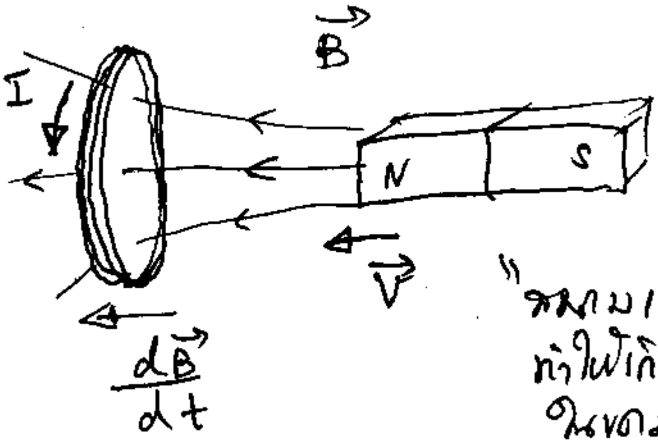
บทที่ 5
ความเหนี่ยวนำไฟฟ้า และวงจรไฟฟ้ากระแสสลับ

$$
\begin{tikzcd}
q \arrow[r] \arrow[d] & \frac{dq}{dt} = I \arrow[d] \\
\vec{E} & \vec{B} \arrow[l, "?"']
\end{tikzcd}
\qquad
\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B})
$$

กฎของฟาราเดย์ (Faraday's Law)



"สนามแม่เหล็กที่เปลี่ยนแปลง ทำให้เกิดแรงเคลื่อนไฟฟ้าเหนี่ยวนำ ในขดลวดได้"

$$\boxed{\mathcal{E} = -\frac{d\Phi_B}{dt}}$$

"Faraday - Lenz's Law" กฎของฟาราเดย์ - เลนซ์

Induced e.m.f. แรงเคลื่อนไฟฟ้าเหนี่ยวนำ [V]

Magnetic Flux [Wb] ฟลักซ์แม่เหล็ก

$[V] \equiv [\frac{Wb}{s}]$

"แรงเคลื่อนไฟฟ้าเหนี่ยวนำ เกิดในทิศทางต้านการเปลี่ยนแปลงฟลักซ์แม่เหล็ก"

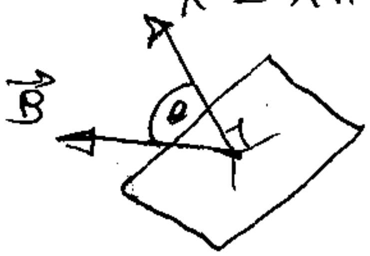
ฟลักซ์แม่เหล็ก (Magnetic Flux)

$$\Phi_E = \vec{E}\cdot\vec{A}$$
$$d\Phi_E = \vec{E}\cdot d\vec{A} \quad \Longrightarrow \quad \boxed{\begin{aligned}\Phi_B &= \vec{B}\cdot\vec{A}\\ \Phi_B &= BA\cos\theta\end{aligned}}$$

Weber
เวเบอร์

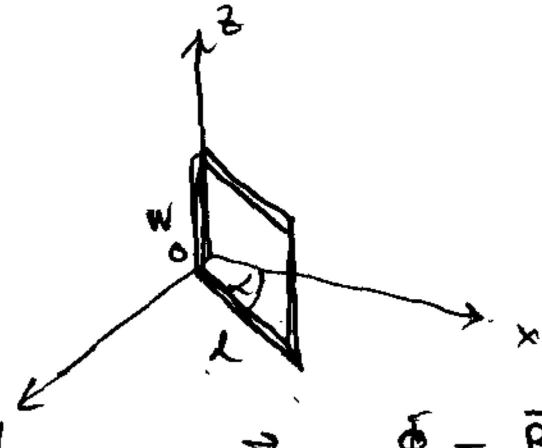
$$\underbrace{\Phi_B}_{[Wb]} \qquad \underbrace{BA\cos\theta}_{[T\,m^2]}$$

$$\vec{A} = A\hat{n}$$

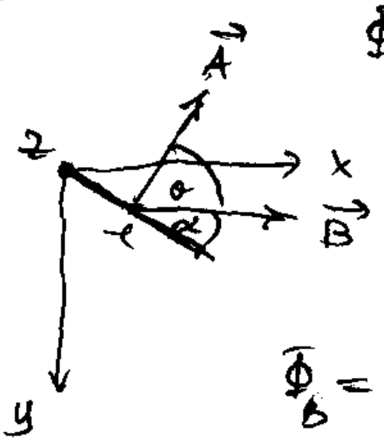


$$\Phi_B = \vec{B}\cdot\vec{A} = BA\cos\theta$$
$$-BA \le \Phi_B \le +BA$$

Ex



$$\vec{B} = 2\ [T]\ \hat{i}$$
$$\alpha = 30^\circ$$
$$w = 40\ [cm]$$
$$d = 50\ [cm]$$
$$\Phi_B = ?$$



$$\Phi_B = \vec{B}\cdot\vec{A} = BA\cos\theta$$
$$\alpha + \theta = 90^\circ$$
$$\theta = 90^\circ - \alpha = 60^\circ$$
$$\cos\theta = \frac{1}{2}$$
$$\Phi_B = (2)(0.4)(0.5)(\tfrac{1}{2})$$
$$= (2)(0.2)(\tfrac{1}{2}) = \boxed{0.2\ [Wb]}$$

$$\boxed{\Phi_B = \vec{B}\cdot\vec{A} = BA\cos\theta} \qquad \boxed{\mathcal{E} = -\frac{d\Phi_B}{dt}}$$

→ ฟลักซ์แม่เหล็กเปลี่ยนแปลงตาม B, A, θ

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BA\cos\theta)$$

$$\boxed{\mathcal{E} = -A\cos\theta\,\frac{dB}{dt} - B\cos\theta\,\frac{dA}{dt} + BA\sin\theta\,\frac{d\theta}{dt}}$$

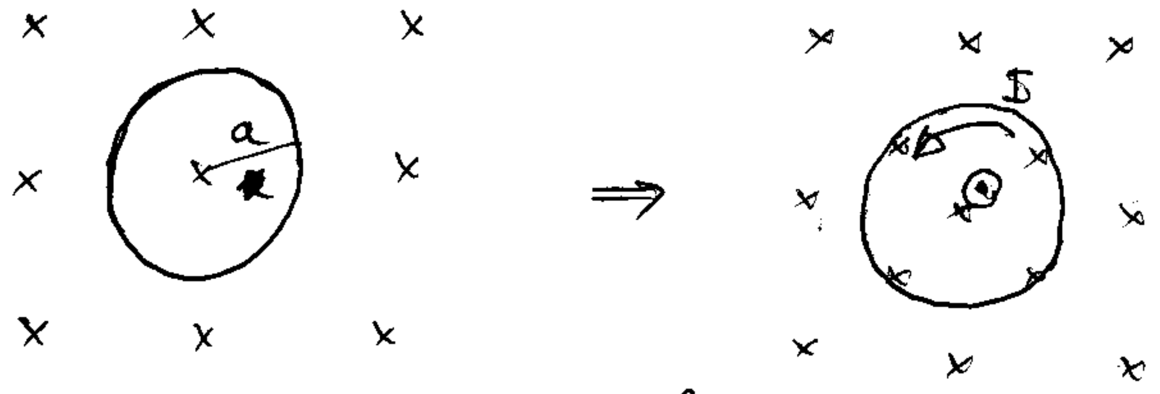
วิธีทำให้เกิดแรงเคลื่อนไฟฟ้าเหนี่ยวนำ

สนามแม่เหล็กเปลี่ยนแปลง

พื้นที่เปลี่ยน

หมุน

Ex



$B_0 = 2\,[T]$ $\qquad \frac{\Delta B}{\Delta t} = 0.1\,[T/s]$ $\qquad a = 10\,[cm]$

$R = 1\,[\Omega]$

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BA\cos\theta) = -A\cos\theta\,\frac{dB}{dt}$$

$$\Phi_{B0} = B_0 A = (2)(\pi)(0.1)^2 \approx \boxed{0.063\,[Wb]}$$

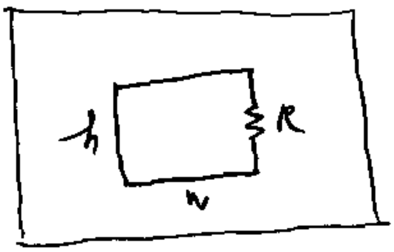
$$\mathcal{E} = -(0.0314)(1)(0.1) = -0.00314\,[V]\ ; \quad |\mathcal{E}| \approx \boxed{3.14\,[mV]}$$

I ไหลทวนเข็มนาฬิกา

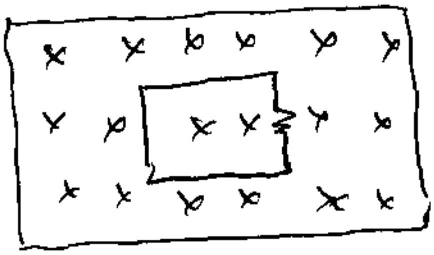
$$|I| = \frac{|\mathcal{E}|}{R} = \frac{3.14\,[mV]}{1\,[\Omega]} = \boxed{3.14\,[mA]}$$

Ex

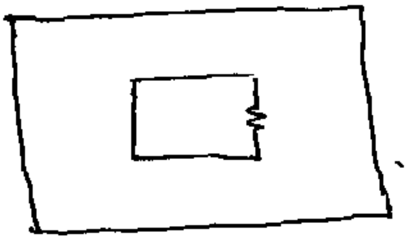
t = 0



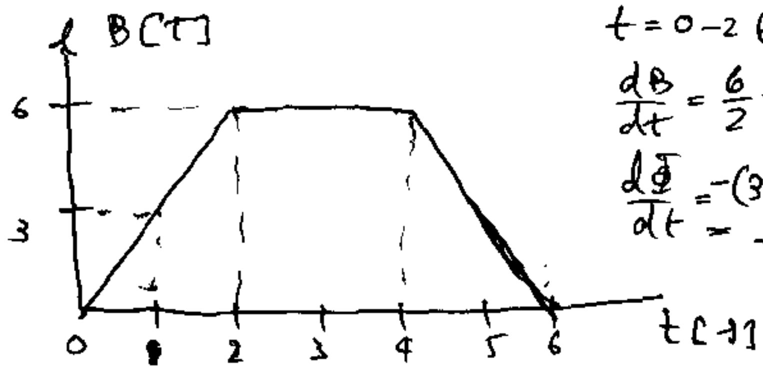
t = 2 - 4 [s]



t = 6 [s]



$w = 1.5$ [m]
$h = 0.6$ [m]
$R = 150$ [Ω]



t = 0 - 2 [s]

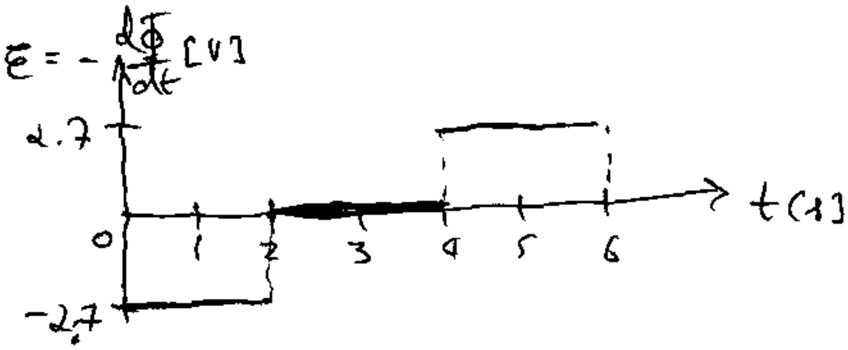
$$\frac{dB}{dt} = \frac{6}{2} = 3 \ \left[\frac{T}{s}\right]$$

$$\frac{d\Phi}{dt} = -(3)(1.5)(0.6) = -2.7 \ [V]$$

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

$$= -\frac{d}{dt}(BA\cos\theta)$$

$$\varepsilon = -A\frac{dB}{dt}$$

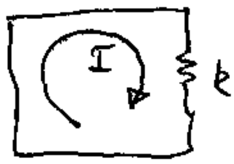


$$I = \frac{\varepsilon}{R}$$

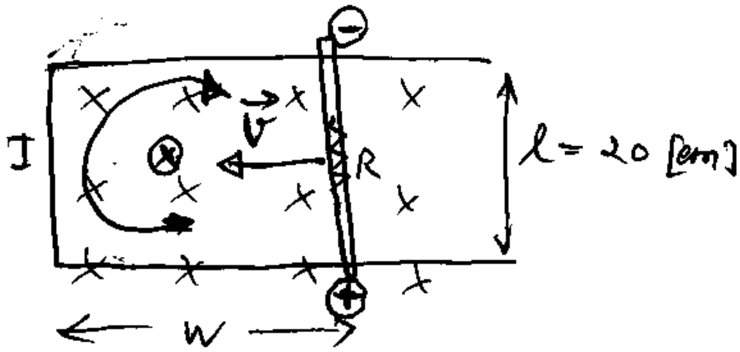
$$= \frac{2.7}{150} = \boxed{18 \ [mA]}$$

t = 0 - 2 [s]

t = 4 - 6 [s]



