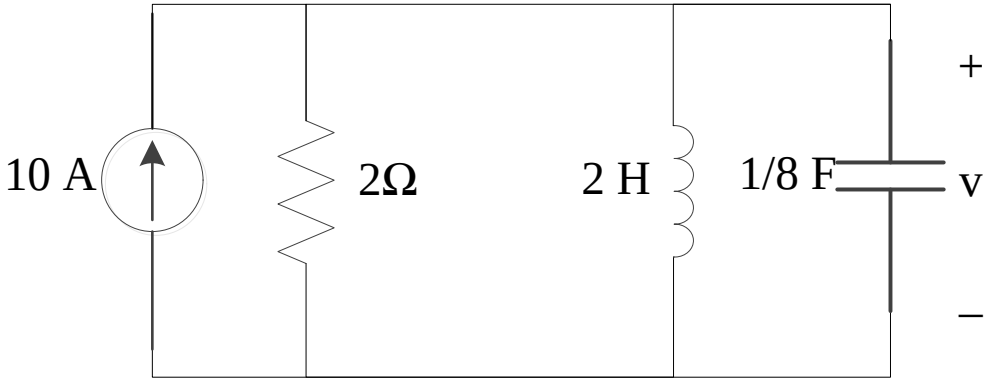
$$v_C(0^+)=0$$



جواب کلی = جواب عمومی + جواب خصوصی

$$s^2+2\alpha s+\omega_0^2=0$$

$t>0$



$$\alpha=\frac{1}{2RC}=\frac{1}{2\times 2\times \frac{1}{8}}=2$$

$$\alpha=\omega_0$$

$$\omega_0^2=\frac{1}{LC}=\frac{1}{2\times \frac{1}{8}}=4$$

$$\omega_0=2$$

Transient state

حالت گذرا

مدارهای RLC موازی

$\alpha = 2$ $\omega_0 = 2$ $\boxed{\alpha = \omega_0}$ $s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$s_1 = -\alpha$ $s_1 = -2$

$s_2 = -\alpha$ $s_2 = -2$

جواب عمومی

$v = e^{-\alpha t}[K_1 t + K_2]$ $v = e^{-2t}[K_1 t + K_2]$

جواب کلی

$v = e^{-2t}[K_1 t + K_2] + K_3$

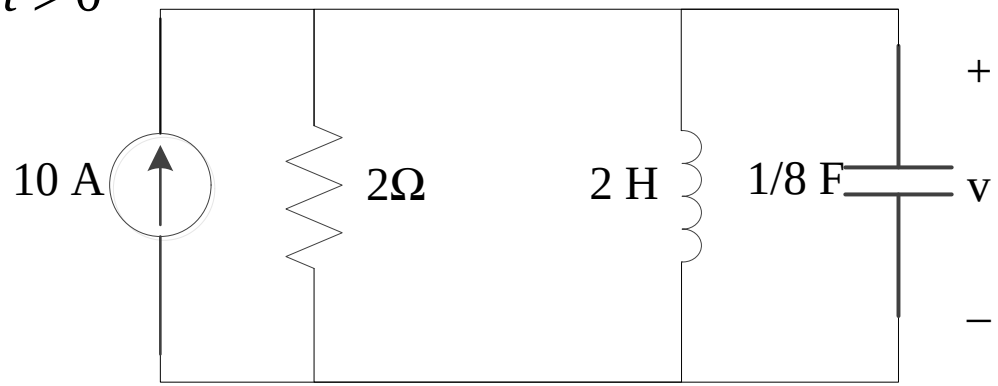
$v_C(\infty) = 0 \longrightarrow K_3 = 0$

Transient state

حالت گذرا

مدارهای RLC موازی

$t > 0$



$$v = e^{-2t}[K_1 t + K_2]$$

$$i_L(0^+) = 0 \qquad v(0^+) = 0$$

$$\frac{dv}{dt} = K_1 e^{-2t} - 2e^{-2t}[K_1 t + K_2]$$

$v(0^+) = 0$

$K_2 = 0$

$i_C(0^+) = ?$ $\qquad v(0^+) = 0 \longrightarrow i_R(0^+) = \frac{v(0^+)}{R} = 0 \qquad i_L(0^+) = 0$

$i_C(0^+) = 10\,A$ $\qquad i_C(0^+) = C\frac{dv(0^+)}{dt} \longrightarrow \frac{dv(0^+)}{dt} = \frac{i_C(0^+)}{C} = \frac{10}{1/8} = 80$

$$\frac{dv(0^+)}{dt} = K_1 - 2[0 + K_2] \longrightarrow K_1 - 2K_2 = 80$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$v = e^{-2t}[K_1 t + K_2]$$