Ex



$B = 1.4$ [T]

$v = 3.0$ [m/s]

$R = 2.8$ [Ω]

$A = wl$

$v = \frac{dw}{dt}$

$\Phi_B = BA\cos 0 = Bwl$

$\frac{d\Phi_B}{dt} = \frac{d}{dt}(Bwl) = Bl\frac{dw}{dt} = Bvl$

$|\mathcal{E}| = Bvl = (1.4)(3)(0.2) = \boxed{0.84 \text{ [V]}}$

I ไหลตามเข็มนาฬิกา

$I = \frac{|\mathcal{E}|}{R} = \frac{0.84}{2.8} = \boxed{0.3 \text{ [A]}}$

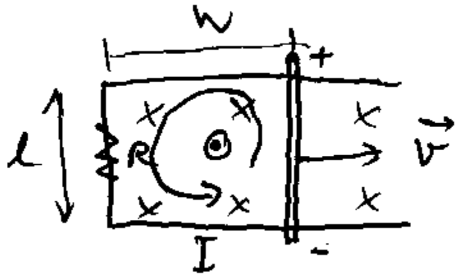
$P = I^2R = Fv$

$I^2R = (0.3)^2(2.8) = \boxed{0.252 \text{ [W]}}$

ต้องออกแรงภายนอก ดึงลวดไปทาง ขวามือ

$F = \frac{P}{v} = \frac{0.252}{3} = \boxed{0.084 \text{ [N]}}$

Ex



$w = 50$ [cm]

$l = 30$ [cm]

$v = 0.2$ [m/s]

$B = 2$ [T]

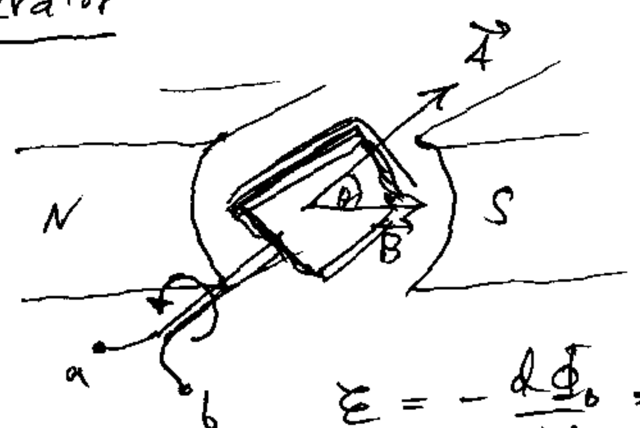
$R = 5$ [Ω]

I ในวงจรทวนเข็มนาฬิกา

$$|\mathcal{E}| = Bvl = (2)(0.2)(0.3) = \boxed{0.12 \text{ [V]}}$$

$$I = \frac{|\mathcal{E}|}{R} = \frac{0.12}{5} = \boxed{24 \text{ [mA]}}$$

AC Generator



$$\frac{d\theta}{dt} = \omega$$

ω คงที่

$$\theta = \omega t$$

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = BA\sin\underbrace{\theta}_{\omega t}\overbrace{\frac{d\theta}{dt}}^{\omega}$$

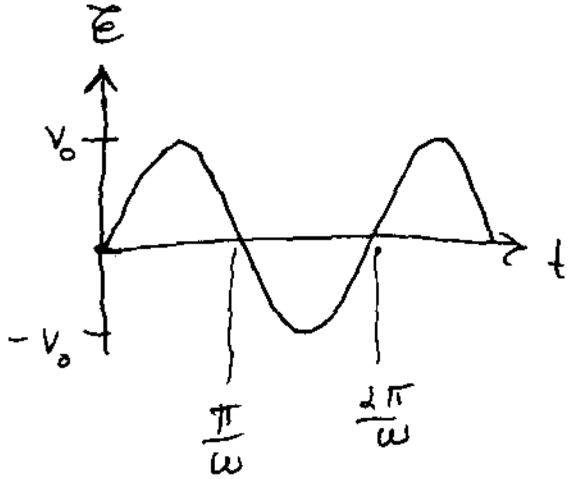
$$\mathcal{E} = \omega BA\sin\omega t$$

N ขด

$$\boxed{\mathcal{E} = \underbrace{\omega NBA}_{V_0}\sin\omega t}$$

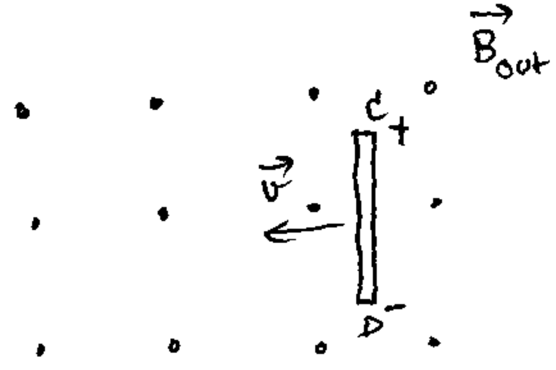
$$\boxed{\mathcal{E} = V_0\sin\omega t}$$

"Sine Wave"



$$V_{ab} = V_0\sin\omega t$$

Ex



$l = 20$ [cm]

$v = 10$ [cm/s]

$B = 1.5$ [T]

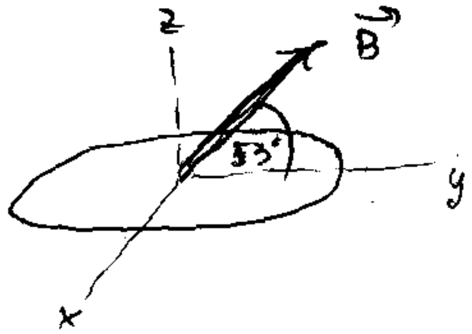
$V_C > V_D$

$$V_{DC} = Bvl = (1.5)(0.1)(0.2) = 0.03 \text{ [V]}$$
$$= 30 \text{ [mV]}$$

$$\boxed{\mathcal{E} = -\frac{d\Phi_B}{dt}}$$

$[V] = [\frac{Wb}{s}]$

Ex

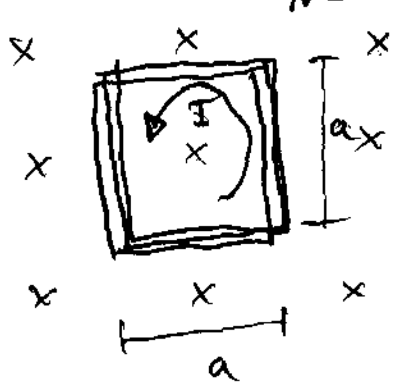


$B = 0.4$ [T]

$A = 0.5$ [m^2]

$$\Phi_B = \vec{B} \cdot \vec{A}$$
$$= BA\cos\theta \quad (\tfrac{4}{5})$$
$$= (0.4)(0.5)(\cos 37°)$$
$$= \boxed{0.16 \text{ [T m}^2]}$$

Ex $N = 500$



$a = 10$ [cm]

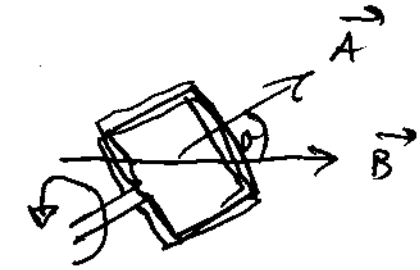
$\frac{\Delta B}{\Delta t} = 0.2$ [T/s]

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -NA\frac{\Delta B}{\Delta t}$$

$$|\mathcal{E}| = NA\left|\frac{\Delta B}{\Delta t}\right| = (500)(0.01)(0.2)$$
$$= \boxed{1 \text{ [V]}}$$

$$\boxed{\mathcal{E} = -\frac{d\Phi_B}{dt} = -A\cos\theta\frac{dB}{dt} - B\cos\theta\frac{dA}{dt} + AB\sin\theta\frac{d\theta}{dt}}$$

<u>Ex</u>

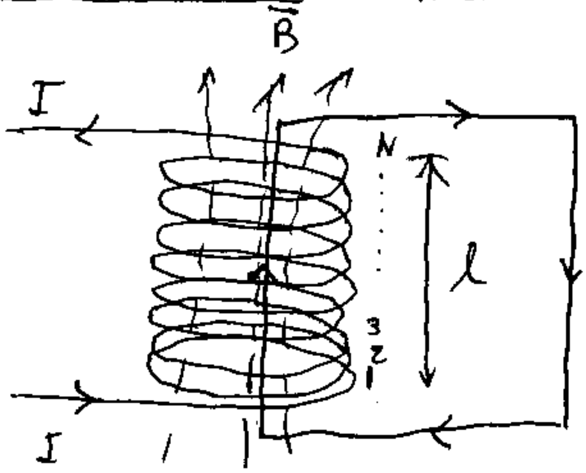


$B = 4$ [T]
$N = 10$
$A = 20$ [cm^2]
$\omega = 100$ [rad/s]

$$\mathcal{E} = \underbrace{\omega NBA}\sin\omega t$$

$$V_0 = (100)(10)(4)(20\times10^{-4}) = \boxed{8 \text{ [V]}}$$

<u>ขดลวดเหนี่ยวนำ (Solenoide)</u>



กระแสไฟฟ้า I
ทำให้เกิด สนามแม่เหล็ก B

1 ขด $\boxed{B = \frac{\mu_0 I}{2R}}$

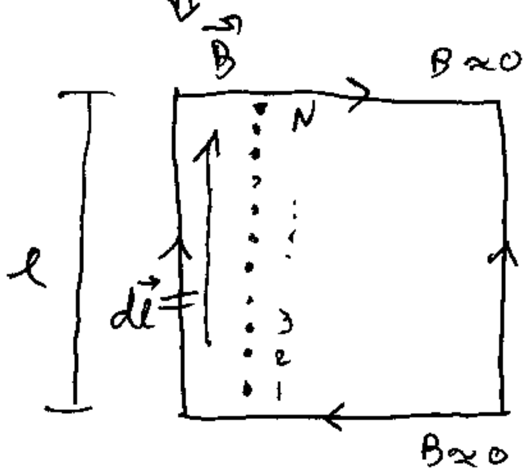
N ขด $B = ?$

Ampere's Law

$$\oint \vec{B}\cdot d\vec{l} = \mu_0 I_{in}$$

$\Downarrow$

$$I_{in} = NI$$

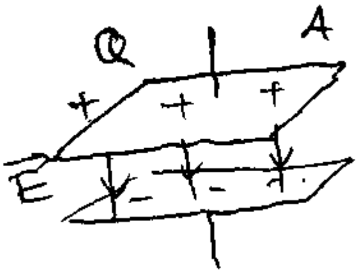


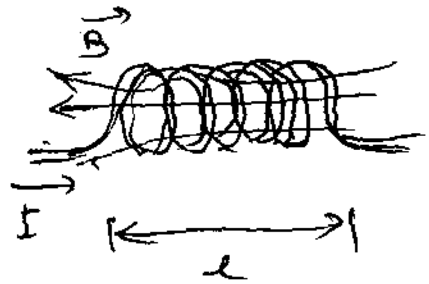
$$Bl = \mu_0 NI$$

$$\boxed{B = \frac{N\mu_0 I}{l}}$$

$$n = \frac{N}{l}$$

$$\boxed{B = \mu_0 nI}$$





$$\sigma = \frac{Q}{A}$$

$$E = \frac{\sigma}{\epsilon_0} = \frac{Q}{\epsilon_0 A}$$

$$B = \mu_0 \frac{NI}{l}$$

ความเหนี่ยวนำ (Inductance)

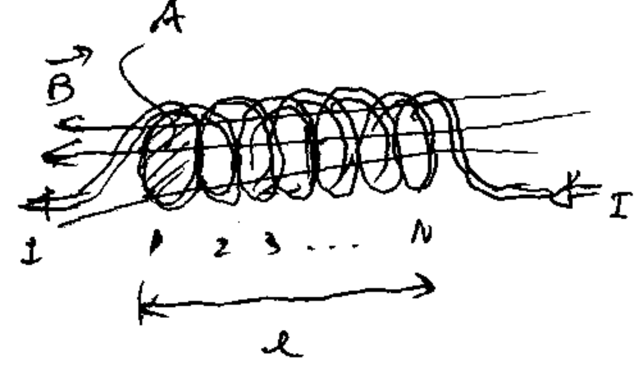
Solenoid $\quad B = \mu_0 \frac{NI}{l}$

$$\boxed{C = \frac{Q}{V}} \longrightarrow \boxed{L = \frac{\Phi_B}{I}}$$

ความเหนี่ยวนำ

เฮนรี่ $[H] \equiv \left[\frac{Wb}{A}\right]$

Solenoid $\quad N$ รอบ ยาว l พื้นที่หน้าตัด A



$$\Phi_B = NBA$$

$$= N\left(N\frac{\mu_0 I}{l}\right)A$$

$$= \mu_0 \frac{N^2}{l} I A$$

$$n = \frac{N}{l}$$

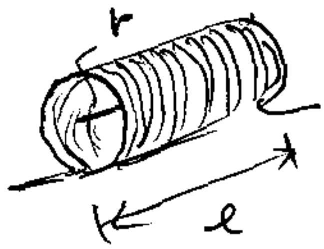
$$L = \frac{\Phi_B}{I} = \boxed{\mu_0 \frac{N^2 A}{l}}$$

$$\boxed{L = \mu_0 n^2 A l}$$

แกนอากาศ

แกน Ferrite $\mu_0 \to \mu$

Ex



$N = 1000$

$l = 3.14$ [cm]