$$K_2 = 0$$

$$K_1 - 2K_2 = 80 \longrightarrow K_1 = 80$$

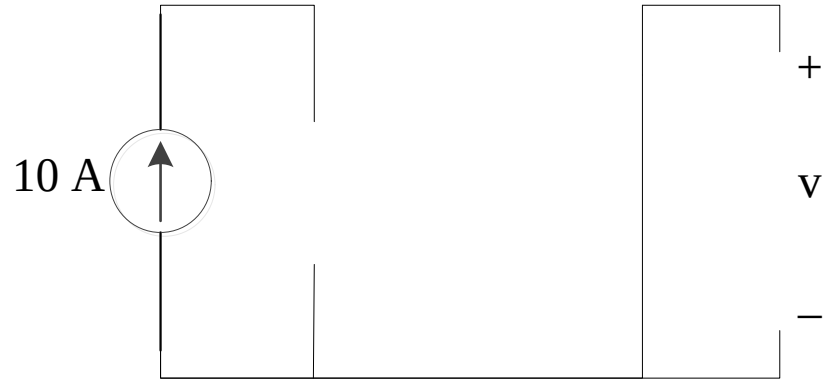
$$\boxed{v = 80te^{-2t}}$$

Transient state

حالت گذرا

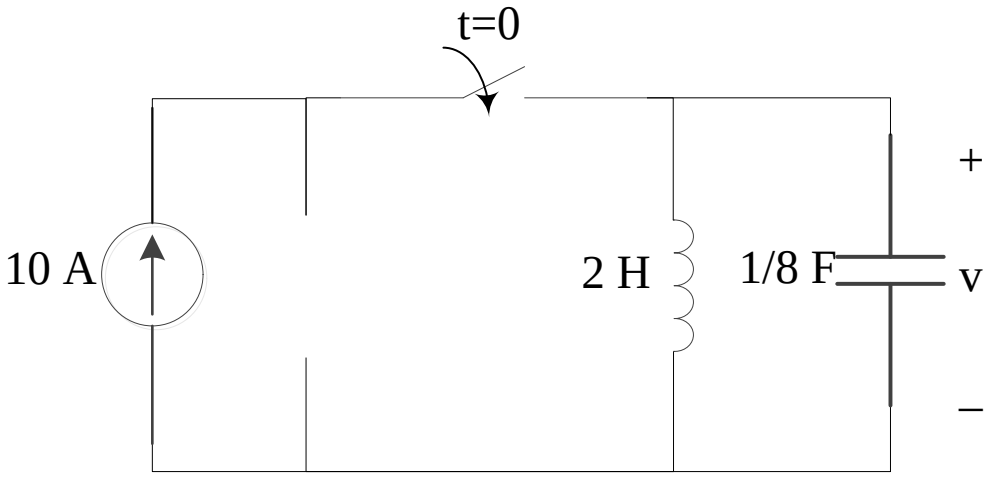
مدارهای RLC موازی

خازن اتصال باز،
سلف اتصال کوتاه



$$i_L(0^+)=0$$

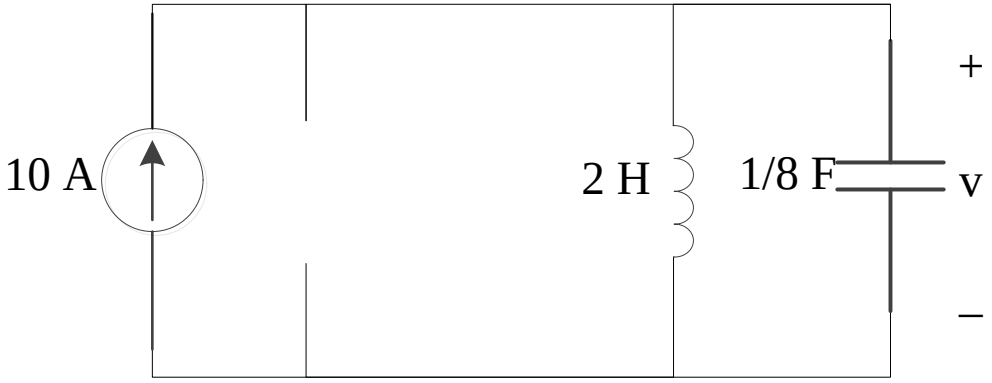
$$v_C(0^+)=0$$



جواب کلی = جواب عمومی + جواب خصوصی

$$s^2+2\alpha s+\omega_0^2=0$$

$t>0$



$$\alpha=\frac{1}{2RC}=\frac{1}{2\times\infty\times 1/8}=0$$

$$\boxed{\alpha=0}$$

$$\omega_0^2=\frac{1}{LC}=\frac{1}{2\times 1/8}=4$$

$$\omega_0=2$$

Transient state

حالت گذرا

مدارهای RLC موازی

$\alpha = 0 \qquad \omega_0 = 2$

$\boxed{\alpha = 0}$

$s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$s_1 = -j\omega_0$

$s_2 = j\omega_0$

$s_1 = -j2$

$s_2 = j2$

جواب عمومی

$v = [K_1 e^{-j\omega_0} + K_2{}^{j\omega_0}]$

$v = K\cos(\omega_0 t + \theta)$

$v = K\cos(2t + \theta)$

جواب کلی

$v = K\cos(2t + \theta) + K_3$

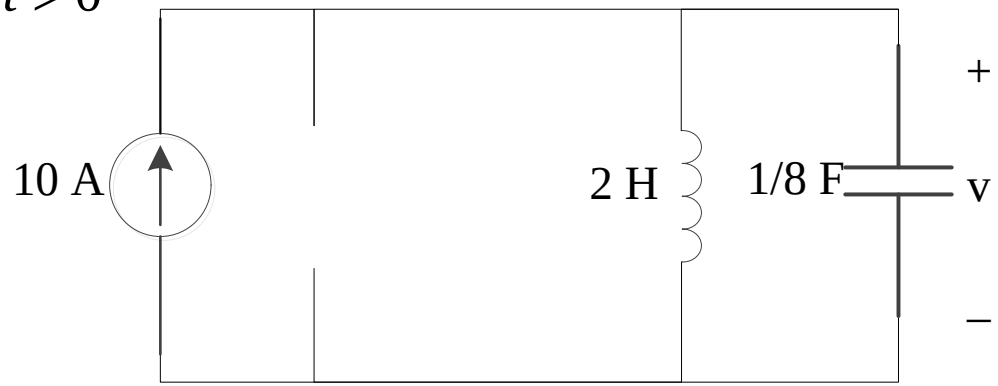
$v_C(Stimulation) = 0 \longrightarrow K_3 = 0$

Transient state

حالت گذرا

مدارهای RLC موازی

$t > 0$



$v = K\cos(2t+\theta)$

$i_L(0^+) = 0 \quad v(0^+) = 0$

$\frac{dv}{dt} = -2K\sin(2t+\theta)$

$v(0^+) = 0$

$\downarrow$

$K\cos(\theta) = 0$

$i_C(0^+) = ? \qquad v(0^+) = 0 \longrightarrow i_R(0^+) = \frac{v(0^+)}{R} = 0 \qquad i_L(0^+) = 0$

$i_C(0^+) = 10\,A \qquad i_C(0^+) = C\frac{dv(0^+)}{dt} \longrightarrow \frac{dv(0^+)}{dt} = \frac{i_C(0^+)}{C} = \frac{10}{1/8} = 80$

$\frac{dv(0^+)}{dt} = -2K\sin(0+\theta) \longrightarrow -2K\sin(\theta) = 80$

Transient state

حالت گذرا

مدارهای RLC موازی

$$v = K\cos(2t+\theta)$$

$$K\cos(\theta)=0 \longrightarrow \cos(\theta)=0 \longrightarrow \theta=\frac{\pi}{2}$$

$$-2K\sin(\theta)=80 \longrightarrow K\sin(\theta)=-40 \longrightarrow K=-40$$

$$\boxed{v=-40\cos(t+\frac{\pi}{2})}$$

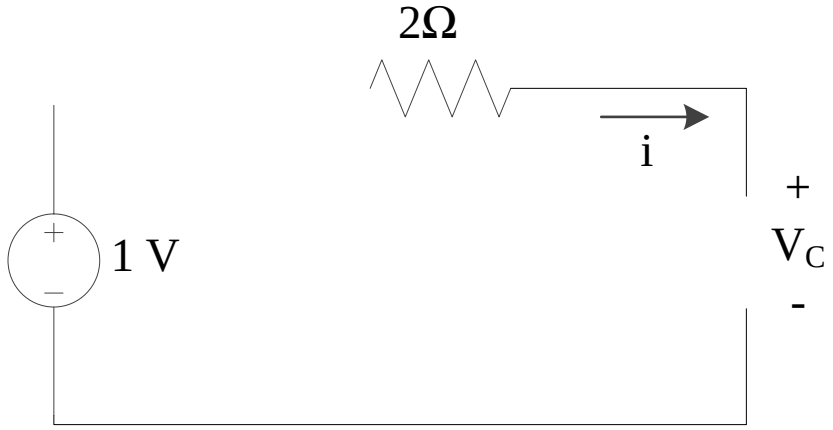
Transient state

حالت گذرا

مدارهای RLC سری

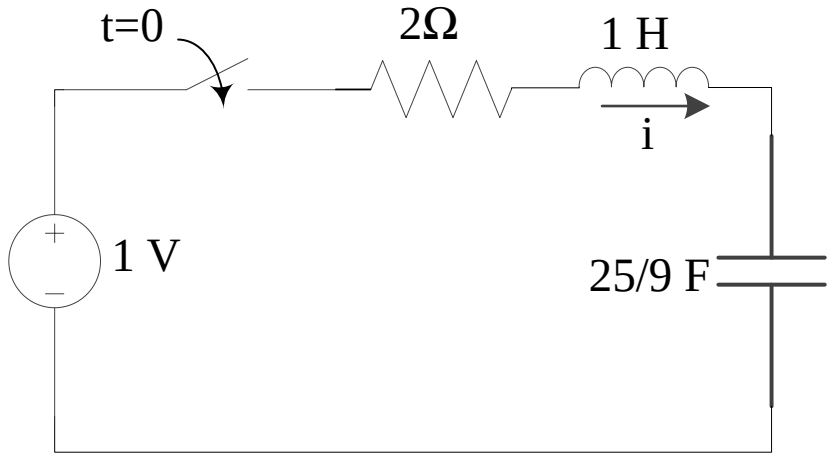
خازن اتصال باز،
سلف اتصال کوتاه

$t < 0$



$$i_L(0^+) = 0$$

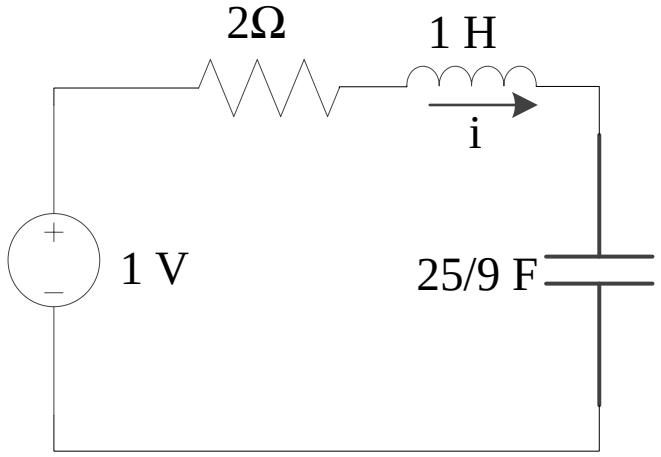
$$v_C(0^+) = 0$$



جواب کلی = جواب عمومی + جواب خصوصی

$$s^2 + 2\alpha s + \omega_0^2 = 0$$

$t > 0$



$$\alpha = \frac{R}{2L} = \frac{2}{2\times 1} = 1$$