$r = 1$ [cm]

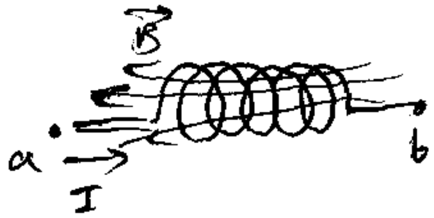
$L = ?$

$$L = \frac{\Phi_B}{I} = \mu_0 \frac{N^2 A}{l} = \frac{(4\pi\times10^{-7})(10^3)^2(\pi)(0.01)^2}{(3.14\times10^{-2})}$$

$$L = \frac{4\pi\times\cancel{\pi}}{\cancel{3.14}}\times 10^{-7+6-4+2} \text{ [H]}$$

$$\approx 13\times10^{-3} \text{ [H]} = \boxed{13 \text{ [mH]}}$$

การต่อตัวเหนี่ยวนำ



$$L = \mu \frac{N^2 A}{l}$$

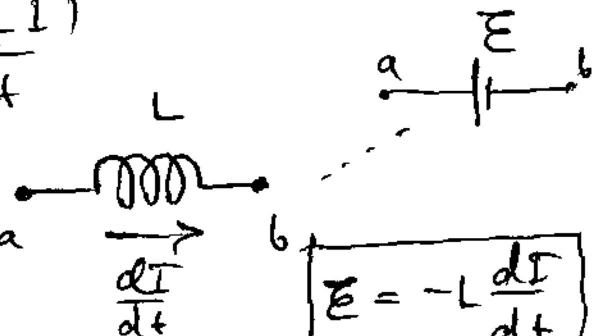
$$L = \frac{\Phi_B}{I}$$

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

$$\Phi_B = LI$$

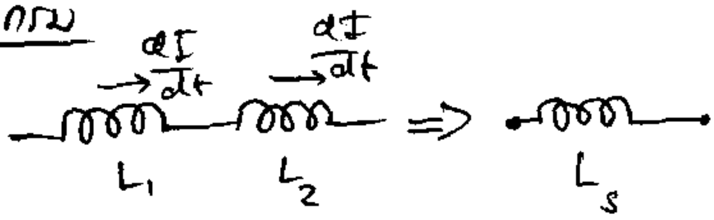
$$\mathcal{E} = -\frac{d(LI)}{dt}$$

$$\boxed{\mathcal{E} = -L\frac{dI}{dt}}$$



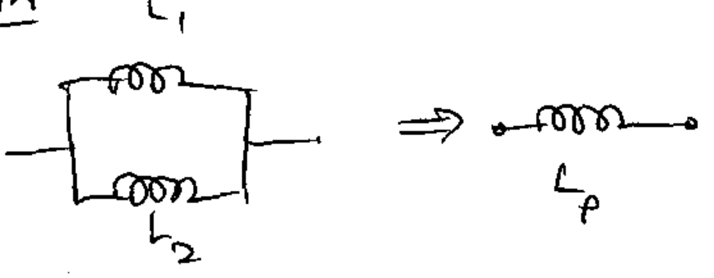
$$\boxed{\mathcal{E} = -L\frac{dI}{dt}}$$

อนุกรม



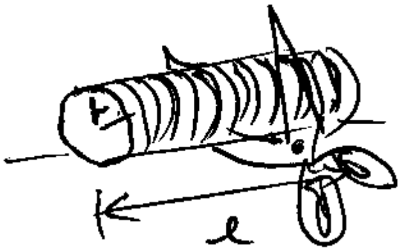
$$\boxed{L_s \approx L_1 + L_2}$$

ขนาน



$$\boxed{L_p \approx \frac{L_1 L_2}{L_1 + L_2}}$$

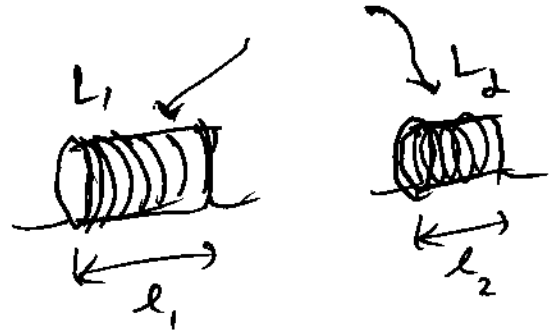
Ex



$l = 10$ [cm]

$N = 1000$

$L = 4$ [mH]



$l_1 = 8$ [cm]

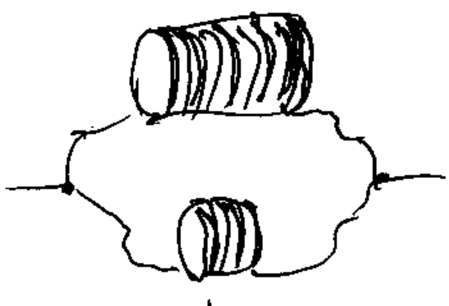
$l_2 = 2$ [cm]

$$L = L_1 + L_2$$

$$\underbrace{\mu n^2 l A}_{4\ [mH]} = \underbrace{\mu n^2 l_1 A}_{\left(\frac{8}{10}\right)(4\ [mH])} + \underbrace{\mu n^2 l_2 A}_{\left(\frac{2}{10}\right)(4\ [mH])}$$

$L_1 = 3.2$ [mH]

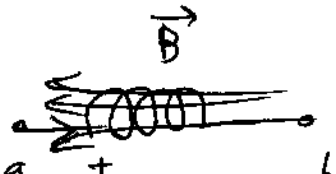
$L_2 = 0.8$ [mH]



$$L_p = \frac{L_1 L_2}{L_1 + L_2} = \frac{(3.2)(0.8)}{(3.2)+(0.8)}$$

$$L_p = \boxed{0.64\ [mH]}$$

พลังงานในตัวเหนี่ยวนำ



$$\mathcal{E} = -L\frac{dI}{dt} = V_L$$

$$P = VI = \frac{dU}{dt}$$

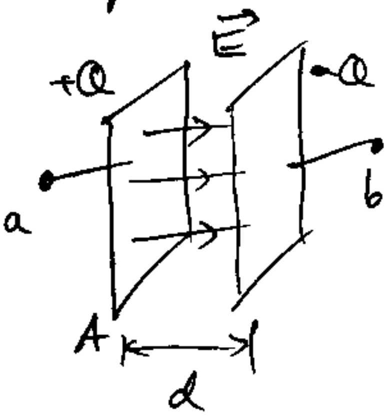
$$dU = P\,dt$$

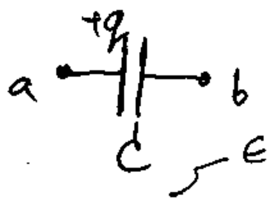
$$= VI\,dt = IL\frac{dI}{\cancel{dt}}\cancel{dt}$$

$$U_L = \int dU = \int_0^I LI\,dI = \boxed{\frac{1}{2}LI^2}$$

ตัวเหนี่ยวนำเก็บพลังงานได้ในรูปของสนามแม่เหล็ก

Capacitor



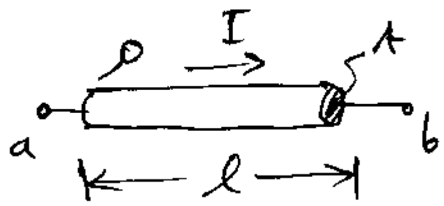


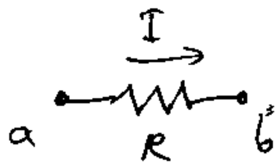
$$C = \frac{\epsilon_0 A}{d}$$

$$V_c = -\frac{q}{C}$$

$$U_c = \frac{1}{2} C V^2$$

Resistor



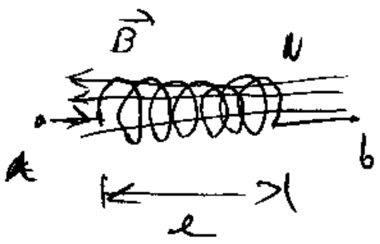


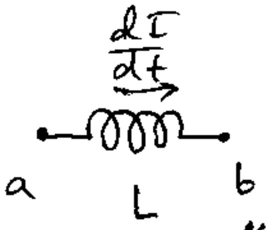
$$R = \frac{\rho \ell}{A}$$

$$V_R = -IR$$

$$P = I^2 R$$

Inductor





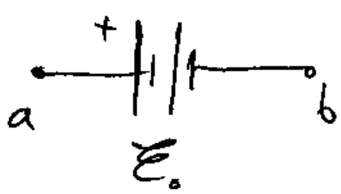
μ

$$L = \mu_0 \frac{N^2 A}{\ell}$$

$$V_L = -L \frac{dI}{dt}$$

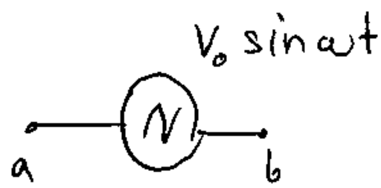
$$U_L = \frac{1}{2} L I^2$$

Battery



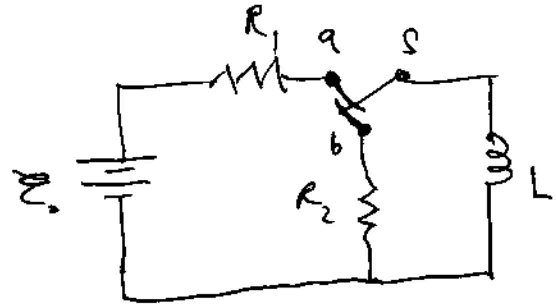
$$V_{ab} = -\mathcal{E}_0$$

AC Generator



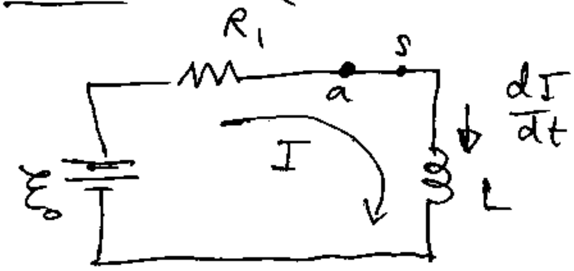
$$V_{ab} = V_0 \sin(\omega t + \phi)$$

RL-circuit



$\Rightarrow$

$t=0 \quad S \to a$



$$-IR_1 - L\frac{dI}{dt} + \mathcal{E}_0 = 0$$

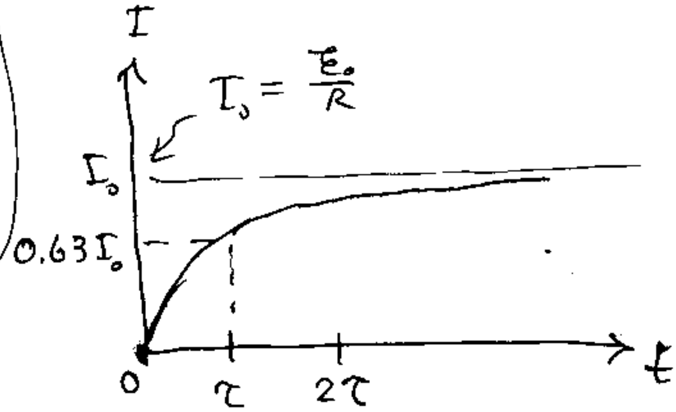
$$L\frac{dI}{dt} = \mathcal{E}_0 - IR$$

$$\int_0^I \frac{dI}{I - \frac{\mathcal{E}_0}{R}} = \int_0^t -\frac{R}{L}\,dt$$

$$\ln\left(\frac{I - \frac{\mathcal{E}_0}{R}}{-\frac{\mathcal{E}_0}{R}}\right) = -\frac{R}{L}t$$

$$I - \frac{\mathcal{E}_0}{R} = -\frac{\mathcal{E}_0}{R}e^{-\frac{R}{L}t}$$

$$\boxed{I = I_0\left(1 - e^{-\frac{R}{L}t}\right)}$$



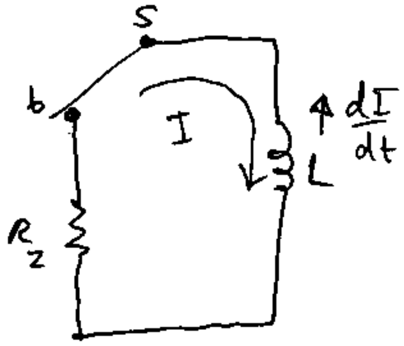
$$\boxed{\tau_{RL} = \frac{L}{R}} \quad [s]$$

$$\left[\frac{H}{\Omega}\right] \equiv [s] \equiv [\Omega F]$$

ค่าคงตัวเวลาของวงจร RL

$\underline{S \to b}$ $\quad t=0 \quad I = I_0$

$$\ln\left(\frac{A}{B}\right) = \ln A - \ln B$$



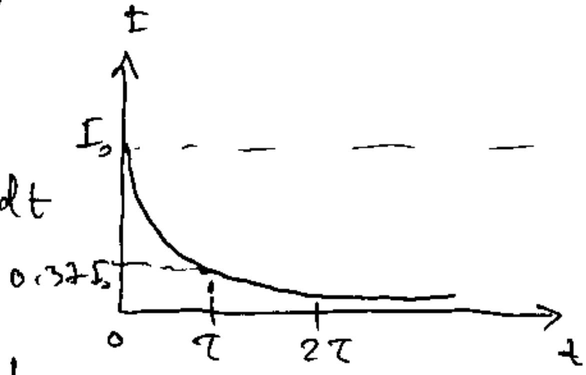
$$L\frac{dI}{dt} - IR = 0$$

$$L\frac{dI}{dt} = -IR$$

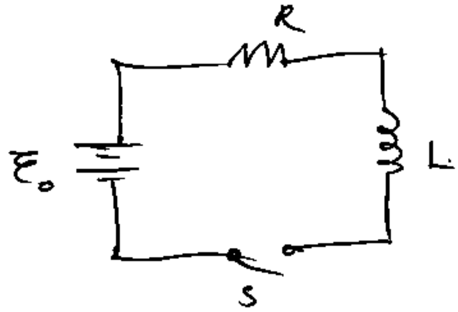
$$\int_{I_0}^{I(t)} \frac{dI}{I} = -\int_0^t \frac{R}{L}\,dt$$

$$\ln\left(\frac{I(t)}{I_0}\right) = -\frac{R}{L}t$$

$$\boxed{I(t) = I_0\, e^{-\frac{R}{L}t}}$$



Ex



$\mathcal{E}_0 = 12$ [V]
$R = 6$ [Ω]
$L = 6$ [H]