$$\alpha > \omega_0$$

$$\omega_0^2 = \frac{1}{LC} = \frac{1}{1\times 25/9} = 9/25$$

$$\omega_0 = 3/5$$

Transient state

حالت گذرا

مدارهای RLC سری

$\alpha = 1$ $\omega_0 = 3/5$ $\alpha > \omega_0$ $s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$$s_1 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} = -\alpha - \beta_n \qquad s_1 = -1 - \sqrt{1 - \frac{9}{25}} \qquad s_1 = -1.8$$

$$s_2 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} = -\alpha + \beta_n \qquad s_2 = -1 + \sqrt{1 - \frac{9}{25}} \qquad s_2 = -0.2$$

جواب عمومی

$$i = K_1 e^{s_1 t} + K_2 e^{s_2 t} \qquad i = K_1 e^{-1.8t} + K_2 e^{-0.2t}$$

جواب کلی

$$i = K_1 e^{-1.8t} + K_2 e^{-0.2t} + K_3$$

شرایط مرزی

$$i_L(0^+) = i_0 \qquad v_C(0^+) = v_0 \qquad i_L(\infty) = ?$$

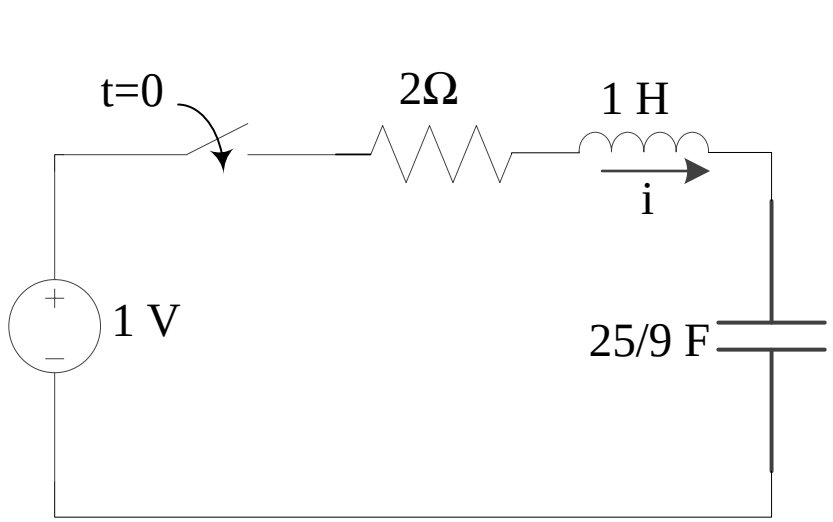
Transient state

حالت گذرا

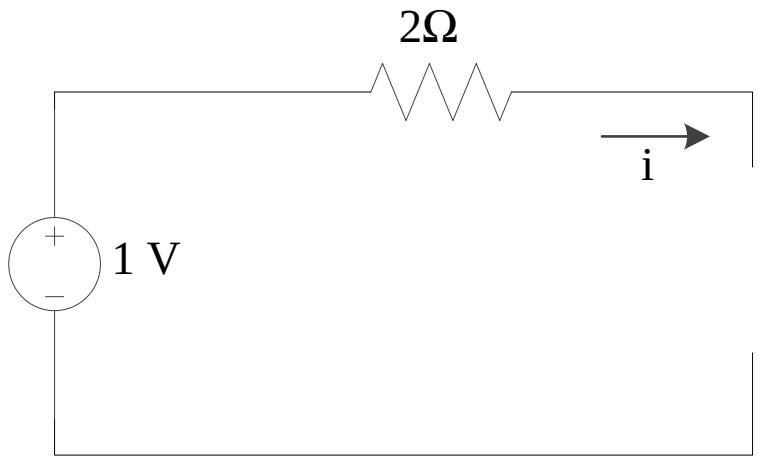
مدارهای RLC سری

خازن اتصال باز،
سلف اتصال کوتاه

$$i(\infty) = 0$$



$t \to \infty$



$$i = K_1 e^{-1.8t} + K_2 e^{-0.2t} + K_3 \qquad i_L(0^+) = 0 \qquad v(0^+) = 0 \qquad i(\infty) = 0$$

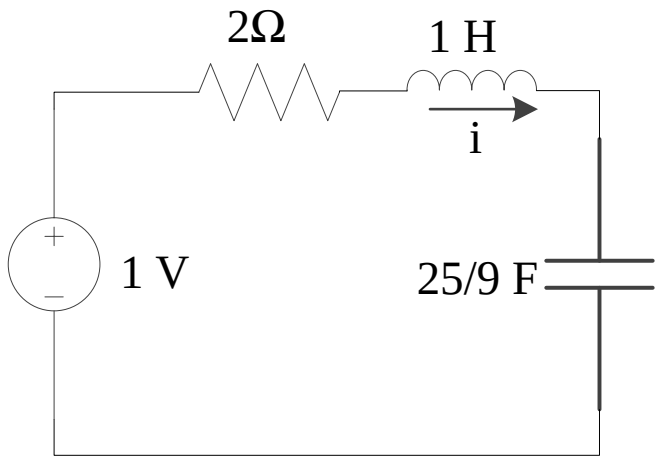
$$i(\infty) = 0 \longrightarrow K_3 = 0 \qquad i = K_1 e^{-1.8t} + K_2 e^{-0.2t}$$

Transient state

حالت گذرا

مدارهای RLC سری

$t > 0$



$$i = K_1 e^{-1.8t} + K_2 e^{-0.2t}$$

$$i_L(0^+) = 0 \qquad v(0^+) = 0 \qquad \frac{di}{dt} = -1.8K_1 e^{-1.8t} - 0.2K_2 e^{-0.2t}$$

$$i(0^+) = 0$$

$$\downarrow$$

$$K_1 + K_2 = 0$$

$$v_L(0^+) = ? \qquad i(0^+) = 0 \longrightarrow v_R(0^+) = Ri(0^+) = 0 \qquad v_C(0^+) = 0$$

$$v_L(0^+) = 1V \qquad v_L(0^+) = L\frac{di(0^+)}{dt} \longrightarrow \frac{di(0^+)}{dt} = \frac{v_L(0^+)}{L} = \frac{1}{1} = 1$$

$$\frac{di(0^+)}{dt} = -1.8K_1 - 0.2K_2 \longrightarrow -1.8K_1 - 0.2K_2 = 1$$

Transient state

حالت گذرا

مدارهای RLC سری

$$i = K_1 e^{-1.8t} + K_2 e^{-0.2t}$$

$$K_1 + K_2 = 0 \qquad K_1 = -K_2 \qquad K_1 = -0.625$$

$$-1.8K_1 - 0.2K_2 = 1 \qquad 1.8K_2 - 0.2K_2 = 1 \qquad 1.6K_2 = 1 \qquad K_2 = 0.625$$

$$\boxed{i = -0.625e^{-1.8t} + 0.625e^{-0.2t}}$$

$$v_C = \frac{1}{C}\int_0^t i dt + v_C(0^+) \qquad i = K_1 e^{-s_1 t} + K_2 e^{-s_2 t} \qquad v_c = \frac{-K_1}{s_1 C}[e^{-s_1 t} - e^0] + \frac{-K_2}{s_2 C}[e^{-s_2 t} - e^0] + 0$$