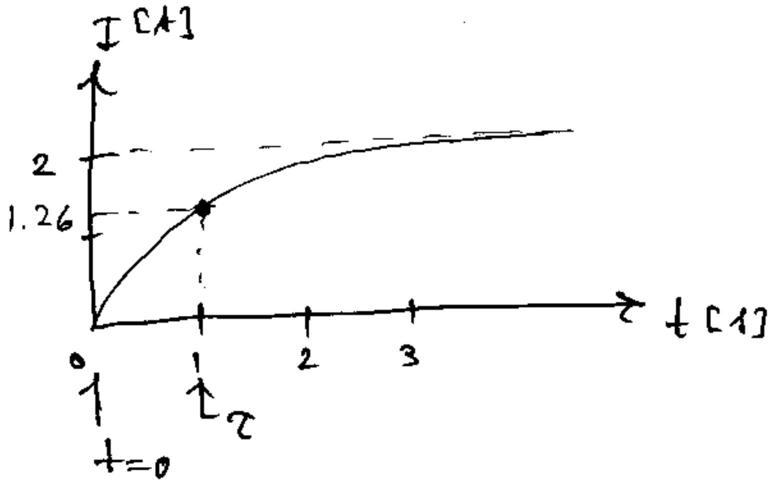
$t = 0 \quad I = ?$

Charging.

$$I(t) = I_0\left(1 - e^{-\frac{t}{\tau}}\right)$$

$$\tau = \frac{L}{R} = \frac{6}{6} = \boxed{1 \text{ [s]}}$$

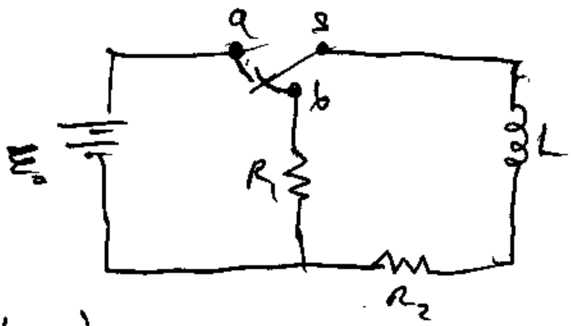
$$I_0 = \frac{\mathcal{E}_0}{R} = \frac{12}{6} = \boxed{2 \text{ [A]}}$$



$t = 0$
$\boxed{I(0) = 0}$

$t = 1$ [s]
$\boxed{I(1) = 1.26 \text{ [A]}}$

Ex



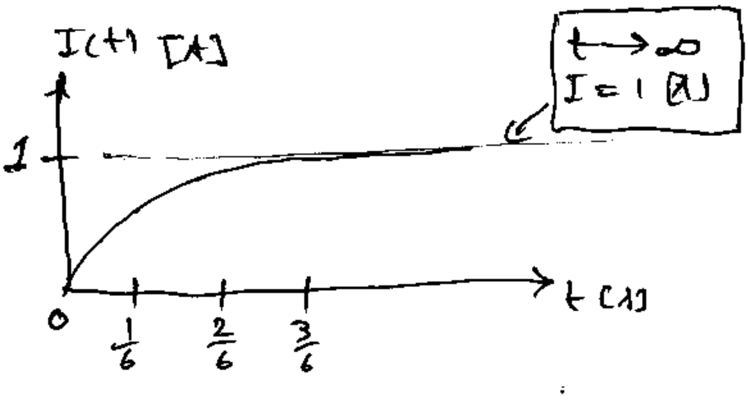
$\mathcal{E}_0 = 12$ [V]
$R_1 = 1200$ [Ω]
$R_2 = 12$ [Ω]
$L = 2$ [H]

Charging $s \to a$

$$I(t) = I_0\left(1 - e^{-\frac{R_2}{L}t}\right)$$

$$\tau_1 = \frac{L}{R_2} = \frac{2}{12} = \frac{1}{6} \text{ [s]}$$

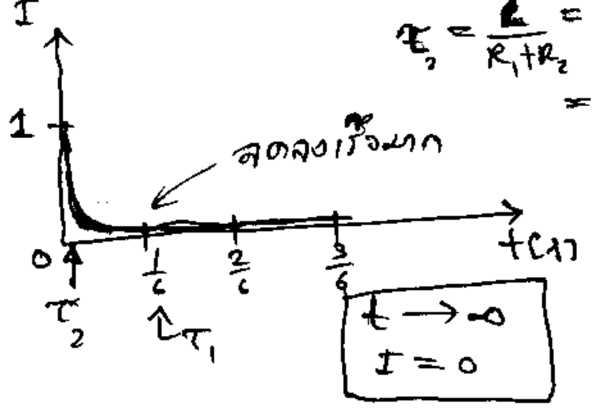
$$I_0 = \frac{\mathcal{E}_0}{R_2} = \frac{12}{12} = 1 \text{ [A]}$$



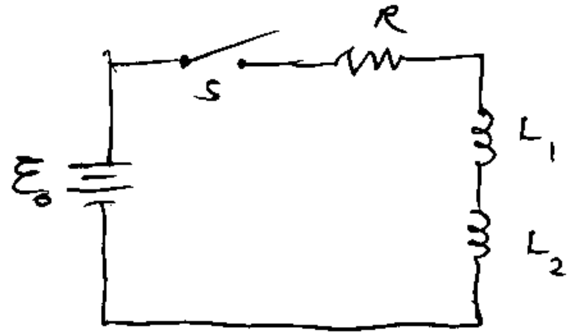
$s \to b$ discharge

$$I(t) = I_0\, e^{-\left(\frac{R_1+R_2}{L}\right)t}$$

$$\tau_2 = \frac{L}{R_1+R_2} = \frac{2}{1212} = \frac{1}{606} \text{ [s]}$$



Ex



$L_1 = 20$ [H]

$L_2 = 30$ [H]

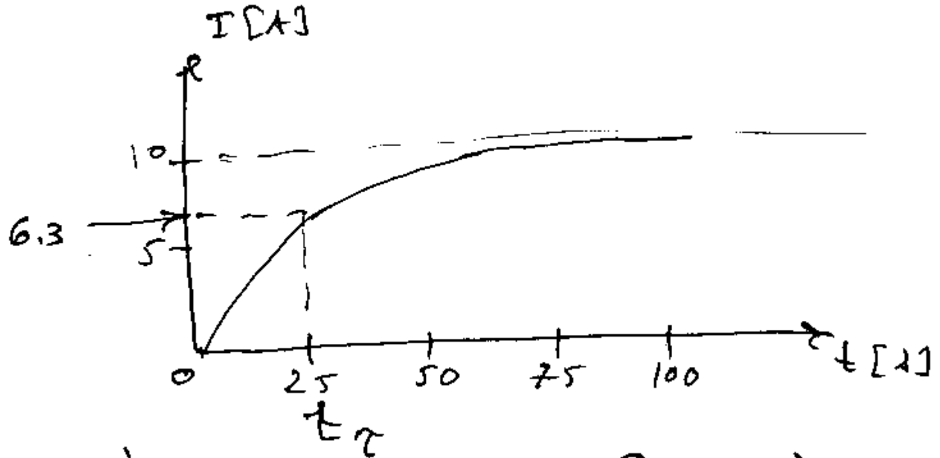
$R = 2$ [Ω]

$\mathcal{E}_0 = 20$ [V]

$$L_s = L_1 + L_2 = 20 + 30 = 50 \text{ [H]}$$

$$\tau = \frac{L}{R} = \frac{50}{2} = \boxed{25 \text{ [s]}}$$

$$I_0 = \frac{\mathcal{E}_0}{R} = \frac{20}{2} = \boxed{10 \text{ [A]}}$$



$t = \tau$

$I(\tau) = \boxed{6.3 \text{ [A]}}$

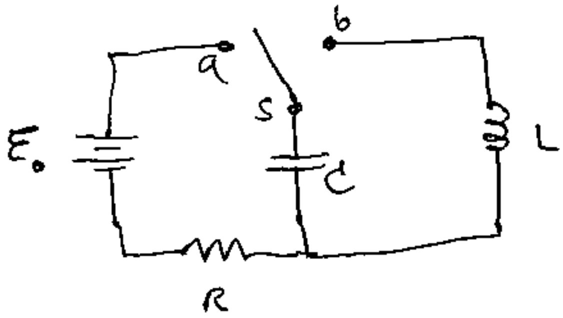
ที่ $t = \tau$ พลังงานที่เก็บในตัวเหนี่ยวนำ L_1 เป็นเท่าใด?

$$U_L = \frac{1}{2} L I^2$$

$$I = I_0\left(1 - e^{-\frac{t}{\tau}}\right) = I_0\left(1 - \underbrace{e^{-1}}_{0.37}\right) = 0.63\, I_0 = 6.3 \text{ [A]}$$

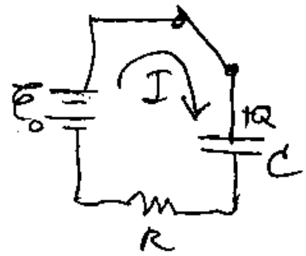
$$U_{L_1} = \frac{1}{2}(20)(6.3)^2 \approx \boxed{397 \text{ [J]}}$$

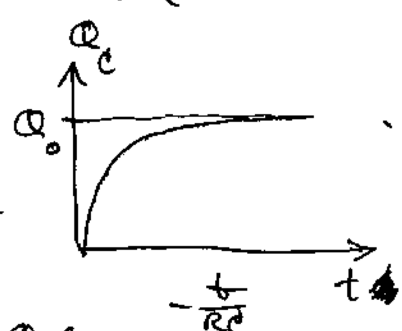
LC circuit



เมื่อ C เต็ม $Q_c = Q_0 = E_0 C$

① Charging C $s \to a$

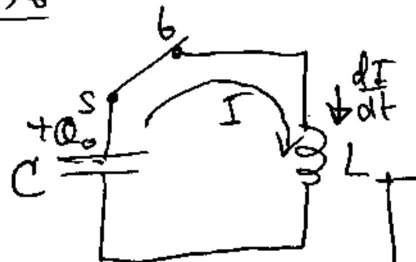




$$Q(t) = Q_0 (1 - e^{-\frac{t}{RC}})$$

$$I(t) = I_0 e^{-\frac{t}{RC}}$$

② $s \to b$



$$+\frac{Q}{C} - L\frac{dI}{dt} = 0$$

ประจุไฟฟ้าที่ออกจากตัวเก็บ เป็นกระแสไฟฟ้า

$$I = -\frac{dQ}{dt}$$

$$\frac{dI}{dt} = -\frac{d^2Q}{dt^2}$$

$$-L\frac{dI}{dt} = +\frac{d^2Q}{dt^2}$$

$$\boxed{L\frac{d^2Q}{dt^2} + \frac{Q}{C} = 0}$$

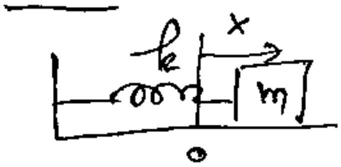
$$\frac{d^2Q}{dt^2} + \underbrace{\frac{1}{LC}}_{\omega_0^2} Q = 0$$

$$\boxed{\omega_0 = \frac{1}{\sqrt{LC}}}$$

"Natural Frequency" of LC circuit

ความถี่ธรรมชาติของวงจร LC

S.H.O.