$$\boxed{v_c = 1 - 1.125e^{-0.2t} + 0.125e^{-1.8t}}$$

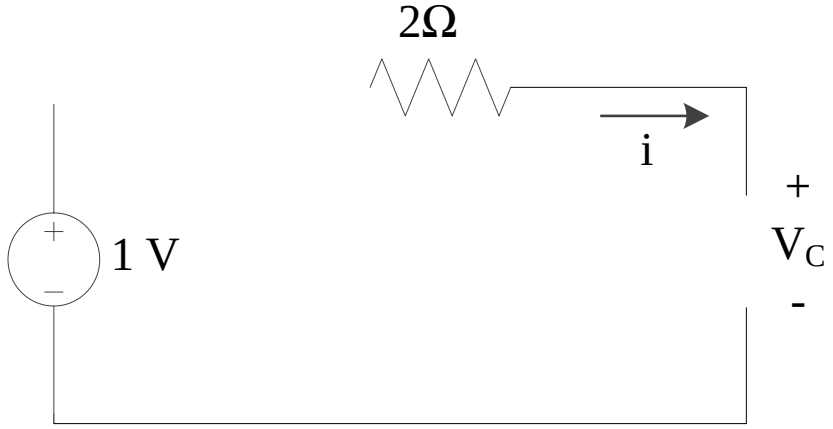
Transient state

حالت گذرا

مدارهای RLC سری

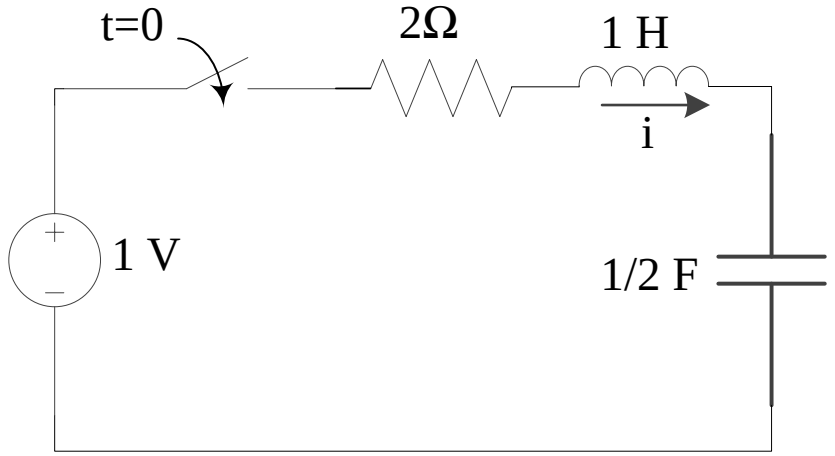
خازن اتصال باز،
سلف اتصال کوتاه

$t < 0$



$$i_L(0^+) = 0$$

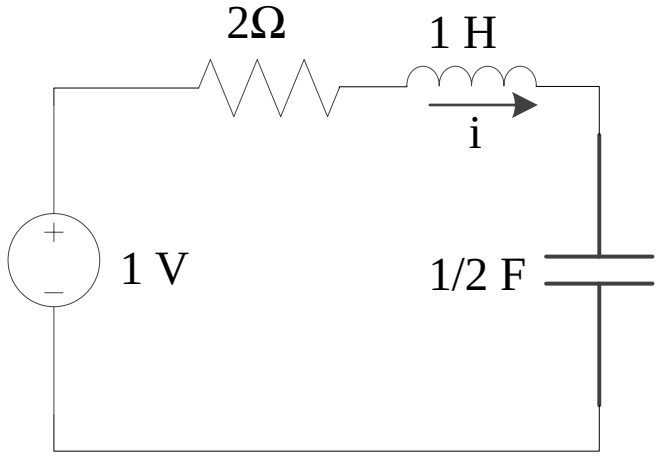
$$v_C(0^+) = 0$$



جواب کلی = جواب عمومی + جواب خصوصی

$$s^2 + 2\alpha s + \omega_0^2 = 0$$

$t > 0$



$$\alpha = \frac{R}{2L} = \frac{2}{2\times 1} = 1$$

$$\boxed{\alpha < \omega_0}$$

$$\omega_0^2 = \frac{1}{LC} = \frac{1}{1\times \frac{1}{2}} = 2$$

$$\omega_0 = \sqrt{2}$$

Transient state

حالت گذرا

مدارهای RLC سری

$\alpha = 1 \qquad \omega_0 = \sqrt{2} \qquad \boxed{\alpha < \omega_0} \qquad s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$s_1 = -\alpha - j\sqrt{\omega_0^2 - \alpha^2} = -\alpha - j\omega_n \qquad s_1 = -1 - j\sqrt{2-1} \qquad s_1 = -1 - j1$

$s_2 = -\alpha + j\sqrt{\omega_0^2 - \alpha^2} = -\alpha + j\omega_n \qquad s_2 = -1 + j\sqrt{2-1} \qquad s_2 = -1 + j1$

جواب عمومی

$i = e^{-\alpha t}[K_1 e^{-j\omega_n t} + K_2 e^{+j\omega_n t}] \qquad i = Ke^{-t}\cos(t+\theta)$

جواب کلی

$i = Ke^{-\alpha t}\cos(\omega_n t + \theta) \qquad i = Ke^{-t}\cos(t+\theta) + K_3$

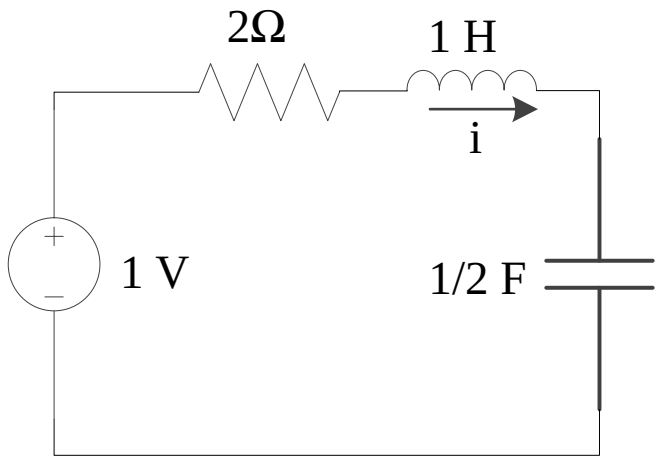
$v_C(\infty) = 0 \longrightarrow K_3 = 0$

Transient state

حالت گذرا

مدارهای RLC سری

$t > 0$



$$i = Ke^{-t}\cos(t+\theta)$$

$$i_L(0^+) = 0 \qquad v(0^+) = 0 \qquad \frac{di}{dt} = -Ke^{-t}\cos(t+\theta) - Ke^{-t}\sin(t+\theta)$$

$$i(0^+) = 0 \qquad v_L(0^+) = ? \qquad i(0^+) = 0 \longrightarrow v_R(0^+) = Ri(0^+) = 0 \qquad v_C(0^+) = 0$$

$$v_L(0^+) = 1V \qquad v_L(0^+) = L\frac{di(0^+)}{dt} \longrightarrow \frac{di(0^+)}{dt} = \frac{v_L(0^+)}{L} = \frac{1}{1} = 1$$

$$K\cos(\theta) = 0$$

$$\frac{di(0^+)}{dt} = -K\cos(\theta) - K\sin(\theta) \longrightarrow -K\cos(\theta) - K\sin(\theta) = 1$$

Transient state

حالت گذرا

مدارهای RLC سری

$$i = Ke^{-t}\cos(t+\theta)$$

$$K\cos(\theta) = 0 \longrightarrow \cos(\theta) = 0 \longrightarrow \theta = \frac{\pi}{2}$$

$$-K\cos(\theta) - K\sin(\theta) = 1 \longrightarrow -K\sin(\theta) = 1 \longrightarrow K = -1$$

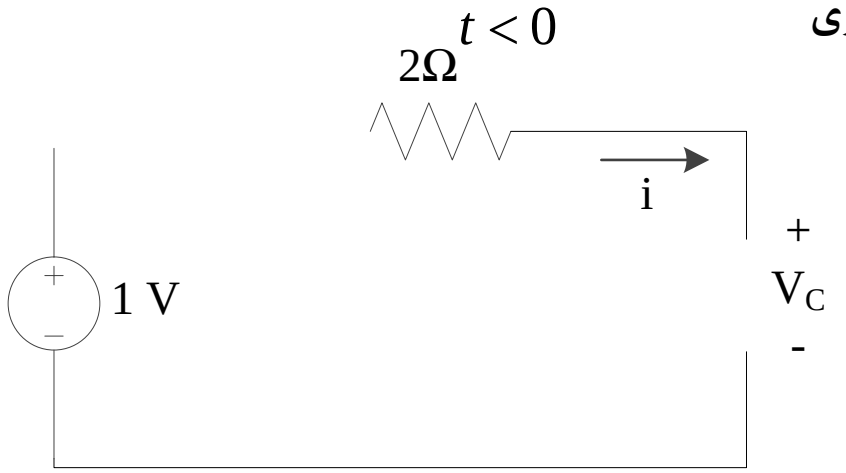
$$\boxed{i = -e^{-t}\cos(t+\frac{\pi}{2})}$$