$$m\frac{d^2x}{dt^2} + kx = 0$$

$$\frac{d^2x}{dt^2} + \underbrace{\frac{k}{m}}_{\omega_0^2} x = 0$$

$$x = A\sin(\omega t + \phi)$$

$$v = \omega A\cos(\omega t + \phi)$$

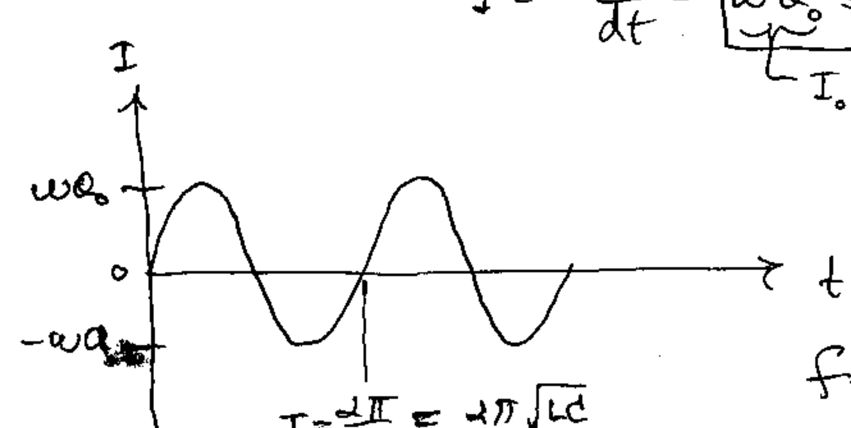
$$Q = Q_0 \sin(\omega t + \phi)$$

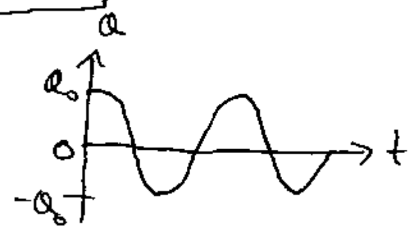
$\underline{t=0}$ $Q = Q_0$ $\sin\phi = 1$

$$\phi = \frac{\pi}{2}$$

$$Q = Q_0 \sin(\omega t + \frac{\pi}{2}) = \boxed{Q_0 \cos(\omega t)}$$

$$I = -\frac{dQ}{dt} = \boxed{\underbrace{\omega Q_0}_{I_0} \sin \omega t}$$

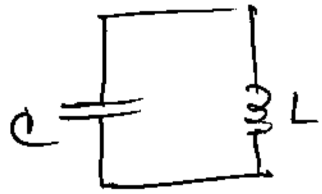




$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

* วงจร LC ใช้ในการกำเนิดสัญญาณ "LC oscillator"

Ex



$C = 5$ [μF]

$L = 18$ [mH]

$\omega_0 = ?$

$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{(18\times10^{-3})(5\times10^{-6})}} = \frac{1}{\sqrt{90\times10^{-9}}} \text{ [rad/s]}$$

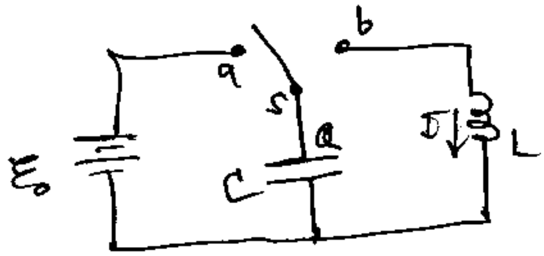
$$= \frac{1}{\sqrt{9}\sqrt{10^{-8}}} = \frac{1}{3}\times\frac{1}{10^{-4}}$$

$$= 0.33\times10^{4}$$

kHz $\rightarrow$ $= 3.3\times10^{3}$ [rad/s]

วิทยุคลื่นยาว

Ex



$C = 200$ [μF]

$L = 5$ [mH]

$\mathcal{E}_0 = 15$ [V]

$\underline{S \to a}$ charging C

$$Q_0 = \mathcal{E}_0 C = (15)^{[V]}(200)[\mu F]$$

$$= 3000 \ [\mu C]$$

$$= 3 \ [mC]$$

$\underline{S \to b}$ LC oscillation

$$Q = Q_0 \cos(\omega_0 t)$$

$$I = \omega_0 Q_0 \sin(\omega_0 t)$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$= \frac{1}{\sqrt{(5\times10^{-3})(200\times10^{-6})}} \ (\text{rad/s})$$

$$= \frac{1}{\sqrt{(1000)(10^{-9})}} = \frac{1}{\sqrt{10^{-6}}}$$

$$= \frac{1}{10^{-3}} = \boxed{1000 \ [\text{rad/s}]}$$

$$I_0 = \omega_0 Q_0$$

$$= (1000)(3\times10^{-3}) \ [A]$$

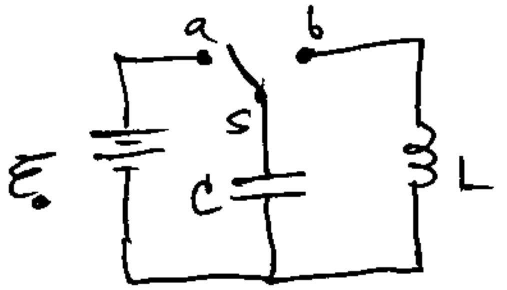
$$= \boxed{3 \ [A]}$$

$$U = U_C + U_L = \underbrace{\frac{1}{2}\frac{Q^2}{C}}_{\text{พลังงานไฟฟ้า}} + \underbrace{\frac{1}{2}LI^2}_{\text{พลังงานแม่เหล็ก}}$$

$$= \frac{1}{2}\frac{Q_0^2}{C}\cos^2(\omega_0 t) + \frac{1}{2}\underbrace{L\omega_0^2}_{\frac{1}{C}} Q_0^2 \sin^2(\omega_0 t) = \underbrace{\boxed{\frac{1}{2}\frac{Q_0^2}{C}}}_{\text{พลังงาน คงที่}}$$

Ex LC circuit $C = 500\,[\mu F]$ $L = 5\,[H]$

$\mathcal{E}_0 = 10\,[V]$



$s \to a$ charging C

$$Q_0 = C\mathcal{E}_0 = (500\times10^{-6})(10) = 5000\,[\mu C]$$

$$Q_0 = \boxed{5\times10^{-3}\,[C]}$$

$$U_0 = \frac{1}{2}\frac{Q_0^2}{C} = \frac{1}{2}\frac{(5\times10^{-3})^2}{(500\times10^{-6})} = \frac{1}{2}\frac{(25\times10^{-6})}{5\times10^{-4}} = \frac{5}{2}\times10^{-2}\,J = \boxed{2.5\times10^{-2}\,[J]}$$

$\boxed{t=0}$

$s \to b$ LC oscillator

$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{(5)(5\times10^{-4})}} = \frac{1}{5\times10^{-2}} = \frac{100}{5} = \boxed{20\,[rad/s]}$$

$$Q_C = Q_0\cos(\omega_0 t) = \boxed{(5\times10^{-3})\cos(20t)\quad[C]}$$

$$I_L = -\frac{dQ_C}{dt} = \omega_0 Q_0 \sin(\omega_0 t) = \boxed{\frac{1}{10}\sin(20t)\quad[A]}$$

⇒ หาพลังงานในขดลวดเหนี่ยวนำที่เวลา $t = \frac{\pi}{2}$ [s]

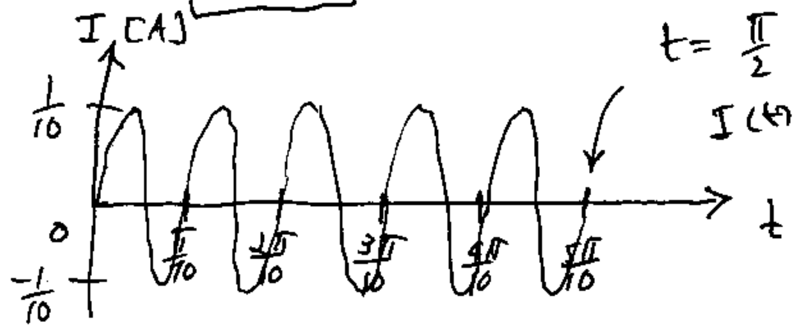
$\omega_0 = 20$ [rad/s]

$T = \frac{2\pi}{\omega_0} = \frac{\pi}{10}$ [s]

$$U_L = \frac{1}{2}LI^2$$

$$I = \frac{1}{10}\sin 20t = \frac{1}{10}\sin\left(20\,\frac{\pi}{2}\right) = \frac{1}{10}\sin(10\pi) = 0$$

$$U_L\left(\frac{\pi}{2}\right) = \boxed{0\,[J]}$$

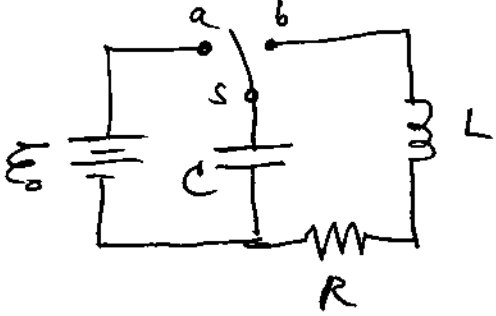


$t = \frac{\pi}{2} = \frac{5\pi}{10}$

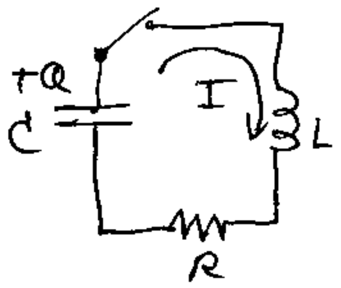
$I(t) = 0$

$U_L = 0$

LC - circuit ที่มีความต้านทาน



$\Rightarrow$



$$I = -\frac{dQ}{dt}$$

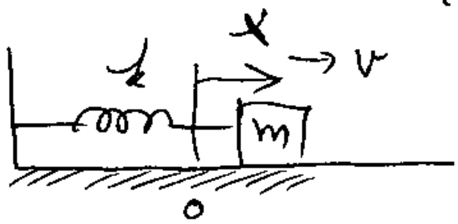
$$\frac{dI}{dt} = -\frac{d^2Q}{dt^2}$$

$$-L\frac{dI}{dt} = L\frac{d^2Q}{dt^2}$$

$$+\frac{Q}{C} + L\frac{d^2Q}{dt^2} - IR = 0$$

IR ความต้านทาน

$$\boxed{L\frac{d^2Q}{dt^2} + R\frac{dQ}{dt} + \frac{Q}{C} = 0}$$

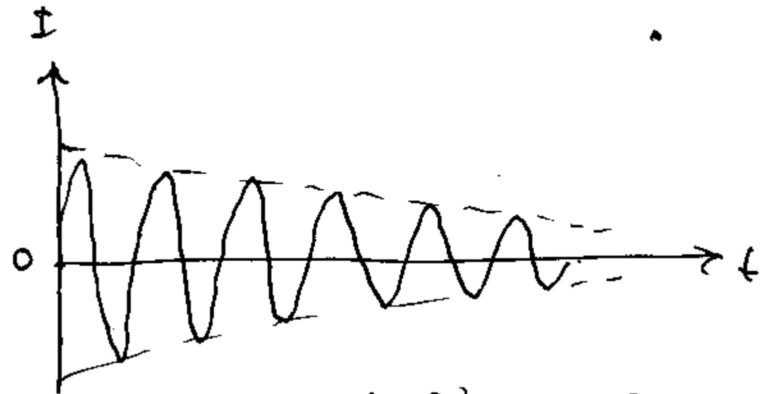


$$\boxed{m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0}$$

"Damped Oscillation"

→ พลังงานลดลงตามเวลา

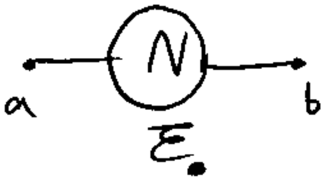
→ ขนาดสูงสุดของการแกว่งกวัดลดลง



ต้องมีแหล่งกำเนิดพลังงานมาชดเชย
จึงจะสามารถแกว่งกวัดต่อไปได้

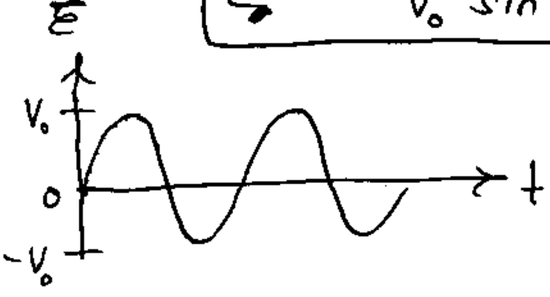
→ AC RLC circuit

AC circuit วงจรไฟฟ้ากระแสสลับ

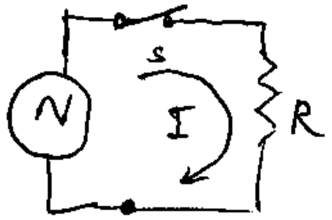


$$\mathcal{E}_o = N\omega BA \sin\omega t$$

$$\boxed{\mathcal{E}_o = V_o \sin\omega t}$$

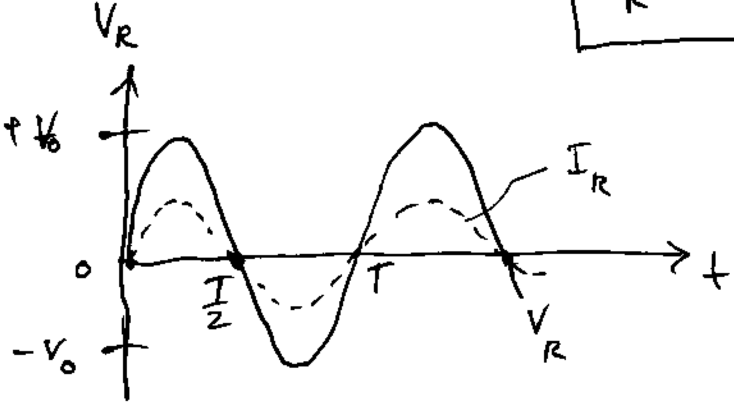


$\boxed{R}$ Resistance



$$V_o \sin\omega t - I_R R = 0$$

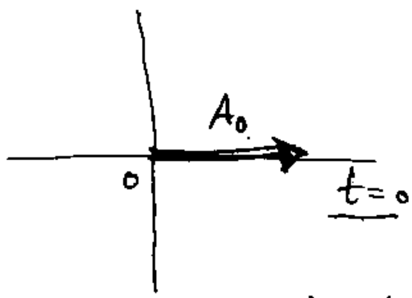
$$\boxed{\begin{aligned} I_R(t) &= \frac{V_o}{R}\sin\omega t = I_o \sin\omega t \\ V_R(t) &= V_o \sin\omega t \end{aligned}}$$



I_R, V_R เฟสตรงกัน

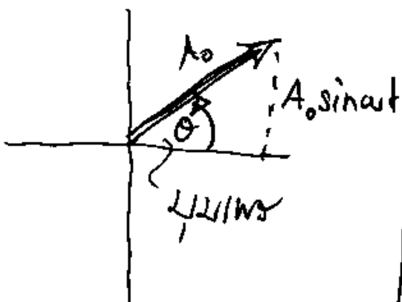
$$\theta = \omega t$$

Phasor Diagram

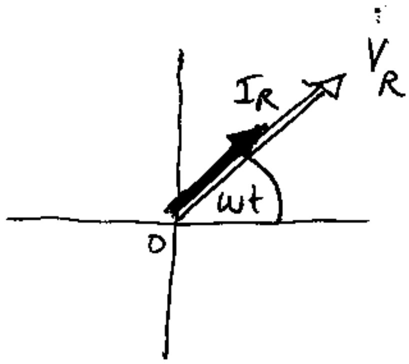


$\Rightarrow$

$\theta = \omega t$



$A(t) = A_o \sin\omega t$



I_R, V_R

เฟสตรงกัน

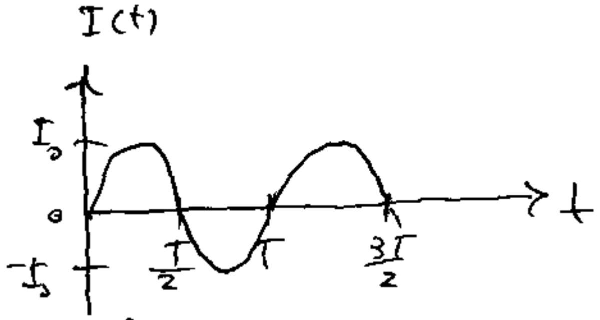
$\mathcal{E} \rightarrow$ ให้พลังงาน Power generation

$R \rightarrow$ ใช้พลังงาน Power Consumption

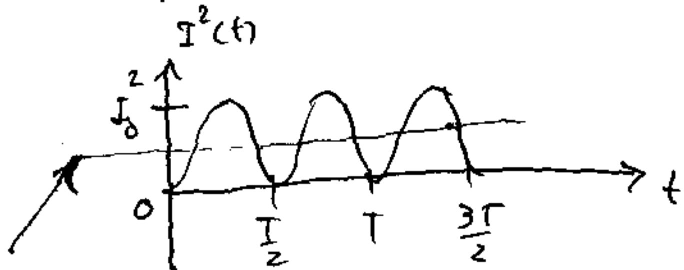
$$P = IV = I_0 \sin\omega_0 t \, V_0 \sin\omega t$$

$I_0 R$

$$\boxed{P(t) = I_0^2 R \sin^2 \omega t}$$



$$\to P(t) = \underline{(I(t))}^2 R$$



$$\langle I^2 \rangle_{ave} = \frac{I_0^2}{2}$$

ค่าเฉลี่ย

$$P_{ave} = \langle (I(t))^2 R \rangle_{ave}$$

$$\boxed{P_{ave} = \frac{I_0^2 R}{2}} \; * \quad \Longleftrightarrow \quad \boxed{P = I^2 R} \; (D.C)$$

(A.C)

$$\to \boxed{P_{ave} = \left(\frac{I_0}{\sqrt{2}}\right)^2 R = I_{rms}^2 R}$$

$$\langle I^2 \rangle_{ave} = \frac{I_0^2}{2}$$

$$\sqrt{\langle I^2 \rangle_{ave}} = \sqrt{\frac{I_0^2}{2}}$$

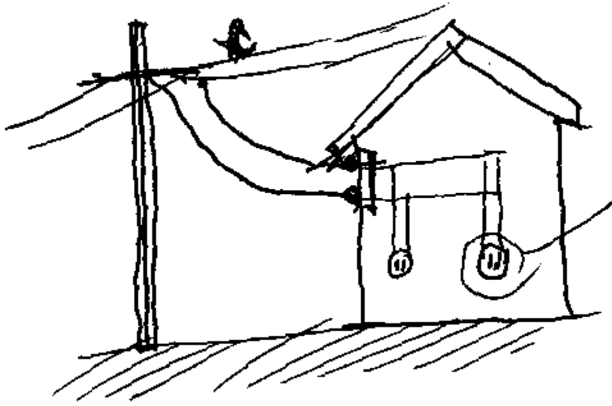
$$I_{rms} = \frac{I_0}{\sqrt{2}}$$

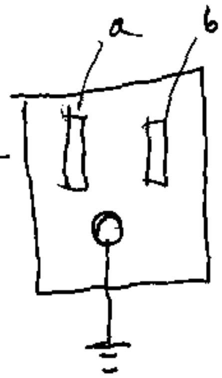
$$\boxed{I_{rms} = \frac{I_0}{\sqrt{2}}}$$

"root' mean squre"

หารากที่สอง　　กำลังสองเฉลี่ย

$$\boxed{V_{rms} = \frac{V_0}{\sqrt{2}}} \qquad \boxed{P_{ave} = I_{rms} V_{rms}}$$





$V_0 \sin\omega t$

__USA__

$f = 60$ [Hz]

$V_{rms} = 110$ [V]

__Thailand__

$f = 50$ [Hz]

$\omega = 2\pi f = 100\pi$ [rad/s]

$V_{rms} = 220$ [V]

Ex $V_0 = 300$ [V] $R = 20$ [Ω] $\omega = 100$ [rad/s]

$$V_R = V_0 \sin \omega t$$
$$= \boxed{300 \sin(100t) \ [V]}$$

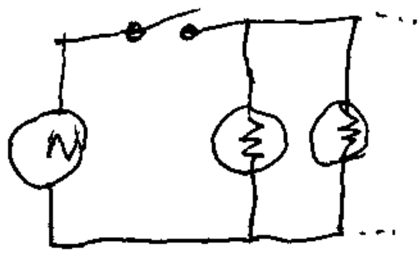
$$I_R = I_0 \sin \omega t$$
$$= \boxed{15 \sin(100t) \ [A]}$$

$$I_0 = \frac{V_0}{R} = \frac{300}{20} = \boxed{15 \ [A]}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}} = \frac{15}{\sqrt{2}} \approx \frac{15}{1.41} \approx \boxed{10.6 \ [A]}$$

$$P_{ave} = I_{rms}^2 R = \left(\frac{15}{\sqrt{2}}\right)^2 (20) = \left(\frac{225}{2}\right)(20) = \boxed{2250 \ [W]}$$
$$= \boxed{2.25 \ [kW]}$$

Ex เปิดหลอดไฟฟ้า 60 วัตต์ 5 หลอด วันละ 12 ชั่วโมง ทุกวัน เป็นเวลา 1 เดือน ใช้พลังงานเท่าใด?



$$P = \sum_i P_i = 5 \times 60 \ [W] = \boxed{300 \ [W]}$$

$$P = \frac{\Delta U}{\Delta t} \implies \Delta U = P \Delta t$$

1 day

$$\Delta U_d = P \Delta t_d = \overset{[W]}{(300)}\left(\frac{1}{2} \text{day}\right) + (\cancel{300}^{0})\left(\frac{1}{2} \text{day}\right)$$
$$= \frac{300}{2} \ [Wd] = 300 \times 12 \ [Wh] \quad \frac{24}{2}$$

$$\Delta U_d = 3600 \ [Wh] = 3.6 \ [kWh]$$

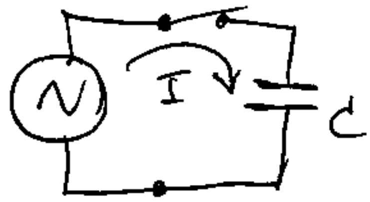
30 day

$$\Delta U_m = 30 \Delta U_d = (30)(3.6) \ [kWh]$$
$$= \boxed{108 \ [kWh]}$$

ค่าไฟฟ้า Unit ละ 5 บาท

เดือนละ: 540 บาท

[C] Capacitor
Capacitance

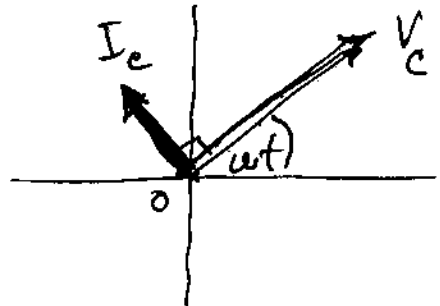


$$V_0 \sin\omega t - \frac{q}{C} = 0$$

$$q(t) = V_0 C \sin\omega t$$

$$I(t) = \frac{dq}{dt} = \frac{d}{dt}(V_0 C \sin\omega t)$$

$$I(t) = V_0 C\omega \cos(\omega t)$$

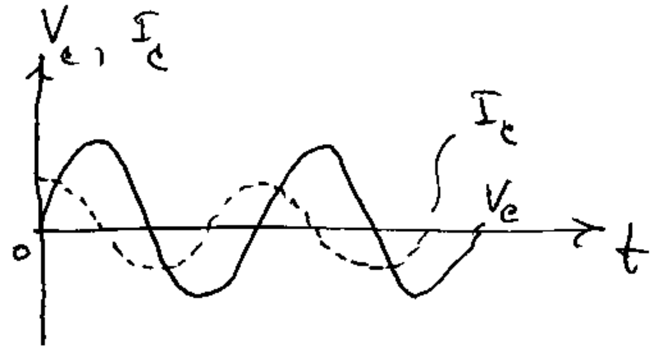


$$\boxed{\begin{aligned} I_c(t) &= \frac{V_0}{\left(\frac{1}{\omega C}\right)} \sin\left(\omega t + \frac{\pi}{2}\right) \\ V_c(t) &= V_0 \sin(\omega t) \end{aligned}}$$

* I_c นำหน้า V_c อยู่ 90°

$$I_{0R} = \frac{V_0}{R}$$

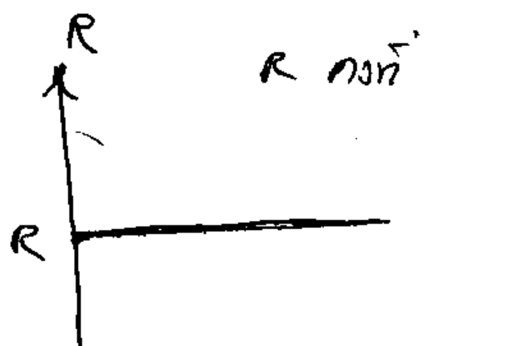
$$I_{0C} = \frac{V_0}{\left(\frac{1}{\omega C}\right)} = \boxed{\frac{V_0}{X_c}}$$

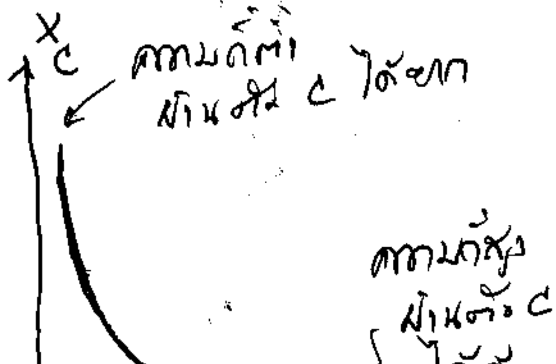


$$\boxed{X_c = \frac{1}{\omega C}}$$ $[\Omega]$

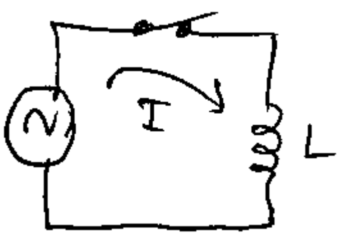
ความต้านทานเชิงภาพของตัว C
"Capacitive Reactance"