Transient state

حالت گذرا

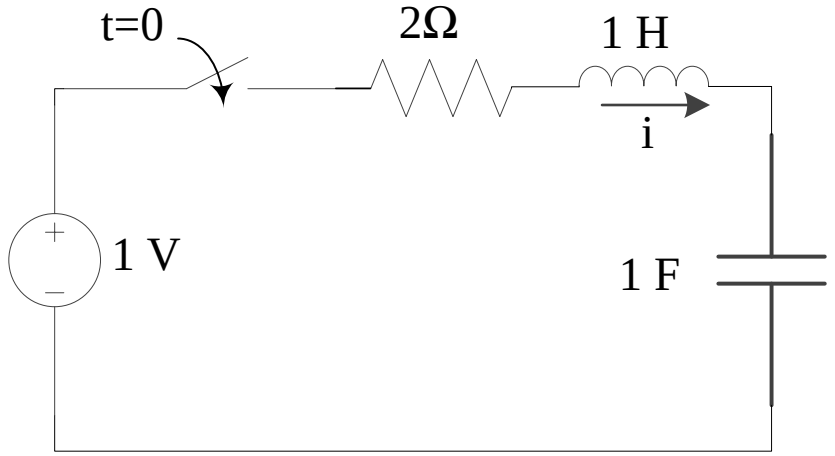
مدارهای RLC سری

خازن اتصال باز،
سلف اتصال کوتاه



$$i_L(0^+)=0$$

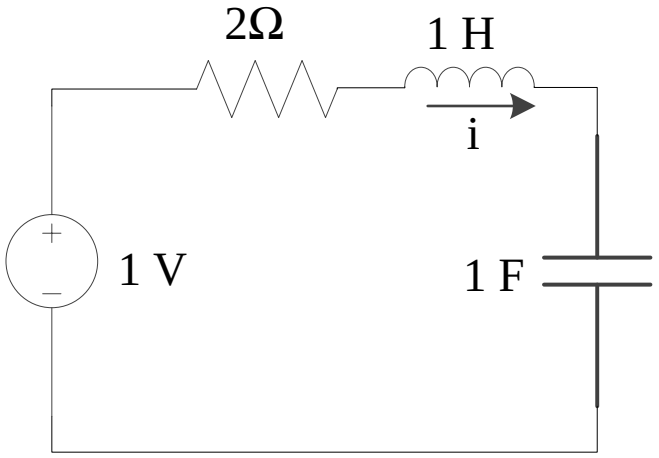
$$v_C(0^+)=0$$



$t>0$

جواب کلی = جواب عمومی + جواب خصوصی

$$s^2+2\alpha s+\omega_0^2=0$$



$$\alpha=\frac{R}{2L}=\frac{2}{2\times1}=1$$

$$\boxed{\alpha=\omega_0}$$

$$\omega_0^2=\frac{1}{LC}=\frac{1}{1\times1}=1$$

$$\omega_0=1$$

Transient state

حالت گذرا

مدارهای RLC سری

$\alpha = 1$ $\omega_0 = 1$ $\boxed{\alpha = \omega_0}$ $s = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$

$s_1 = -\alpha$ $s_1 = -1$

$s_2 = -\alpha$ $s_2 = -1$

جواب عمومی $i = e^{-\alpha t}[K_1 t + K_2]$ $i = e^{-t}[K_1 t + K_2]$

جواب کلی $i = e^{-t}[K_1 t + K_2] + K_3$

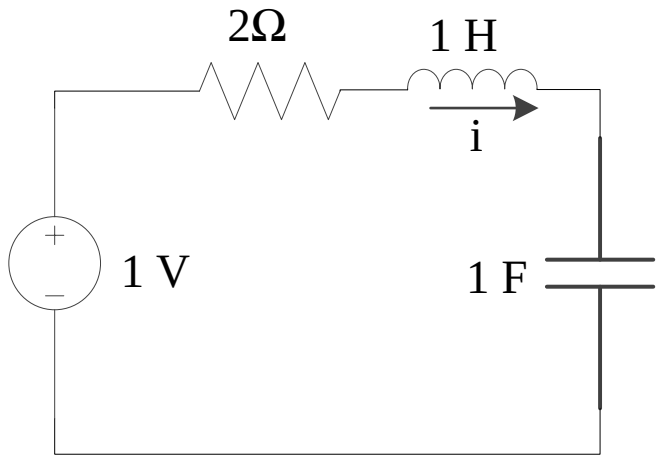
$i_L(\infty) = 0 \longrightarrow K_3 = 0$