* ความต้านทานไฟฟ้าของตัว C นั้นแปรผกผันกับความถี่





$\boxed{L}$ Inductor



$$V_0 \sin\omega t - L\frac{dI}{dt} = 0$$

$$\frac{dI}{dt} = \frac{V_0}{L}\sin\omega t$$

$$\int_0^I dI = \int_0^t \frac{V_0}{L}\sin\omega t \, dt$$

$$I_L(t) = -\frac{V_0}{\omega L}\cos\omega t = \frac{V_0}{\omega L}\sin(\omega t - \tfrac{\pi}{2})$$

$$V_L(t) = V_0 \sin\omega t$$

" I_L ตามหลัง V_L อยู่ $90°$ "

$$\boxed{X_L = \omega L}$$ "Inductive Reactance"

$V_L = V_0 \sin\omega t$

$I_L = \frac{V_0}{X_L}\sin(\omega t - \frac{\pi}{2})$

$X_L = \omega L$

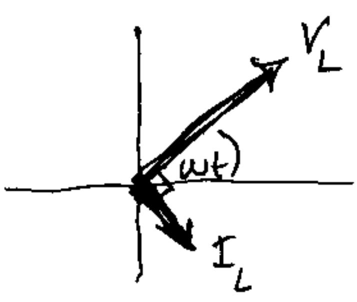
$V_R = V_0 \sin\omega t$

$I_R = \frac{V_0}{R}\sin\omega t$

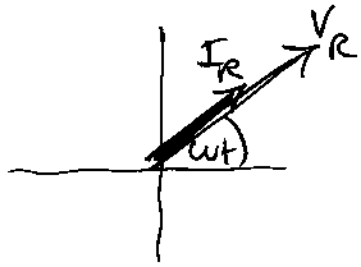
$V_C = V_0 \sin\omega t$

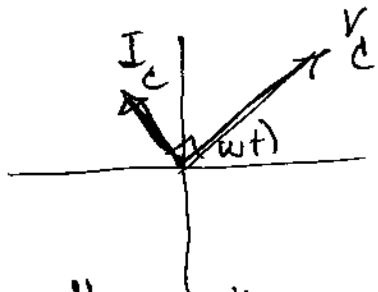
$I_C = \frac{V_0}{X_C}\sin(\omega t + \frac{\pi}{2})$

$X_C = \frac{1}{\omega C}$

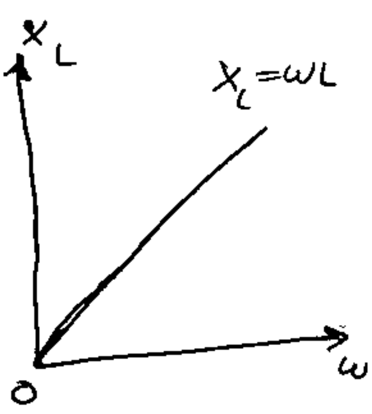


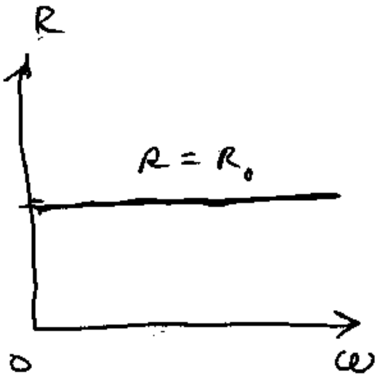
"ELI"

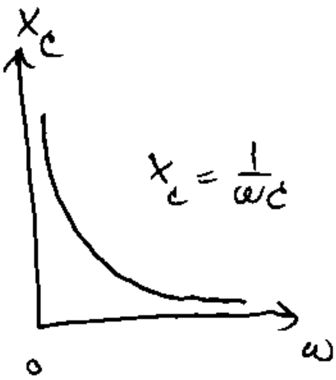




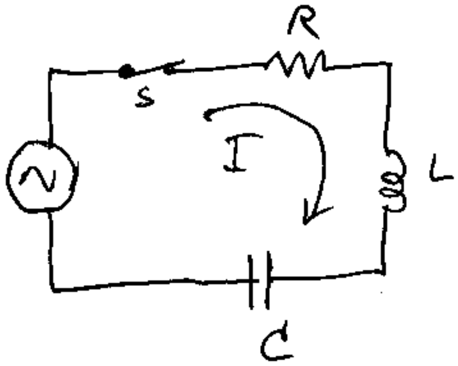
"ICE"



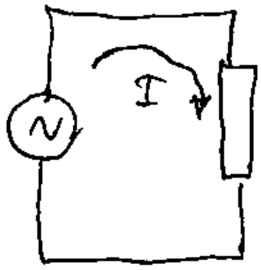




RLC Series – AC circuit



$\Rightarrow$



Z "Impedance"

ความต้านทานเชิงซ้อน

$I = ?$

$P_{ave} = ?$

$$V_0 \sin\omega t - IR - L\frac{dI}{dt} - \frac{q}{C} = 0$$

$$\boxed{L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = V_0 \sin\omega t} \Leftrightarrow \boxed{m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = f_0 \sin\omega t}$$

Forced Oscillation

$$x = A\sin(\omega t - \phi')$$

→ หาคำตอบในรูป $\boxed{I = I_0 \sin(\omega t - \phi)}$

$$\underbrace{L\frac{dI}{dt}}_{V_L} = L\omega I_0 \cos(\omega t - \phi) \quad : \quad \underbrace{\frac{q}{C}}_{V_C} = -\frac{I_0}{\omega C}\cos(\omega t - \phi)$$

$$\overset{X_L}{\omega L}\, I_0 \cos(\omega t - \phi) + R I_0 \sin(\omega t - \phi) - \frac{I_0}{\omega C}\cos(\omega t - \phi) = V_0 \sin\omega t$$

$$\frac{1}{\omega C} = X_C$$

$$(X_L - X_C)\cos(\omega t - \phi) + R\sin(\omega t - \phi) = \underbrace{\frac{V_0}{I_0}}_{Z}\sin\omega t$$

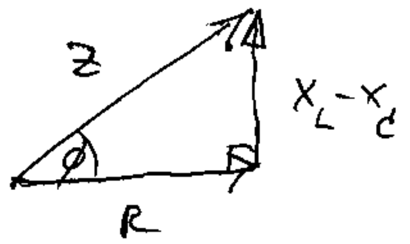
$$\boxed{Z = \frac{V_0}{I_0}}$$

$$\boxed{\frac{(X_L - X_C)}{Z}\cos(\omega t - \phi) + \frac{R}{Z}\sin(\omega t - \phi) = \sin\omega t}$$

$$\sin(A+B) = \sin A\cos B + \sin B\cos A \quad : \quad B = \omega t - \phi,\ A = \phi,\ A + B = \omega t$$

$$\boxed{\begin{aligned} \sin\phi &= \frac{X_L - X_C}{Z} \\ \cos\phi &= \frac{R}{Z} \end{aligned}}$$

"Power Factor" แฟกเตอร์กำลัง



$$\boxed{Z = \sqrt{R^2 + (X_L - X_C)^2}}$$

$$\boxed{Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \quad *$$

กรณี $X_L = X_C$ $\quad \sin\phi = 0 \Rightarrow \boxed{\phi = 0}$

$\cos\phi = 1 \quad \boxed{R = Z}$ ความต้านทานเชิงซ้อนมีค่าต่ำสุด

$\omega L = \frac{1}{\omega C} \Rightarrow \omega^2 = \frac{1}{LC} = \omega_0^2 \quad \boxed{\omega = \omega_0}$

วงจรทำงานที่ความถี่เรโซแนนซ์

* ต้องเลือก L และ C ให้เหมาะสม

$V = V_0 \sin\omega t \qquad I = \underbrace{\frac{V_0}{Z}}_{I_0} \sin(\omega t - \phi) \qquad \cos\phi = \frac{R}{Z}$

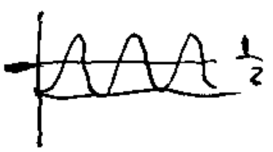
$Z = \sqrt{R^2 + X^2}$

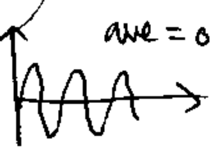
$P(t) = VI = V_0 I_0 \sin\omega t \sin(\omega t - \phi)$

$P_{ave} = I_0 V_0 \langle \sin\omega t \sin(\omega t - \phi) \rangle_{ave}$

$P_{ave} = I_0 V_0 \langle \sin\omega t (\sin\omega t \cos\phi - \sin\phi \cos\omega t) \rangle_{ave}$

$= I_0 V_0 \langle \sin^2\omega t \cos\phi - \sin\phi \underbrace{\cos\omega t \sin\omega t}_{\frac{\sin 2\omega t}{2}} \rangle_{ave}$





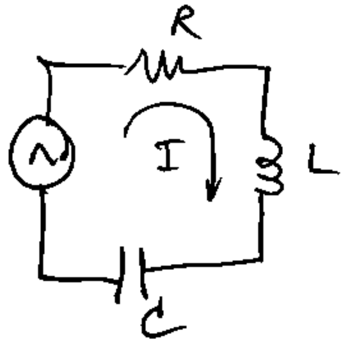
$$\boxed{P_{ave} = \frac{I_0 V_0}{2} \cos\phi = I_{rms} V_{rms} \cos\phi} \quad *$$

$\cos\phi = \frac{R}{Z}$

$V_{rms} \cos\phi = \frac{V_0}{\sqrt{2}} \cdot \frac{R}{Z} = I_{rms} R$ $\quad I_0$

$$\boxed{P_{ave} = I_{rms}^2 R} \quad *$$

Ex



$V_0 = 100$ [V]

$\omega = 100$ [rad/s]

$R = 17.3$ [Ω]

$C = 1$ [mF]

$L = 0.2$ [H]

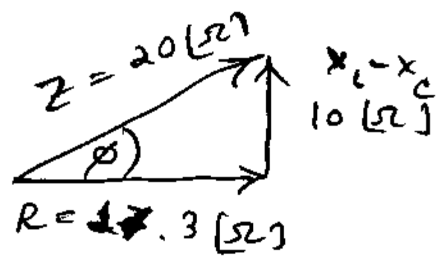
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$X_L = \omega L = (100)(0.2) = \boxed{20\ [\Omega]}$$

$$X_C = \frac{1}{\omega C} = \frac{1}{(100)(1\times10^{-3})} = \frac{1}{(0.1)} = \boxed{10\ [\Omega]}$$

$$\Big\} \ X_L - X_C = 20 - 10 = \boxed{10\ [\Omega]}$$

$$Z = \sqrt{(17.3)^2 + (10)^2} = \boxed{20\ [\Omega]}$$

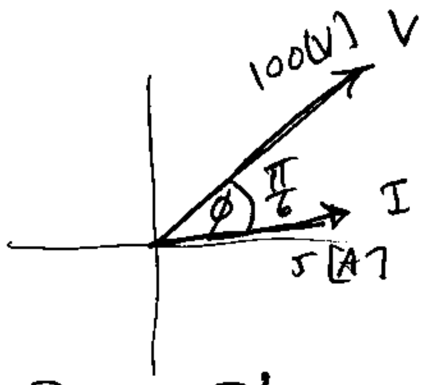


$$\sin\phi = \frac{X_L - X_C}{Z} = \frac{10}{20} = \boxed{\frac{1}{2}}$$

$$\cos\phi = \frac{R}{Z} = \frac{17.3}{20} \approx \boxed{0.866}$$

$$\phi = 30^\circ = \boxed{\frac{\pi}{6}}$$

$$I_0 = \frac{V_0}{Z} = \frac{100}{20} = \boxed{5\ [A]}$$



$$\boxed{\begin{aligned} V &= 100 \sin(100t) \\ I &= 5 \sin\left(100t - \frac{\pi}{6}\right) \end{aligned}} \begin{aligned} &[V] \\ &[A] \end{aligned}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}} = \frac{5}{\sqrt{2}} \approx \boxed{3.6\ [A]}$$

$$P_{ave} = I_{rms}^2 R = \left(\frac{5}{\sqrt{2}}\right)^2 (17.3) = \left(\frac{25}{2}\right)(17.3) = \boxed{216\ [W]}$$

หรือ $P_{ave} = I_{rms} V_{rms} \cos\phi = \left(\frac{5}{\sqrt{2}}\right)\left(\frac{100}{\sqrt{2}}\right)(0.866) = \boxed{216\ [W]}$

P_{ave} เป็น 87% ของ กำลังไฟฟ้าสูงสุด ($\phi = 30^\circ$)

$\omega = 100 \text{ rad/s}$

$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{(0.2)(0.001)}} = \frac{1}{\sqrt{2\times10^{-4}}} = \frac{100}{\sqrt{2}} \text{ [rad/s]}$$

$$= 70.7 \text{ [rad/s]}$$

ต้องเพิ่มความถี่เรโซแนนซ์ของวงจรนี้
ให้เป็น 100 rad/s

$$\omega_0' = \frac{1}{\sqrt{L'C}} = \frac{1}{\sqrt{LC'}} = \frac{1}{\sqrt{L''C''}}$$ → เปลี่ยน L หรือ C