Transient state

حالت گذرا

مدارهای RLC سری

$t > 0$



$$i = e^{-t}[K_1 t + K_2]$$

$$i_L(0^+) = 0 \qquad v(0^+) = 0$$

$$\frac{dv}{dt} = K_1 e^{-t} - e^{-t}[K_1 t + K_2]$$

$$i(0^+) = 0$$

$$\downarrow$$

$$K_2 = 0$$

$$v_L(0^+) = ? \qquad i(0^+) = 0 \longrightarrow v_R(0^+) = Ri(0^+) = 0 \qquad v_C(0^+) = 0$$

$$v_L(0^+) = 1V \qquad v_L(0^+) = L\frac{di(0^+)}{dt} \longrightarrow \frac{di(0^+)}{dt} = \frac{v_L(0^+)}{L} = \frac{1}{1} = 1$$

$$\frac{di(0^+)}{dt} = K_1 - [0 + K_2] \longrightarrow K_1 - K_2 = 1$$

Transient state

حالت گذرا

مدارهای RLC سری

$$i = e^{-t}[K_1 t + K_2]$$

$$K_2 = 0$$

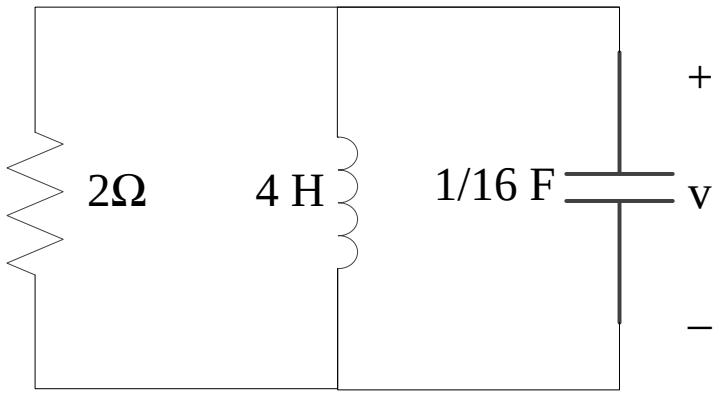
$$K_1 - K_2 = 1 \longrightarrow K_1 = 1$$

$$\boxed{i = te^{-t}}$$

Transient state

حالت گذرا

مدارهای RLC موازی



$$i_L(0^+) = -1A$$

$$v_C(0^+) = 2V$$

$t \to \infty$

خازن اتصال باز،
سلف اتصال کوتاه

$$v(\infty) = 0$$

$$\alpha = \frac{1}{2RC} = \frac{1}{2 \times 2 \times \frac{1}{16}} = 4$$

$$\omega_0^2 = \frac{1}{LC} = \frac{1}{4 \times \frac{1}{16}} = 4$$

$$\omega_0 = 2$$

$\alpha > \omega_0$

$$s_1 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} = -\alpha - \beta_n \qquad s_1 = -4 - \sqrt{16-4}$$

$$s_2 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} = -\alpha + \beta_n \qquad s_2 = -4 + \sqrt{16-4}$$

$$s_1 = -7.46 \qquad s_2 = -0.54$$

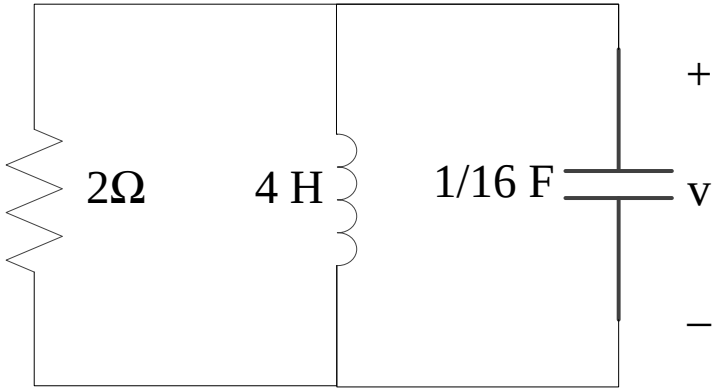
$$v = K_1 e^{-7.46t} + K_2 e^{-0.54t} + K_3$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$v = K_1 e^{-7.46t} + K_2 e^{-0.54t} + K_3$$



$$i_L(0^+) = -1A$$

$$v_C(0^+) = 2V$$

$$v_C(\infty) = 0$$

$$i_R(0^+) + i_L(0^+) + i_C(0^+) = 0$$

$$v(0^+) = 2V \longrightarrow i_R(0^+) = \frac{v(0^+)}{R} = \frac{2}{2} = 1A \qquad i_L(0^+) = -1A \qquad i_C(0^+) = -1-(-1) = 0\,A$$

$$i_C(0^+) = C\frac{dv_C(0^+)}{dt} \longrightarrow \frac{dv_C(0^+)}{dt} = \frac{i_C(0^+)}{C} = 0 \qquad \frac{dv}{dt} = -7.46K_1 e^{-7.46t} - 0.54K_2 e^{-0.54t}$$

$$\frac{dv}{dt}(0^+) = -7.46K_1 - 0.54K_2 = 0$$

Transient state

حالت گذرا

مدارهای RLC موازی

$$v = K_1 e^{-7.46t} + K_2 e^{-0.54t} + K_3$$

$$v_C(\infty) = 0 \qquad K_3 = 0$$

$$v_C(0^+) = 2V \qquad K_1 + K_2 = 2 \qquad K_2 = 2.15$$

$$\frac{dv}{dt}(0^+) = 0 \qquad -7.46K_1 - 0.54K_2 = 0 \qquad K_1 = -0.15$$

$$v = -0.15e^{-7.46t} + 2.15e^{-0.54t}$$