① ลด L → $L' = \frac{L}{2}$

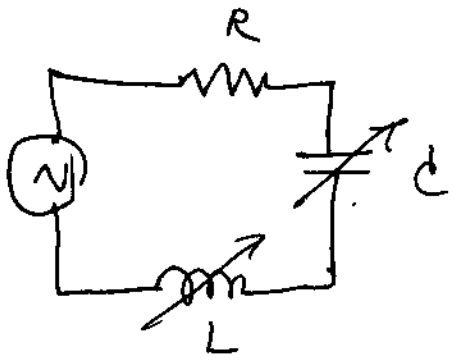
$$\omega_0' = \frac{1}{\sqrt{(0.1)(0.001)}} = 100 \text{ [rad/s]}$$

② ลด C → $C' = \frac{C}{2}$

$$\omega_0' = \frac{1}{\sqrt{(0.2)(0.0005)}} = 100 \text{ [rad/s]}$$

③ $L \rightarrow L'' = \frac{L}{\sqrt{2}}$ $\quad C \rightarrow C'' = \frac{C}{\sqrt{2}}$

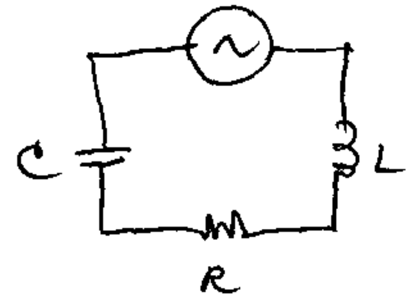
$$\omega_0' = \frac{1}{\sqrt{\left(\frac{0.2}{\sqrt{2}}\right)\left(\frac{0.001}{\sqrt{2}}\right)}} = 100 \text{ [rad/s]}$$



← capacitor Bank
ใช้ปรับค่า ϕ

$\phi \approx 0$
ให้พลังงานส่งมีประสิทธิภาพมากที่สุด

Ex



$V_{rms} = 220$ [V]

$\omega = 400$ [rad/s]

$C = 2.5$ [μF]

$L = 500$ [mH]

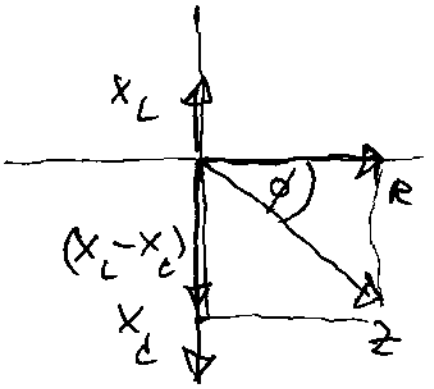
$R = 800$ [Ω]

$$V_0 = \sqrt{2}\,V_{rms} = (\sqrt{2})(220) \approx \boxed{311\ [V]}$$

$$X_L = \omega L = (400)(500\times10^{-3}) = \boxed{200\ [\Omega]}$$

$$X_C = \frac{1}{\omega C} = \frac{1}{(400)(2.5\times10^{-6})} = \frac{1}{(1\times10^{+3})(10^{-6})} = \boxed{1000\ [\Omega]}$$

$$X_L - X_C = 200 - 1000 = \boxed{-800\ [\Omega]} \qquad R = \boxed{800\ [\Omega]}$$



$$\sin\phi = \cancel{\frac{-800}{800}}\ \frac{(X_L - X_C)}{Z} = \frac{-800}{800\sqrt{2}} = \boxed{\frac{-1}{\sqrt{2}}}$$

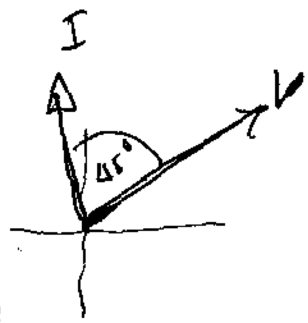
$$\cos\phi = \frac{R}{Z} = \frac{800}{800\sqrt{2}} = \boxed{\frac{1}{\sqrt{2}}}$$

$$Z = \sqrt{R^2 + X^2}$$

$$= \sqrt{800^2 + 800^2} = 800\sqrt{2} = \boxed{1131\ [\Omega]}$$

$$\phi = -45^\circ = \boxed{-\frac{\pi}{4}}$$

$$I_0 = \frac{V_0}{Z} = \frac{\cancel{(\sqrt{2})}(220)}{(800)\cancel{\sqrt{2}}} = \boxed{0.275\ [A]}$$



$$\boxed{\begin{aligned} V &= V_0 \sin\omega t = (311)\sin(400t)\ [V] \\ I &= I_0 \sin(\omega t - \phi) = (0.275)\sin\left(400t + \frac{\pi}{4}\right)\ [A] \end{aligned}}$$

$$P_{ave} = \frac{I_0 V_0}{2}\cos\phi = \frac{(0.275)(\overset{(\sqrt{2})(220)}{311})}{2}\left(\frac{1}{\sqrt{2}}\right) = \frac{(0.275)(\cancel{220}^{110})}{\cancel{2}}$$

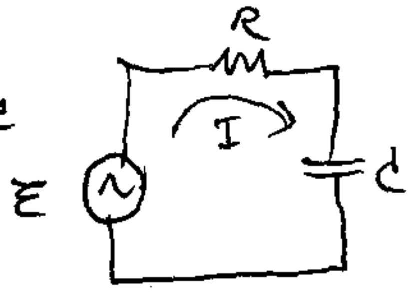
$$= \boxed{30.25\ [W]}$$

Ex $\quad C = 10\,[nF] \quad f = 5\,[MHz] \quad X_C = ?$

$$X_C = \frac{1}{\omega C} = \frac{1}{(2\pi \times 5\times10^{6})(10\times10^{-9})} = \frac{1}{\pi \times 10^{2}\times10^{6}\times10^{-9}}$$

$$= \frac{10^{1}}{\pi} = 0.318\times10^{1} \approx \boxed{3.18\,[\Omega]}$$

Ex



$V_0 = 10\,[V]$

$\omega = 120\pi\,[rad/s]$

$R = 5\,[\Omega]$

$C = 100\,[\mu F]$

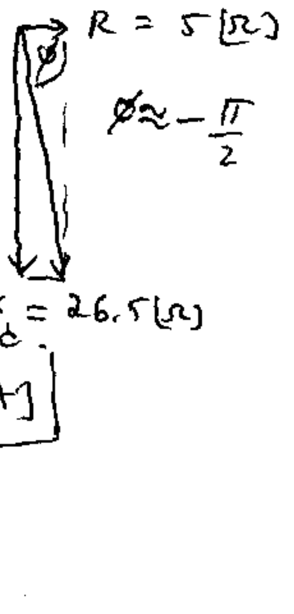
$L = 0\,[H]$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$R^2 = 25\,[\Omega^2]$

$$X_C = \frac{1}{\omega C} = \frac{1}{(120\pi)(100\times10^{-6})} = \frac{1}{12\pi}\times10^{3} = 26.5\,[\Omega]$$

$$X_C^2 = \frac{1}{(12\pi)^2}10^{6} \approx 704\,[\Omega^2]$$



$$Z = \sqrt{25 + 704} \approx \boxed{27\,[\Omega]}$$

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

$$I_0 = \frac{V_0}{Z} = \frac{10}{27}$$

$$I = I_0 \sin(\omega t - \phi)$$

$$I = \boxed{\frac{10}{27}\sin\left(120\pi t + \frac{\pi}{2}\right)\,[A]}$$

$$\mathcal{E} = V_0 \sin(\omega t)$$

$$= \boxed{10\sin(120\pi t)\,[V]}$$

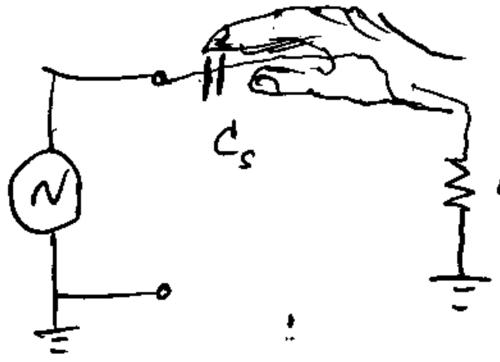
$$V_R = I_R R$$

$$= I(t)R = \left(\frac{10}{27}\right)(5)\sin\left(120\pi t + \frac{\pi}{2}\right)$$

$$V_R = \boxed{\frac{50}{27}\sin\left(120\pi t + \frac{\pi}{2}\right)\,[V]}$$

$\mathcal{E}$ ตามหลัง V_R

Ex



ไฟฟ้าศักย์สูง

$V_0 = 5\times10^3$ [V]

$C_s = 10$ [pF] $f = 50$ [Hz]

$R_b = 20$ [kΩ]

$Z = ?$ $I_0 = ?$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$X_L = 0$: $\omega = 2\pi f$

$= 100\pi$ [rad/s]

$$X_C = \frac{1}{\omega C} = \frac{1}{(100\pi)(10\times10^{-12})}$$

$$R^2 = (20\times10^3)^2 \ [\Omega^2]$$

$$= 4\times10^8 \ [\Omega^2]$$

$$= \frac{1}{\pi}\times10^9 \ [\Omega]$$

$$X_C^2 = \left(\frac{1}{\pi}\right)^2\times(10^9)^2 \approx 10^{17} \ [\Omega^2]$$

$$(X_L - X_C)^2 \gg R^2$$

$$Z \approx \sqrt{(X_L - X_C)^2} \approx \boxed{\frac{1}{\pi}\times10^9 \ [\Omega]}$$

$$\phi \approx -\frac{\pi}{2}$$

$$Z = 0.318\times10^9 \ [\Omega]$$

$$= 318\times10^6 \ [\Omega] = \boxed{318 \ [M\Omega]}$$

$$\mathcal{E} = V_0 \sin\omega t = \boxed{(5\times10^3)\sin(100\pi t) \ [V]}$$

$$I = I_0 \sin(\omega t - \phi)$$

$$\approx (16\times10^{-6})\sin(100\pi t + \frac{\pi}{2})$$

$$\approx \boxed{(16\times10^{-6})\cos(100\pi t) \ [A]}$$

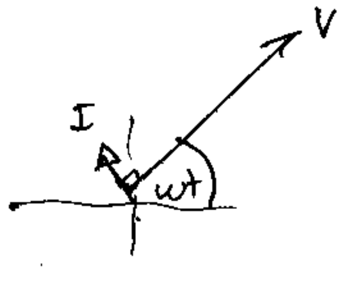
$$I_0 = \frac{V_0}{Z}$$

$$= \frac{5\times10^3}{318\times10^6}$$

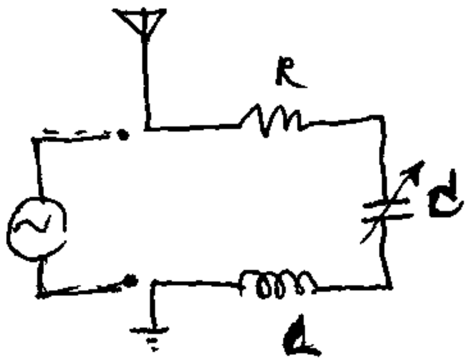
$$= 0.016\times10^{-3}$$

$$= 16\times10^{-6} \ [A]$$

$$= \boxed{16 \ [\mu A]}$$



Ex



FM - Receiver

$R = 50\ [\Omega]$

$L = 5\ [\mu H]$

$f = 100\ [MHz]$

$C = ?$

$$f = 100\ [MHz]$$

$$\omega = 200\pi\ [M\,rad/s] = 2\pi\times 10^{8}\ [rad/s]$$

Resonance

$$\omega = \omega_0 = \frac{1}{\sqrt{LC}} \Rightarrow \omega^2 = \frac{1}{LC}$$

$$C = \frac{1}{L\omega^2}$$

$$C = \frac{1}{(5\times10^{-6})(2\pi\times10^{8})^2} = \frac{1}{5\times4\times\pi^2\times\underbrace{10^{-6}\times10^{16}}_{10^{10}}}$$

$$\approx \frac{10^{-10}}{20\times\underbrace{\pi^2}_{\approx 10}} \approx \frac{1}{2}\times10^{-10-2} = 0.5\times10^{-12}$$

$$\approx \boxed{0.5\ [pF]}$$

คลื่นแม่เหล็กไฟฟ้า (Electromagnetic Wave)

$$\begin{tikzcd}
Q \arrow[r, "I=\frac{dQ}{dt}"] \arrow[d, "E=\frac{F}{Q}"'] & I \arrow[d, "|B|=\frac{F}{qv\sin\theta}"] \\
E & B \arrow[l, dashed, "\mathcal{E}=-\frac{d\Phi_B}{dt}"]
\end{tikzcd}$$

$\vec{E} = \int k\frac{dq}{r^2}\hat{r}$

$\vec{B} = \int k_m \frac{I\,d\vec{l}\times\hat{r}}{r^2}$

สนามแม่เหล็กเปลี่ยนแปลง
ทำให้เกิด
สนามไฟฟ้าเหนี่ยวนำ

$\Downarrow$

คลื่นแม่เหล็กไฟฟ้า